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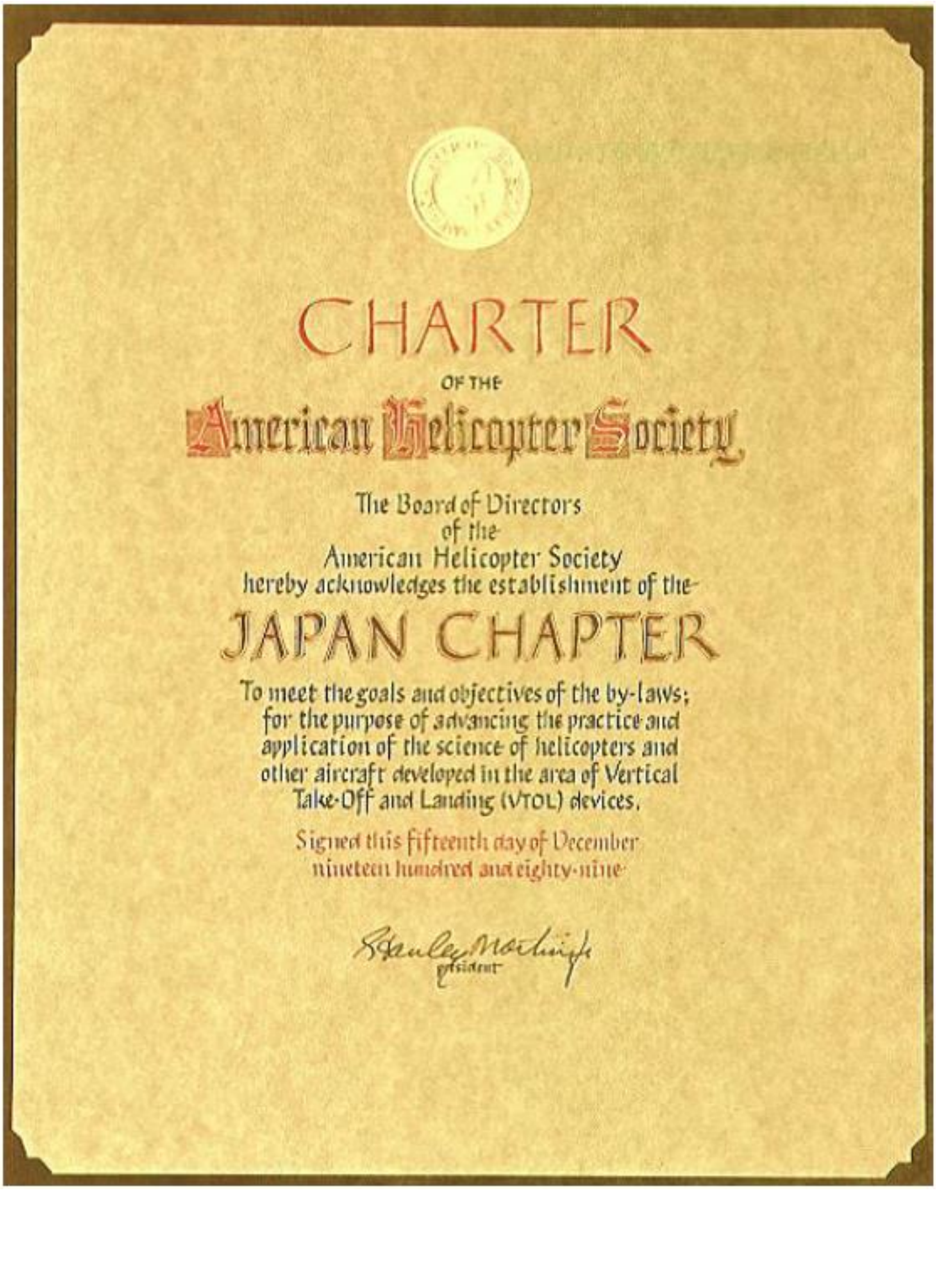
日本ヘリコプタ協会
The Japan Helicopter Society

AHS 日本支部認定書



CHARTER

OF THE

American Helicopter Society

The Board of Directors
of the
American Helicopter Society
hereby acknowledges the establishment of the

JAPAN CHAPTER

To meet the goals and objectives of the by-laws;
for the purpose of advancing the practice and
application of the science of helicopters and
other aircraft developed in the area of Vertical
Take-Off and Landing (VTOL) devices.

Signed this fifteenth day of December
nineteen hundred and eighty-nine

President

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巻頭言

日本ヘリコプタ協会

第１７代会長　青山　剛史

私が会長職のバトンを引き継がせていただいたのは、2021 年度からの 2 年間ですが、この間はコロナ禍の真っ只中で、その制限された状況下で如何にして日本ヘリコプタ協会の活動を存続させるか、理事・幹事の皆さんと色々と模索させていただいたことが昨日のことのように思い出されます。最初に手をつけたのが、オンライン会議の環境整備でした。対面での活動が困難であったことから、理事会・幹事会も開けない状況でしたが、それを打開すべく、保江かな子総務担当幹事が大車輪の活躍をしてくれました。また、自由を拘束された状況を逆に活かして、これまで放置されてきた規約などの不整合を整理し直すことに力を注ぎました。さらに、Asian Rotorcraft Forum などで培ってきた海外とのパイプが細くなってしまうことを懸念して、まずはこれまで最も親密な関係を構築してきたお隣の国、韓国との交流を再開したいと考えました。そこで、韓国との強いパイプをお持ちの田辺安忠総務担当理事および小曳昇国際担当理事らにご尽力いただき、Japan-Korea Joint Workshop on Rotorcraft をオンライン開催することができました。その際に衝撃を受けたのは、韓国における活動の華やかさでした。いつの間にかコミュニティの大きさではだいぶ水をあけられてしまった印象で、改めて我が協会の活性化が急務であることを思い知りました。それを具体化するためにも、新たな潮流である eVTOL を積極的に活動に取り込むべく、協会の名称変更についても議論が端緒についたところですが、その具体化と活動のさらなる活性化については次の理事・幹事の皆様に期待したいと思います。

思い返すと、本協会が設立された 1989 年には、私は大学院の学生としてヘリコプタの数値シミュレーションに関する研究に取り組んでおりました。設立に当たって、大学やメーカなどの錚々たる方々が集まって議論する活気に溢れた様子が、若輩者であった私の目に眩しく映ったのを記憶しています。また、その意志を継いで活動を維持発展させてくださった先人の皆様のご尽力に思いを致すとき、設立当初から American Helicopter Society International 日本支部として承認された由緒正しい本協会の益々の発展を祈念せずにはいられません。

最後に一つ、本協会のホームページ（http://helijapan.org/index.html）を開くと最初に目に飛び込んでくるのは有名なレオナルド・ダ・ヴィンチの考案した回転翼機です。ネットを見ると、メリーランド大学のエンジニアリングチームが、このスクリューのようなデザインを用いて無人クアッドコプタードローン「Crimson Spin」の開発に成功し、Transformative Vertical Flight 2022 で飛行の様子を紹介したとのニュースが出ていました。留学先であったメリーランド大学の快挙を祝福するとともに、世界にはコロナ禍でも果敢に夢の実現に

挑んでいた若者達がいたのかと、改めて感動させられました。我が国でも、技術を担う若い皆さんが育ってくださることを期待するとともに、本協会が人材育成にもさらに大きく貢献できる方策を打ち出すことが必要ではないかと感じました。

日本ヘリコプタ協会

２０２２年度活動報告

1. 総会・講演会

・日時：2022 年 7 月 6 日（水）13:30～16:40

・場所：宇宙航空研究開発機構　調布航空宇宙センター　講堂

・総会：

1　Japan Vertical Flight Education Team (JVFET）発足報告

2　規約改定報告

3　前年度事業報告、会計報告等の承認

4　新年度事業計画等の承認

・講演会：

1　「VFS Annual Forum 参加報告」

木村　桂大　氏（国立研究開発法人宇宙航空研究開発機構）

杉浦　正彦　氏（国立研究開発法人宇宙航空研究開発機構）

柘植　春輝　氏（ヤマト運輸株式会社）

2　「無人航空機の有人機に対する衝突回避について　ＳＵＢＡＲＵの取り組みの紹介」

芝尾　裕規　氏（株式会社ＳＵＢＡＲＵ）

2. 理事会・幹事会

第 1 回理事会・幹事会

・日時：2022 年 6 月 8 日（水）16:00～17:30

・場所：オンライン

・議題：前回審議繰越案件に関する審議及び規約改定に関する審議

第 2 回理事会・幹事会

・日時：2022 年 7 月 6 日（水）10:00～12:00

・場所：宇宙航空研究開発機構　調布航空宇宙センター　講堂

・議題：総会議題等の審議及び規約改定に関する審議

3. 特別講演会・風動試験見学

・日時：2022 年 11 月 4 日（金）10:00～12:00

・場所：宇宙航空研究開発機構　調布航空宇宙センター飛行場分室　大会議室

・特別講演会：

1　Comprehensive Validation on Aeromechanics Test Data for Mach-scaled Helicopter Rotors
Prof. Sung Nam Jung (School of Mechanical & Aerospace Engineering, Konkuk University)

・風動試験見学：

1　宇宙航空研究開発機構　航空技術部門　模型ヘリ HERACLES　ハイミューロータ

4. 日韓回転翼機ワークショップ

・日時：2023 年 2 月 10 日（金）9:00～17:05

・場所：オンライン

5. 将来回転翼機研究会・回転翼解析技術交流会

・日時：2023 年 3 月 24 日（金）13:00～17:20

・場所：電力中央研究所 大手町地区 733 会議室　及びオンライン

VFS Annual Forum 参加報告

国立研究開発法人宇宙航空研究開発機構　木村　桂大
国立研究開発法人宇宙航空研究開発機構　杉浦　正彦

Vertical Flight Society 78th Annual Forum & Technology Display

THE FUTURE OF VERTICAL FLIGHT

開催報告

2022/7/6

JAXA 航空技術部門
航空環境適合イノベーションハブ
杉浦正彦、木村桂大

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- 概要
- Opening General Session
- Special Sessions
- Technical Sessions
- 展示会
- テクニカルツアー
- まとめ

VFS 78th Annual Forum概要

日本ヘリコプタ協会
Japan Helicopter Society

■ 開催方法

- 5/10(火)-12(木), Fort Worth Convention Center, Fort Worth, Texas
- 5/13(金), テクニカルツアー, Bell Training Academy

■ 開催規模

- 登録者数は1,250名（昨年度より200名ほど減少）
- 技術論文は219件

■ 2022 Alexander A. Nikolsky Honorary Lectureship

- Prof. Marilyn Smith, Georgia Institute of Technology, “Computational Vertical Lift Aeromechanics and Its Future in the Twenty-First Century”

■ セッション

- Opening General Session、9のSpecial Sessions、22のTechnical Sessionsで構成
- 日本からは3件発表（ヤマト運輸1件、JAXA2件）

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VFS 78th Annual Forum概要

日本ヘリコプタ協会
Japan Helicopter Society

■ セッション

- Special Sessions: International VTOL R&D, Future Vertical Workforce, PEO Aviation’s MOSA Collaboration and Progress, US Army Programs, Flight Test, US Navy/ US Marine Corps Programs, Expanding the Supply Chain, Challenges in Electric VTOL, Progress in Electric VTOL
- Technical Sessions: Acoustics, Advanced Vertical Flight, Aerodynamics, Aircraft Design, Avionics and Systems, Crash Safety, Crew Stations and Human Factors, Dynamics, Electric Vertical Takeoff and Landing (eVTOL), Handling Qualities, Health and Usage Monitoring System (HUMS) – Condition Based Maintenance (CBM), History, Manufacturing Technology and Processing, Modeling and Simulation, Operations, Product Support Systems Technology, Propulsion, Safety, Structures and Materials, System Engineering Tools/Processes, Test and Evaluation, Unmanned VTOL Aircraft and Rotorcraft

■ 次回

5/16-5/18, 2023, West Palm Beach, FL, USA

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VFS 78th Annual Forum概要

日本ヘリコプタ協会 Japan Helicopter Society

■ Opening General Session

- Chair: Mike Hirschberg – Vertical Flight Society
- Panelist: **British Army**
- Panelist: Tomasz Krysinski – VP, Research & Innovation, **Airbus**
- Panelist: Shane Openshaw – VP, Tiltrotor Programs, **Boeing Co.**
- Panelist: Roberto Garavaglia – SVP Strategy & Innovation, **Leonardo Helicopters Division**
- Panelist: Paul Lemmo – President, **Sikorsky, a Lockheed Martin Co.**
- Panelist: Glenn E. Isbell – **Bell**

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日本ヘリコプタ協会 Japan Helicopter Society

OPENING GENERAL SESSION

6

Special Sessions

- #1 International VTOL R&D
- #2 Future Vertical Workforce
- #3 PEO Aviation’s MOSA Collaboration and Progress
- #4 US Army Programs
- #5 Flight Test
- #6 US Navy/ US Marine Corps Programs
- #7 Expanding the Supply Chain
- #8 Challenges in Electric VTOL
- #9 Progress in Electric VTOL

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SPECIAL SESSION #1: INTERNATIONAL VTOL R&D

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Special Session: International VTOL R&D

- "**Franco-German Rotorcraft Research**", Arnaud Le Pape, ONERA and Florian Antrack, DLR
- " **NATO NGRC –Next Generation Rotorcraft Capability**", Pat Collins, Senior Fellow, Helicopters Operating Centre, Defense Equipment & Support, UK MOD (Ministry of Defense)
- "**Vertical Lift Research at the Aerospace Research Center**", Derek Gowanlock, NRC Canada
- "**State of NASA's Revolutionary Vertical Lift Technology Project**", Dr. Noah Schiller, NASA

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SPECIAL SESSION #2: FUTURE VERTICAL WORKFORCE

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Special Session: Future Vertical Workforce

日本ヘリコプタ協会
Japan Helicopter Society

- "**Advanced Air Mobility Realized**", Russell Julian, Texas UASWERX
- "**Workforce Development & the Future of Advanced Mobility**", Victoria Natalie, Oklahoma State University
- "**TULSA**", Daniel Plaisance, Helmerich Research Center, OSU-Tulsa
- "**DEI Survey Report Briefing**", Sharon Rossmark, Women and Drones
- "**SBD International Airport, San Bernardino, CA**", Mike Burrows, San Bernardino International Airport
- "**Future Vertical Workforce**", Vineet Saharasrabudhe, Sikorsky, a Lockheed Martin

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SPECIAL SESSION #3: PEO AVIATION'S MOSA COLLABORATION AND PROGRESS

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Special Session: PEO Aviation's MOSA Collaboration and Progress

- "**PEO Aviation Discussion Panels**", Pat Mason, Deputy PEO Aviation, US Army

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SPECIAL SESSION #4: US ARMY PROGRAMS

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Special Session: US Army Programs

- "**Advanced Air Mobility Realized**", Russell Julian, Texas UASWERX
- "**Workforce Development & the Future of Advanced Mobility**", Victoria Natalie, Oklahoma State University
- "**TULSA**", Daniel Plaisance, Helmerich Research Center, OSU-Tulsa
- "**DEI Survey Report Briefing**", Sharon Rossmark, Women and Drones
- "**SBD International Airport, San Bernardino, CA**", Mike Burrows, San Bernardino International Airport
- "**Future Vertical Workforce**", Vineet Saharasrabudhe, Sikorsky, a Lockheed Martin

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SPECIAL SESSION #5: FLIGHT TEST

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Special Session: Flight Test

- "**Advanced Air Mobility Realized**", Russell Julian, Texas UASWERX
- "**Workforce Development & the Future of Advanced Mobility**", Victoria Natalie, Oklahoma State University
- "**TULSA**", Daniel Plaisance, Helmerich Research Center, OSU-Tulsa
- "**DEI Survey Report Briefing**", Sharon Rossmark, Women and Drones
- "**SBD International Airport, San Bernardino, CA**", Mike Burrows, San Bernardino International Airport
- "**Future Vertical Workforce**", Vineet Saharasrabudhe, Sikorsky, a Lockheed Martin

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SPECIAL SESSION #6: US NAVY/ US MARINE CORPS PROGRAMS

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Special Session: US Navy/ US Marine Corps Programs

- "**Advanced Air Mobility Realized**", Russell Julian, Texas UASWERX
- "**Workforce Development & the Future of Advanced Mobility**", Victoria Natalie, Oklahoma State University
- "**TULSA**", Daniel Plaisance, Helmerich Research Center, OSU-Tulsa
- "**DEI Survey Report Briefing**", Sharon Rossmark, Women and Drones
- "**SBD International Airport, San Bernardino, CA**", Mike Burrows, San Bernardino International Airport
- "**Future Vertical Workforce**", Vineet Saharasrabudhe, Sikorsky, a Lockheed Martin

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SPECIAL SESSION #7: EXPANDING THE SUPPLY CHAIN

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Special Session: Expanding the Supply Chain

- “**CONNEX Marketplace – The AAM Supply Chain Connection Solution**”, Alan Davis, CEO, i5 Services
- “**Strategically Hardening the Entire Supply Chain**”, Chad Molter, Managing Director, Deloitte Consulting
- “**Expanding the global battery supply chain**”, Andrew Miller, Benchmark Mineral Intelligence
- “**hypoint**”, Rhonda Staudt, HyPoint

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SPECIAL SESSION #8: CHALLENGES IN ELECTRIC VTOL

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Special Session: Challenges in Electric VTOL

- “**Challenges in eVTOL**”, Steve Caravella, Siemens
- “**The Intersection of Hybrid Power & SAF**”, David Eichstadt, VerdeGo Aero
- “**CAAM**”, JR Hammond, CAAM
- “**Challenges in Electric VTOL**”, Starr Ginn, NASA

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SPECIAL SESSION #9: PROGRESS IN ELECTRIC VTOL

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Special Session: Progress in Electric VTOL

- “**Urban Mobility**”, Jorg Mueller, Airbus
- “**The Case for Advanced Air Mobility Beginning with the Current NAS and Beyond**”, Erick Corona, Wisk
- “**The Future of Logistics**”, Manal Habib, CEO, MightyFly
- “**Textron eAviation**”, Robert Scholl, Textron eAviation

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Technical Sessions (1/2)

- Acoustics
- Advanced Vertical Flight
- Aerodynamics
- Aircraft Design
- Avionics and Systems
- Crash Safety
- Crew Stations and Human Factors
- Dynamics
- Electric Vertical Takeoff and Landing (eVTOL)
- Handling Qualities
- Health and Usage Monitoring System (HUMS) – Condition Based Maintenance (CBM)

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Technical Sessions (2/2)

- History
- Manufacturing Technology and Processing
- Modeling and Simulation
- Operations
- Product Support Systems Technology
- Propulsion
- Safety
- Structures and Materials
- System Engineering Tools/Processes
- Test and Evaluation
- Unmanned VTOL Aircraft and Rotorcraft

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日本ヘリコプタ協会
Japan Helicopter Society

TECHNICAL SESSIONS

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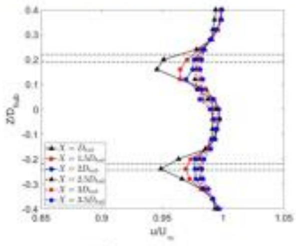
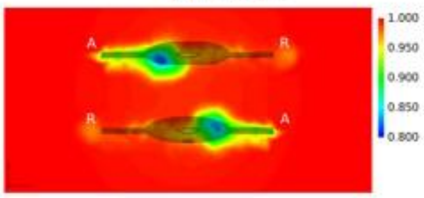
Technical Session: Manufacturing & Tech. II:

Computational Analysis of a Model Coaxial Rotor Hub Wake (1233) Forrest Mobley*, James Coder, University of Tennessee Knoxville

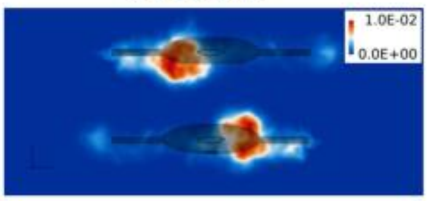
二重反転ロータのハブ周りのCFD解析。非定常条件(回転)条件下における評価がされており、ハブ左右でのレイノルズ応力の非対称性や、後流構造の考察がされている。

計算モデル概要


(a) Streamwise component
後流域の速度欠損



(a) Streamwise component
ハブ断面の主流方向速度



(a) $\overline{u'u'}/U_\infty^2$
レイノルズ応力の分布

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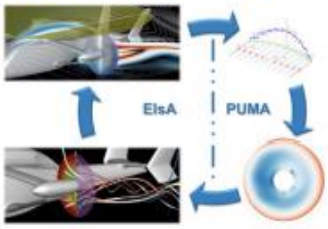
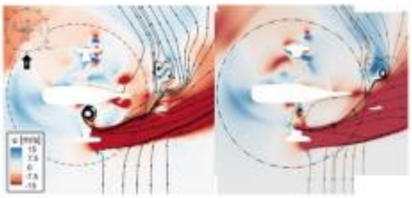
Technical Session: Aerodynamics II

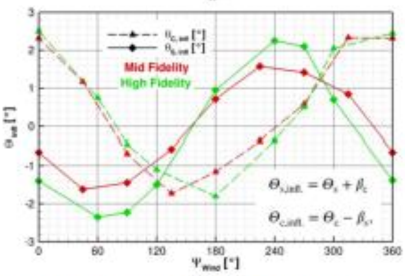
Time Efficient Methodology for the Evaluation of Aerodynamics and Flight Mechanics of the RACER Compound Helicopter in Hover under Cross Wind Conditions (1121) Ronan Boisard, * ONERA

Airbus Helicopters社が開発しているRACERのサイドプロペラ周りをアクチュエータディスクに置き換えて、中位忠実度のCFDを実施。計算条件として横風条件下のホバリングを解析しており、飛行試験に先立って飛行安定性などの考察を行っていた。





機体回りの流れ分布(左:Full-CFD 右:AL/AD+CFD)

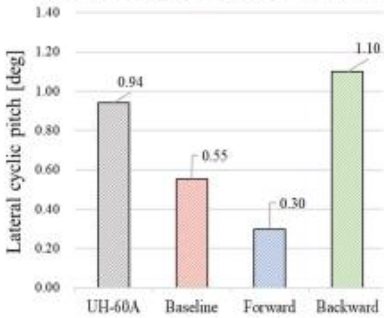


横風条件に対するプロペラ操作量(Full-CFD vs AL/AD+CFD) 31

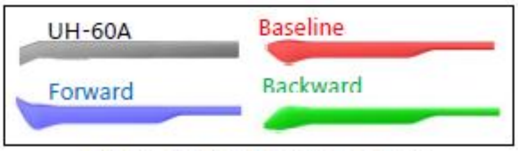
Technical Session: Aircraft Design II

The Effect of Blade Tip Sweep Angle on Forward Flight Performance of a High-speed Helicopter (1236)
Keita Kimura*, Masahiko Sugiura, Yasutada Tanabe, Japan Aerospace Exploration Agency

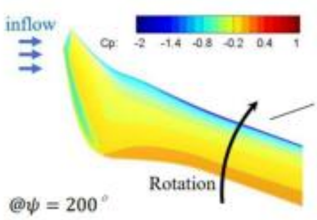
ロータを水平に保つ状態で高前進率比の前進飛行を行う場合、前進角が付加されたブレードが前進飛行性能が大きくなることをCFDにて示した。これは前進角の付加によって翼端近傍に作用する動圧が変化し、結果として横サイクリックピッチ角を小さくなることに起因している。



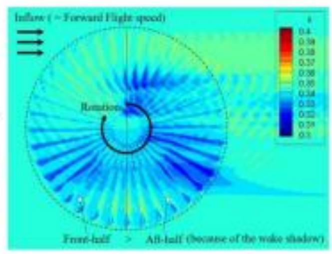
横サイクリックピッチθ1Cの履歴



参照ブレード(UH-60A)とJAXAハイミューブレード



Forwardタイプブレードの翼端近傍の圧力分布
(上面、ψ=200°)

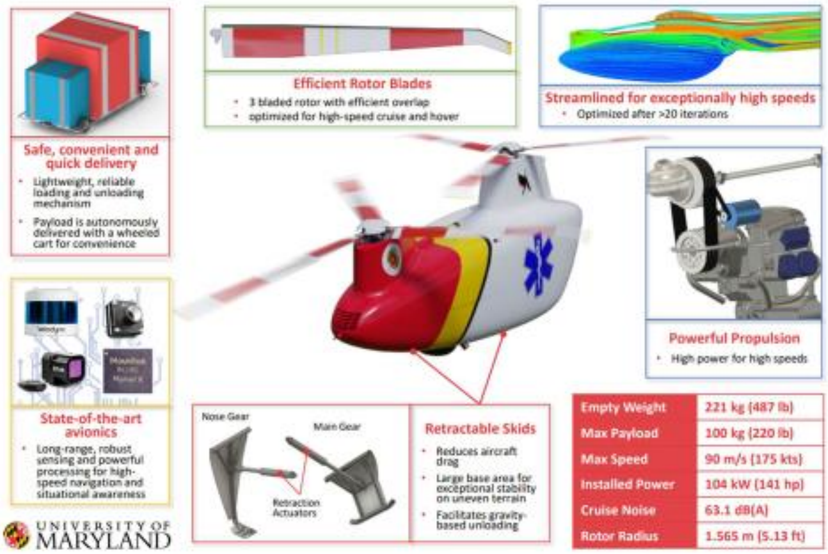


Forwardタイプブレードの翼端近傍の圧力分布
(上面、ψ=200°) 32

Technical Session: Aircraft Design III

38th Student Design Competition Graduate Winner: ALICORN – 2025 Unmanned Vertical Lift for Medical Equipment Distribution (1323) Dilhara Jayasundara*, Spencer Fishman*, University of Maryland

VFS学生機体設計コンペティションの優勝機体の発表。タンデム型の無人機で、ロータ直径1.5m、最大ペイロード100kg。医療・災害用途での物資搬送ミッションを想定して設計されており、空力・構造・駆動系・騒音・制御と包括的な検討の元システムを構築していた。



Empty Weight	221 kg (487 lb)
Max Payload	100 kg (220 lb)
Max Speed	90 m/s (175 kts)
Installed Power	104 kW (141 hp)
Cruise Noise	63.1 dB(A)
Rotor Radius	1.565 m (5.13 ft)

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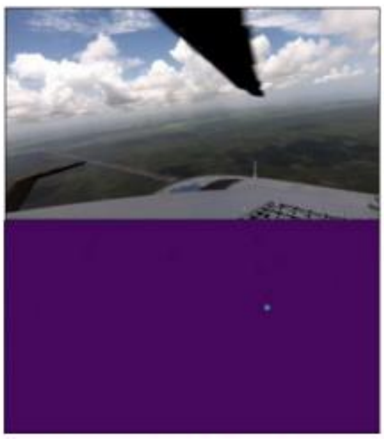
Technical Session: Test & Ecaluation I

Automated Optical Rotor Blade Tip Clearance Tracking Using Artificial Intelligence Algorithms(1325) Timothy Schmidt*, Sikorsky, a LMCO

飛行中のブレード先端位置をリアルタイムに把握し、武装の弾道軌道と先端位置とのクリアランスをパイロットが把握しやすいようなシステムを構築する、というもの。

ブレード先端が通りうる点の集合（緑）と武装弾道（赤）

パイロットへのガイドイメージ



カメラ画像とAIによって処理された先端位置

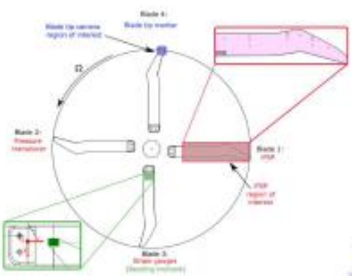
34

Technical Session: Test & Evaluation II

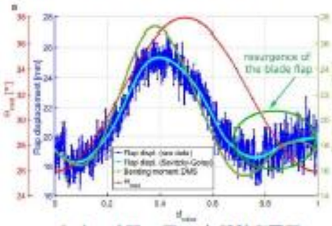
日本ヘリコプタ協会
Japan Helicopter Society

Dynamic Stall Investigation on a Rotating semi-elastic Double-swept Rotor Blade at the Rotor Test Facility Göttingen (110) Martin Müller*, Johannes Niklas Braukmann, Armin Weiss, German Aerospace Center

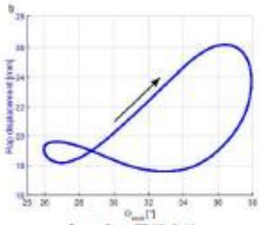
4枚ブレードのロータ装置にひずみゲージ、PSP、圧力孔、翼端変位計測用マーカーをそれぞれ用意し、弾性変形と空力分布の同時計測を実施



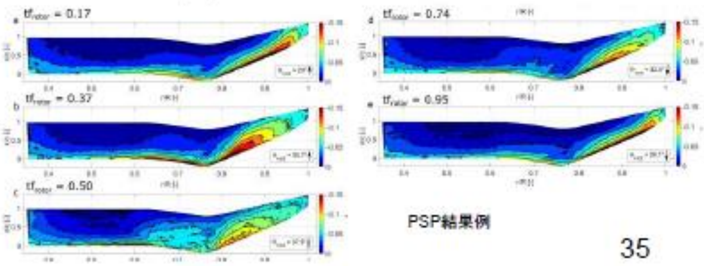
計測セットアップ



無次元時間(/1周)－各種計測履歴



ピッチ角 - 翼端変位



PSP結果例

35

Technical Session: Acoustics II

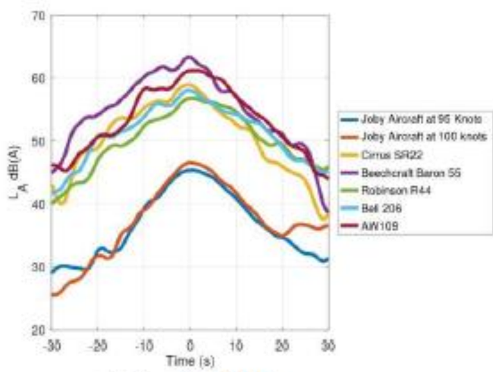
日本ヘリコプタ協会
Japan Helicopter Society

Flyover Noise Comparison Between Joby Aircraft and Similar Aircraft (1180)
Jeremy Bain*, Greg Goetchius, David Josephson, Joby Aviation
Jobyの静音性に関する研究。Jobyのエアタクシーと類似機体を100kt・高さ450mで飛行させ、音響計測を行った。結果Joby機体は10dB(A)～程度音圧レベルが低いという結果が得られた。

Joby 機体

検討機体と結果概要一覧

Aircraft	Airspeed	Airspeed	$L_{A,S,max}$
Joby Aircraft	95 knots	49 m/s	45 dB(A)
Joby Aircraft	100 knots	51 m/s	46 dB(A)
Cirrus SR22	100 knots	51 m/s	59 dB(A)
Beechcraft Baron 55	100 knots	51 m/s	63 dB(A)
Leonardo AW109	100 knots	51 m/s	61 dB(A)
Bell 206	100 knots	51 m/s	58 dB(A)
Robinson R44	100 knots	51 m/s	57 dB(A)



フライオーバー騒音比較

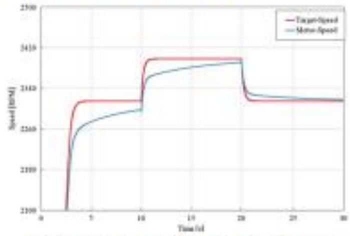
36

Technical Session: eVTOL II

Comprehensive Simulation for eVTOL AircraftDiagnosing Coupled Airframe-Propulsion Dynamic Instabilities (53) Felix Brenner, Llorenc Foraste Gomez, Patrick O'Heron*, Gamma Tech.; J. Goericke, M. Hasbun, ART

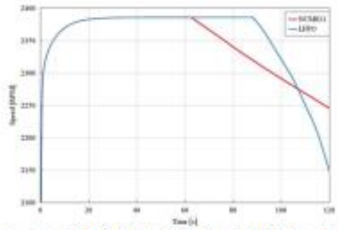
電気推進系のシミュレータと空力シミュレータを統合し、航続距離の推定に重要なバッテリー消費の評価等を適切に実施できるツール群の開発を目指した研究。

解析対象(Uber Elevate eCRM001)



プロペラ・motorモデル のInput/Output Torque

解析ツールイメージ(FLIGHTLAB(空力)+GT-SUITE(電気推進)



バッテリー消費を考慮したプロペラ回転数変化の履歴

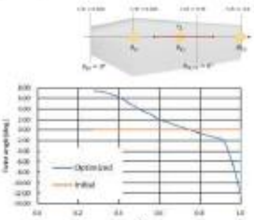
37

Technical Session: Adv. Vertical Flight I

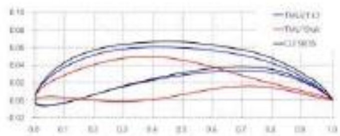
Blade Shape Optimization of Mars Helicopter Exploring Pit Craters (93) Masahiko Sugiura*, Keita Kimura, Akira Oyama, Hideaki Sugawara, Yasutada Tanabe, Japan Aerospace Exploration Agency; Y. Buto, M. Sato, K. Yoshikawa, Kogakuin University; M. Kanazaki, D. Kikuchi, Y. Kishi, Tokyo Metropolitan University; T. Minajima, Tokyo University of Agriculture & Tech.

火星ヘリ用のロータブレードの最適化。平面形状に加えて翼型についても最適化を行い、真空チャンバー内にて回転試験を行った。NASAの火星ヘリIngenuity用翼型と比較して設計点でホバリング効率が向上することを確認した。

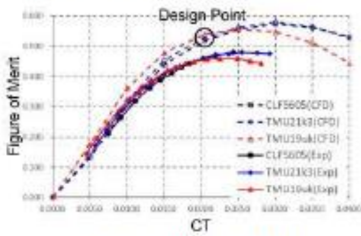
火星ヘリコプター概念機 HAMILTON



ブレードのねじり角分布



火星ヘリ用翼型



推力 - ホバリング効率(FoM)

チャンバー内に設置されたロータ装置

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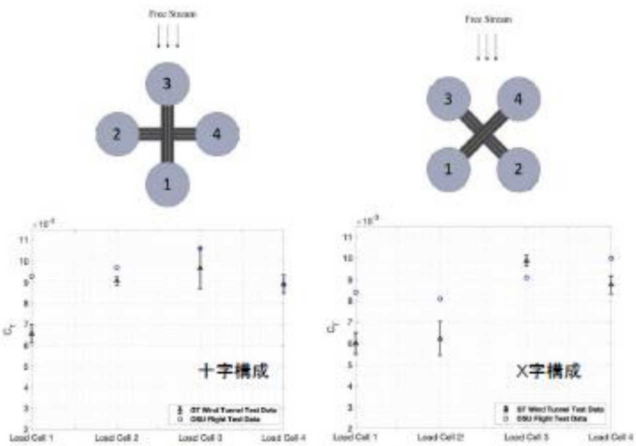
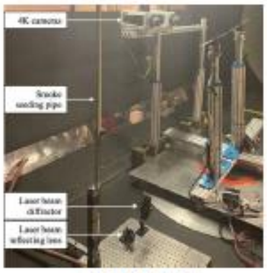
Technical Session: Aerodynamics II

日本ヘリコプタ協会
Japan Helicopter Society

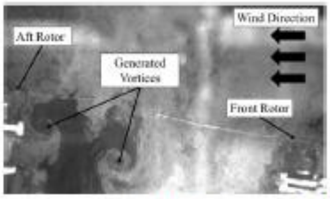
Experimental Evaluation of MultiRotor Aerodynamic Interactions (1182) Daley Wylie,* Abraham Atte,* Juergen Rauleder, Georgia Institute of Technology
マルチロータの干渉実験。クアッドロータの構成を十字とX字の2種類で各ロータの推力・トルクを計測しており、後流干渉による影響を実験的に評価。



各ロータの推力履歴（風試 vs 飛行試験）



可視化試験装置



可視化例

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展示会

日本ヘリコプタ協会
Japan Helicopter Society

テクニカルツアー

- 5/13(金)Bell Training Academy
- 高度化した3Dモデリング、実機を模擬したフライトシミュレータ、教育用ヘリコプタ全機メカニズム模型等を見学
- 実機を使わず、忠実度を上げたトレーニングにより、教育効果を高めていた

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まとめ

- 例年通り、防衛・民間分野の発表を網羅していたが、eVTOLは一分野となりつつある
- 今年度は3年ぶりのオンサイト開催となったが、米国人も例年より少なく、外国人は独仏日がメインであった
- オンサイトということで展示会や工場見学が再開された
- オンサイトではあったがSpecial Sessionsについてはビデオ録画され、後日視聴可能
- 来年度も引き続き、オンサイト開催で進む可能性が高い

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特別講演会

Comprehensive Validation on Aeromechanics Test Data for Mach-scaled Helicopter Rotors

Prof. Sung Nam Jung

Presented for Chofu Aerospace Center, JAXA
Organized by Japan Helicopter Society

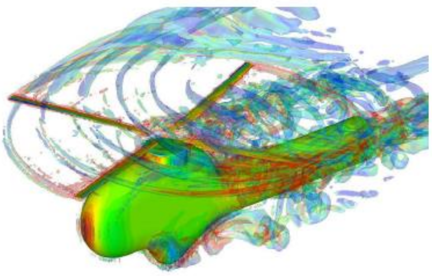
Comprehensive Validation on Aeromechanics Test Data for Mach-Scaled Helicopter Rotors

Prof. Sung N. Jung
School of Mechanical & Aerospace Eng.
Konkuk University, Seoul, Republic of Korea

11/04/2022

Part I

Introduction



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Intelligent Rotorcraft Structures Lab

Intro: Speaker's Bio

- **Prof. Sung Nam Jung**
- **Education**
  - B.S., M.S., Ph.D, Seoul National University
- **Area of Research:**
  - Rotorcraft Aeromechanics / Composite Structures
- **Work Experience**
  - 2006 – Current, Professor, **Konkuk University**, Seoul
  - 2018 – 2018, Visiting Scientist, DLR
  - 2011 – 2012, Visiting Scientist, NASA Ames
  - 1997 – 1999, Visiting Scholar, University of Maryland, College Park
  - 1994 – 2006, Professor, Chonbuk National University
- **Professional Service**
  - AIAA Associate Fellow (Since 2014)
  - Associate Editor, Journal of the American Helicopter Society (Since 2015)
  - President, Rotorcraft Systems Division, KSAS (2014 – 2015)
  - President, VFS Korean Chapter (2018 – 2021)
  - Tech Program Chair/Co-Chair, ARF 2018/2012, Rotor Korea 2007/2009

A doll in glasses, 2000

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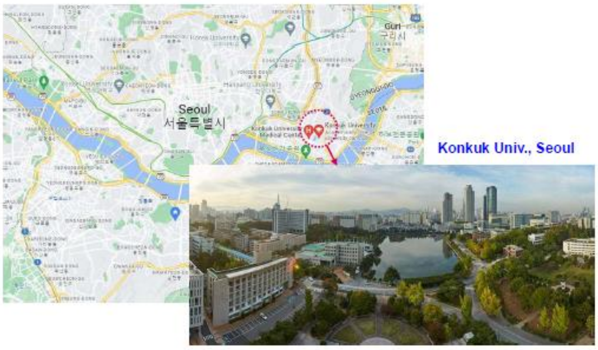
Where Is Konkuk University?



- **Konkuk University (KU):**
  - Located in the northeastern region of Seoul
  - About 30k undergraduate plus graduate students
  - Aerospace Eng. program started in 1990
  - Currently 12 faculty members at Aerospace Eng.

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Mutual Visits & Talks: Some History

JAXA

Special Lecture at Konkuk University
Seoul, Korea, March 15, 2018

Recent Research Activities on Rotary Wings in JAXA

Yasutada Tanabe

Advanced Technologies for Helicopter Development

Prof. Yung H. Yu

Director, Institute of Intelligent Vehicle System and Technology
Department of Aerospace Information Engineering
Konkuk University
Seoul, Korea

July 1, 2008
Japanese Helicopter Society Meeting

Active Vibration Reduction Study for Composite Helicopter Blades with Dissimilar Characteristics

Sung N. Jung
Konkuk University

日本ヘリコプタ協会

Presented at Japan Helicopter Society Meeting, University of Tokyo, July 1, 2008

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Sharing Some Memory with Dr. Aoyama

From left to right: Dr. Aoyama Takashi, Dr. Ben W. Sim (late), Myself
(Univ. of Maryland, College Park; Jan. 15, 2001)

Chonbuk National Univ., Jeonju;
June 28, 2006

From left to right: Myself, Dr. Choong Yang, Dr. Aoyama Takashi
(Geumsan Temple, Gimje; June 28, 2006)

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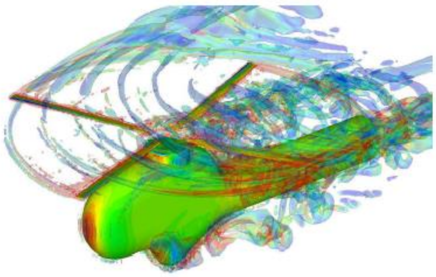
Part II

Validation of HART I/II Rotors



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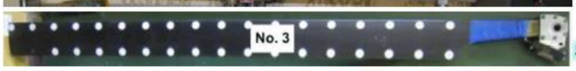
Mach-Scaled Rotors

❖ **Comparison of Mach-Scaled BO-105 Rotors**

	HART I	HART II	STAR
WT test performed	May-June 1994	October 2001	2024 (planned)
Actuation method	Fixed frame - HHC	Fixed frame - HHC	On board ATC
Blade manufacturer	DEI (US)	MBB (Germany)	DLR
Blade weight	2.67 kg (H1Y)	2.14 kg (H2Y)	3.4 kg
Rotor type	Hingeless	Hingeless	Articulated
Blade main spar	D-type	C-type	C-type plus rear flange
No. of air stations	3 (0.75, 0.87, 0.97R)	1 (0.87R)	4 (0.675, 0.77, 0.875, 0.975R)
No. of pressure sensors	124	51	392
No. of strain gages	34 (32)	6	129

HART I (H1S)

HART II (H2B)



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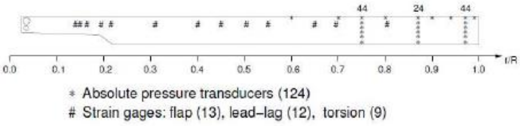
Structures Lab

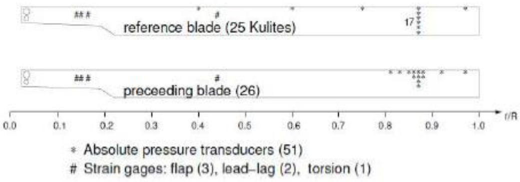
Mach-Scaled Rotors

❖ **Comparison of Mach-Scaled BO-105 Rotors**

HART I: **No. 1 (H1Y)**



HART II: **No. 1 (H2Y)** **No. 4 (H2R)**



HART I airfoil blade section (H1Y)

HART II airfoil blade section
(H2Y; Built based on X-ray images)

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Validation of HART II Rotor

Motivation:

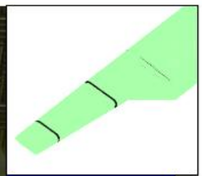
- HART II test performed at DNW in 2001
- Wind tunnel test data released to public in 2006
- High resolution test data enabled demonstrating the prediction capability

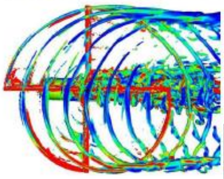
Approaches:

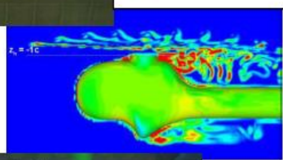
- Step-by-step approaches for CFD/CSD coupling
  - CSD code validation: CAMRAD II alone or with prescribed (CFD or measured) airloads
  - CFD code validation: KFLOW with measured blade motions
  - Loose CFD/CSD coupling

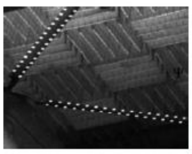
Outcomes:

- Code-to-code validation proved efficient for improved correlation of HART II data
- Mechanism of BVI noise reduction via HHC inputs explained
- KU team emerged in the rotorcraft community (2009-2013)









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HART II Validation Steps Taken

❖ **Step-by-step approach used for the validation of HART II data**

- 1st: **CSD** validation using lifting-line based aerodynamics (1-2)
- 2nd: **CFD** validation using measured blade motions (3-4)
- 3rd: **CSD** validation using prescribed CFD airloads (5)
- 4th: Loose **CFD/CSD** coupled approach (6-7)

(1) "Comparison of Rotor Structural and Aerodynamic Loads Using the HART II Test Data," *European Rotorcraft Forum*, Hamburg, Germany, Sept. 22-25, 2009

(2) "Validation of Comprehensive Dynamics Analysis Results for a Rotor in Descending Flight", Aircraft Eng. & Aerospace Tech., Vol. 83, No. 2, 2011

(3) "KFLOW Results of Airloads on HART II Rotor Blades with Prescribed Blade Deformation," *Rotor Korea*, Seoul, Korea, Oct. 19-20, 2009

(4) "Prediction of HART II Airloads Considering Fuselage Effect and Elastic Blade Deformation," *Heli Japan*, Saitama, Japan, Nov. 1-3, 2010

(5) "Validation of HART II Structural Dynamics Predictions Based on Prescribed Airloads," *Aeromechanics Specialists' Meeting*, San Francisco, CA, Jan. 20-22, 2010

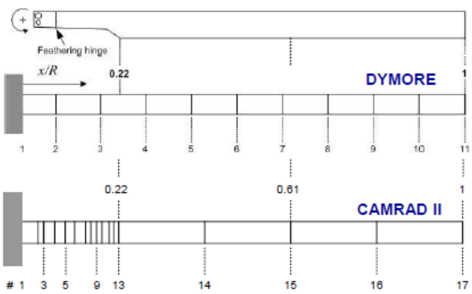
(6) "Correlation of Aeroelastic Response and Structural Loads for HART II Rotor using CFD/CSD coupling," *European Rotorcraft Forum*, Paris, France, Sept. 7-9, 2010

(7) "Assessment of CFD/CSD Coupled Aeroelastic Analysis Solution for HART II Rotor Incorporating Fuselage Effects," *Annual AHS Forum*, Virginia Beach, VA, May 3-5, 2011

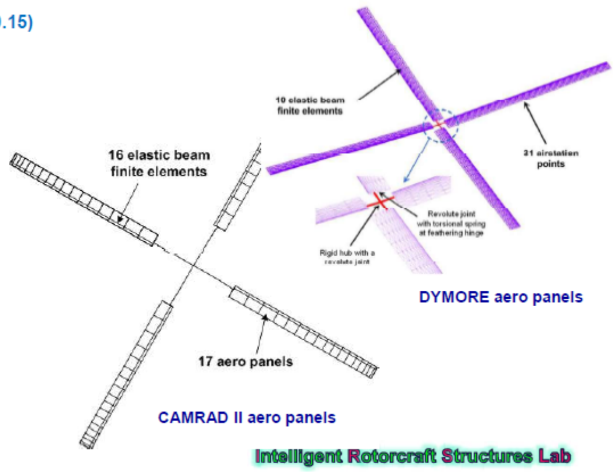
Rotor CSD Models

❖ **Structural/Aerodynamic models used for rotor CSD analysis**

Flight condition: HART II rotor in descent (μ = 0.15)



FE structural analysis model

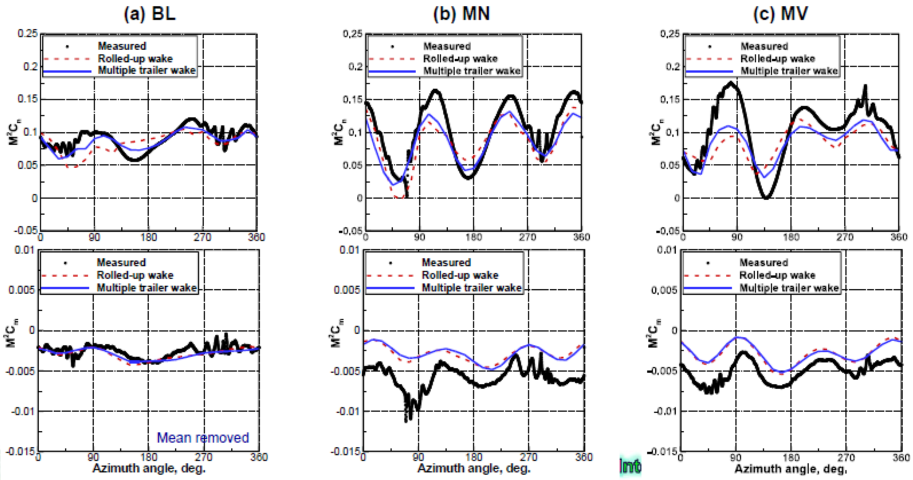


Validation of CSD Predictions

❖ Validation of CSD predictions on section airloads (CAMRAD II)

M^2C_n

M^2C_m

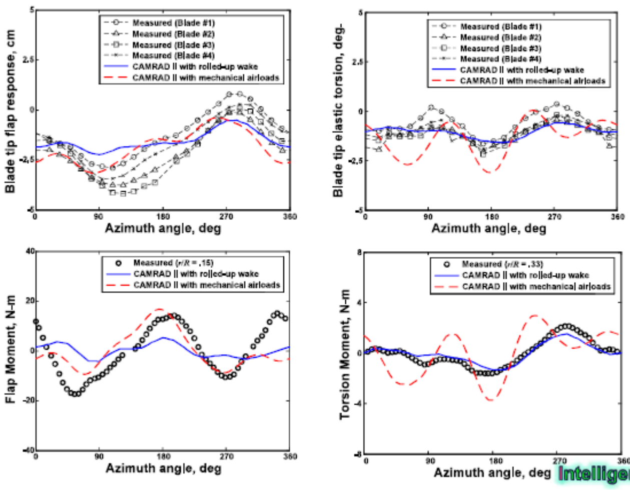


Validation of CFD Codes

❖ Validation of CFD codes via the mechanical airloads approach

Blade elastic motions:

Blade structural loads:



Mechanical airloads results indicate:

- Reasonable prediction on mean values
- Large oscillatory response due to the lack of damping (→ Requires large amount of damping to stabilize the response*)

* Sa, J. H., et al., "Validation of HART II Structural Dynamics Predictions Based on Prescribed Airloads," International Journal of Aeronautical and Space Sciences, Sept. 2012

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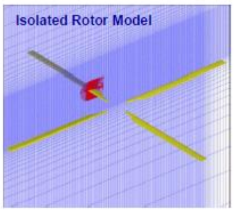
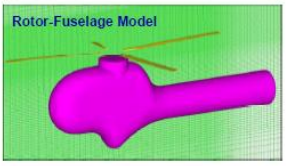
Loose CFD/CSD Coupled Approach

❖ CFD computational conditions

Grid type	Isolated Rotor	Rotor + Fuselage
Background grid (off-body)	111 × 401 × 401 (17.8M cells)	161 × 449 × 401 (29.0M cells)
Blade grid (near-body)	321 × 97 × 49 (1.53M cells)	321 × 97 × 49 (1.53M cells)
Fuselage grid	-	177 × 289 × 49 (2.51M cells)
Total	**23.95M cells**	**37.6M cells**
Background grid spacing (level-1 uniform spacing)	0.1 c	
First cell size	1×10^{-5} c (y+ < 3)	
Time step size	0.2 deg.	





CFD/CSD: KFLOW (Compressible 3D RANS solver) / **CAMRAD II** or **DYMORE**

Spatial discretization: 5^{th}-order WENO scheme

Turbulence model: k-ω Wilcox-Durbin (WD+) scheme

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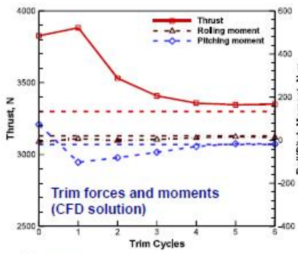
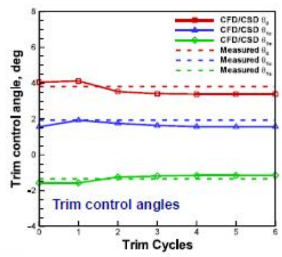
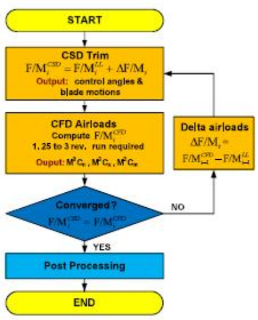
Loose CFD/CSD Coupled Approach

❖ Iteration history for CFD/CSD convergence (Delta airloads approach)

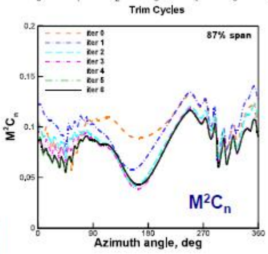
Rotor trim:

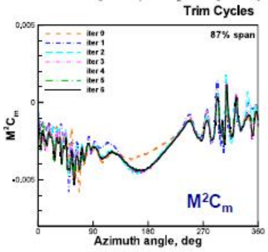






Section airloads:





CFD/CSD LC algorithm

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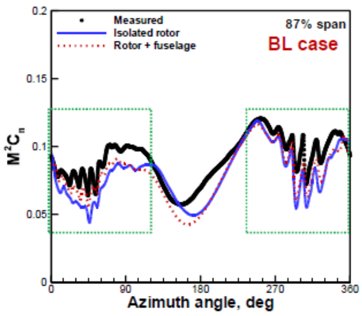
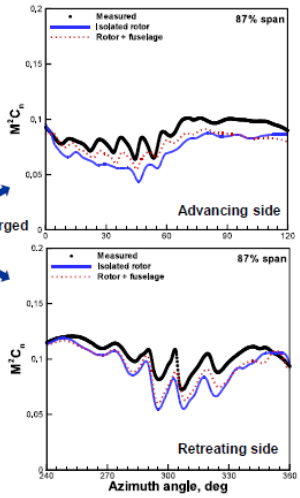
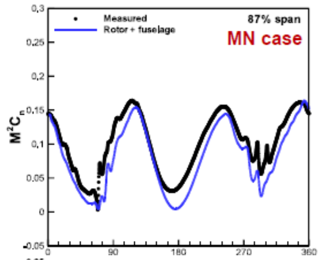
Loose CFD/CSD Coupled Approach

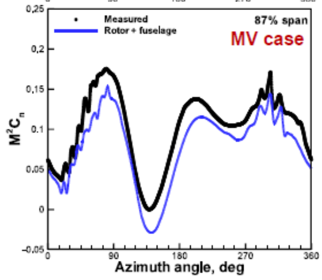
❖ Validation of section normal forces M^2C_n



Enlarged view





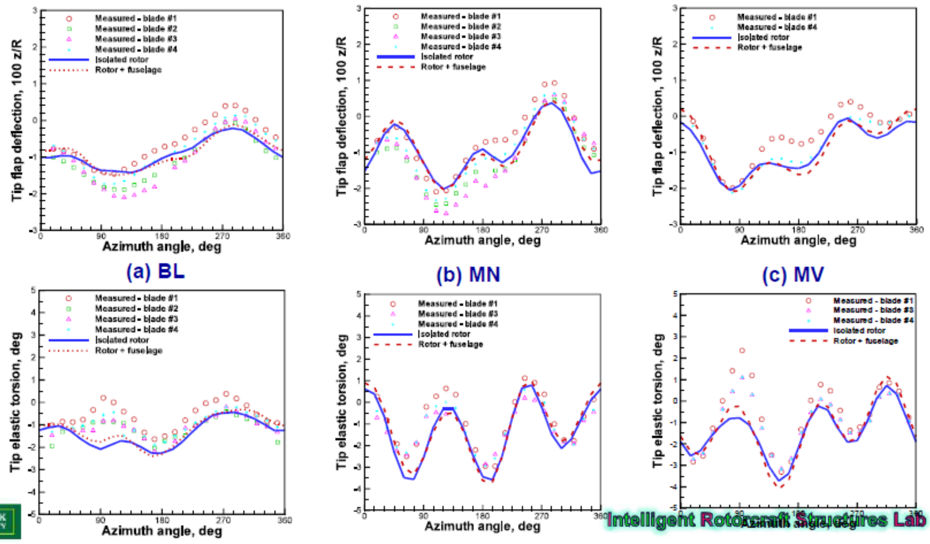


➢ Good correlation (BVI peaks, phase) obtained, particularly with R-F model

Validation of Blade Elastic Motions

Flap motion:

Torsion motion:



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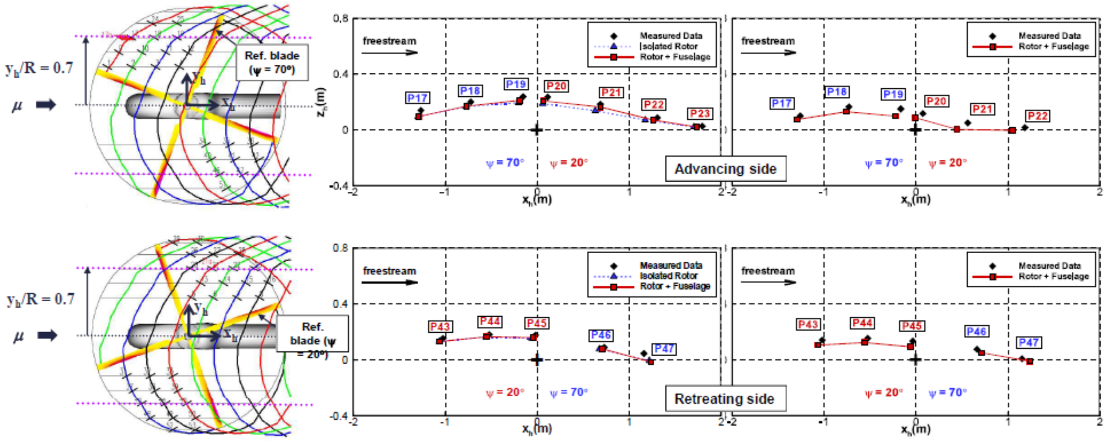
Validation of Vortex Trajectories



(a) BL case (b) MN case

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Publications: Validation of HART II Rotor

- You, Y. H., Sa, J. H., Park, J. S., Park, S. H., and Jung, S. N., "Modern Computational Fluid Dynamics/Structural Dynamics Simulation for a Helicopter in Descent," Journal of Aircraft, Vol. 50, No. 5, Sept. 2013
- Park, J. S., Sa, J. H., Park, S. H., You, Y. H., and Jung, S. N., "Loosely-coupled Multibody Dynamics-CFD Analysis for a Rotor in Descending Flight," Aerospace Science and Technology, Vol. 29, No. 1, Aug. 2013
- Jung, S. N., Sa, J. H., You, Y. H., Park, J. S., and Park, S. H., "Loose Fluid-Structure Coupled Approach for a Rotor in Descent Incorporating Fuselage Effects," Journal of Aircraft, Vol. 50, No. 4, July 2013
- Smith, M. J., Lim, J. W., van der Wall, B. G., Baeder, J. D., Biedron, R. T., Boyd, Jr, D. D., Jayaraman, B., Jung, S. N., and Min, B. Y., "The HART II International Workshop: An Assessment of the State of the Art in CFD/CSD Prediction," CEAS Aeronautical Journal, Vol. 4, No. 4, Dec. 2013
- van der Wall, B. G., Lim, J. W., Smith, M. J., Jung, S. N., Bailly, J., Baeder, J. D., and Boyd, Jr, D. D., "The HART II International Workshop: An Assessment of the State-of-the-art in Comprehensive Code Prediction," CEAS Aeronautical Journal, Vol. 4, No. 3, July 2013
- Sa, J. H., You, Y. H., Park, J. S., Park, S. H., and S. N. Jung, "Validation of HART II Structural Dynamics Predictions Based on Prescribed Airloads," International Journal of Aeronautical and Space Sciences, Vol. 13, No. 3, Sept. 2012
- Jung, S. N., You, Y. H., Kim, J W., Sa, J. H., Park, J. S., and Park, S. H., "Correlation of Aeroelastic Responses and Structural Loads for a Rotor in Descending Flight," Journal of Aircraft, Vol. 49, No. 2, Mar.-Apr. 2012
- Park, J. S., and Jung, S. N., "Comprehensive Multibody Dynamics Analysis for Rotor Aeromechanics Predictions in Descending Flight," Aeronautical Journal, Vol. 116, No. 1176, Mar. 2012
- Park, J. S., Jung, S. N., You, Y. H., Park, S. H., and Yu, Y. H., "Validation of Comprehensive Dynamics Analysis Results for a Rotor in Descending Flight," Aircraft Engineering and Aerospace Technology, Vol. 83, No. 2, Apr. 2011
- Park, J. S., Jung, S. N., Park, S. H., and Yu, Y. H., "Correlation Study of a Rotor in Descending Flight using DYMORE with a Freewake Model," Journal of Mechanical Science and Technology, Vol. 24, No. 8, 2010
- You, Y. H., Park, J. S., Jung, S. N., and Kim, D. H., "Comprehensive Code Validation on Airloads and Aeroelastic Responses of the HART II Rotor," International Journal of Aeronautical and Space Sciences, Vol. 11, No. 2, June 2010

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HART I Blade Property Test

Motivation:

- No systematic measured blade properties available for HART I rotor
- Original set of HART I blades demolished during a follow-on test

Approaches:

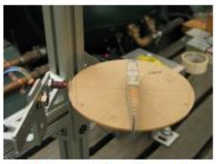
- In collaboration with NASA, DLR, KU
- Use the original blade set tested in DNW (1994)
- Well-established test techniques employed
- Destructive-type of test techniques adopted

Outcomes:

- Property table completed for HART I blades and documented as NASA report (NASA/CR-2012-216039)
- Published also in JAHS 2013

HART I blades for structural test

Mirror method for flap bending



Trifillar pendulum for section MOI

Chord bending

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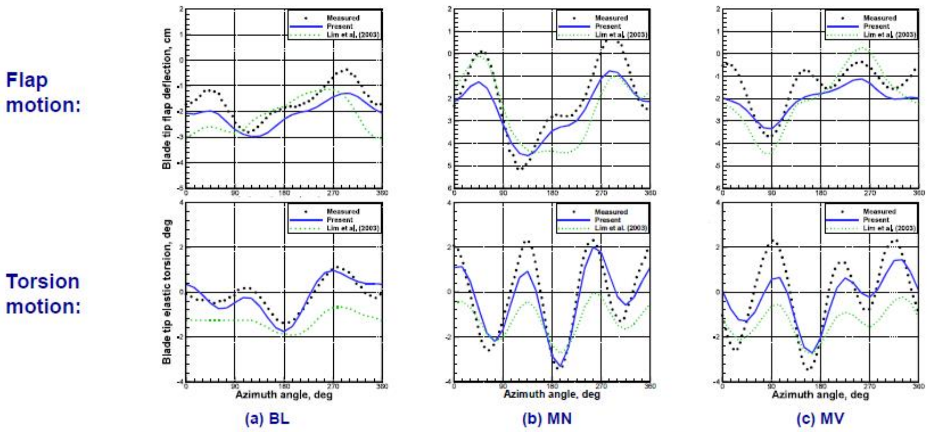
Result: HART I Blade Property Test



➤ Improved correlation in terms of waveform/phase & p-p values obtained, as compared with the earlier predictions (Lim, et al.)

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HART II Blade Property Test

Motivation:

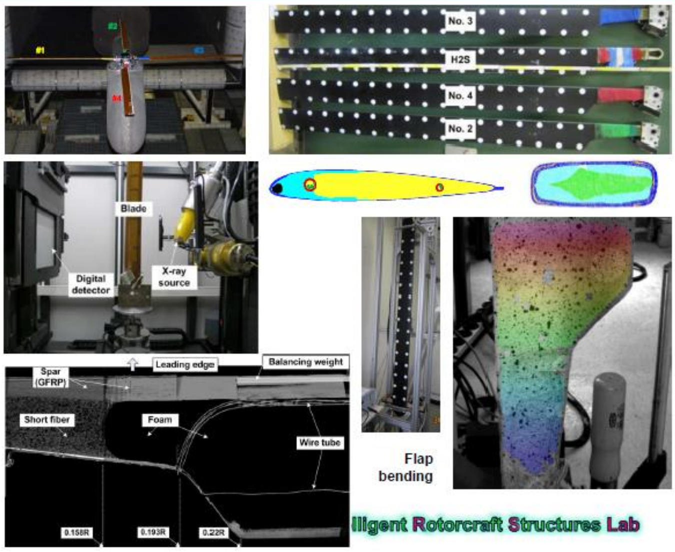
- No measured properties available for HART II blades
- Reliable measured properties needed for accurate predictions

Approaches:

- In collaboration with NASA & DLR
- Use the original set of HART II blades tested in DNW (2001)
- Non-destructive test techniques (x-ray CT-scan coupled with 2D FE section code Ksec2d) adopted
- Assess the measurement quality

Outcomes:

- Updated structural properties of HART II blades released
- Published as journal papers: AIAA J & Comp Str (2015)



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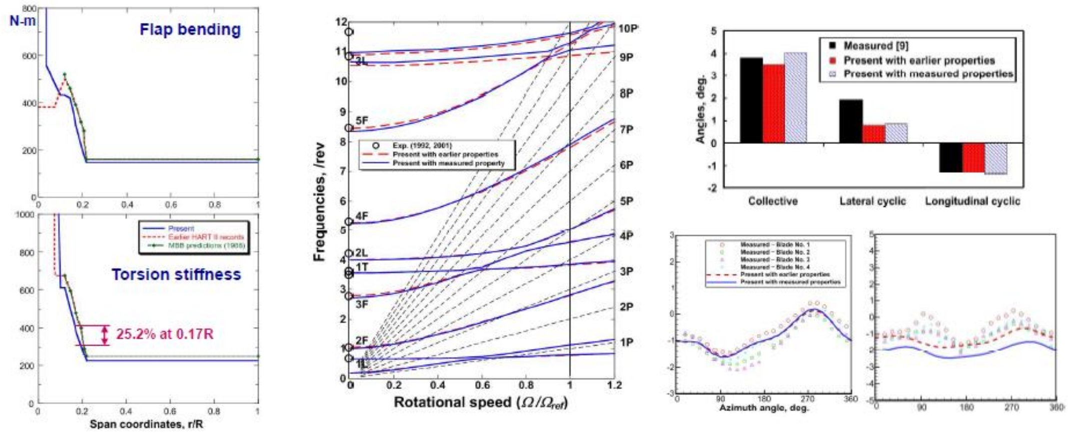
Result: HART II Blade Property Test



- Measured values show substantial deviations in the blade properties, especially in the blade root, while indicating marginal influences on trim and blade motions

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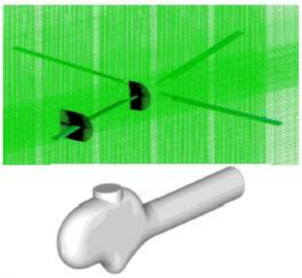
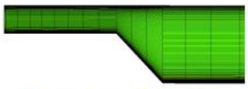
Validation of HART I Rotor

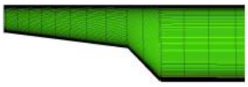
❖ CFD computational conditions

Case	Near-body grid	Off-body grid	Fuselage	Total	Off-body grid spacing
Isolated rotor	321×101×49 (1.5M cells)	161×451×401 (29.0M cells)	None	20.9M cells	0.1c
Rotor-fuselage	321×101×49 (1.5M cells)	161×451×401 (29.0M cells)	177×289×49 (2.5M cells)	37.5M cells	0.1c

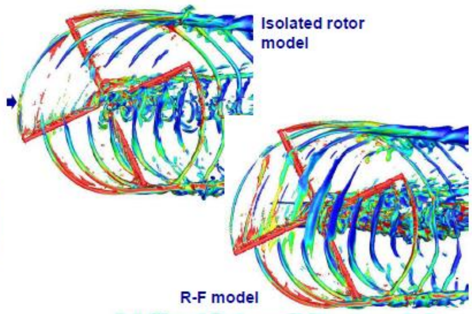




(a) HART I shank region



(b) HART II shank region



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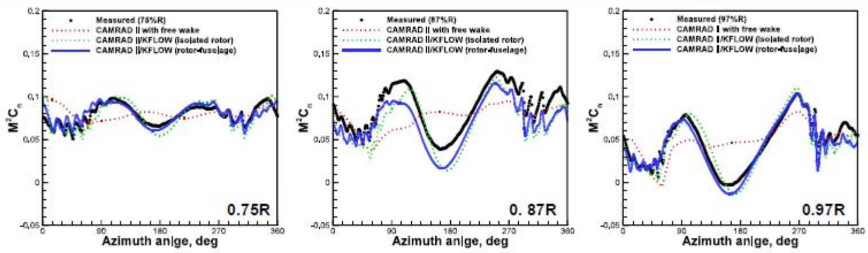
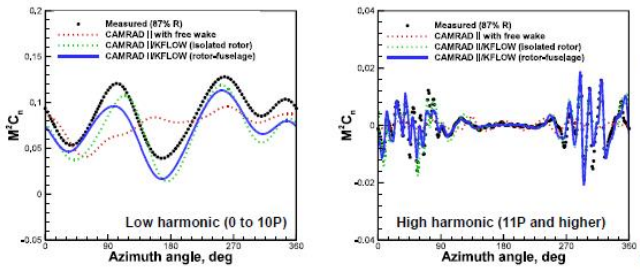
Validation of HART I Test Data

Section airloads:



Harmonic analysis on M^2C_n:



- ➢ Excellent correlation (p-p & phase) shown for all stations, with R-F model

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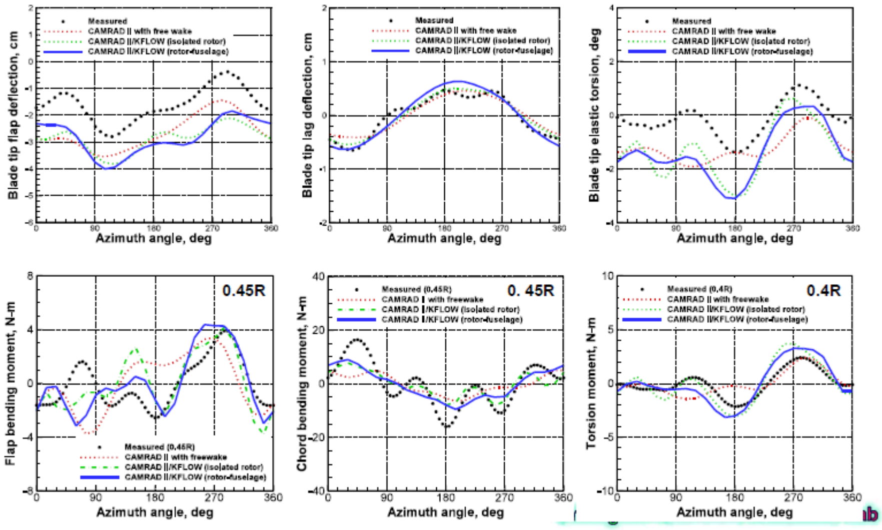
Validation of HART I Test Data

Blade tip motions:

Blade structural loads:



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Publications: HART I/II Rotors

❖ Validation of HART I rotor test data

- You, Y. H., Na, D. H., and Jung, S. N., "Improved Rotor Aeromechanics Predictions using a Fluid-Structure Interaction Approach," Aerospace Science and Technology, Vol. 73, No. 2, Feb. 2018
- You, Y. H., Na, D. H., and Jung, S. N., "Data Transfer Schemes in Rotorcraft Fluid-Structure Interaction Predictions," International Journal of Aerospace Engineering, Vol. 2018, Article ID 3426237, Mar. 2018
- Na, D. H., You, Y. H., and Jung, S. N., "Comprehensive Aeromechanics Predictions on Air and Structural Loads of HART I Rotor," International Journal of Aeronautical and Space Sciences, Vol. 18, No. 1, Mar. 2017

❖ Measurement of HART I blade properties

- Jung, S. N., You, Y. H., Lau, B., Johnson, W., and Lim, J. W., "Evaluation of Rotor Structural and Aerodynamic Loads Using Measured Blade Properties," Journal of the American Helicopter Society, Vol. 58, No. 4, Oct. 2013
- Jung, S. N., and Lau, B., "Determination of HART I Rotor Blade Structural Properties by Laboratory Testing," NASA CR-2012-216039, Aug. 2012.

❖ Measurement of HART II blade properties

- Jung, S. N., You, Y. H., Dhadwal, M., Riemenschneider, J., and Hagerty, B., "Study on Blade Property Measurement and Its Influence on Air/Structural Loads," AIAA Journal, Vol. 53, No. 11, 2015
- Jung, S. N., M. Dhadwal, Kim, Y. W., Kim, J. H., and Riemenschneider, J., "Cross-section Constants of Composite Blades Using Computed Tomography Technique and Finite Element Analysis," Composite Structures, Vol. 129, Oct. 2015

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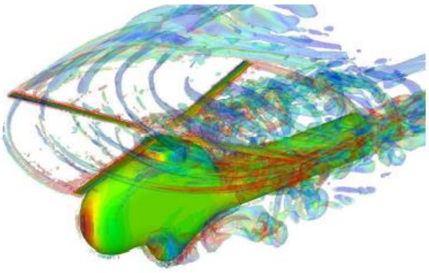
Part III

Other Rotorcraft Research Activities at KU



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Intelligent Rotorcraft Structures Lab

KSEC2D: Beam Section Analysis System

Motivation

- Need is to develop a general-purpose beam cross-section analysis program (sponsored by KARI)
- Evaluate rotor blade section properties
- Optimum design of blade structures

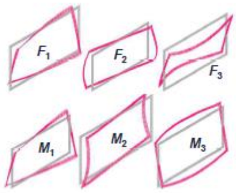
Approaches

- 2D finite element-based approach
- Beam theory based on a Helinger-Reissner mixed variational principle
- Validation with 3D FEA and experimental data

Outcomes

- Successful application to KHP blades
- Other applications: KARI Smart UAV, KARI BMR, KARI OPPAV, UAM, …
- KSEC2D evolved into 2nd generation beam section models (RDSAC, MVSAC)

Flow diagram of 2D cross-sectional analysis program KSC2D



3D sectional warping

	Giavotto et al. (1983)	VABS (1997)	Jung et al. (2002)	Present
Master field	Displacements	Displacements	Displacements & forces	Displacements
Material constitutive	3D	3D	Reduced (beam)	3D
Warping	3D	3D	Torsion & shear	3D
Stiffness model	Timoshenko (6×6)	Timoshenko (6×6) Vlasov (5×5)	Timoshenko – Vlasov (7×7)	Timoshenko (6×6) Vlasov (9×9)
Section model	FE	FE	Analytical	FE

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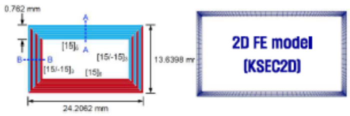
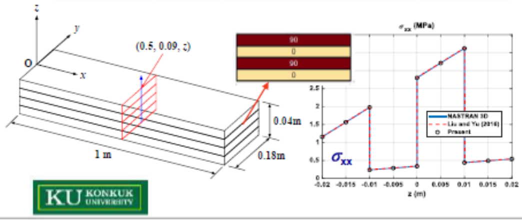
KSEC2D: Validations & Applications

❖ Validations

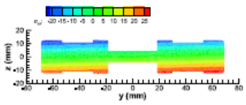


Stiffness	NABSA	Jung et al. (%)	VABS (%)	Present (%)
$K_{11} \cdot 10^6$ (lb)	1.438	1.431 (-0.5)	1.437 (-0.1)	1.437 (-0.1)
$K_{14} \cdot 10^5$ (lb-in)	-1.075	-1.064 (-1.0)	-1.074 (-0.1)	-1.074 (-0.1)
$K_{22} \cdot 10^4$ (lb)	9.018	9.089 (0.8)	9.027 (0.1)	8.984 (-0.4)
$K_{25} \cdot 10^4$ (lb-in)	5.204	5.391 (3.6)	5.201 (-0.1)	5.200 (-0.1)
$K_{33} \cdot 10^4$ (lb)	3.932	3.822 (-2.8)	3.943 (0.3)	3.894 (-0.9)
$K_{36} \cdot 10^4$ (lb-in)	5.637	5.605 (-0.6)	5.635 (0.0)	5.604 (-0.6)
$K_{44} \cdot 10^4$ (lb-in²)	1.678	1.662 (-1.0)	1.679 (0.1)	1.674 (-0.2)
$K_{55} \cdot 10^4$ (lb-in²)	6.622	6.873 (3.8)	6.621 (0.0)	6.611 (-0.2)
$K_{66} \cdot 10^5$ (lb-in²)	1.726	1.728 (0.1)	1.725 (-0.1)	1.714 (-0.7)

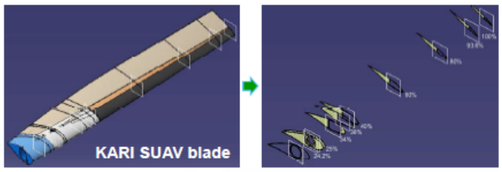


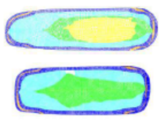
❖ Applications

STAR AT3 blade



KARI BMR flexbeam section





HART II blade

BO-105 small-scaled blade

KHx blade

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Analytical Beam Section Analysis: CORBA

Motivation:

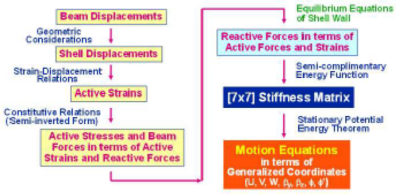
- Need is to develop a simple, analytical beam section analysis for high efficiency cross-section analysis program
- Exploit the benefit of mixed approaches
- Consider non-classical composites effects

Approaches:

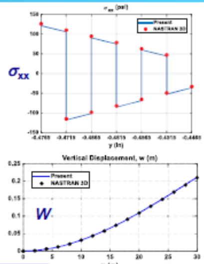
- Mixed beam formulation based on Reissner functional
- Considering shell-wall thickness, transverse shear, torsion warping, warping restraint effects in rigorous manner

Outcomes:

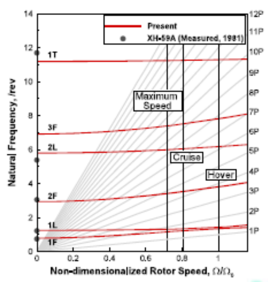
- A shear flexible [7x7] stiffness constants resulted
- Extensive validation conducted
- MDO simulations for helicopters & wind turbine blades performed



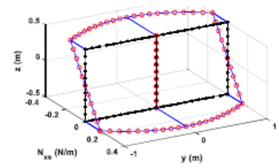
Flow diagram of CORBA



NASTRAN 3D	CORBA
1,260 s	0.24 s



Rotor fan diagram (XH-59A)



Distribution of shear flows

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Publications: Composite Blade Sections

KSEC2D

- Dhadwal, M., and Jung, S. N., "Free-edge stress evaluation of laminated composites using a novel multifield variational beam formulation," Composite Structures, Vol. 233, Article 111705, Feb. 2020
- Dhadwal, M., and Jung, S. N., "Generalized Multifield Variational Formulation with Interlaminar Stress Continuity for Multilayered Anisotropic Beams," Composites Part B: Engineering, Vol. 168, July 2019
- Dhadwal, M., and Jung, S. N., "Multifield Variational Sectional Analysis for Accurate Stress Computation of Multilayered Composite Beams," AIAA Journal, Vol. 57, No. 4, Apr. 2019
- Dhadwal, M., and Jung, S. N., "Effect of Three-dimensional Warping on Stiffness Constants of Closed Section Composite Beams," International Journal of Aeronautical and Space Sciences, Vol. 18, No. 3, Sept. 2017
- Dhadwal, M., and Jung, S. N., "On Boundary Effects Due To Nonuniform Shear and Torsional Warping for Open Section Anisotropic Beams," Composite Structures, Vol. 161, Feb. 2017
- Dhadwal, M., and Jung, S. N., "Refined Sectional Analysis with Shear Center Prediction for Nonhomogeneous Anisotropic Beams with Nonuniform Warping," Meccanica, Vol. 51, No. 8, Aug. 2016
- Park, I. J. and Jung, S. N., "General Purpose Cross-section Analysis Program for Composite Rotor Blades," International Journal of Aeronautical and Space Sciences, Vol. 10, No. 2, Nov. 2009

CORBA

- Bae, J. S., and Jung, S. N., "Closed-Form Analysis of Thin-Walled Composite Beams Using Mixed Variational Approach," Aerospace, Vol. 9, 2022
- Jung, S. N., Kim, C. J., Ko, J. W. and Kim, C. W., "Theory of Thin-walled, Pretwisted Composite Beams with Elastic Couplings," Advanced Composite Materials, Vol. 18, No. 2, 2009
- Jung, S. N., and Park, I. J., "Theory of Thin-walled Composite Beams with Single and Double-cell Sections," Composites Part B: Engineering, Vol. 38, Mar. 2007
- Jung, S. N., and Park, I. J., "A Simple Mixed-Based Approach for Thin-walled Composite Blades with Two-cell Sections," Journal of Mechanical Science & Technology, Vol. 19, No. 11, 2005
- Jung, S. N., and Park, I. J., "Structural Behavior of Thin and Thick-walled Composite Blades with Multi-cell Sections," AIAA Journal, Vol. 43, No. 3, Mar. 200.
- S. N. Jung, I. J. Park, E. S. Shin, and I. Chopra, "A Study on Assessment of Composite Couplings for Helicopter Rotor Blades with Multi-cell Sections," International Journal of Aeronautical and Space Sciences, Vol. 4, No. 1, May 2005
- Jung, S. N. and Lee, J. Y., "Closed-Form Analysis of Thin-Walled Composite I-Beams Considering Non-Classical Effects," Composite Structures, Vol. 60, 2003
- Jung, S. N., Nagaraj, V. T., and Chopra, I., "Refined Structural Model for Thin- and Thick-Walled Composite Rotor Blades," AIAA Journal, Vol. 40, No. 1, 2002
- Jung, S. N., Nagaraj, V. T., and Chopra, I., "Refined Structural Dynamics Model for Composite Rotor Blades," AIAA Journal, Vol. 39, No. 2, 2001
- Jung, S. N., Nagaraj, V. T., and Chopra, I, "Assessment of Composite Rotor Blade Modeling Techniques," Journal of the American Helicopter Society, Vol. 44, No. 3, July 1999

Structural Optimization of Rotor Blades

Motivation

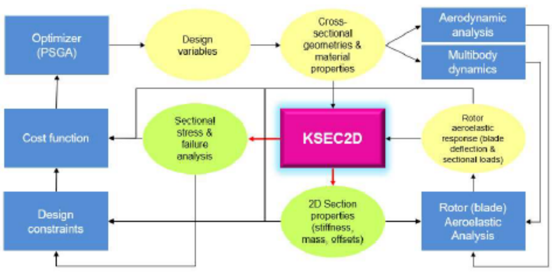
- Develop efficient modeling methods for helicopter/wind turbine blades
- Integrate structural optimization framework by combining evolutionary algorithm PSGA with KSEC2D, NASTRAN, etc.

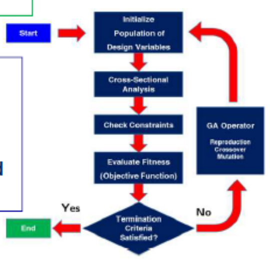
Approaches

- Use of Bezier/B-spline curves to model thin-walled cross-section profiles
- Analytical or FE-based, mixed beam formulation for cross-sectional properties

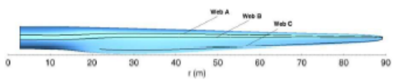
Outcomes

- Construction of PSGA-based MDO structural design framework
- Application to DTU wind turbine & HCUR blade sections
- High efficiency optimum sections resulted while satisfying all design constraints





PSGA flow diagram:



DTU 10MW WT blade (Bak et al. 2013)

Computing time	3D FE	2D FE	Present 1D
Each section	10 min	1 min	1 sec
Overall optimum	25000 hrs	2500 hrs	40 hrs

- Computed using 30 cross-sections & 5000 function evaluations

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Structural Optimization of WT Blades

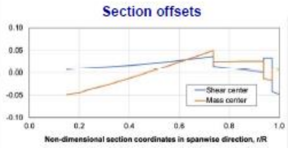
❖ HCUR blade sections

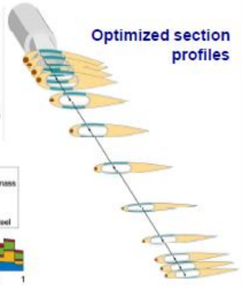
Minimize: $f(\mathbf{x}) = \frac{m}{m_0}$

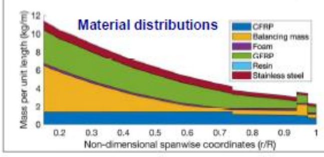
Subject to: $a_i(N_p + 0.15) \le \frac{\omega}{\Omega_0} \le a_i(N_p + 0.85)$

$\left|\frac{y_{sc} - y_{ac}}{c}\right| \le 0.05 \qquad \left|\frac{y_{mc} - y_{ac}}{c}\right| \le 0.05$

$I_R \ge 0.8 I_R^0 = 44.86 kgm^2 \qquad m \le m_0$







❖ Optimum design of DTU 10 MW WT blades

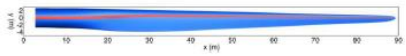
Minimize: $f(\mathbf{x}) = \frac{m}{m_0}$

Subject to: $g_1(\mathbf{x}) = \frac{v}{v_0} \le 1 \quad g_2(\mathbf{x}) = \frac{w}{w_0} \le 1$

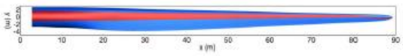
$g_3(\mathbf{x}) = \frac{m}{m_0} \le 1 \quad g_4(\mathbf{x}) = SR_{\max} \le 1$

with bounds for design variables as: $\mathbf{x}^L \le \mathbf{x} \le \mathbf{x}^U$

Baseline:



Optimum:



- 6% blade weight savings w/o violating constraints
- Run time: about 5 hrs (using OpenMP)

Rotor Aeromechanics Analysis System

Goals:

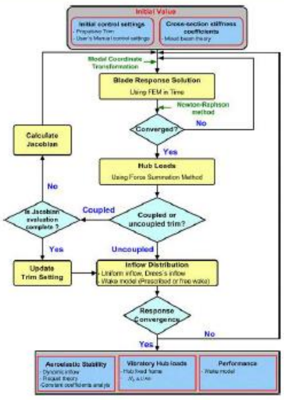
- Develop comprehensive aeromechanics analysis with the capability of predicting:
  - Rotating free vibration frequencies
  - Blade & hub vibratory loads
  - Trim, blade response, stability

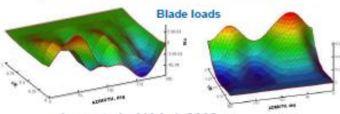
Approaches:

- Based on moderately large deformation beam theory
- Quasi-steady or Leishman-Beddoes unsteady aerodynamic theory adopted
- Extension to free wake inflow model & loosely coupled CFD/CSD approach planned

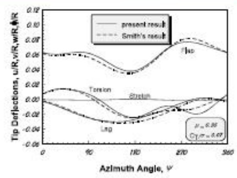
Outcomes:

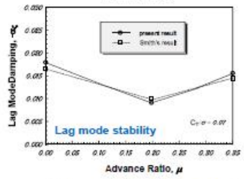
- Predicted aeroelastic responses in forward flight validated
- Effect of composite couplings on rotating frequencies, aeroelastic stability & hub vibration investigated
- May extend to a general purpose CSD system

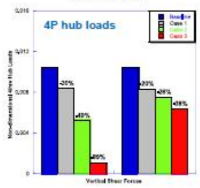




Jung et al., AIAA J, 2002







Summary

- ❖ Some of the rotorcraft research activities performed at KU briefed. These include:
  - Validation results of March-scaled HART I/II test data
  - Measurement of structural properties of HART I/II blades
  - Development of blade cross-sectional analysis systems: KSEC2D, CORBA
  - MDO outcomes for composite helicopters & WT blades
- ❖ Suggestions on future collaboration between the two parties
  - Continue effort in cooperation of STAR project
  - Encourage mutual visits (technical seminar, meetings) and exchange of personnel (students, professors, researchers)
  - Seek potential MoU research collaboration for emerging areas (e.g., UAM)

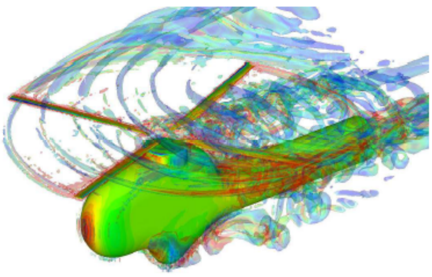
KU KONKUK UNIVERSITY

Intelligent Rotorcraft Structures Lab

Q & A

Thank you!

Contact: snjung@konkuk.ac.kr



KU KONKUK UNIVERSITY

Intelligent Rotorcraft Structures Lab

日韓回転翼機ワークショップ

（日本側発表）

0-1

Japan-Korea Joint Workshop on Rotorcraft
February 10, 2023, Online

Keynote Speech

Overview on Rotorcraft R&D in Japan

Takashi Aoyama
Chairperson
Japan Helicopter Society

Program Director of Aviation Technology
Aviation Technology Directorate
Japan Aerospace Exploration Agency (JAXA)

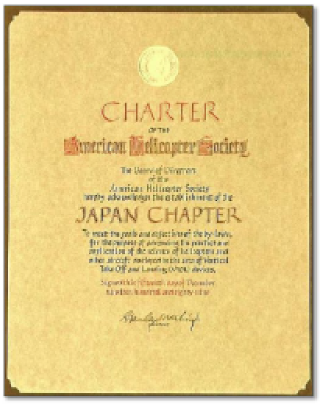
Outline

- Introduction of Japan Helicopter Society (JHS)
- Activities of Manufacturers
  - Kawasaki Heavy Industries (KHI)
  - SUBARU
  - Mitsubishi Heavy Industries (MHI)
  - Yamaha Motor
  - Yamato Transport
- Activities of Universities
  - Nagoya University
  - Kanazawa Institute of Technology
  - Shizuoka Institute of Science and Technology
- Activities of Research Institute
  - Japan Aerospace Exploration Agency (JAXA)

Japan Helicopter Society (JHS)

日本ヘリコプタ協会
Japan Helicopter Society

- Established in 1989 with the aim of contributing to the community of helicopter and VTOL, from R&D, design, testing, manufacturing to operation
- Approved as the Japan Chapter of the American Helicopter Society (AHS) since its foundation and evaluated as one of the most active chapters outside U.S.
- Members: researchers, engineers, pilots, government officials, journalists, trading company workers, students…
- Main activities: Asian Rotorcraft Forum (ARF)/Heli Japan, Japan Helicopter Safety Team (JHST), publication of annual report, research meetings …

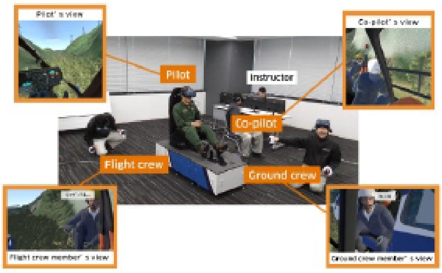


Kawasaki Heavy Industries


Delivery to National Police Agency

Delivery of H145/BK117 D-3

- The latest version of BK117 codeveloped with Airbus Helicopters
- 5 bladed, GW=3.8ton, ducted fan, Rotor dia.=10.8m
- T/C by JCAB in 2021
- 14 aircraft had been ordered by the end of 2022 in Japan



CRM training

CRM: Crew Resource Management

- CRM training services using a virtual reality (VR) simulator, intended to foster safer helicopter operations
- Training is intended to integrate not only the pilot, but also ground crew and other flight crew functioning in various capacities
- The goals include improving team communication, situational assessment skills and decision-making skills, which enable safer flight operations.

SUBARU BELL 412EPX: Civil version

SUBARU

SUBARU BELL 412EPX

- The latest version of BELL 412 codeveloped with BELL Helicopter
- T/C by FAA in 2018
- GW=5.5ton, Rotor dia.=14.02m
- 3 aircraft had been ordered by the end of 2022 in Japan

UH-2: Military version

UH-2 for Japan Ground Self Defense Force

- In 2015, Ministry of Defense selected SUBARU BELL 412EPX as a platform of UH-2, the successor of UH-1J
- Maiden flight of mass production model and delivery started in 2022
- 26 aircraft were procured by the end of 2022
- Total 150 aircraft will be delivered by 2041

Mitsubishi Heavy Industries

Patrol helicopter XSH-60L

- New helicopter based on the SH-60K for the Japan Maritime Self Defense Force with improved on-board systems and flight performance
- Maiden flight and delivery of prototype in 2021

CoasTitan™ Networked Security System with Uncrewed Vehicles

- Provides security solution with networked sensors and uncrewed aerial/surface/underwater vehicles
- UAV demonstrated its stable take off/landing capability on high-speed cruising ship in 2021

Yamaha Motor

FAZER R AP: New type of unmanned agricultural helicopter

- Automatic flight application "agFMS-IIH" installed
  to reduce workload for novice pilots
  to increase efficiency of pesticide/fertilizer spray operation

YMR-II: New type of industrial use multirotor YMR series

- Sales start in 2023 spring, ¥1,859,000
- Automatic flight application "agFMS-IIH" installed
- GW=24.9kg, Size=L1,970mm W2,157mm H786mm

FAZER R G2 with enhanced transportation capability

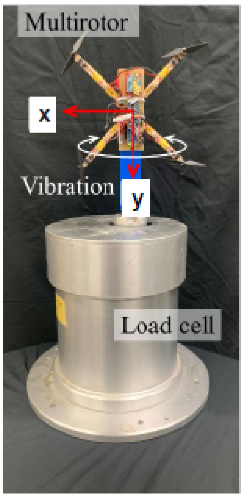
- Larger main rotor Dia.=3.115m ➡ 3.6m
  Payload 35kg ➡ 50kg
- For long distance automatic cargo transportation over unmanned area.

Yamato Transport

CycloRotors: mid-class cargo eVTOL

- Yamato Holdings Co., Ltd. + CycloTech GmbH (Austria) have successfully completed a joint feasibility study on applying a new thrust vectoring propulsion technology
- Key features for urban airborne logistic operations
  = compact in size
  + precision landing into confined areas (5 m in diameter)
  + handling quality of challenging wind conditions
  + transporting 45 kg payload over a distance of 40 km
- The unique characteristics of CycloRotors were used to design a mission optimized for unmanned cargo eVTOL.

Nagoya University



Stability derivative measurement of multirotor

- Stability characteristics of multirotor on hover conditions are studied analytically and experimentally.
- Especially, Mu and Mq are measured for analysis validation.
- Mq is measured with respect to q as shown in figure.

Vibration reduction by shifting c.g. position

- Analytical work by CAMRAD II demonstrated the effect without airframe instability.

Methodology to design multirotor type flying car

- JAXA developed rFlow3D and rNoise are utilized with aerodynamic performance and noise as evaluation function.

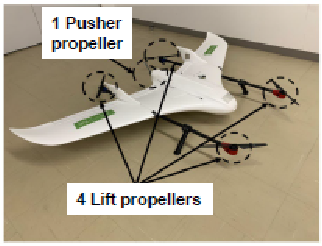
Aerodynamic interaction between rotor and wing when encountering crosswinds

- Studied by rFlow3D and wind tunnel test.

Kanazawa Institute of Technology

Aerodynamic interaction between rotor and wing

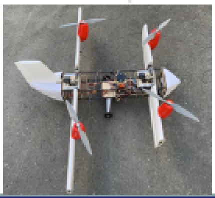
- Aerodynamic interaction of compound helicopter on hover and forward flight conditions are studied.
- Experimentally, 1m diameter radio-controlled helicopter with wing equipped with flaps is flight tested as shown in figure.
- It is shown that the flaps have favorable effect to reduce download during hover at the cost of diminishing roll damping.
- Analytical works are performed by JAXA developed rFlow3D.



Flying wing (tailless fixed wing) type drone

- Prototyped, flight-tested and dynamic model formulated.
- Stable hover capability is demonstrated by flight test.
- Dynamic analysis shows wing aerodynamic effect becomes favorably dominant to static/dynamic stability along with velocity increase.

Shizuoka Institute of Science and Technology



Downwash prediction by LMT (Local Momentum Theory) on hover

- Effective inboard blade plan form of YAMAHA FAZER to generate engine cooling airflow is studied by LMT.
- Analysis by LMT and wind tunnel test result had excellent agreement.

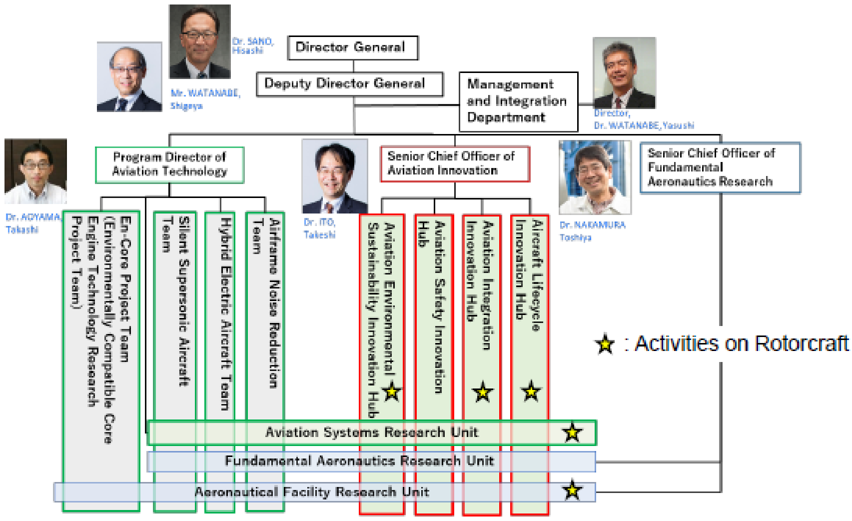
Optimization of multirotor arrangement by LMT

- Reducing aerodynamic interaction and airframe size is studied by LMT and validated by a test using rotors of YMR-08

eVTOL prototyping

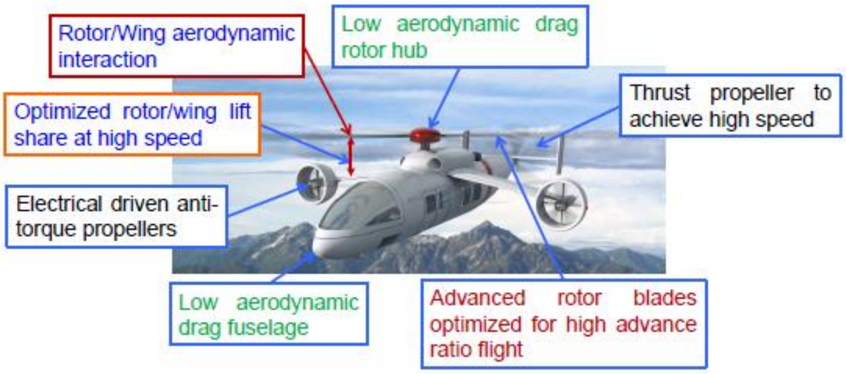
- Production design and prototyping for JAXA conceptual designed QTW
- Commercial "Pixhawk" is utilized for flight controller

Organization of JAXA ATD



JAXA: high-speed compound helicopter

Technical challenges for high-speed compound helicopter



Overview on Rotorcraft R&D in Japan, Aoyama, JHS, Japan-Korea Joint Workshop on Rotorcraft, Online 12

JAXA: SAVERH

SAVERH (Situation Awareness and Visual Enhancer for Rescue Helicopter)

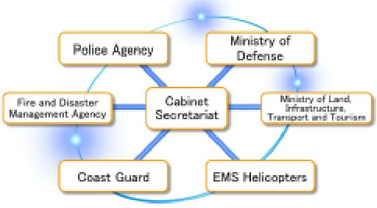
- Guaranteeing low altitude mission under the DVE (Degraded Visual Environment).
- JAXA together with Shimadzu Co. has been conducting joint research project aiming at inventing method of presenting suitable information to the pilot to support search and rescue missions in DVE.
- An integrated system comprising an HMD (Helmet Mounted Display) and a variety of image sensors were installed in the JAXA research helicopter.

Overview on Rotorcraft R&D in Japan, Aoyama, JHS, Japan-Korea Joint Workshop on Rotorcraft, Online 13

JAXA: D-NET

Disaster Relief Aircraft Management System – Network

- Enables safe and efficient disaster response
- Connects helicopters and ground operation centers/ headquarters
- Enables information sharing
  - Flight plans
  - Telemetry data (positions)
  - Disaster mission type (rescue, reconnaissance, etc.)

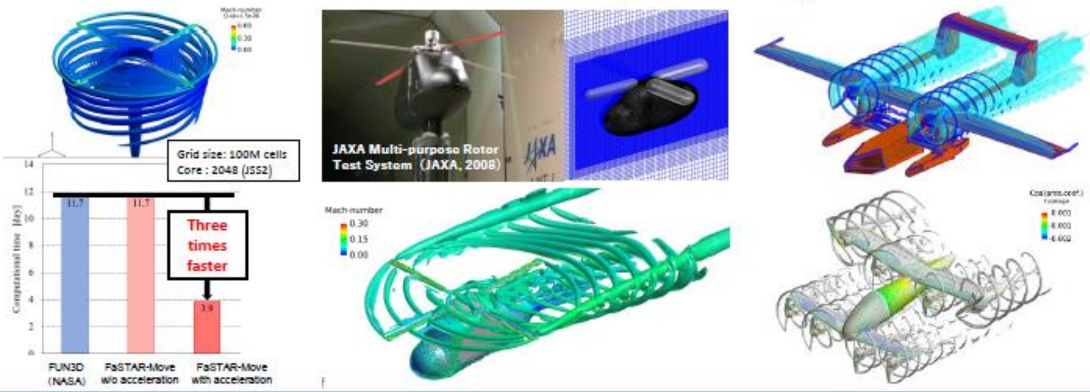


Adopted by the Japan Disaster Relief Agencies

- D-NET is adopted by most disaster relief agencies in Japan.
- D-NET enables intra-agency information sharing which contributes to efficient large-scale disaster response

Unstructured Based CFD Solver for Rotorcraft and its Applications

- JAXA has been devoted to developing a fast CFD solver, FaSTAR-Move (Fast Aerodynamic Routine-Move) in order to be applied complex shaped moving objects according to industrial needs.
- Recently, several rotorcraft simulations have been performed using FaSTAR-Move.



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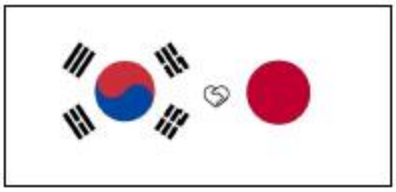
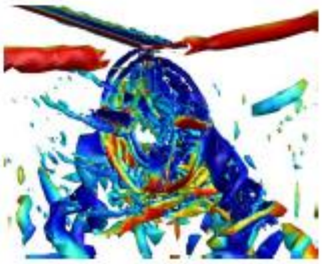


Japan-Korea Joint Workshop
on Rotorcraft
February 10, 2023, online

Simulation and design of propellers for a winged compound helicopter



〇Keita Kimura, Hideaki Sugawara, Yasutada Tanabe
(Japan Aerospace Exploration Agency(JAXA)

2023.2.10 1

Topics

1. Introduction
2. Methodologies
3. Results Summary
   3-1 Side propeller
   3-2 Tail propeller
4. Concluding remark

2023.2.10 2

Development of High-speed helicopter

Sikorsky Raider [1][2]

SB-1 DEFIANT [1][2]

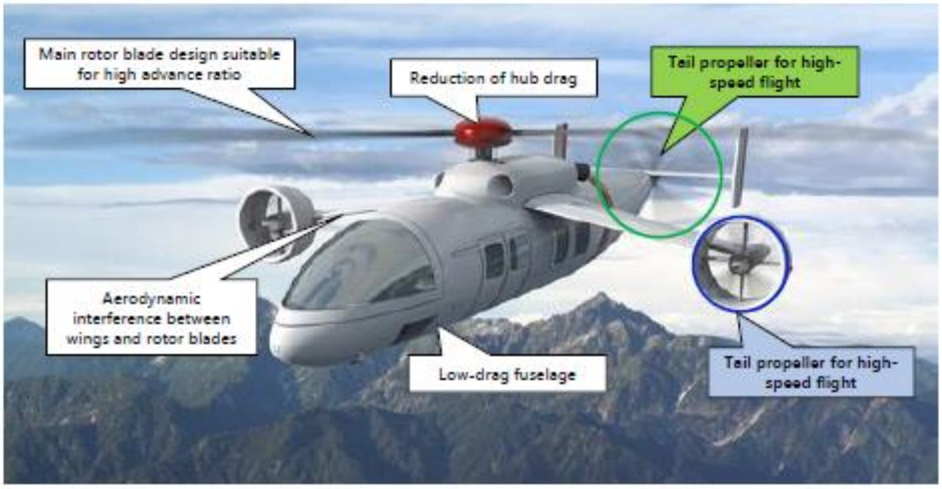
Airbus RACER[3]

JAXA conceptual compound helicopter [4]

- ✓ Compound helicopters with a fixed wing and propellers are promising way to higher speeds [1][2]
- ✓ In 2013, JAXA presented a concept for a compound helicopter that aims for a flight speed of 500km/h (fixed wing + side propellers + tail propellers)[4]

[1][2] "LOCKHEED MARTIN HP,". [Online].
[3] Airbus, "Airbus Helicopters reveals Racer high-speed demonstrator," 20 6 2017. [Online].
[4] Y. Tanabe, et al. "A Conceptual Study of High Speed Rotorcraft," 40th ERF, Southampton, UK, September, 2014.

Technical Issues

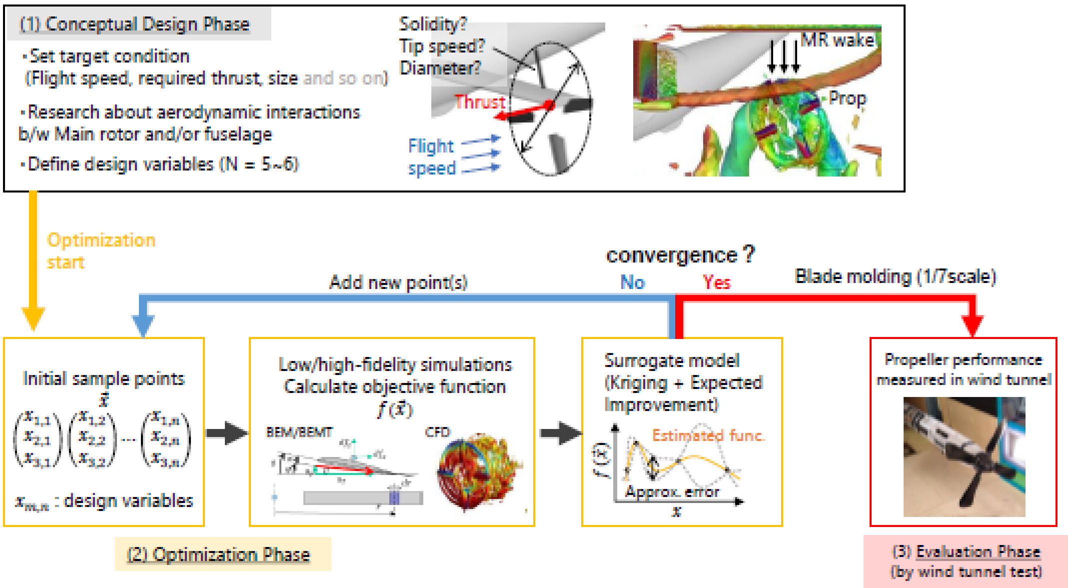


JAXA conceptual compound helicopter

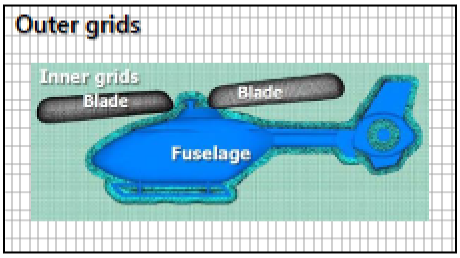
In this study, focus on <u>Side/Tail propeller design</u>

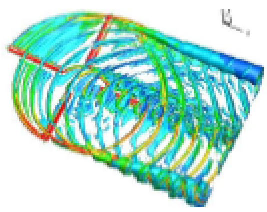
Overview for methodologies

Propeller design flow



CFD solver : rFlow3D





Numerical methodologies in this study

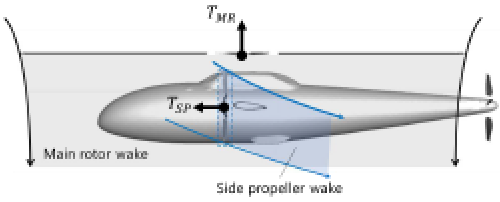
Governing equations	Three-dimensional compressible Navier-Stokes equations
Spatial discretization	Finite volume method
Time integration	4 stages Runge-Kutta (Background) Dual-time stepping, LU-SGS (Blade, Fuselage)
Viscous terms	2^{nd} order central difference method
Reconstruction	Structured grid : FCMT (Fourth-order compact MUSCL TVD) [9] Unstructured grid : MUSCL+Green-Gauss with Hishida's limiter
Advection terms	mSLAU (modified SLAU)

- ✓ Moving overlapped grid method provides a direct representation of the rotor blade motion
- ✓ Trim analysis function can reproduce various flight conditions such as analysis with target thrust maintained

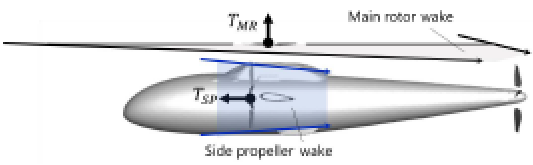
Side-propeller design note (1/2)

1. Aerodynamic interference with the downwash of the main rotor (especially when hovering)

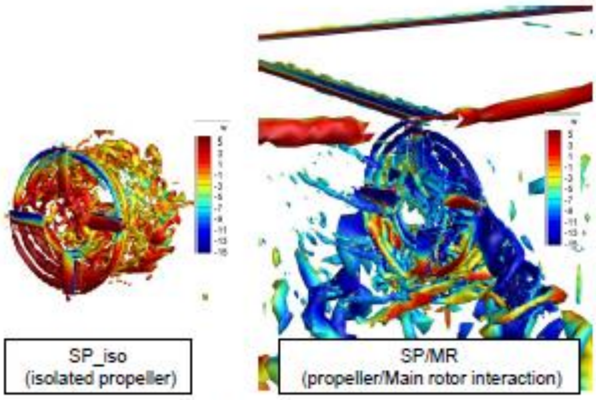
・Hover : having a major impact



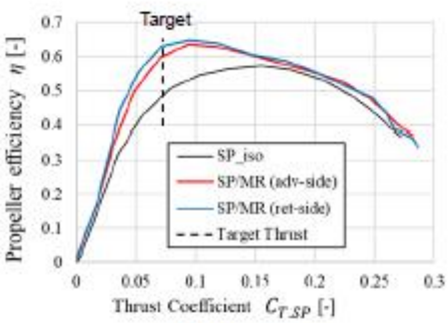
・Cruise : relatively small impact



Side propeller/ Main rotor interaction



Flow visualization



Thrust - efficiency

✓ CFD analysis under isolated propeller (SP_iso) and interference condition (SP/MR)

✓ In hovering, thrust increase due to wake interference > improved performance

Verification of propeller performance

Contents before making it into Paper

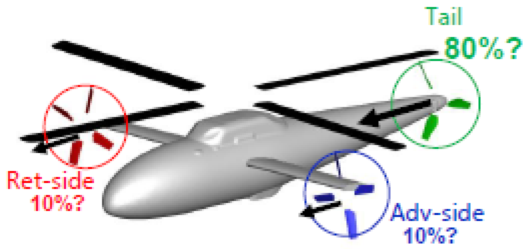
- ✓ Designed propeller made in 1/7 scale (RC helicopter scale)
- ✓ Wind tunnel test to confirm propeller performance
- ✓ Obtain Thrust/Torque to get propeller efficiency $\eta = \frac{TV}{Q\omega}$

⇒ <u>Confirmed significant performance improvement</u>

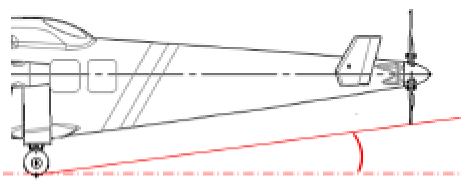
Difficulty in tail-propeller design

Points to note :

- ✓ Thrust large enough to balance fuselage drag at high flight speed (assuming 500 km/h)
- ✓ Thrust distribution between side props and tail prop (see figure)
- ✓ Aerodynamic interference with Main rotor/fuselage ?
- ✓ Sizing to avoid contact with the ground



Example of Thrust distribution
(different from the actual numbers)

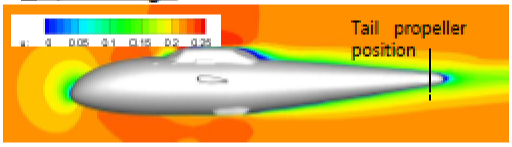


Some spacing between
propeller and ground

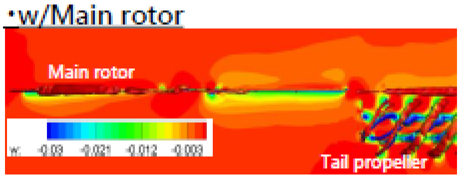
Aerodynamic Interactions

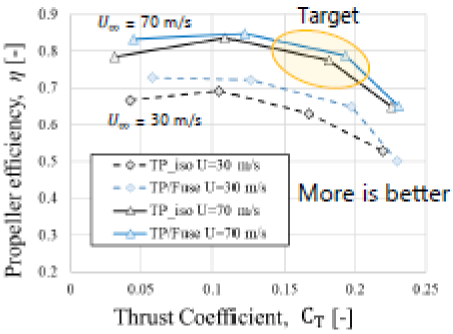
- ✓ 2 kinds of effects were investigated by using CFD
  - ✓ Fuselage/Tail propeller : positive effect on propeller efficiency
  - ✓ Main rotor/Tail propeller : small impact

・w/Fuselage

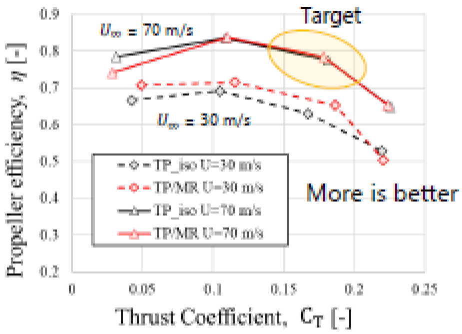


・w/Main rotor





Thrust – efficiency (w/&w/o Fuselage)



Thrust – efficiency (w/&w/o Main rotor)

Concluding remarks

An overview of JAXA's achivements on propeller design for high-speed compound helicopters is presented.

- **Side propeller**
  - ✓ CFD analysis confirms trend of increased thrust generated during hover (improved performance)
  - ✓ Presented a concept to enhance system performance by applying different shapes on the Adv-side and Ret-side propellers.

- **Tail propeller**
  - ✓ Confirm the effect of interference between the fuselage and the main rotor (Positive effect by fuselage interaction)
  - ✓ Propeller design for Full-scale application. Appropriate solidity and shape were obtained.

- **Future works**

  Flight test with RC helicopter equipped with opt-propellers to demonstrate performance improvement

1-3

teTra
aviation corp.

The Vision of the Flying Car World with Developing the eVTOL Mk-5

2023 VFS Online Workshop

Tasuku Nakai
tetra-aviation.com

1

Problem

Far destinations are hard for planning and travelling

Management of schedule

Its volatility relies on length, traffic and how much you know.

The path

Consuming time, energy and vital.
not the one way, not sustainable, and you get older.

No advice

There is sometimes no guideline,
because of the rare purpose and uniqueness.

2

Solution

A personal air mobility : PeVTOL

Jump over congestion
Non-stop as a private helicopter with more safety low-cost.

Electric Vertical take off and landing
With speed, sustainability and great view, without runway.

On your demand
Trip from your favorite, where never know, when you want.

3

Product

60 miles for 30 min.
Affordable Private mobility for any city surroundings.

Safety
Multiple redundancy for more safety with 1/2 cost.

Scalable production design
Old-fashion style production and repairing much easier.

Company Introduction

Tasuku Nakai
[CEO, Founder]

Hidemi Arai
[Director]

GoFly disrupter award team [2020 Feb.]

GO FLY
SPONSORED BY BOEING

Name	: teTra aviation corp.
Established	: 1st Jun. 2018
R&D in JP	: Tokyo, Saitama, Fukushima
in US	: California
Target	: USA Experimental aircraft
Team	: 16 (JP, KO, US, IN, CH)
Raised	: $ 5M

MS&AD 三井住友海上キャピタル
T-Tech TS TECH Co.,Ltd.
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DRONE FUND
三菱ガス化学
TOKO
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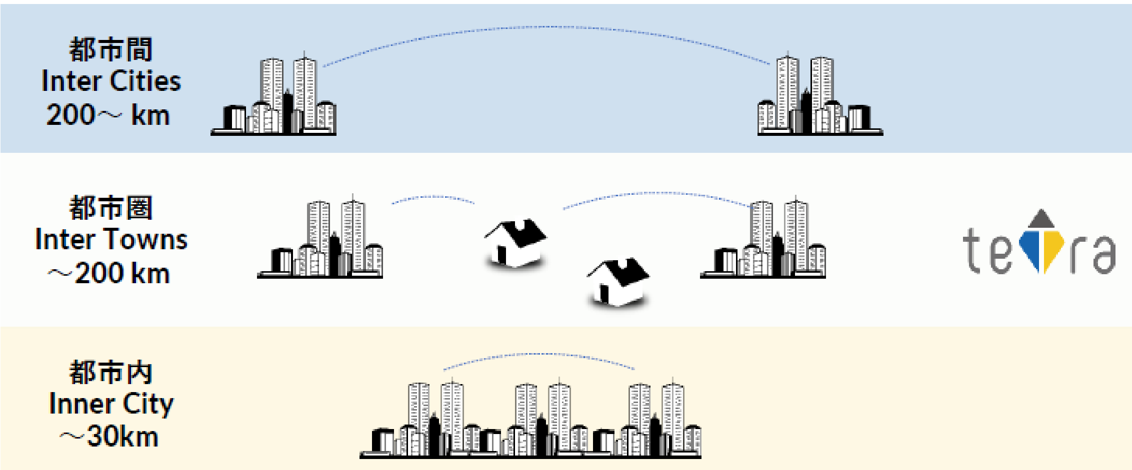
株式会社 吉増製作所 Yoshimasu Seisakusho Co., Ltd.
UCHIDA

5

Target range



6

Market

USA

2.4 Active U.S. General Aviation and On-Demand Part 135 Aircraft by Type (2000–2018) and Forecast (2019–2028)

		Airplane			Rotorcraft		Balloons, Dirigibles, Gliders	Experimental	Light-Sport Aircraft		
Year	Total Aircraft	Piston	Turboprop	Business Jet	Piston	Turbine			Total	Experimental	Special
2018	212,885	143,040	9,925	14,596	3,082	6,907	4,114	27,531	-	3,580	2,554

JAPAN

4.4 Japan—Number of Aircraft by Type (2000–2019)

Year	Airplanes					Rotorcraft		Gliders	Airships	Total Aircraft
	Piston		Turboprop		Turbojet or Turbofan					
	Single-Engine	Multi-Engine	Single-Engine	Multi-Engine		Piston-Engine	Turbine-Engine			
2018	502	56	50	99	662	168	657	645	1	2,840

Source: Civil Aviation Bureau (航空局), www.mlit.go.jp

General Aviation Manufacturers Association 2019 DATABOOK 8

US Market circumstances

NEWS

US Senate supports advanced air mobility legislation

Monday March 28, 2022

Aviation associations are applauding a new U.S. legislation focused on creating policies, procedures, and programs to support future eVTOL operations in the country.

https://evtol.com/news/us-senate-supports-advanced-air-mobility-legislation/?fbclid=IwAR15AN2f1jOmagnYt5Vv1oqf1euvqEgKfdX1Y612E3Ug7dnFnlONeJicl

NEWS

New bill would ban non-essential helicopter flights over New York City

This has been going on for far too long, residents say

June 16, 2022 Mary Frost

A helicopter. Photo by Don Evans

https://brooklyneagle.com/articles/2022/06/16/new-bill-would-ban-non-essential-helicopter-flights-over-new-york-city/?fbclid=IwAR1jLv7gtp_Yd7OSJDhMKUo85BrEvpG9fDZAtT4t-_K6arUmO4TJYrqsNQ

9

Product Development Plan

Experimental KIT eVTOL

Personal Desire creation and Researching Data
- Conceptual flight model
- Single-seater
- Owner/purchasing only
- Factory build: JPN(Kit) -> USA(ASSY) -> Customers
- Experimental homebuilt category

Production eVTOL

Reflection from KIT as a type certified market product
- Service flight model
- Two-seater
- Owner to Service level
- Autonomous flight function
- Type design certified by FAA
- Development start from 2023-

1. Recreational

2. Industrial

3. Commercial

10

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Thank You

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https://www.tetra-aviation.com/

1-5

Aerodynamic Interference Analysis between Propeller/Wing for High Performance Electric Aircraft Using FaSTAR-move

〇Shota Taniguchi (ISAS/JAXA),
Kanako Yasue (JAXA), Ryota Fukuchi (SUBARU),
Atsushi Shinozuka, Akira Oyama (ISAS/JAXA)

1

Electric aircraft

Alternative means of transportation

- eVTOL aircraft

Eco-friendly airplane

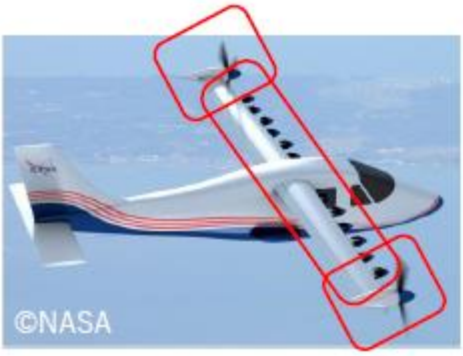
- Airplane with DEP

- Airplane with BLI

Propeller layout for electric aircraft
3

Propeller layout taking advantage of
aerodynamic interference between propeller/wing

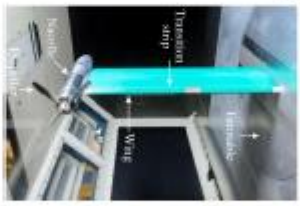
- **Wingtip mounted propeller**
- **Distributed electric propulsion (DEP)**



Research on aerodynamic interference
4

Wingtip mounted propeller

Experiments show smaller drag than mid-span mounted configuration.



[Sinnige et al., 2019]

eVTOL with distributed electric propulsion (DEP)

Experiments show complex aerodynamics due to propeller.

[Geuther et al., 2020]

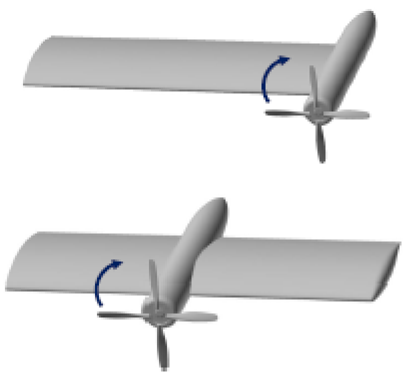
Lack of understanding of how propellers change the aerodynamic characteristics of the fixed-wing.

5

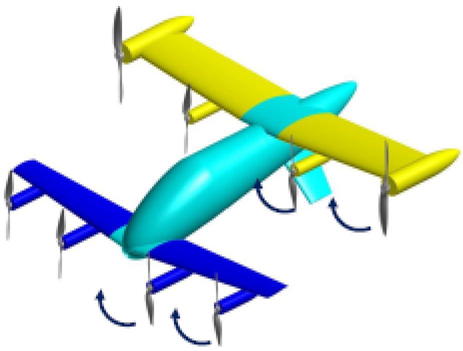
Objective

- Clarify the mechanism by which propellers change the aerodynamic characteristics of a wing.
- Verify the URANS accuracy of predicting aerodynamic characteristics of propeller and fixed-wing .

1. Tip-mounted propeller



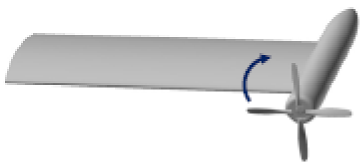
2. eVTOL with DEP



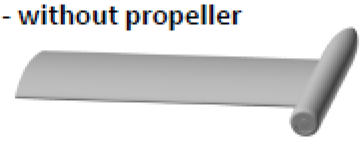
Tip-mounted propeller Analytical model

6

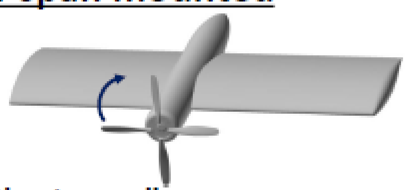
Tip-mounted



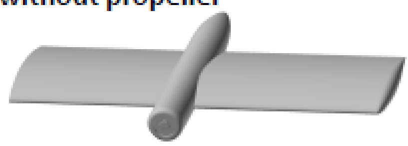
- without propeller



Mid-span mounted



- without propeller



Flow conditions

※Same as Sinnige et al., 2019

Reynolds number	Re_c [-]	640,000
Mach number	M [-]	0.11
Angle of attack	α [deg]	2.0, 6.0
Propeller advance ratio	J [-]	0.7

Computational settings

7

Numerical methods

Unsteady RANS using overset mesh

solver : FaSTAR MOVE

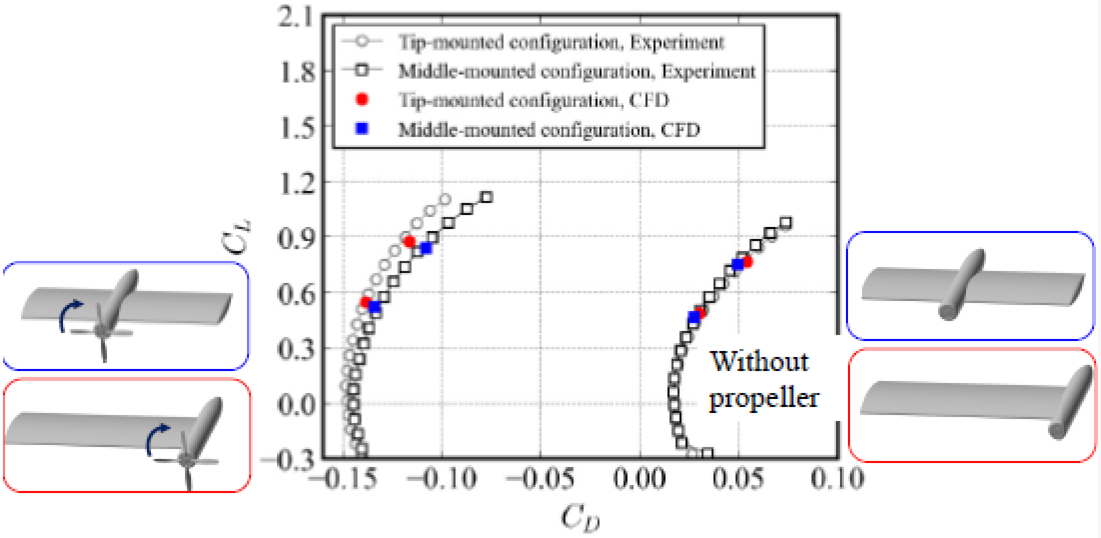
Governing equations	3D compressible Navier-Stokes equations
Time integration	LU-SGS
Convection terms	SLAU
Reconstruction	MUSCL
Turbulence model	SA-noft2

Computational grid

Consists of fixed-wing grid and four propeller blade grids

Comparison of URANS and experiment

8

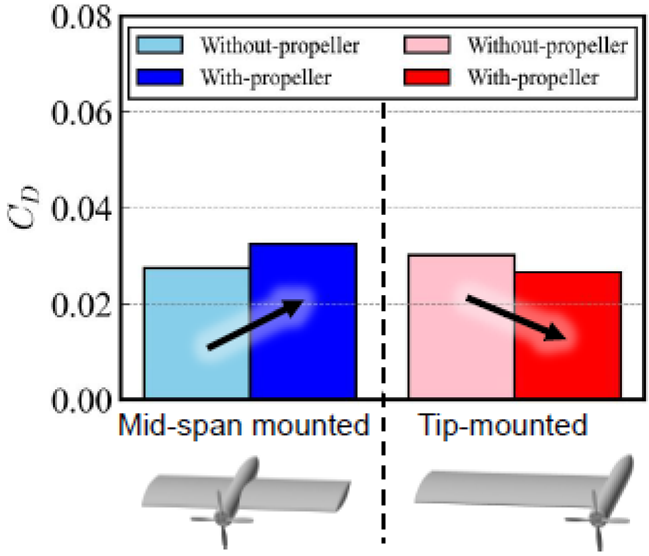


The results of URANS and experimental results are in good agreement.

Propeller effect on drag coefficient of wing and nacelle

9

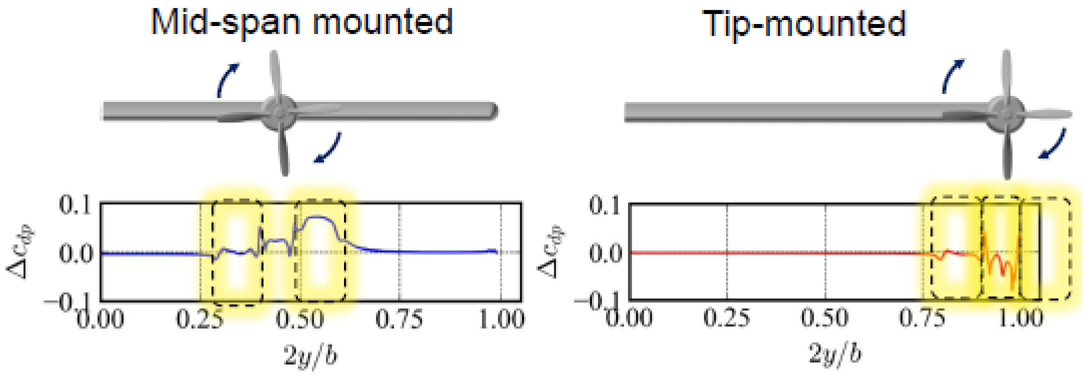
AOA=2 [degree]



Mid-span mounted propeller increases C_D of wing and nacelle, while tip-mounted propeller decreases that.

Propeller effect on drag distribution

10



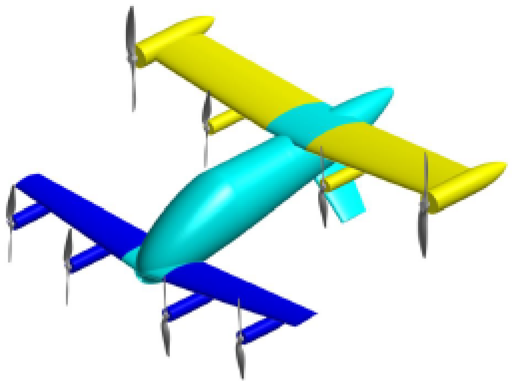
$$\Delta c_{dp} = c_{dp} - c_{dp\ without\ propeller}$$

- Propeller downwash increases c_{dp} .
  ➡Larger C_D for mid-span mounted configuration
- Tip-mounted propeller decrease c_{dp} of the nacelle.
  ➡Smaller C_D for tip-mounted configuration

eVTOL with DEP analytical model

11

Tandem tilt-wing aircraft model



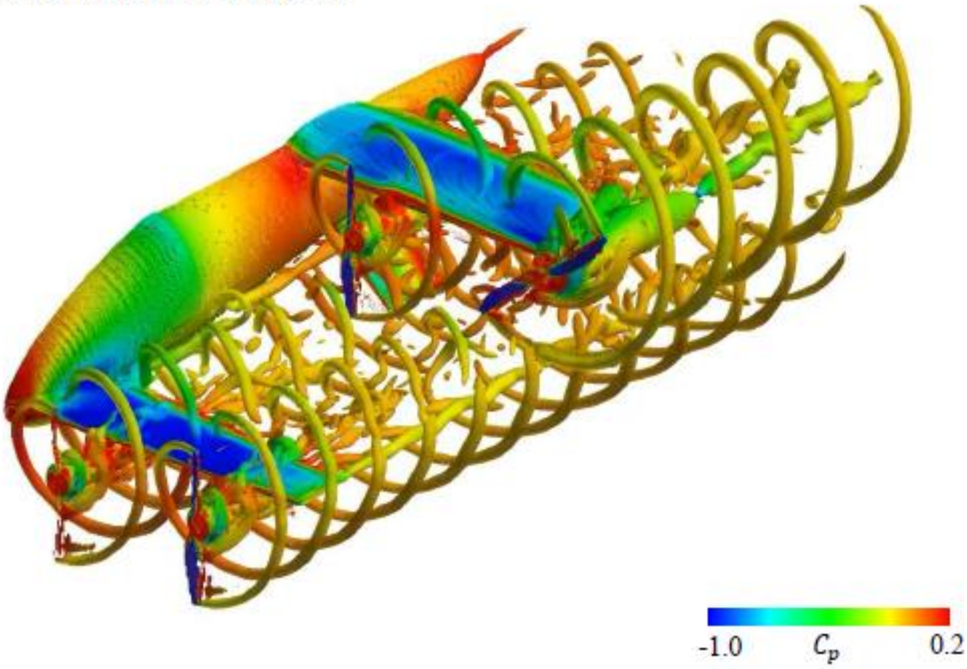
	AR [-]
後翼	5.45
前翼	7.96

Reynolds number	Re_{MAC} [-]	260,000
Mach number	M [-]	0.044

Flow field obtained by URANS

12

Angle of attack is 4 degree



Summary

We conducted URANS for the wingtip-mounted propeller and eVTOL with DEP to clarify the propeller effect and validate prediction accuracy.

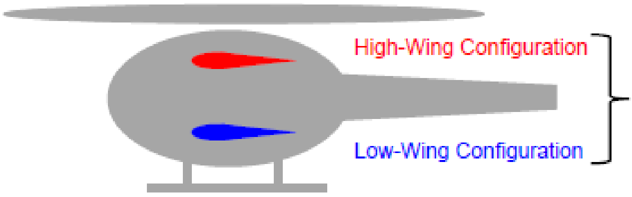
Wingtip-mounted propeller

- There was a good agreement in C_L, C_D with the experiment.
- URANS confirmed drag reduction of the wing.

eVTOL with DEP

- With respect to C_L, there was qualitative agreement on the propeller effect on the stall with experiment.
- There was a quantitative agreement on the pressure coefficient with experiment.

Effect of Wingspan on the Trend of Download for Winged Helicopters in Hover



Which is more efficient for hovering ?

Experimental Research

Shunsaku ARITA, Noriaki ITOGA
National Defense Academy

Background

Winged helicopter has long been studied for enhancing maneuverability or high-speed flight.

Background

There are high and low-wing configurations for winged helicopters

High-Wing Configuration

https://vtol.org/qr/march-2012

https://www.airbus.com/en/who-we-are/our-history/helicopters-history/x3

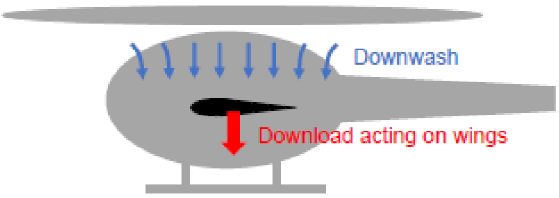
Low-Wing Configuration

https://en.wikipedia.org/wiki/Piasecki_16H_Pathfinder

https://www.popsci.com/technology/bell-360-invictus/

Background

One problem with winged helicopters

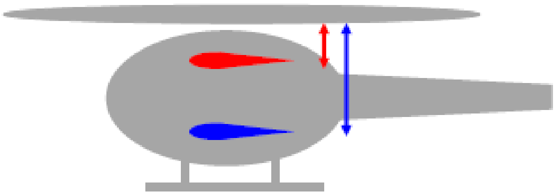


Low-speed flight
or
Hovering

Studies (including for tiltrotors) have been conducted to reduce wing downloads.

These researches are summarized in the paper (Sugawara et al. 2020)

Background



The distance between the rotor and wing affects the hovering performance

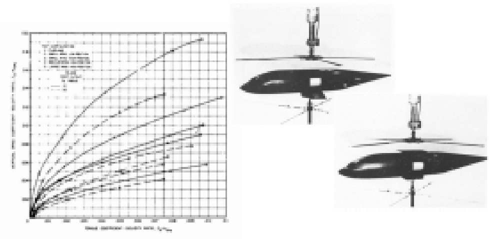
High-wing configuration is more efficient for hovering!

Low-wing configuration is more efficient for hovering!

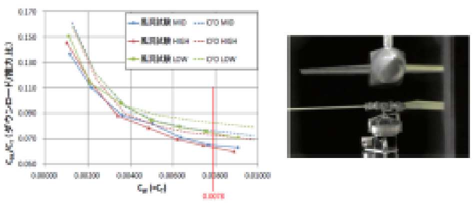
There is no unified view…
It is worthwhile to examine!

Background

High-wing configuration is better(smaller download)



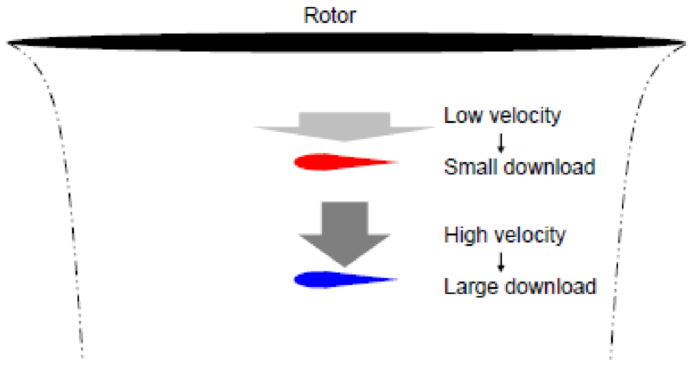
Cassarino, 1970



Kobayashi et al., 2019

Background

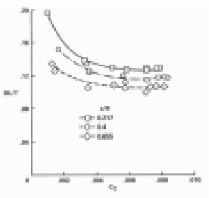
High-wing configuration is better(smaller download)

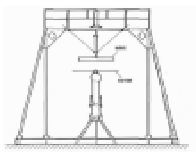


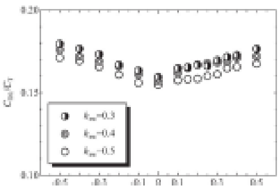
Explanation by momentum theory

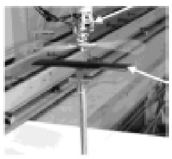
Background

Low-wing configuration is better(smaller download)







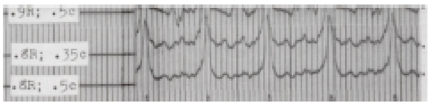


Felker and Light, 1988

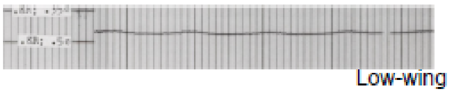
Nakashima and Itoga, 2018

Background

Low-wing configuration is better(smaller download)



High-wing



Low-wing

Time history of pressure on the wing surface
(Makofski and Menkick, 1958)

Explanation by periodic load

Background

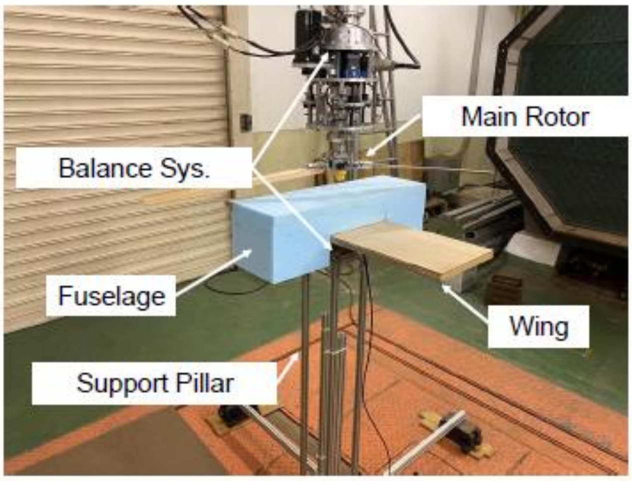
Experimental conditions of previous studies

	High-wing is better		Low-wing is better	
	Cassarino,1970	Kobayashi et al., 2019	Felker and Light, 1988	Nakashima and Itoga, 2018
Fuselage	**exist**		**none**	
Wingspan (ratio to rotor diameter)	**0.50 (Relatively short)**	**0.61 (Relatively short)**	**0.75 (Relatively long)**	**0.79 (Relatively long)**

Objectives of this research

- Confirming if the relationship between the download and rotor-wing distance is reversed by the existence of fuselage or changing wingspan.
- If it is reversed, consider the cause of it.

Experimental Apparatus



Details of Rotor	
Rotor Radius	569mm
Blade Chord	60mm
Airfoil	NACA0015
Twist	None
Number of blades	2
Hinge offset	17mm
Root cutout	113mm

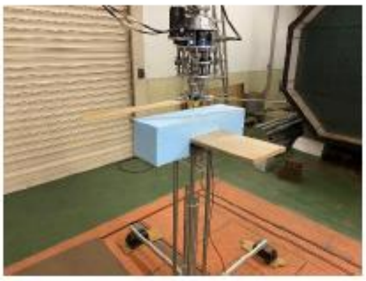
Details of Fuselage	
Length	644mm (1.13R)
Width	189mm (0.33R)

Details of Wing	
Span	897mm(0.79D), 569mm(0.5D)
Cord	242mm (0.43R)

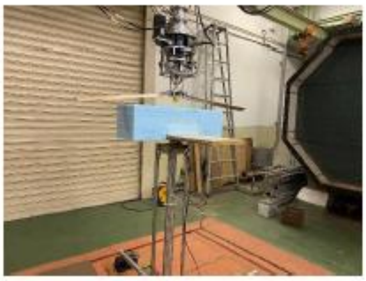
12

Experimental Conditions

z/R=0.2



z/R=0.3

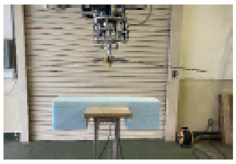


z/R=0.4

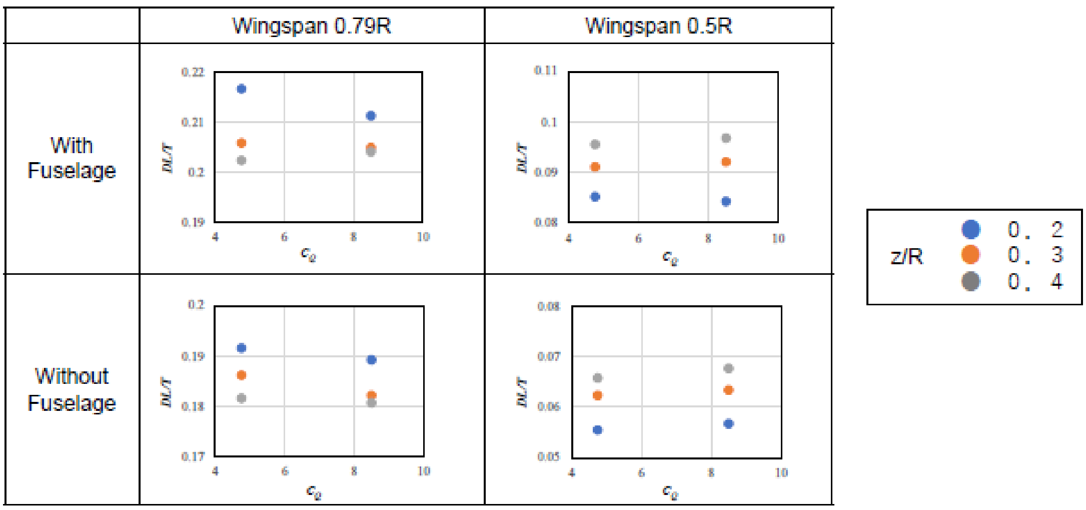
z: Distance between rotor and wing
R: Rotor radius

13

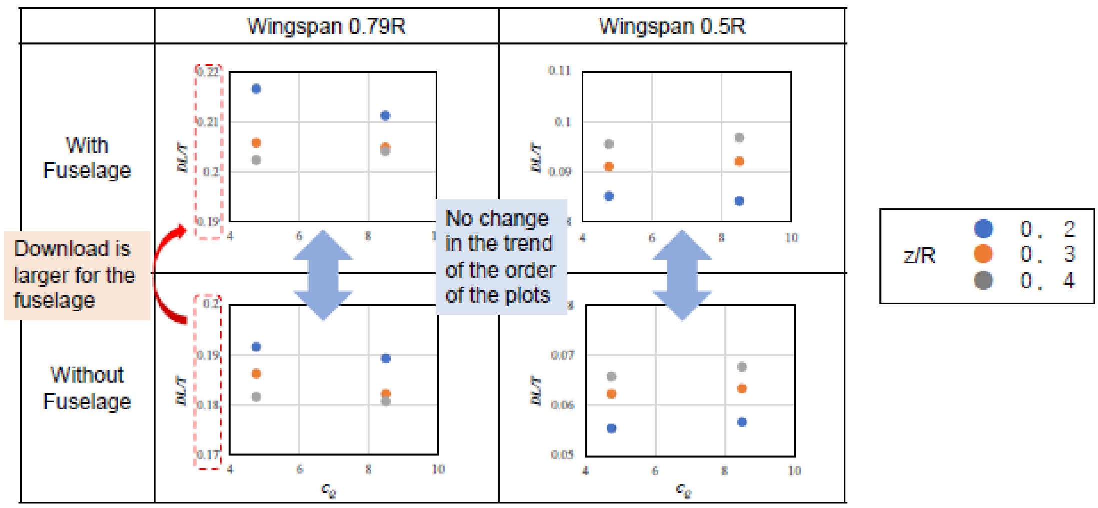
Experimental Conditions

Rotor operating torque	Wingspan	With or without fuselage
$C_Q = 4.75 \times 10^{-4}$ (Corresponding to approximately $C_T = 5 \times 10^{-3}$)	 0.79R	
$C_Q = 8.5 \times 10^{-4}$ (Corresponding to approximately $C_T = 8 \times 10^{-3}$)	 0.5R	

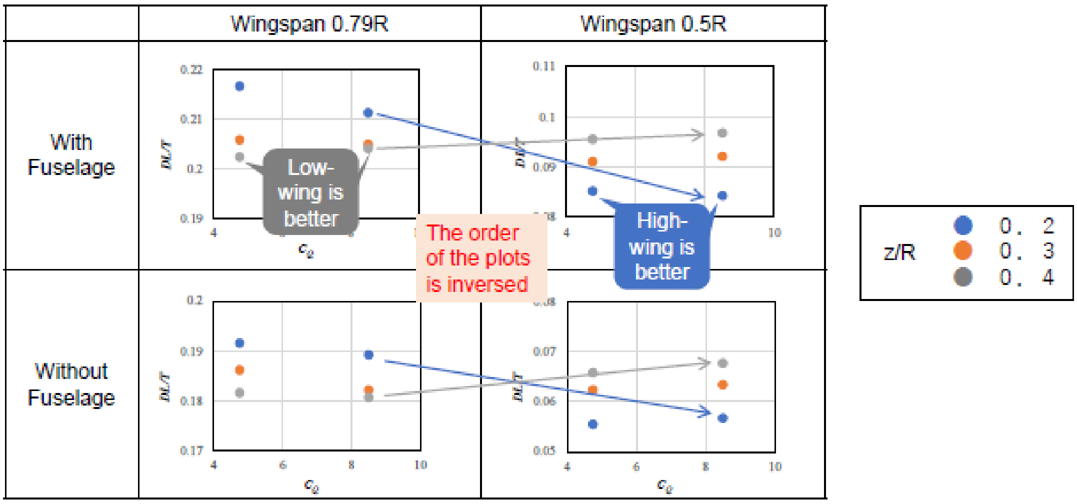
Results



Results



Results

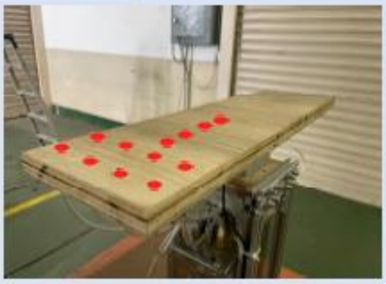


Verification and Discussion

Details of Rotor	
Rotor Radius	360mm
Blade Chord	60mm
Airfoil	NACA0015
Twist	None
Number of blades	2
Hinge offset	17mm
Root cutout	113mm

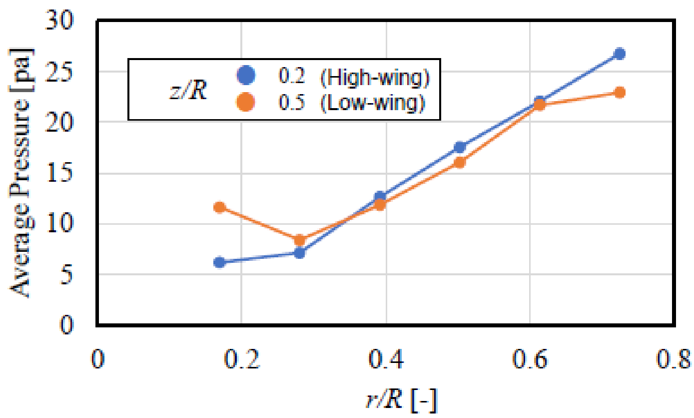
Details of Wing	
Span	582mm(0.81D)
Cord	157mm(0.44R)

$C_Q = 4.75 \times 10^{-4}$
Corresponding to Approximately $C_T = 7 \times 10^{-3}$



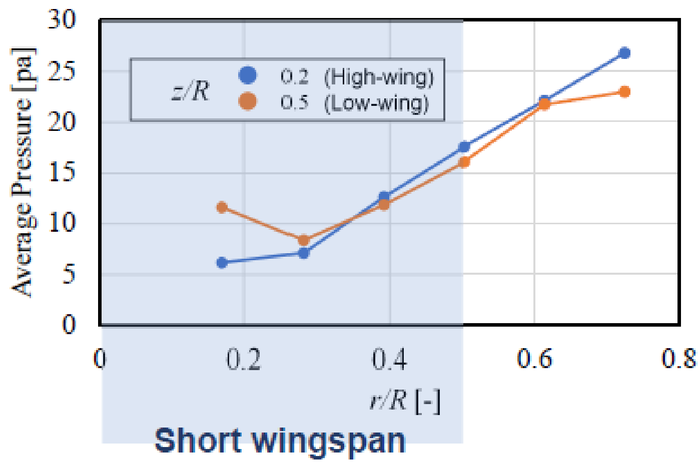
● Pressure ports

Verification and Discussion

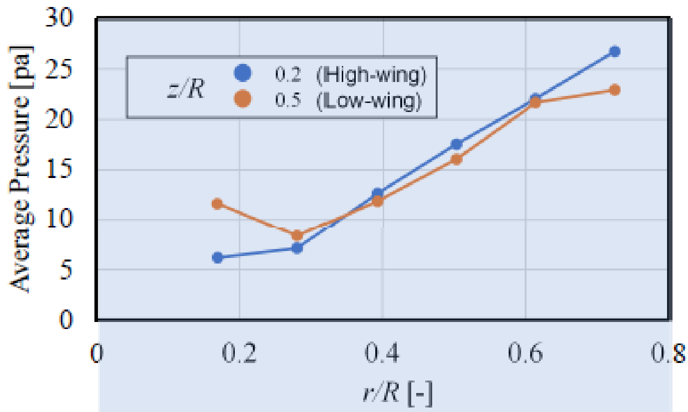


r: Distance from the rotor center
R: Rotor radius

Verification and Discussion

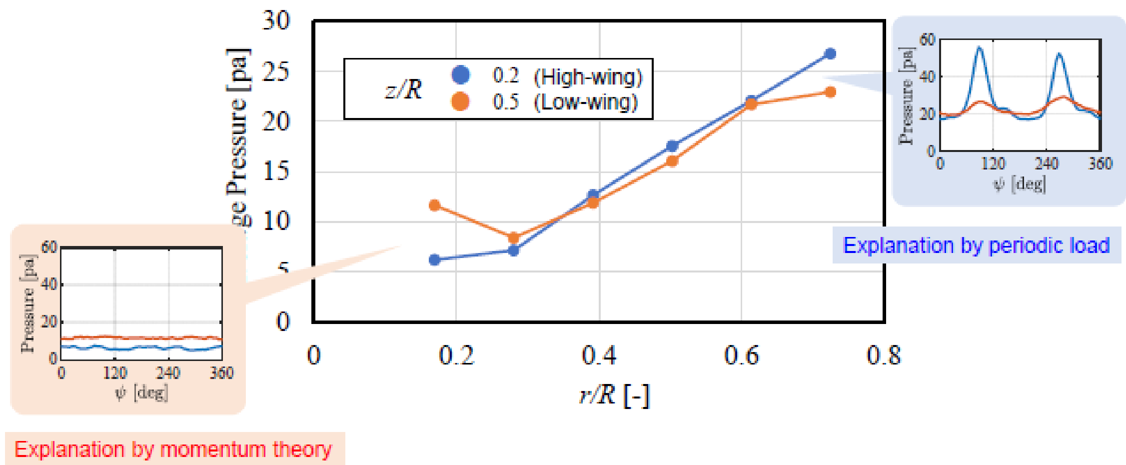


Verification and Discussion



Long wingspan

Verification and Discussion



Conclusion

- Download of winged helicopter in hover is experimentally investigated.
- There are both cases where the download becomes larger and smaller as the rotor-wing distance increases.
- The download trend was inversed by changing wingspan; it can at least partially be explained by mixing the momentum theory and periodic load.

MOVE THE WORLD FORWARD MITSUBISHI HEAVY INDUSTRIES GROUP

2023 Online Workshop on Rotorcraft between Japan and Korea

2023.2.10

Mitsubishi Heavy Industries, Ltd.

MITSUBISHI HEAVY INDUSTRIES

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Analysis of Rotorcraft Vibration Reduction Using a Center-of-Gravity Offset

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Shigeru Sunada
Dept. of Aerospace Engineering, Nagoya University

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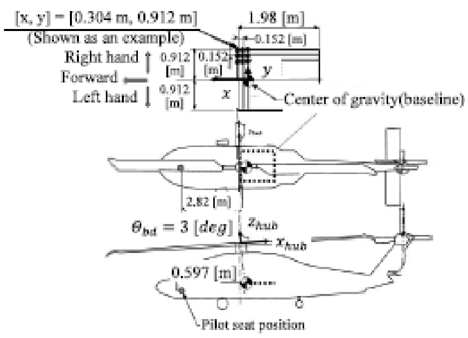
Introduction

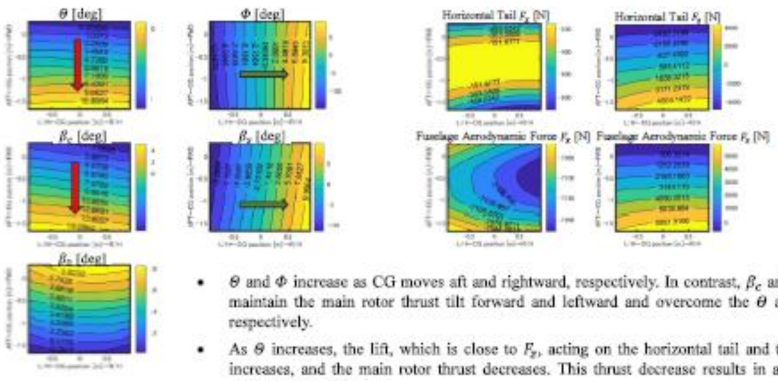
- Rotorcraft suffers from high level of vibration especially during high-speed cruise flight.
- So called “N/rev” vibration is dominant, various efforts have been made such as passive vibration absorbers, active vibration devices.
- The passive absorbers weighs a lot, the active devices are expensive.
- Intentional offset of CG from the right below a main rotor hub is introduced.
- CAMRAD II analysis was conducted to verify how vibration changes and why.

Baseline Helicopter

- The middle-sized rotorcraft , SH-60K, was chosen to conduct the analysis.
- CAMRAD II trim calculations were conducted at 182 CG locations including the baseline CG as [x, y]=[0,0] when the rotorcraft was cruising at 61.7 [m/s] (120[kt]).
- The fuselage was deemed as a rigid body.
- Free wake method was employed.

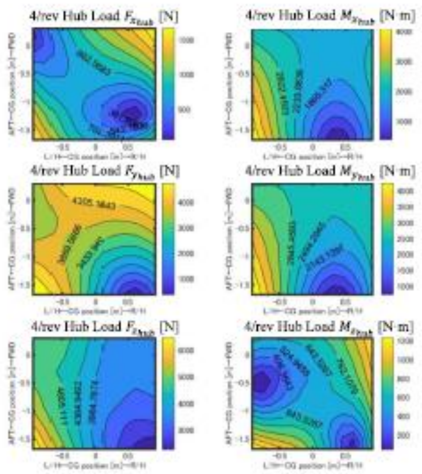


Trim analysis results(vehicle attitude, flapping angle fuselage forces)



- Θ and Φ increase as CG moves aft and rightward, respectively. In contrast, β_c and β_s increase to maintain the main rotor thrust tilt forward and leftward and overcome the Θ and Φ increases, respectively.
- As Θ increases, the lift, which is close to F_z, acting on the horizontal tail and the fuselage also increases, and the main rotor thrust decreases. This thrust decrease results in a decrease in the coning angle β_0 as well.
- As the difference in Θ from 5 deg increases, the drag, which is close to $-F_x$, acting on the horizontal tail and the fuselage increases and decreases, respectively. Θ is expected to relate to the angle determined by the downwash of the main rotor and the cruise speed. Moreover, $-F_x$ acting on the fuselage is not strongly affected by the increase in Φ.

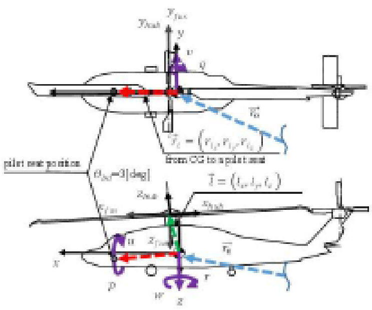
Trim analysis results(main rotor hub forces and moments)



- The 4/rev vibration is dominant relative to other harmonic vibrations, where a rotor with four blades is considered.
- The magnitude of the 4/rev vibration is shown, the phase is also obtained for each force and moment.
- The moments are expected to be small by considering the moment of inertia of this fuselage.
- Each load component at the MRH has its own minimum value at a different specific CG location.

Where should CG be positioned to obtain the minimum vibration?
"Maybe RHS AFT, But…"

Pilot seat acceleration



- Derived 4/rev vibratory forces and moments are substituted into the Euler EOM.
- u, v, w, p, q, r are numerically solved.
- The 4/rev pilot seat acceleration is also derived.

➢ Euler EOM

$$m(\dot{u} + qw - rv) = F_x$$
$$m(\dot{v} + ru - pw) = F_y$$
$$m(\dot{w} + pv - qu) = F_z$$
$$I_x\dot{p} - I_{yz}(q^2 - r^2) - I_{zx}(\dot{r} + pq) - I_{xy}(\dot{q} - rp) - (I_y - I_z)qr = M_x$$
$$I_y\dot{q} - I_{zx}(r^2 - p^2) - I_{xy}(\dot{p} + qr) - I_{yz}(\dot{r} - pq) - (I_z - I_x)rp = M_y$$
$$I_z\dot{r} - I_{xy}(p^2 - q^2) - I_{yz}(\dot{q} + rp) - I_{zx}(\dot{p} - qr) - (I_x - I_y)pq = M_z$$

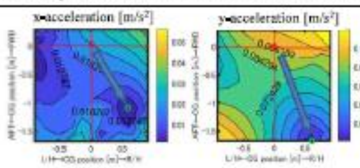
➢ Pilot seat acceleration

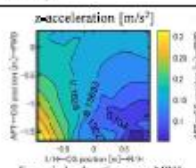
$$\vec{a} = \frac{d^2\vec{r_0}}{dt^2} + \frac{d^*\vec{\omega}}{dt} \times \vec{r_i} + (\vec{\omega} \cdot \vec{r_i})\vec{\omega} - (\vec{\omega} \cdot \vec{\omega})\vec{r_i}$$

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} \dot{u} + qw - rv + r_{i_y}(pq - \dot{r}) + r_{i_z}(pr + \dot{q}) - r_{i_x}(q^2 + r^2) \\ \dot{v} + ru - pw + r_{i_z}(qr - \dot{p}) + r_{i_x}(pq + \dot{r}) - r_{i_y}(p^2 + r^2) \\ \dot{w} + pv - qu + r_{i_x}(pr - \dot{q}) + r_{i_y}(qr + \dot{p}) - r_{i_z}(p^2 + q^2) \end{bmatrix}$$

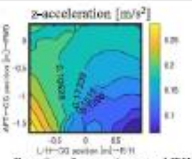
 7

Results(The 4/rev Pilot seat accelerations)

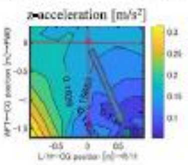


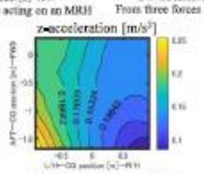


From six loads acting on an MRH



From three forces acting on an MRH



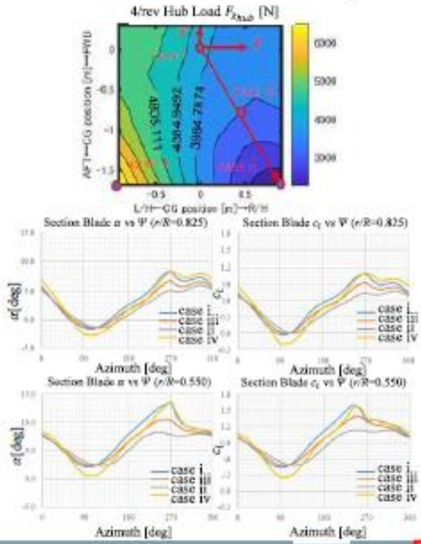


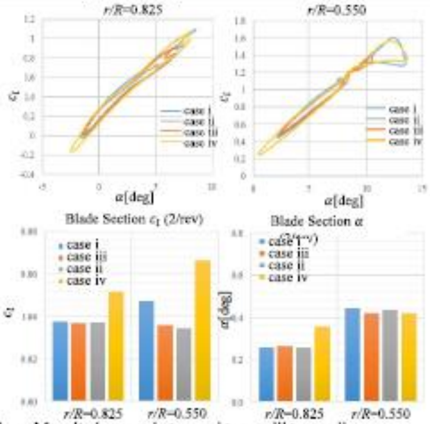
From $F_{z_{hub}}$ acting on an MRH

- Each x-, y-, and z-acceleration component reaches its own minimum value at each different CG position, but generally, every component decreases as the CG moves toward the right side and backward.
- A pilot inherently has physical characteristics to feel mainly the z-acceleration. In addition, the plots show that the z-acceleration at the pilot seat position is dominant in contrast to the x- and y-acceleration. The z-acceleration reaches no more than 40% of its baseline value.
- The pilot z-acceleration contour plots caused by six loads and by three forces are similar, which means that the 4/rev moments have small influences on pilot z-acceleration. In addition, the z-acceleration contour plot caused by the 4/rev $F_{z_{hub}}$ force is also similar to those caused by six loads and by three forces, which means that the $F_{x_{hub}}$ and the $F_{y_{hub}}$ have small influences on pilot z-acceleration. The 4/rev force $F_{z_{hub}}$ itself can become the simplest vibration index.

 8

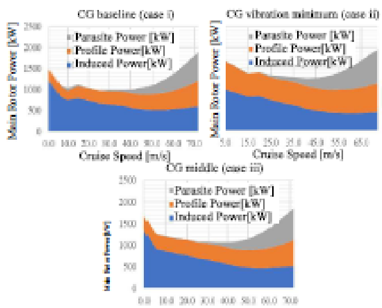
Insight into 4/rev F_{zhub} vibration force

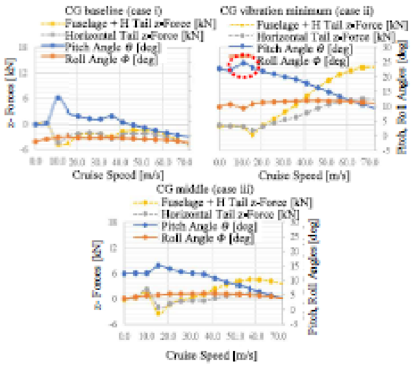




- F_{zhub} Magnitude : case iv > case i > case iii > case ii
- The $c_l(\Psi)$ azimuthal plots are not proportional to the $\alpha(\Psi)$ plots.
- The hysteresis of $\alpha - c_l$ plot was observed due to dynamic stall.
- the order of the 4/rev F_{zhub} among the four cases agrees with that of the amplitudes of the 2/rev $c_l(\Psi)$.

Main rotor power and trim attitude





- Especially, in hover, the total powers in (cases ii, iii) are 30% and 10% larger than that in (case i), respectively.
- The differences in the total power among these cases in a high cruise speed flight are smaller than those at hover.
- The maximum pitch angle of 23 deg for (case ii) is not acceptable for a pilot.

Conclusions

- Main rotor hub 4/rev vibration forces and moments were calculated with CAMRAD II when CG is intentionally offset from the baseline position.
- The z-directional acceleration was dominant and reached at least 40% of the baseline value.
- The dynamic stall influences the order of the 2/rev $c_l(\Psi)$ and that the order is in accordance with that of the 4/rev F_{zhub}.
- By considering degradation of 30% increase in hovering power, CG should be positioned within case iii. At that point, we can still obtain 20% vibration reduction.
- It should be easier to accomplish CG offset for a light-weight single rotor eVTOL than to do it for heavy preexisting rotorcraft.

References

1) Yoshizaki.Y., and Sunada. S., "Analysis of Rotorcraft Vibration Reduction Using a Center-of-Gravity Offset," Trans. Jpn. Soc. Aeronaut. Space Sci., 66, (2023) pp. 1–9.

3-1

Japan-Korea Joint Workshop on Rotorcraft
February 10, 2023, Online

Advanced Compound Helicopter Research and Development

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Aviation Technology Directorate
Japan Aerospace Exploration Agency (JAXA)

Outline

- Background and objectives
  - History and recent developments of compound helicopters
  - A conceptual study of high-speed compound helicopter at JAXA
- Technology Issues related to high-speed compound helicopters
  - Optimal rotor design for high advance ratio flight
  - Rotor/Wing Interaction and Single-rotor Lift-offset
  - Rotor/Propeller Interaction
  - Low drag fuselage
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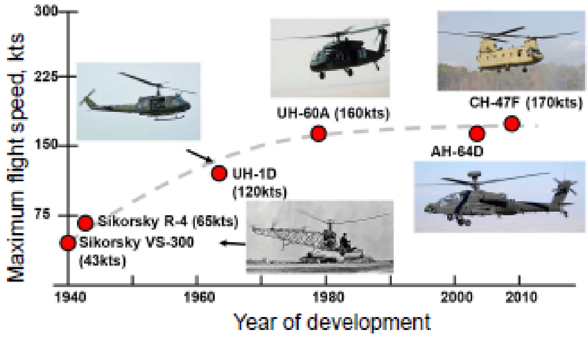
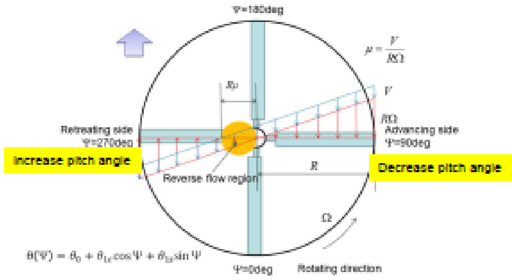
Background: the conventional helicopter performance limitation



Conventional helicopter maximum flight speed history



Inflow to the rotor blade and control of the rotor blade pitch angle

History of Compound Helicopters

Fig. 2-5. The Fairey Rotodyne was successfully developed, but British Government and civil funding eroded in the late 1950s. This was the largest compound helicopter ever flown. Its maximum advance ratio was below 1.

Fig. 2-4. The McDonnell Aircraft Corp., Helicopter Division's XV–1 Convertiplane. At maximum speed, the rotor operated at an advance ratio just below 1.

Lockheed AH-56 Cheyenne
Development: 1966-1972, 215kt, mu~0.52

Fig. 2-9. The DARPA funded Groen Brothers Heliplane is expected to reach 400 mph with the rotor operating at an advance ratio near 2.

Ref) Harris

Recent Developments of High-Speed Rotorcraft

Bell-Boeing V-22 Osprey
Development: 1982-1997;
In production: 1997~,
max 275 kt, cruise 241 kt

Sikorsky X-2
Development: 2008-2010, max 250 kt, mu~0.65

Airbus Helicopters X3
Development: 2010-2013, max 255 kt, mu~0.7

On-going Developments of Compound Helicopters

Sikorsky S-97 Raider
Vne 240 kt, Cruise 220 kt
In test flight

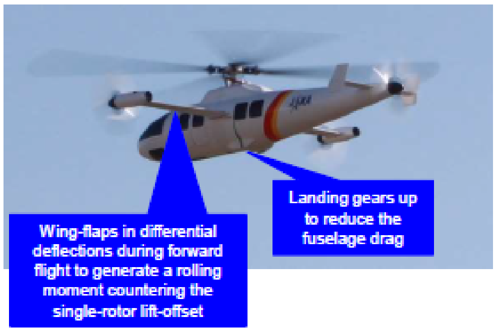
Airbus Racer
Cruise 217 kt ?
First flight expected in 2022

A Concept of Compound Helicopter Proposed by JAXA

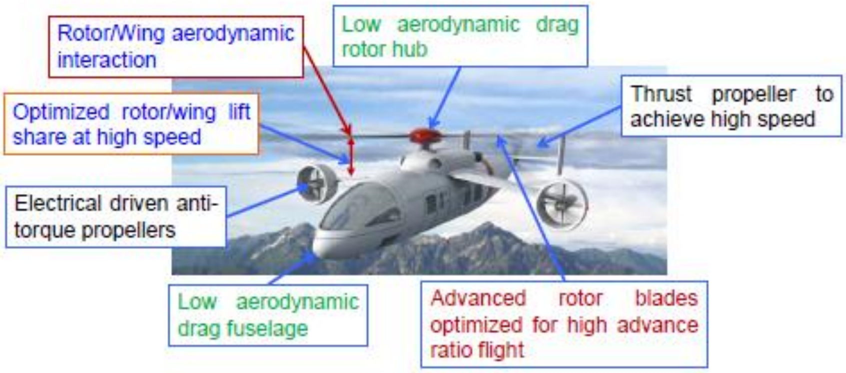
- Designed for EMS of 4 ton class
- Electric driven anti-torque propellers at wing-tips
- Aft-mounted pusher propeller
- Target max speed: 500km/hr (270 kts)
- Max advance ratio, mu=0.8

Ref) Tanabe Y, Aoyama T, Kobiki N, Sugiura M, Miyashita R, Sunada S, Kawachi K, and Nagao M, ***A conceptual study of high speed rotorcraft***, 40th European Rotorcraft Forum, Southampton, UK, Sept. 02-05, 2014.

Additional Design Features



Technology issues for high-speed compound helicopter



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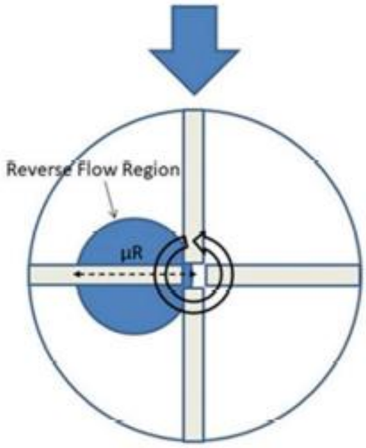
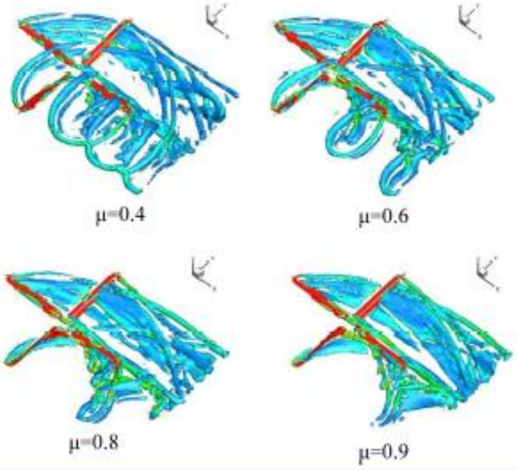
JAXA

Optimal Rotor Design for High Advance Ratio Flight

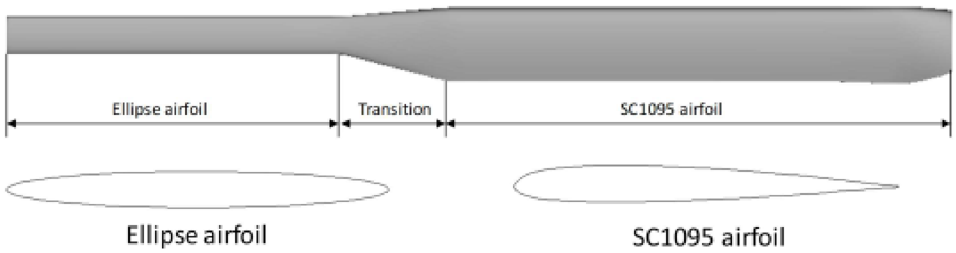


Reversed flow region at high advance ratio

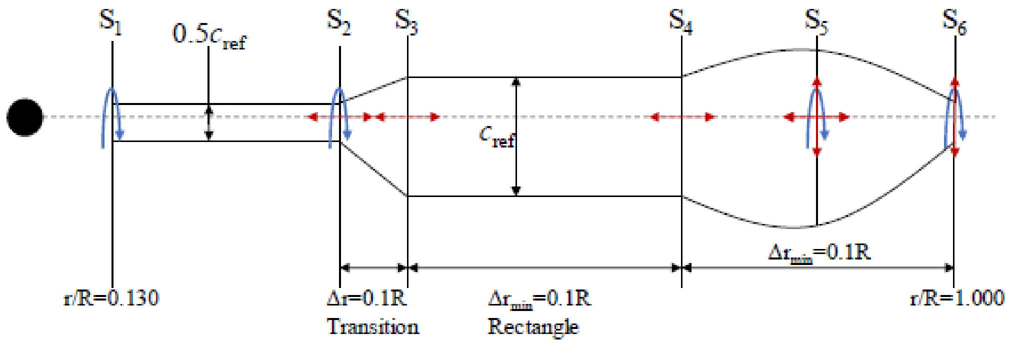


JAXA

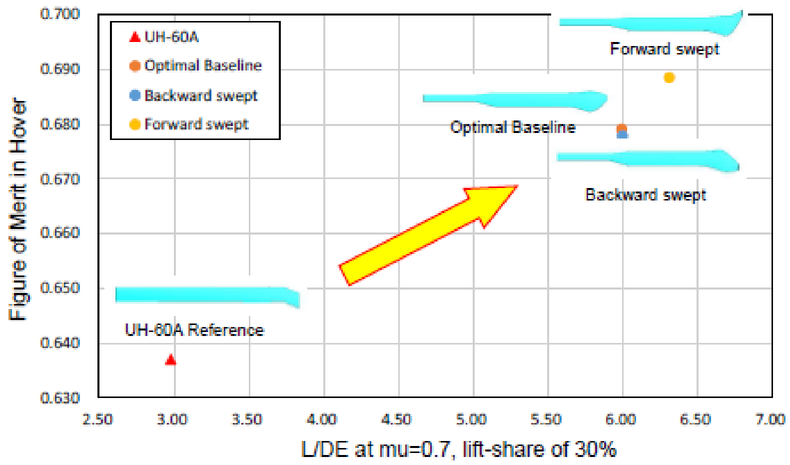
Large root-cut blade design for high-mu flight



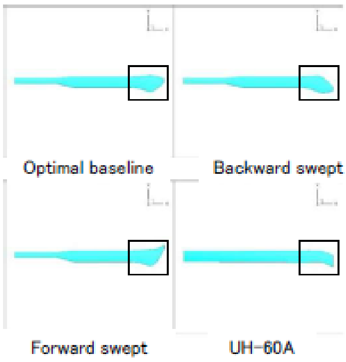
Design variables for chord and twist



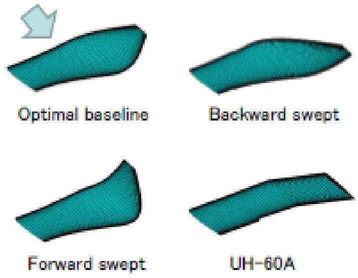
Optimal rotor for flight at mu=0.7, effect of swept angle



Wind-tunnel testing of the tip portions

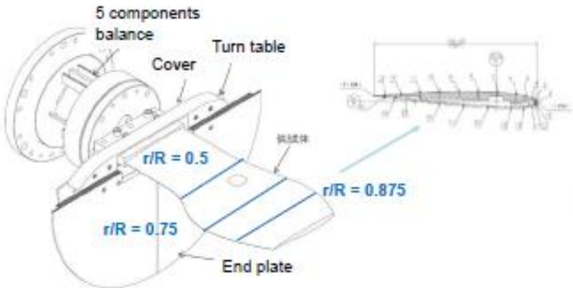


Portion of blade tips (20%) are picked up

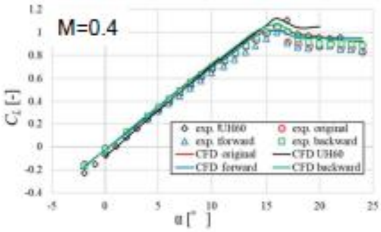


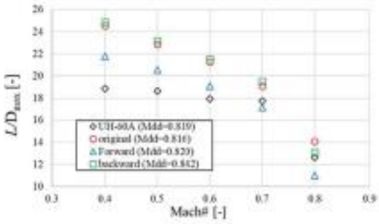
Blade-tip models

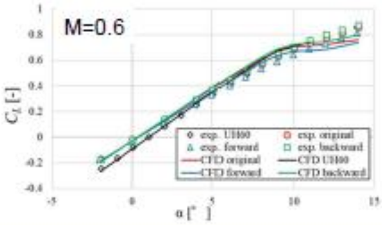
About 1/2 scale



Aerodynamics of blade tips

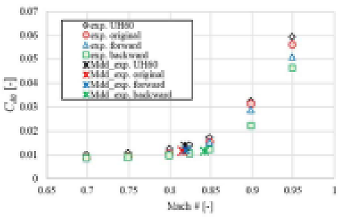






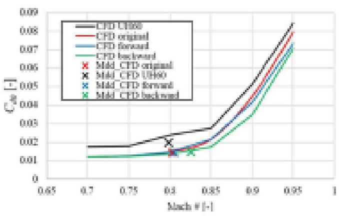
Ranking of L/Dmax at M=0.6:
1) Backward
2) Baseline
3) Forward
4) UH-60A

Drag divergence Mach number of blade tips



	Mdd (exp.)	Mdd (CFD)	Swept Back Angle
Baseline	0.82	0.80	0.0°
Backward	0.84	0.83	-30.5 °
Forward	0.82	0.81	25.3°
UH-60A	0.82	0.80	20.0°

Mdd: dCd/dM>0.1



Ranking of Mdd:
1) Backward
2) Forward
3) Baseline
4) UH-60A

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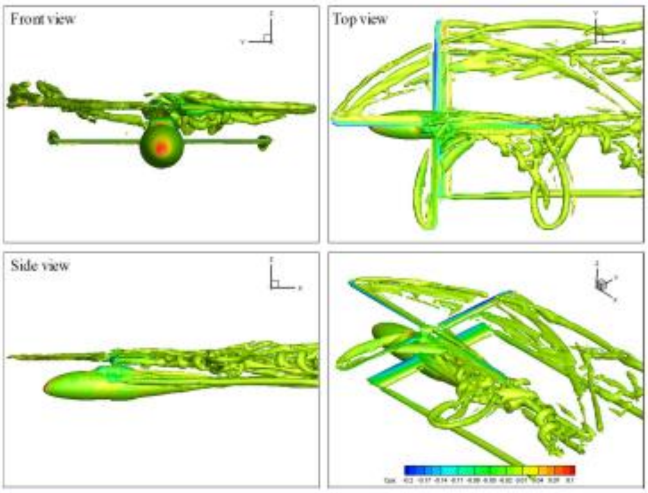
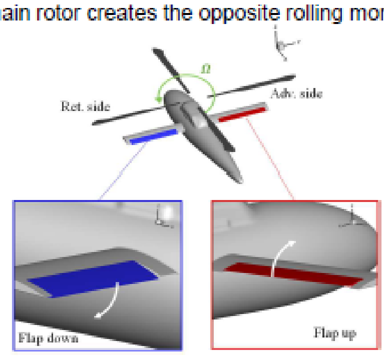
Rotor/Wing Interaction

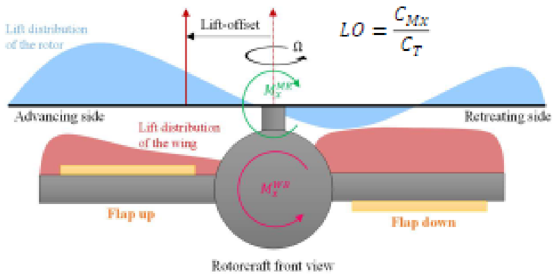


Single-Rotor Lift-Offset System

- Proposed differential flap system
  - Deflect upward under the advancing side, and deflect downward under the retreating side
    - ➢ Generate an imbalance of lift on the left and right wings resulting in a rolling moment
  - Expected to obtain a large rolling moment by small flap deflections
    - ➢ Occur rolling moment due to aerodynamic interaction

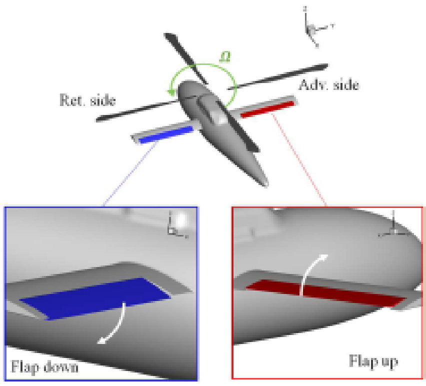
- The main rotor creates the opposite rolling moment and results in a single-rotor lift-offset state.

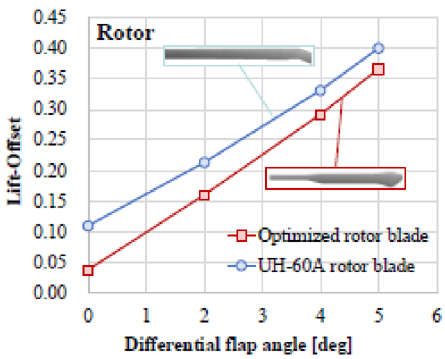




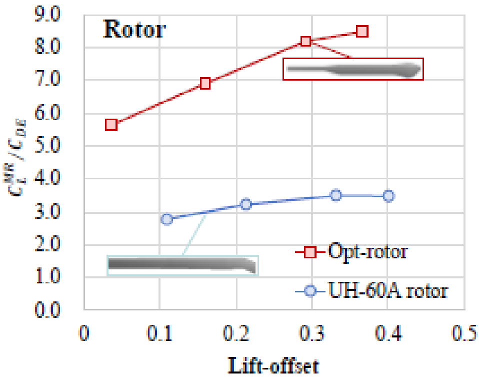
Lift-Offset by the Differential Flaps

- Obtain the maximum lift-offset values at the differential flap angle of 5 deg
- Arise the lift-offset due to the aerodynamic interaction even with zero flap deflection
  - ➢ Cause the effect of aerodynamic interaction on the wing with different type of rotors



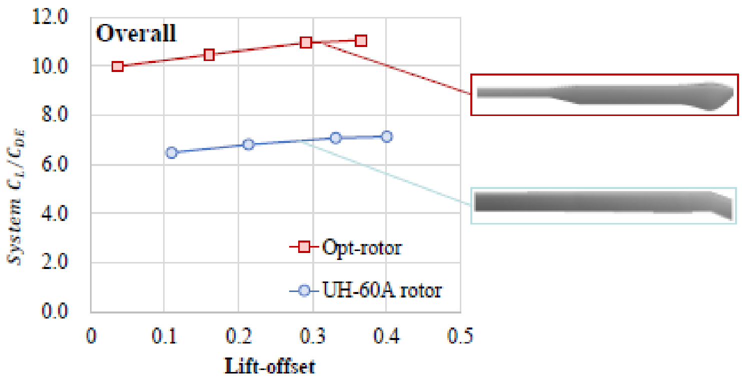


Effect of Lift-Offset on Rotor Performance



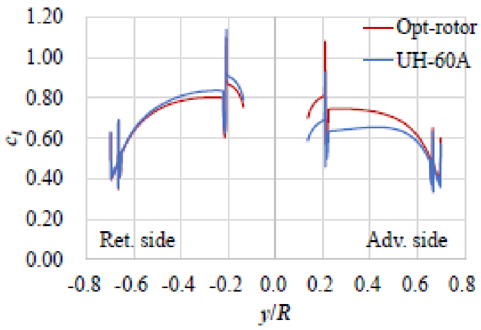
- Opt-rotor
  - Provide higher aerodynamic performance, approximately two times of the UH-60A rotor
  - Enhance by approximately 50% at the lift-offset of 0.37 compared with zero flap deflections
- UH-60A
  - Improves 25% at the lift-offset of 0.40 compared with zero flap deflections

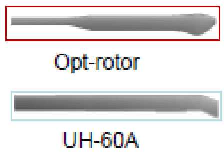
Overall Performance



- The lift-to-drag ratio increases by 10% compared with zero flap deflections
- The opt-rotor is higher than the UH-60A rotor.
- The combination of improved rotor performance through optimization and lift-offset technology by the differential flap system can further enhance the overall aerodynamic performance.

Sectional Lift Distributions on the Wing





- Both rotors reduces the sectional lift on the wing under the advancing side.
  - UH-60A rotor causes stronger aerodynamic interaction.
- Under the retreating side, the sectional aerodynamic performance of the wing with the opt-rotor reduces partially than with the UH-60A.
  - The induced velocity distribution from the rotor around the wing is different between the rotors.

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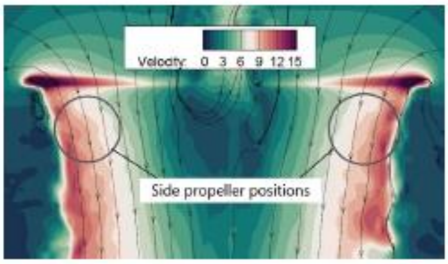
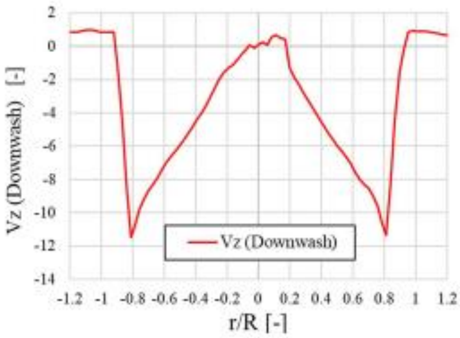
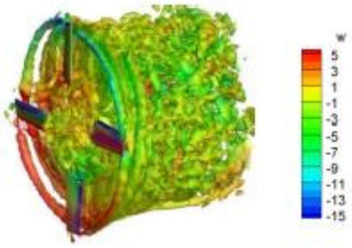
Rotor/Propeller Interaction

Downwash from the main rotor in hover

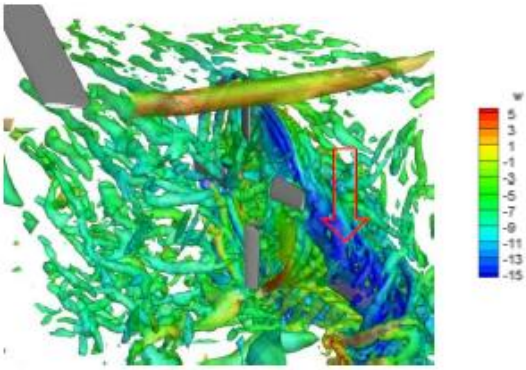




Flowfields of Rotor/Propeller Interaction



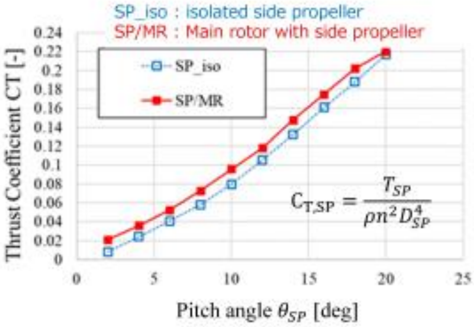
Isolated propeller

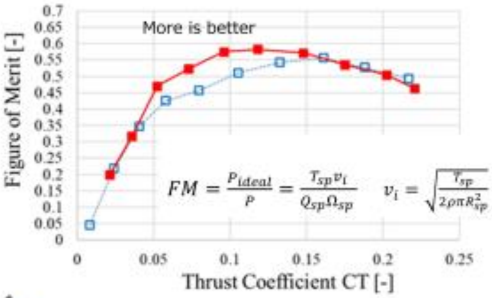


Rotor/Propeller Interaction

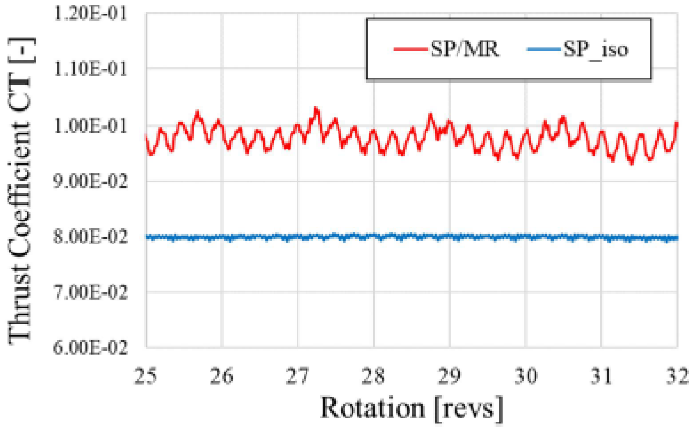
Performance of side propeller

SP_iso : isolated side propeller
SP/MR : Main rotor with side propeller





Side propeller thrust fluctuations with/without the main rotor



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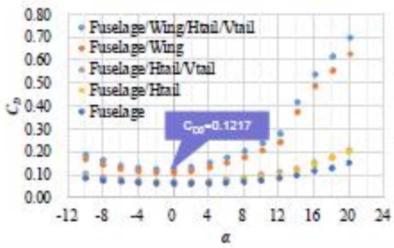
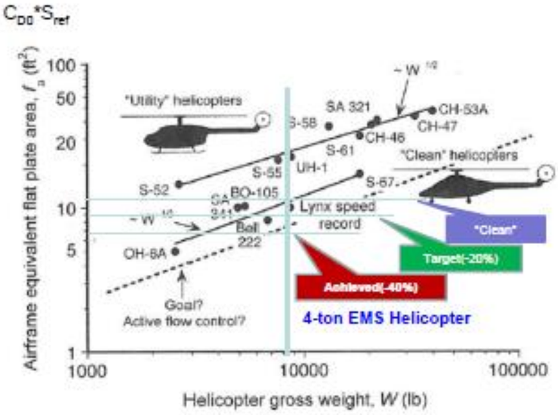
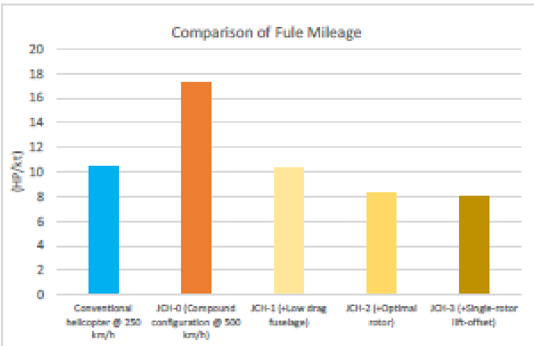
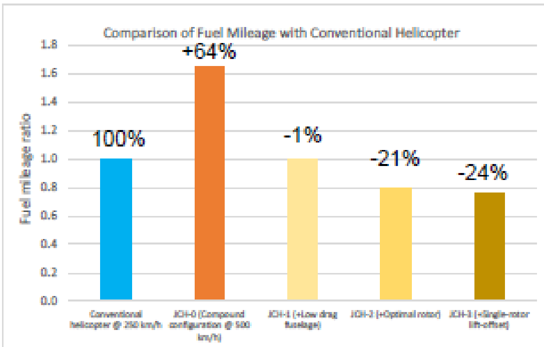
Low drag fuselage design





Realization of a high-efficiency compound helicopter through applying the advanced technologies

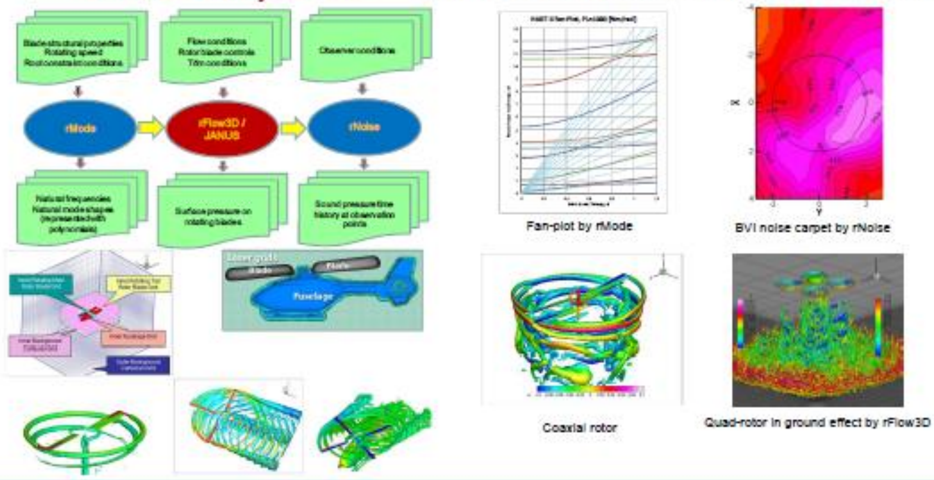




Comparison of fuel mileage with conventional helicopter

Spin-off Effects

Numerical Analysis Flow rFlow3D is being widely used for rotor analysis in Japan



Fan-plot by rMode

BVI noise carpet by rNoise

Coaxial rotor

Quad-rotor in ground effect by rFlow3D

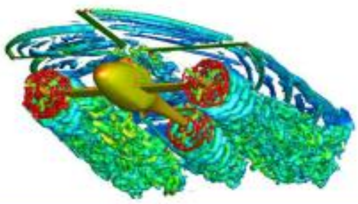
Summary

- A new concept of compound helicopter proposed by JAXA is illustrated. Technology issues related to the high-speed compound helicopter are addressed.
  - （1）Optimal design of rotor for high advance ratio flight
  - （2）Single-rotor lift-offset to improve the rotor performance in high-speed flight
  - （3）Rotor/propeller interaction
  - （4）Low drag fuselage design
- Through applying of the above advanced technologies, a high-efficiency compound helicopter can be realized where the flight speed is doubled while the fuel mileage can be kept the same or even less than the conventional helicopters.
- Spin-off effects of this research is introduced. The multi-disciplinary CFD/CSD/Trim/Noise prediction tool-chain (rFlow3D) developed alongside with this research has been applied to wind-turbines, multiple rotors, Mars helicopter and others.

Future Works

Optimal high-mu rotor design and other related technologies will be applied to a larger rotorcraft.

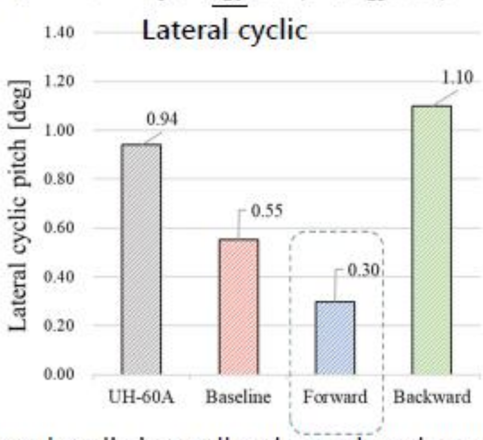

Thank you for your kind attentions!

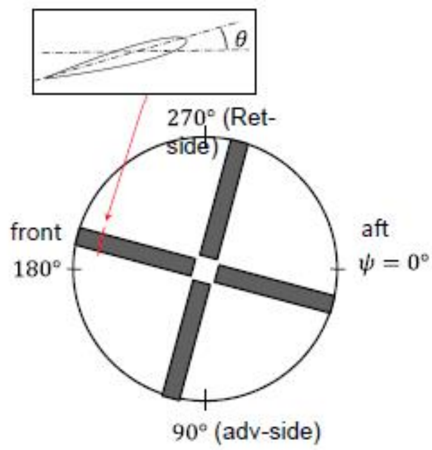



Appendix

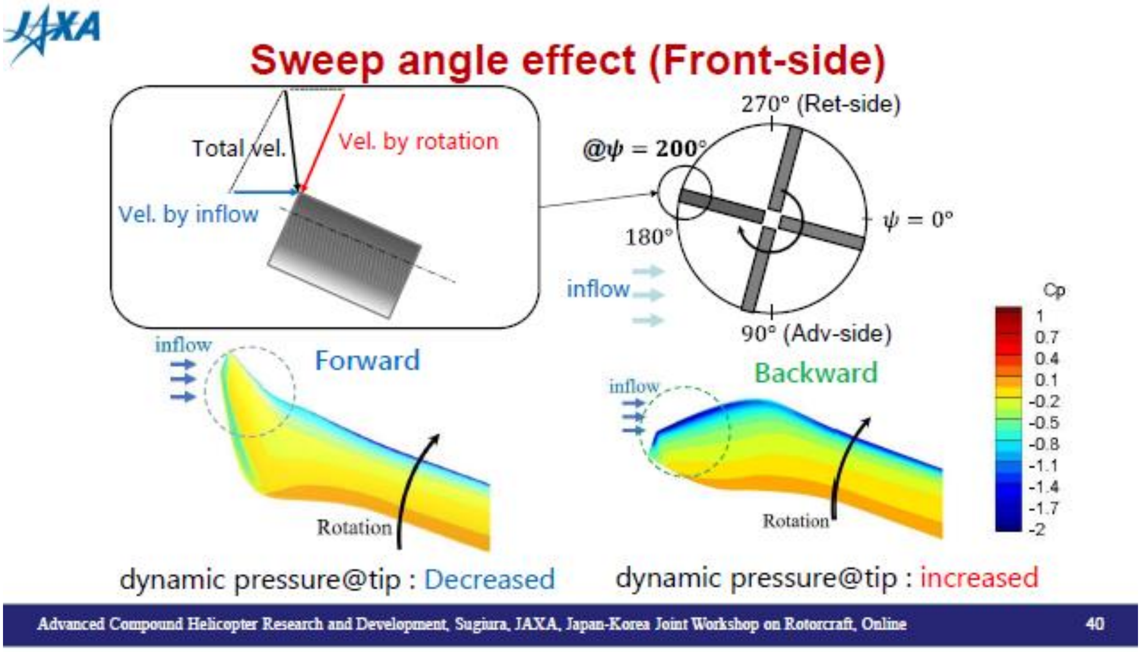
Effect on cyclic pitch angle

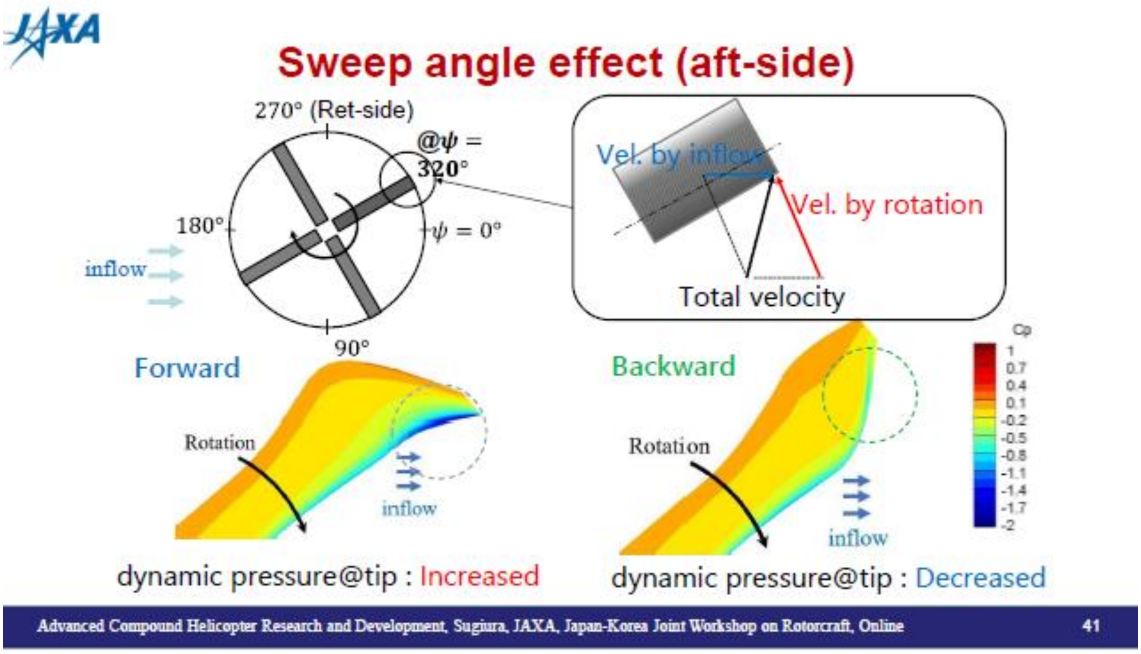
Pitch angle : $\theta = \theta_0 + \boldsymbol{\theta_{1c}} \cos\psi + \theta_{1s} \sin\psi$





✓ lateral cyclic is smaller than other shapes ⇒ more efficient AoA available!


JAXA
Sweep angle effect (Front-side)
Total vel.
Vel. by rotation
Vel. by inflow
@ψ = 200°
270° (Ret-side)
ψ = 0°
180°
inflow
90° (Adv-side)
inflow
Forward
Rotation
inflow
Backward
Rotation
Cp
1
0.7
0.4
0.1
-0.2
-0.5
-0.8
-1.1
-1.4
-1.7
-2
dynamic pressure@tip : Decreased
dynamic pressure@tip : increased
Advanced Compound Helicopter Research and Development, Sugiura, JAXA, Japan-Korea Joint Workshop on Rotorcraft, Online
40


JAXA
Sweep angle effect (aft-side)
270° (Ret-side)
@ψ = 320°
180°
ψ = 0°
inflow
90°
Vel. by inflow
Vel. by rotation
Total velocity
Forward
Rotation
inflow
Backward
Rotation
inflow
Cp
1
0.7
0.4
0.1
-0.2
-0.5
-0.8
-1.1
-1.4
-1.7
-2
dynamic pressure@tip : Increased
dynamic pressure@tip : Decreased
Advanced Compound Helicopter Research and Development, Sugiura, JAXA, Japan-Korea Joint Workshop on Rotorcraft, Online
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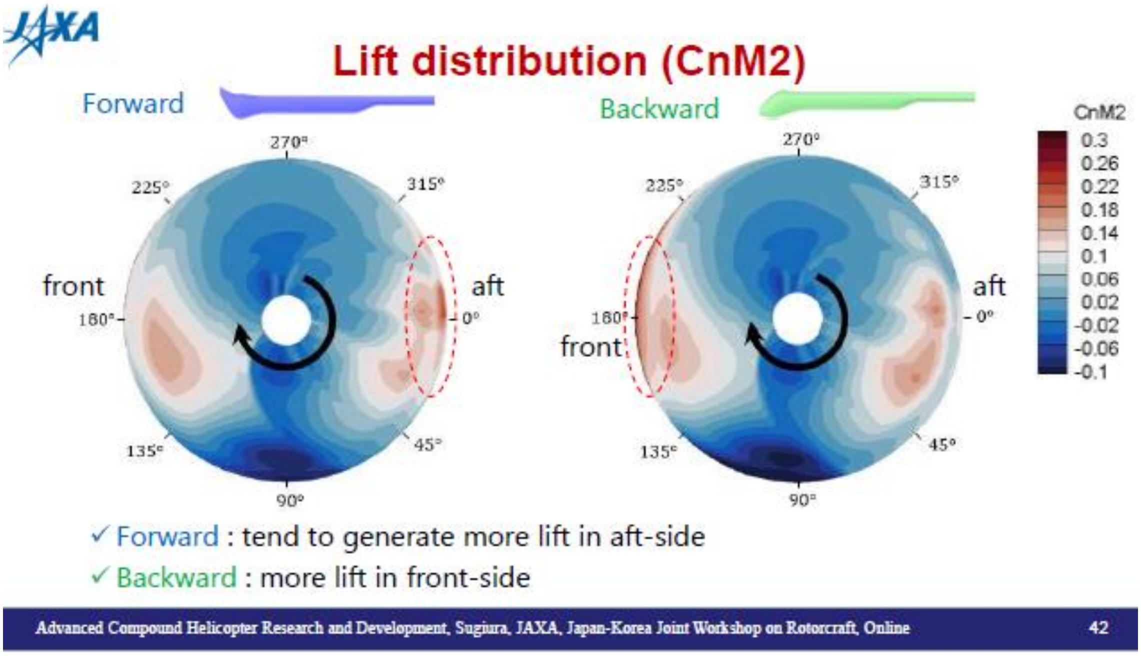
Lift distribution (CnM2)
Forward
Backward
CnM2
0.3
0.26
0.22
0.18
0.14
0.1
0.06
0.02
-0.02
-0.06
-0.1
270°
225°
315°
front
aft
180°
0°
135°
45°
90°
✓ Forward : tend to generate more lift in aft-side
✓ Backward : more lift in front-side
Advanced Compound Helicopter Research and Development, Sugiura, JAXA, Japan-Korea Joint Workshop on Rotorcraft, Online
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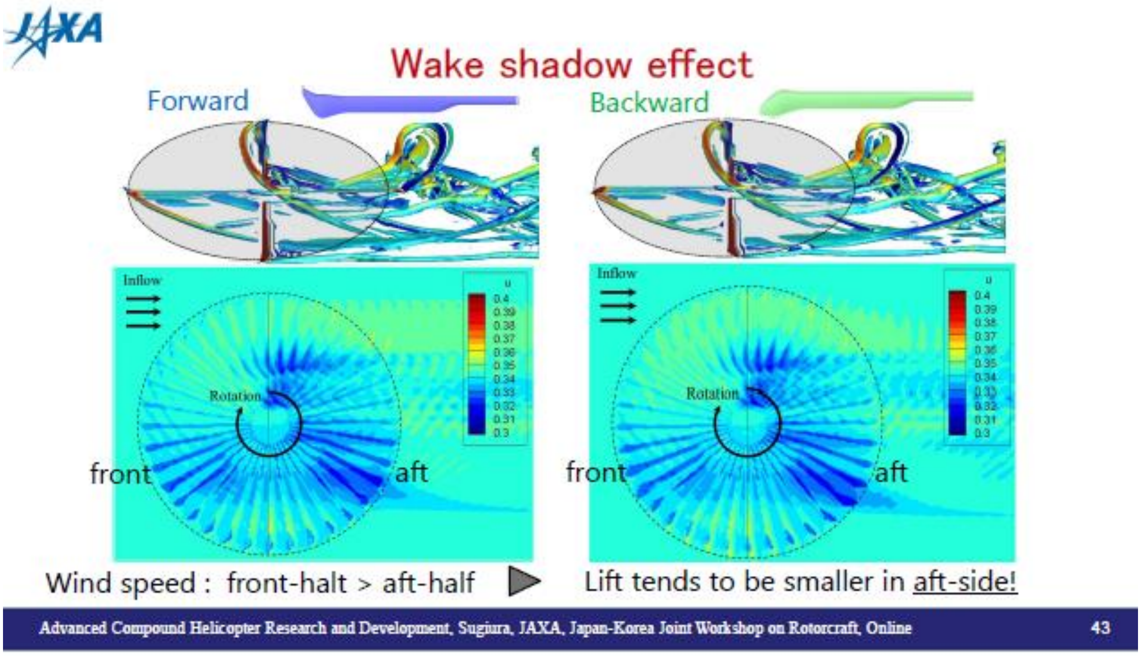
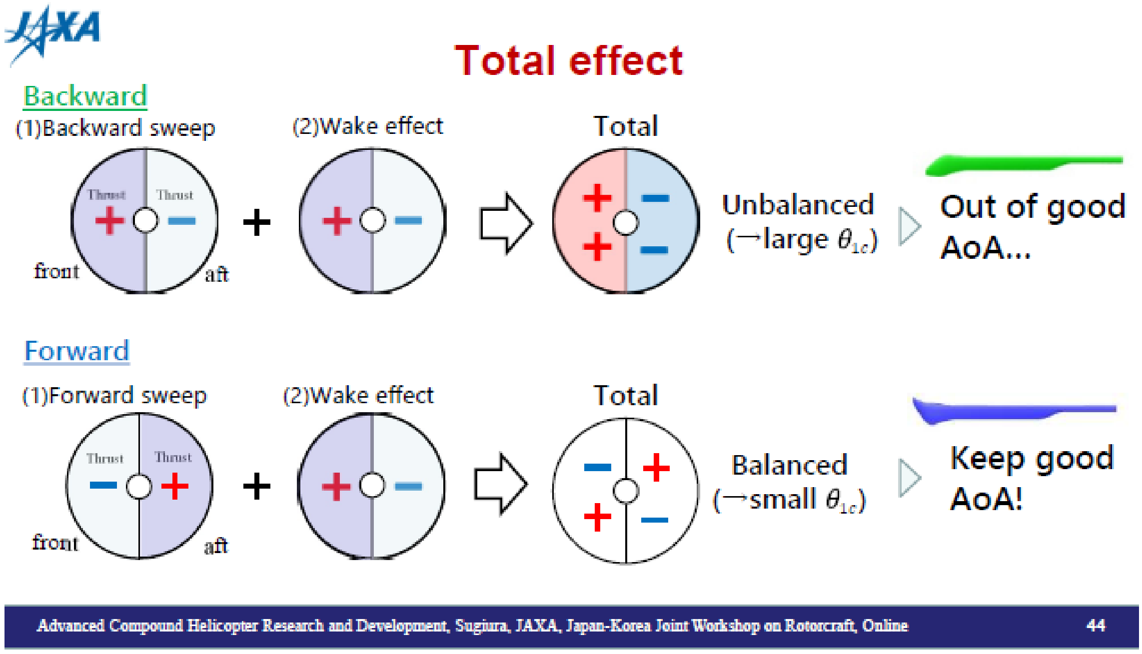

Wake shadow effect
Forward
Backward
Inflow
Rotation
front
aft
Wind speed : front-halt > aft-half
Lift tends to be smaller in aft-side!
Advanced Compound Helicopter Research and Development, Sugiura, JAXA, Japan-Korea Joint Workshop on Rotorcraft, Online
43


Total effect
Backward
(1)Backward sweep
Thrust
Thrust
front
aft
(2)Wake effect
Total
Unbalanced
(→large θ_{1c})
Out of good AoA...
Forward
(1)Forward sweep
Thrust
Thrust
front
aft
(2)Wake effect
Total
Balanced
(→small θ_{1c})
Keep good AoA!
Advanced Compound Helicopter Research and Development, Sugiura, JAXA, Japan-Korea Joint Workshop on Rotorcraft, Online
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3-3

Japan-Korea Joint Workshop on Rotorcraft
Sponsored by Japan Helicopter Society and KSAS VTOL Committee
2023.02.10 (Friday)

Aerodynamics Theories for Estimating Flight Profile of eVTOL Aircraft

Prof. Zhong Lei
Suwa University of Science, Japan

Contact: lei@rs.sus.ac.jp

Original Papers:
1. Yuto Fukumine, Zhong Lei, : "Estimation of eVTOL Performance Using Rotorcraft Theory", the 33rd Congress of the International Council of the Aeronautical Sciences, Stockholm, Sweden, 2022.9
2. Haruki Takizawa, Zhong Lei: "Operational Feasibility Study of Air Taxi Service using eVTOL in Japan" the 33rd Congress of the International Council of the Aeronautical Sciences, Stockholm, Sweden, 2022.9

Outline of content

- Research Objectives and Approach
- eVTOL Airplane of UAM
- Synthesis of Propeller and Rotor Theories
- Results and Discussions
- Conclusion

Research Objective

Objectives

- ✓ to investigate flight performance of representative eVTOL aircrafts, which including hovering, climb and descent, and forward flights,
- ✓ to provide technical information for aircraft design and operational feasibility.

The method is based on theories of rotorcraft and fixed-wing aircraft that are modified to be used for the eVTOL aircraft.

It is expected that this tool may be used for design and operation of eVTOL aircrafts.

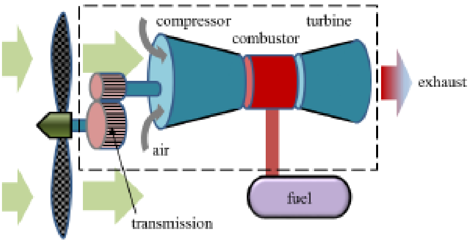


Fig. Turboprop propulsion

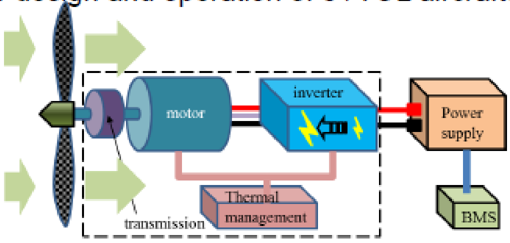


Fig. Electric propulsion

3

Research Approach

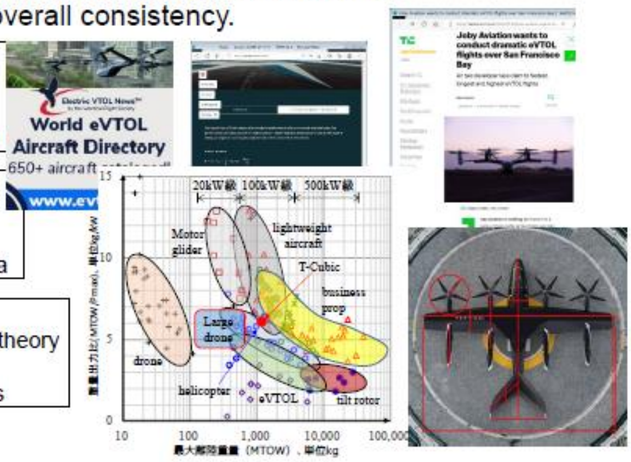
- Information of eVTOL aircraft are very limited.
- A synthesis of rotary blade theory was developed to estimate flight performance using statistical data, empirical rules, aircraft engineering theory.
- Calculations were adjusted for overall consistency.

Aircraft data collection
- Data published by aircraft maker
- Data read from published graph
- New, articles, web resource and so on

Parameter determination:
- Database of existing aircraft
- Statistical and empirical formula
- overall consistency with published data

Performance evaluation:
- fixed-wing and helicopter engineering theory
- Constraints of shape, performance
- Satisfaction of published specifications

Results



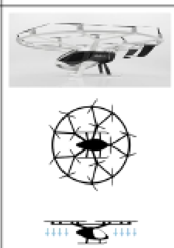
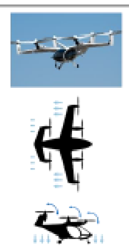
Characteristics of eVTOL Aircraft

Multicopter type:
- coupled rotors, no wing
- flight speed direction are controlled by changing the angle of the rotor axis of rotation

Vectored thrust type:
- coupled tilt-rotors, wing
- transit lift in vertical flight and thrust in forward flight by changing the axis of rotation of the rotor.

Lift & cruise type:
- coupled fixed-rotors and wing
- generates lift on the fixed rotor
- generates thrust in forward direction by the propeller
- generates lift on the wing during cruise

Table. eVTOL aircraft investigated in this study

Category	Wingless (Multicopter)	Vectored Thrust	Lift & Cruise
Maker, Name	Volocopter, Volocity	Joby Aviation, S4	Beta Technologies, Alia 250
photo			
feature	 18 fixed rotor	 6 tilt-rotor, wing	 4 fixed rotor, 1 propeller, wing
Gross weight [lb]	1984	4800	7000
PX	2	5	6
Empty weight [lb]	1543	1724	2631
Rotor diameter [ft]	7.5	9.5	13
propeller diameter [ft]	-	-	8
Wing area [ft^2]	-	170	250

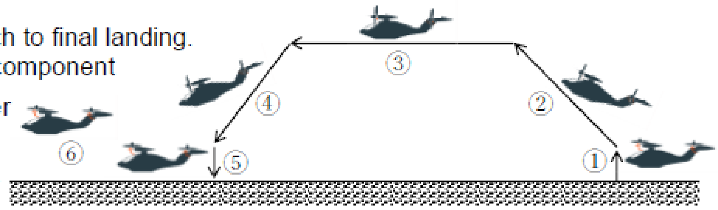
5

Flight Mission

Like conventional helicopter, the flight profile of eVTOL aircraft may be divided into several phases. Mission Includes altitude, flight time, range, speed.

- **Take-off**: Climb vertically at hover power(no horizontal movement)
- **Climb**: Climb to cruise altitude
- **Cruise**: Flight phase that occurs when the aircraft levels after a climb to a cruise altitude and before it begins to descend
- **Descent**: Aircraft begins approach to final landing. Has both horizontal and vertical component
- **Landing**: Vertical landing at hover power (no horizontal movement)
- **Hovering**: Stay in the air by rotor

① Takeoff and vertical flight
② Climb and forward flight
③ Cruise at specified altitude
④ Descent and forward flight
⑤ Vertical descent and landing
⑥ Hovering



Main mission flight profile

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Synthesis of Propeller and Rotor Theories: Fixed-Wing Aircraft

Induced velocity $w = 2v_i$ Advance ratio $J = \dfrac{V}{\Omega R}$ $\Omega = 2\pi n$

According to Bernoulli's principle

$$\Delta p = H_1 - H = \left[p + \frac{1}{2}\rho(V+w)^2\right] - \left[p + \frac{1}{2}\rho V^2\right] = \rho\left(V + \frac{1}{2}w\right)w = 2\rho(V+v_i)v_i$$

Thrust generated by propeller is calculated by momentum equation

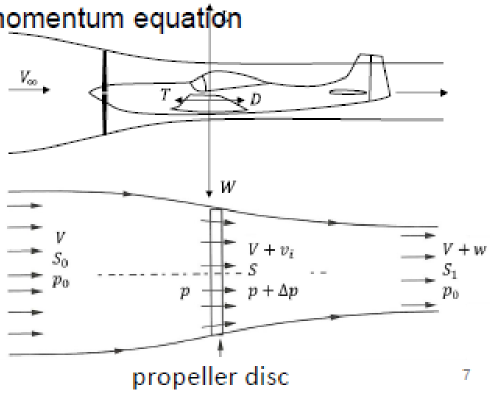
$$T = \Delta p S = \rho S(V+v_i)w = 2\rho S(V+v_i)v_i$$

Then, induced velocity may be solved

$$\frac{v_i}{v_s} = -\frac{V}{2v_s} + \sqrt{\left(\frac{V}{2v_s}\right)^2 + 1}$$

At static condition $(V = 0)$

$$v_s = \sqrt{\frac{T}{2\rho S}}$$



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Synthesis of Propeller and Rotor Theories: Helicopter

Break velocity into normal (n) and tangential (τ) components.

Tip speed ratio Inflow ratio

$$\mu_\tau = \frac{V_\tau}{\Omega R} = \frac{V_\infty \cos\alpha}{\Omega R} \qquad \lambda = \frac{V_n}{\Omega R} + \frac{v_i}{\Omega R} = \mu_n + \lambda_i$$

Induced velocity at hovering

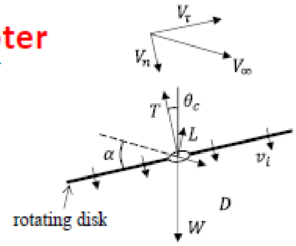
$$v_h = \sqrt{\frac{T}{2\rho\pi R^2}} \quad \text{and} \quad \lambda_h = \sqrt{\frac{C_T}{2}}$$

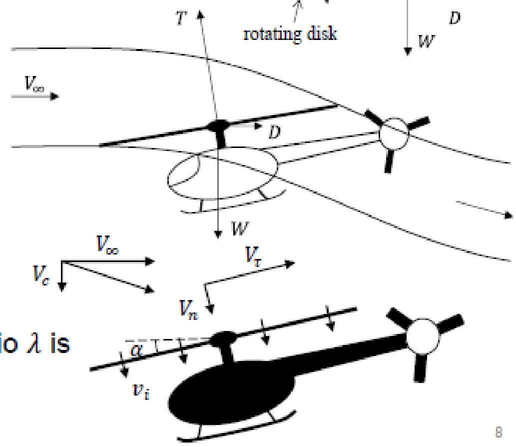
Induced velocity at forward flight

$$v_i = \frac{v_h^2}{\sqrt{(V_\tau)^2 + (V_n + v_i)^2}} = \frac{v_h^2}{U}$$

Substitute into the equation for the inflow ratio λ is

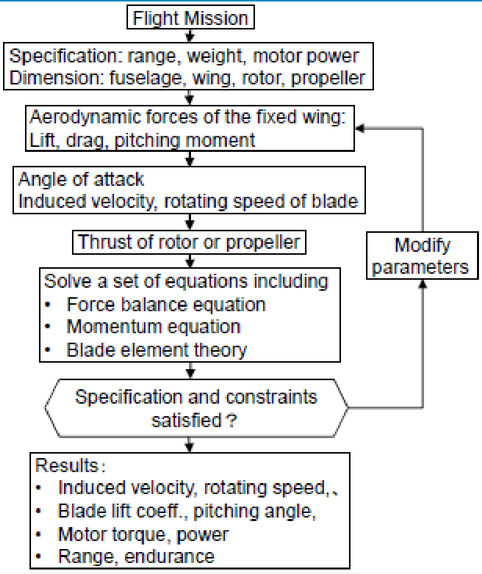
$$\lambda = \mu_n + \frac{C_T}{2\sqrt{\mu_\tau^2 + \lambda^2}}$$ Solved by iteration





8

Flight Performance Estimation Using the Synthesis Theory



Force balance $L = W\cos\theta_{FP}$, $T = D + W\sin\theta_{FP}$

Momentum equation $T = 2\rho A v_i\sqrt{V_\infty^2 + 2V_\infty v_i \sin\alpha + v_i^2}$

Equation of inflow ratio $\lambda = \mu_n + \dfrac{C_T}{2\sqrt{\mu_t^2 + \lambda^2}}$

Relation of thrust coefficient and lift coeff. $C_T = \frac{1}{6}\sigma\bar{C}_L$

Total power required $P = P_i + P_0 + P_p + P_c$

① induced power $P_i = T \times v_i$

② Profile power

$$P_0 = \frac{1}{8}\rho N_b c R(\Omega R)^3(1 + K\mu^2)C_{do} = \frac{1}{8}\rho A V_{tip}^3\sigma(1 + K\mu^2)C_{do}$$

③ Airframe parasite power

$$P_p = D \times V_\infty = \frac{1}{2}\rho V_\infty^2 S C_{Df} \times V_\infty = \frac{1}{2}\rho V_\infty^3 S C_{Df}$$

④ climb power

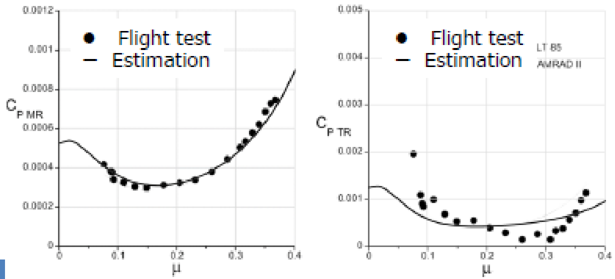
$$P_c = W \times V_c$$

9

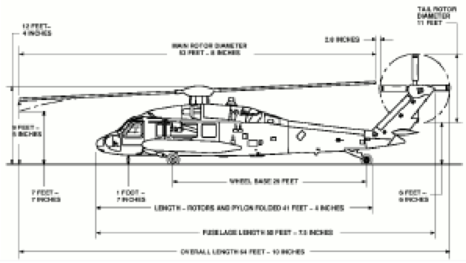
Validation : Performance Estimation of UH-60A (Black Hwak)

- The method is validated by the flight test data of UH-60A helicopter.
- The predicted power coefficients of the main and tail rotors are compared and agreed well with the flight data.

	Main rotor	Tail rotor
airfoil	SC1095/ SC1094	SC1095
radius [m]	8.18	1.68
chord length [m]	0.527	0.250
number of blades	4	4
rotating speed at hovering [rpm]	258	1190



main rotor tail rotor



10

Investigation of Flight Performance of eVTOL Airplanes

11 eVTOL airplanes were investigated, 3 of them were typically picked up, based on the data available in the middle of 2022. Red data are estimated.

Wingless (Multicopter)	EHang 216 Pax：2人 Gross weight：600kg Motor：8kWx16 Battery capacity：40kWh Range：15km Endurance：20min	Volocopter, Velocity Pax：2人 Gross weight：900kg Motor：8kWx18 Battery capacity：74kWh Range：48km Endurance：45min	Airbus, CityAirbus Pax：4人 Gross weight：2200kg Motor：100kWx8 Battery capacity：200kWh Range：53km Endurance：23min	
Vectored Thrust	Joby, S4 Pax：5人 Gross weight：2177kg Motor：120kWx6 Battery capacity：166kWh Range：236km Endurance：69min	Archer Aviation, Maker（100%） Pax：5人 Gross weight：3175kg Motor：90kWx3+120kWx3 Battery capacity：258kWh Range：287km Endurance：90min	Vertical Aerospace, VX4 Pax：5人 Gross weight：3175kg Motor：120kWx4+160kWx4 Battery capacity：260kWh Range：340km Endurance：90min	Lilium Jet, 7-Seater Pax：7人 Gross weight：3175kg Motor：120kWx36 Battery capacity：306kWh Range：293km Endurance：69min
Lift & Cruise	Wisk, Cora (Gen 5#) Pax：2人 Gross weight：1270kg Motor：40kWx12+200kWx1 Battery capacity：88kWh Range：182km Endurance：72min	Beta Technologies, Alia 250 Pax：6人 Gross weight：3175kg Motor：250kWx4+350kWx1 Battery capacity：544kWh Range：267km Endurance：71min	EVE, DreamMaker Pax：4人 Gross weight：998kg Motor：30kWx8+80kWx2 Battery capacity：36kWh Range：116km Endurance：53min	Autoflight, VF1500M Pax：4人 Gross weight：1500kg Motor：50kWx8+180kWx1 Battery capacity：88kWh Range：252km Endurance：80min

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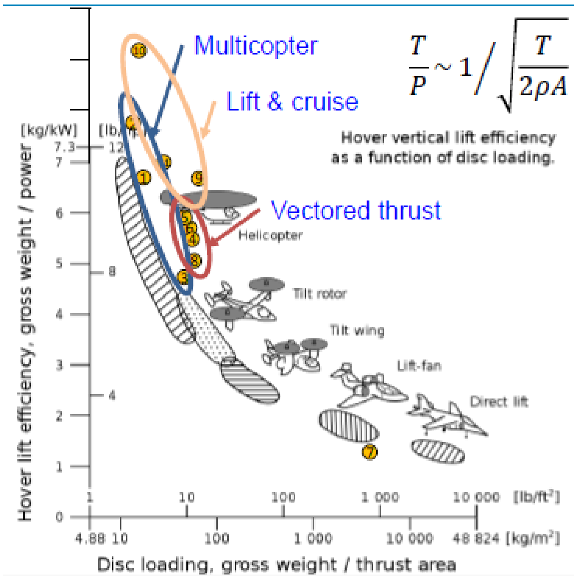
Disc Loading and Weight-to-Power Ratio



Characteristics

Multicopter type:
- Large disc area
- Low disc loading

Vectored thrust type:
- All aircrafts has similar performance, except Lilium Jet

Lift & cruise type:
- High efficiency
- Rotor for hovering
- Propeller for wing-borne flight

Generally, it is recommended that the weight-to-power ratio
- be larger than 5 kg/kW at hovering
- be larger than 20 kg/kW at cruising

Overall Performance

(based on the data available in the middle of 2022)

- Lift & Cruise type has the best performance at cruising.
- #7, Lilium Jet has bad performance, especially at hovering.

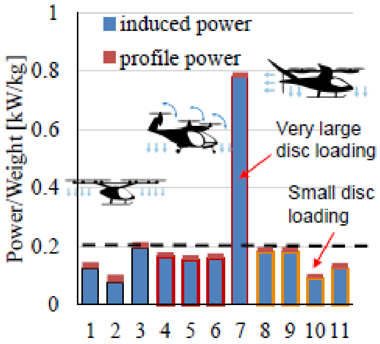


Fig. Power at hovering flight

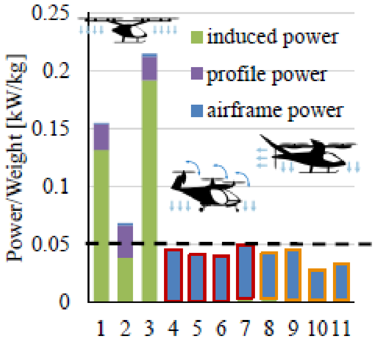


Fig. Power at cruising flight

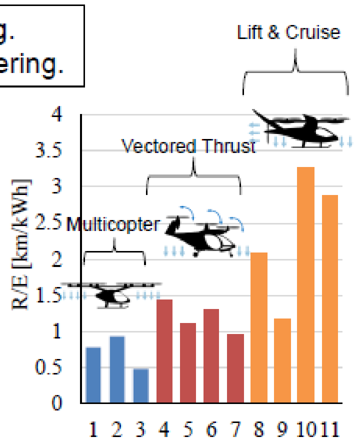


Fig. Cruising rate

Cruising rate $r = R_{\mathrm{total}}/E_{\mathrm{total}}$ Multicopter < Vectored Thrust < Lift & Cruise

Where, R_{total} : range, E_{total} : consumed energy

Results and Discussions: Hovering

- Power is increased as the weight at hovering.
- Power-to-weight ratio is increased with disk loading.

A large rotating area results in a lower disk loading, thus a benefit of power-to-weight ratio.

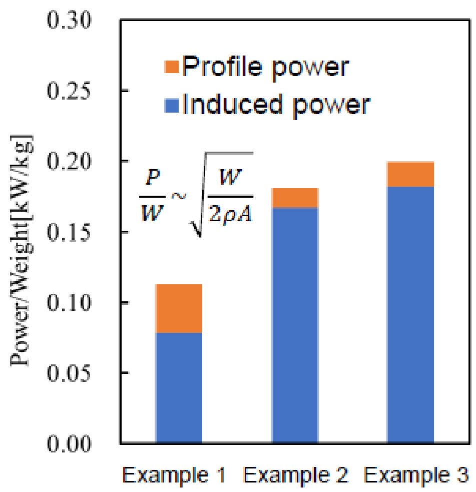


Fig. Power breakdown at hovering

Results and Discussions: Climb and Descent

At vertical climb and descent, total power consumption is decreased with increase of climb and descent rate, respectively.

Suitable rate of climb and descent should be selected to reduce power consumption.

Generally, the rate is recommended to be larger than 4 m/s.

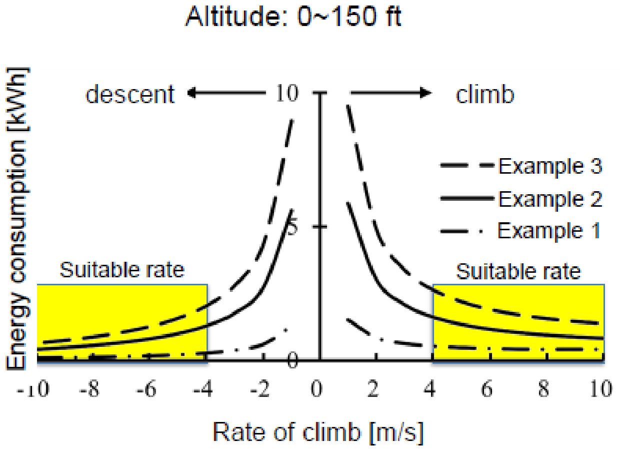


Fig. Estimation results of total power consumption

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Results and Discussions: Performance at Cruising

- Multicopter Volocity is suitable for short range.
- The wing has significant effects on the cruise speed and necessary power at cruising.

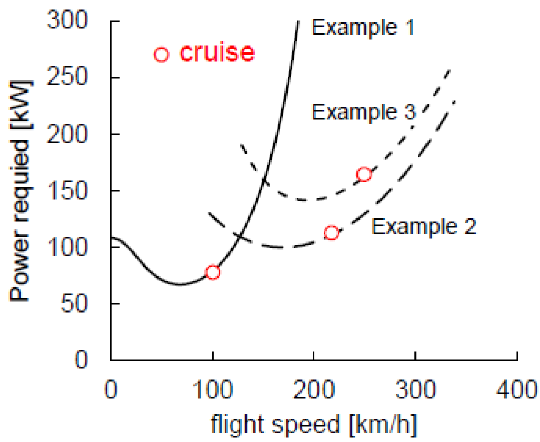

Fig. Power required in level flight

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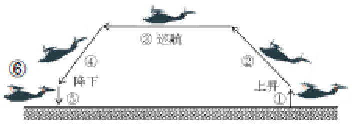
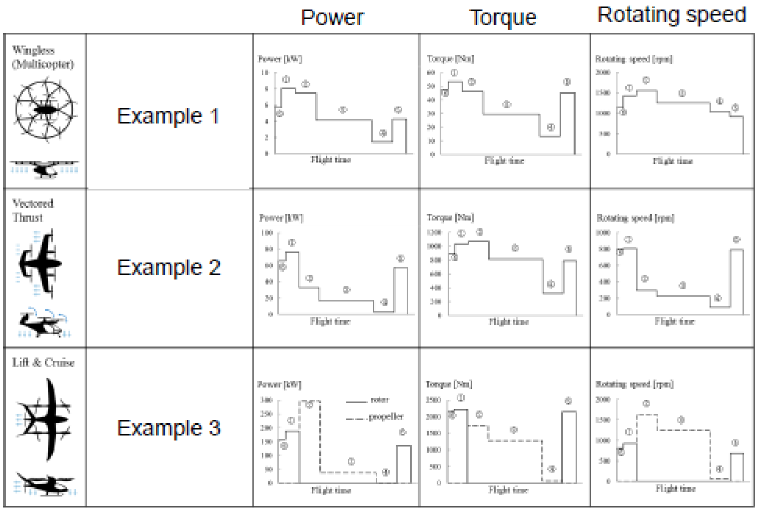
Results and Discussions: Flight Profile of Motor Output

- Different characteristics for fixed-pitch / variable-pitch blade, fixed / tilt rotor, rotor / propeller
- Large changes in output of power, torque, and rotating speed at different phases

It suggests that different type should match different motor.



Flight phases



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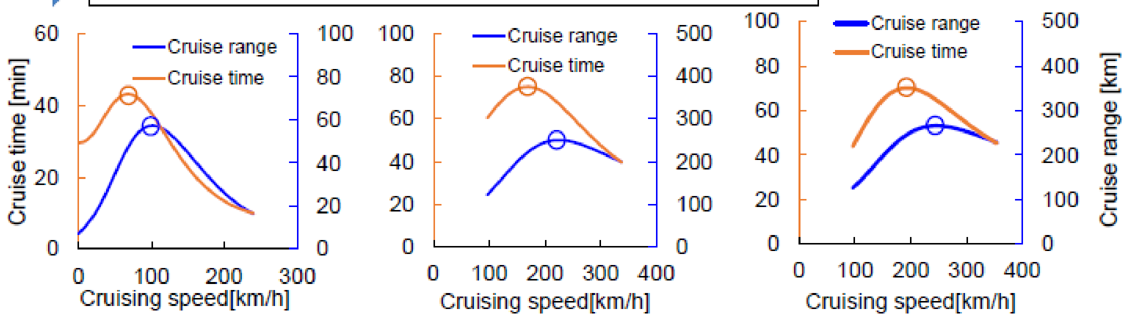
Results and Discussions: Range and Endurance

Factors which most influence range and endurance, include

- **flight profile** : altitude, hovering time, climb rate, cruise speed
- **aerodynamics** : rotor, propeller and airframe
- **propulsion** : efficiency, energy density, battery capacity (especially for eVTOL)

Both lift & cruise type (b) and vectored thrust type (c) may fly more than 1 hour and 150 miles.

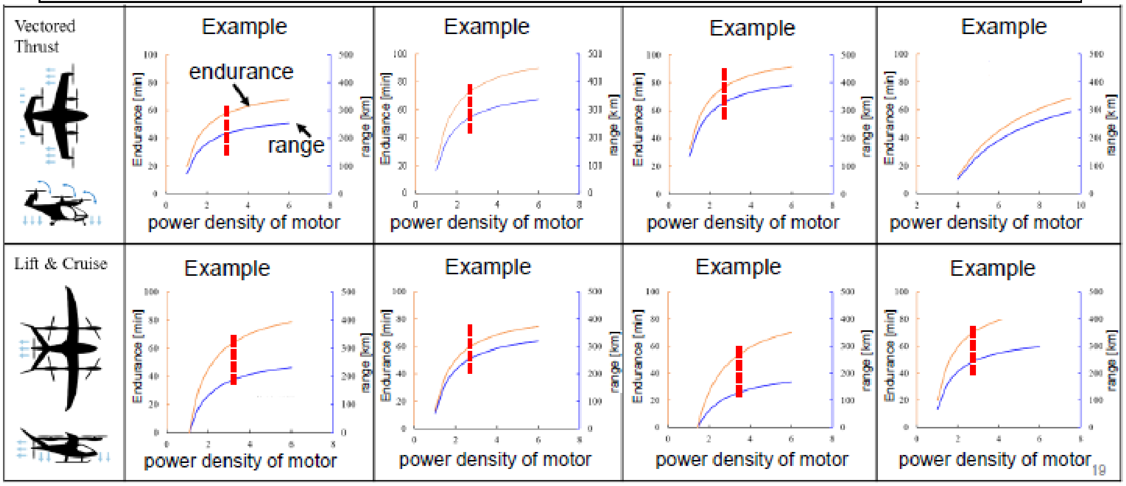
It is suggested that both of them may be used as UAM.



(a) Example 1 (multicopter) (b) Example 2 (vectored thrust) (c) Example 3 (lift & cruise)) 18

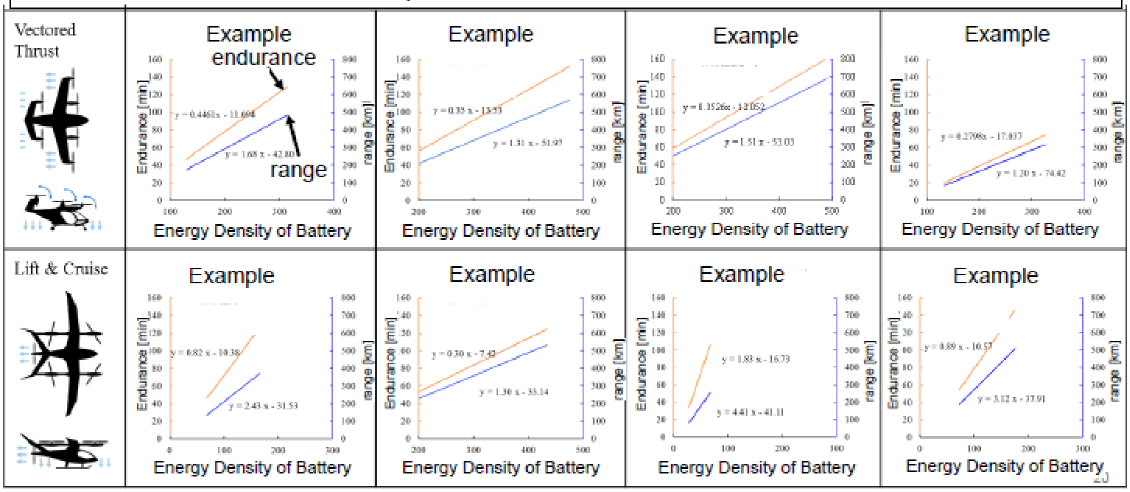
Results and Discussions: Power Density of Motor

With consideration of cost and performance, power density of motor 3~4kW/kg is suitable for eVTOL airplane.



Results and Discussions: Energy Density of Battery

Energy density of battery may be determined to match specified range and endurance with consideration of cost and performance.



Conclusion

The theory of rotorcraft aerodynamics was extended to calculate rotor, propeller and tiltrotor, and a computational tool was developed to estimate various types of eVTOL aircrafts.

Some suggestions for eVTOL design and operation.

- Generally, it is recommended that the ratio of weight-to-power should be larger than 5 kg/kW at hovering, be larger than 20 kg/kW at cruising.
- Suitable rates of climb and descent should be selected to reduce power consumption. Generally, the rate is recommended to be larger than 4 m/s.
- Energy density of motor 3~4 kW/kg is suitable for eVTOL airplane.
- Energy density of battery should be larger than 200Wh/kg, which is dependent on the eVTOL aircraft.
- It suggests that different type of eVTOL aircraft should match different motor.
- Multicopter eVTOL aircraft is suitable for short range with low speed.
- The vectored thrust eVTOL aircraft and lift & cruise eVTOL aircraft are more efficient for longer range with high speed.

21

Research and Development of a Multi-copter for Autonomous Inspection of Headrace Tunnels of Hydraulic Power Stations

Sustainable System Research Lab.
Central Research Institute of Electric Power Industry
Koichi Yonezawa

Japan-Korea Joint Workshop on Rotorcraft
February 10th , 2023

CRIEPI

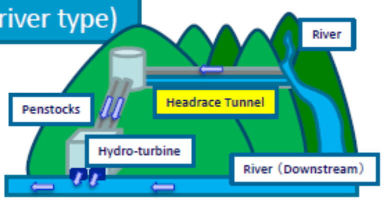
CRIEPI

Background: Maintenance of Hydro Power Stations

Large-scale earthquakes
e. g. 2016 Kumamoto earthquakes: (Magnitude 6.2 -> 7.3 -> 7.1->... 400 times, in a week)

Flood Disasters
Typhoons, Torrential rains -> landslides, floods, etc.

Typical hydraulic power station (run-of-river type)



It is necessary to ascertain damages of facilities.

Inspection by workers is dangerous.
Unmanned inspection systems should be developed.

Autonomous Drone for Disaster Response

Why drones in headrace tunnels ?

1) Water or sediment remains on the floor.
2) There are large step structures or steep slopes.
3) Distances can range to several kilometers.

Technical issues

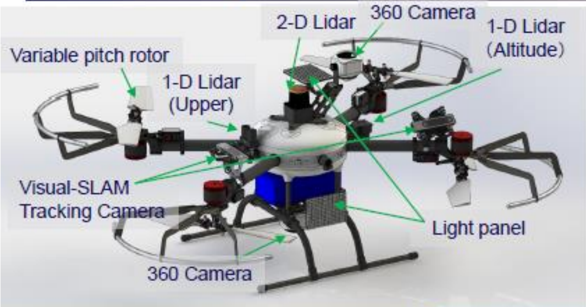
1) Many tunnels have smaller cross-sections than traffic tunnels.
2) GPS is not available and radio control from the outside is difficult.
3) No lighting facilities.
4) Hard environmental conditions, including water leakage from ceilings.

Today's topics

- Development of a prototype of TUNNEL DRONE system
- Investigation of aerodynamic characteristics

DEVELOPMENT OF A PROTOTYPE OF TUNNEL DRONE SYSTEM

Specifications of the Aircraft



Fully autonomous flight system

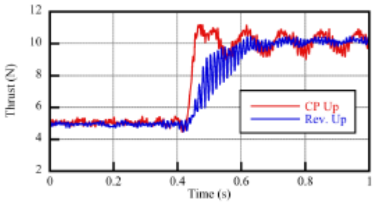
- ✓ High maneuverability
- ✓ Robust sensing and navigation system

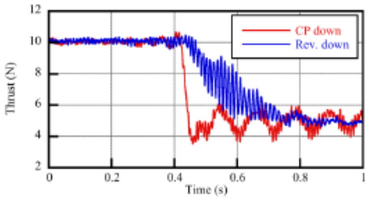
Rotor	4 Units/15 inched/2 blades : 5400r.p.m. +Variable pitch control
Battery	Li-Po 6S 20000mAh （Flight duration 12 minutes）
Dimensions	1074(L) x 806(W) x 320(H) mm
Waterproof / dustproof	IP55
Veridical positioning	Upper/lower wall distance control or Altitude control
Horizontal positioning	Left/right wall distance control

Rotors

Thrust control by variable collective pitch:
Quicker response than rotational speed change

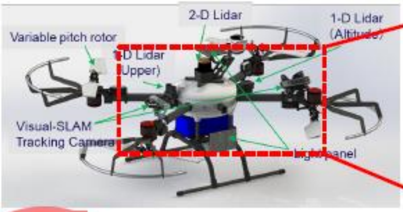
High maneuverability contributes to stabilize the attitude and motion of the aircraft in turbulence in tunnel.

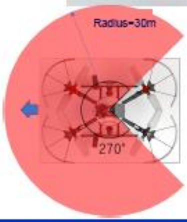




Collective pitch control
vs rotational speed control

Sensors and Navigation



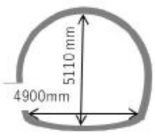


Speed detection using 2 tracking cameras
- ✓ Switching/restarting are possible in case of error →Robustness is enhanced by redundant system
- ✓ View in two directions (Upside and up-left directions): Autonomous flight is possible even when water remains on the floor
- ✓ Seamless flight through tunnels and open conduit is possible

2-D LiDAR detects obstacles and walls in front and on the side. Smooth distance control are realized even when the wall surface has discontinuous curve.

7

Flight Demonstration (1)



MISSION:
A) Flight in low temperature (-5℃)
B) Flight in fog

- Low temperature→ Condensation occurs on optical sensors
- Fog→ Cause of Visual-SLAM error = Significantly exceeded target point

8

Flight Demonstration (2)

MISSION:
1. Flight in tunnels with small cross sections
2. Flight in a water conduit with a series of tunnels and open channel

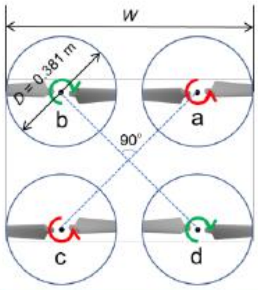
- Small cross sections -> Highly turbulent around the aircraft
- Dirty water droplets from the ceiling in tunnel / Flying leaves in open channel

Variable-pitch-rotors contributed to the flight in turbulence.
Robust optical-system maintained SLAM in various disturbances.

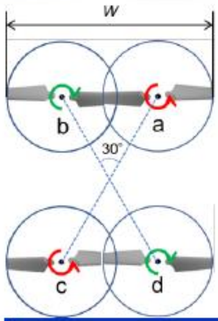
INVESTIGATION OF AERODYNAMIC CHARACTERISTICS

Geometry of the TUNNEL DRONE

D: Rotor diameter (381 mm)



Symmetric configuration



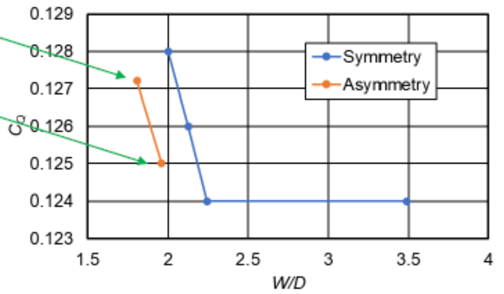
Asymmetric config.
a/d: Upper, b/c: Lower
There is overlap on the left and right propeller rotation planes.
Narrow width is advantage for flight in small tunnel

Aircraft width vs Torque coef. (Hovering)

Aerodynamics are evaluated using CFD (rFLow3D ©JAXA)

Overlap 0.2D

Overlap 0.04D



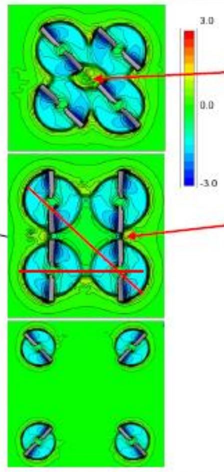
Torque coef. vs Aircraft width at thrust coef. CT=0.0108

- Asymmetric configuration results in a higher efficiency (lower torque).
- Negative effect is small when overlap is small on rotating planes.
- Inter-rotor interference can be more harmful when propellers are placed on the same plane.

rFLow3D
Accuracy in descritization:
4th order in convective terms
2nd order in viscous terms
Unsteady simulation by LU-SGS implicit scheme
Overlap mesh system was used

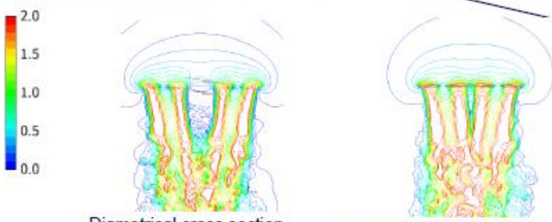
Observation of Flows around Symmetric Config.

CT=0.0108
CQ=0.126
Blade angle=9.26°



Upwash

Tip vortex interaction



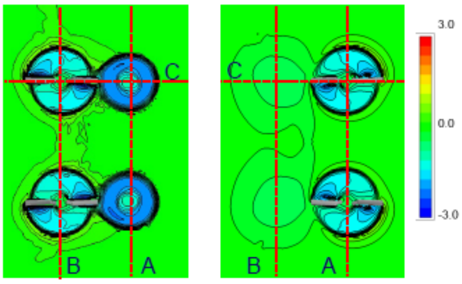
Diametrical cross section

Cross section through adjacent propeller axes

Normalized velocity magnitude for middle W/D

Normalized axial velocity for various W/D

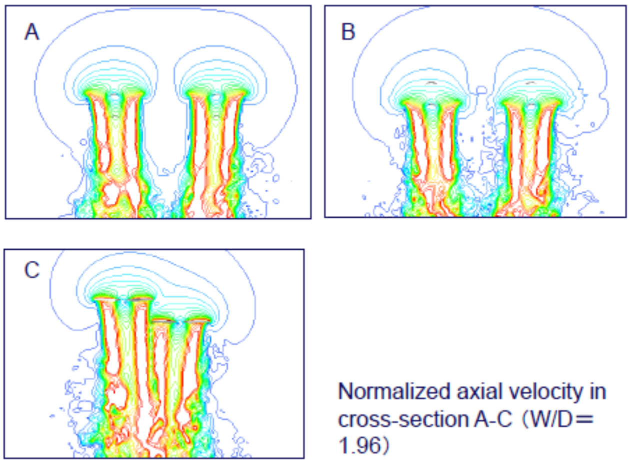
Observation of Flows around Asymmetric Config.



Lower rotational plane

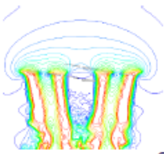
Upper rotational plane

Normalized axial velocity in rotational plane（W/D=1.96）



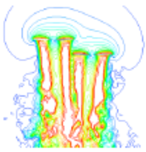
Normalized axial velocity in cross-section A-C（W/D=1.96）

Observation of Flows around Asymmetric Config.



	C_T	C_Q	θ
W/D		2.24	
ALL	0.0108	0.126	9.26

Symmetric config.



	C_T	C_Q	θ
W/D		1.96	
Upper	0.0108	0.127	9.27
Lower	0.0108	0.123	9.04
Ave.	0.0108	0.125	9.16

Asymmetric config.

Upper rotor :
Aerodynamic loss increases
・Interaction between front/rear rotor is small
・Suction flow due to lower propeller induces loss on the upper rotor.

Lower rotor
Aerodynamic loss decreases
・Interaction between front/rear rotor is small
・Downwash from the upper rotor suppress the blade tip vortex and loss.

Propeller interaction effect between the left and right rotors is dominant. Propeller interaction effect between the front and rear rotors is small due to longer distance.

Conclusion

- A drone for unmanned inspection of headrace tunnels of hydraulic power station was developed.
- High maneuverability and robustness of sensing and navigation systems are confirmed by carrying out fully autonomous flight demonstrations in highly disturbed environments.
- An asymmetric aircraft configuration for flying through narrow tunnels was designed and its aerodynamic characteristics were investigated.
- The rotor efficiency increases by overlapping the rotating planes less than 25%.

日韓回転翼機ワークショップ

（韓国側発表）

0-2

Key Note
Presentation
(Korea)
Introduction to Current
VTOL R&D Projects in Korea
2023. 02.10 (Friday)
Choi, Keeyoung
(Prof. @ Inha Univ. , Former President of KSAS VTOL Chapter)

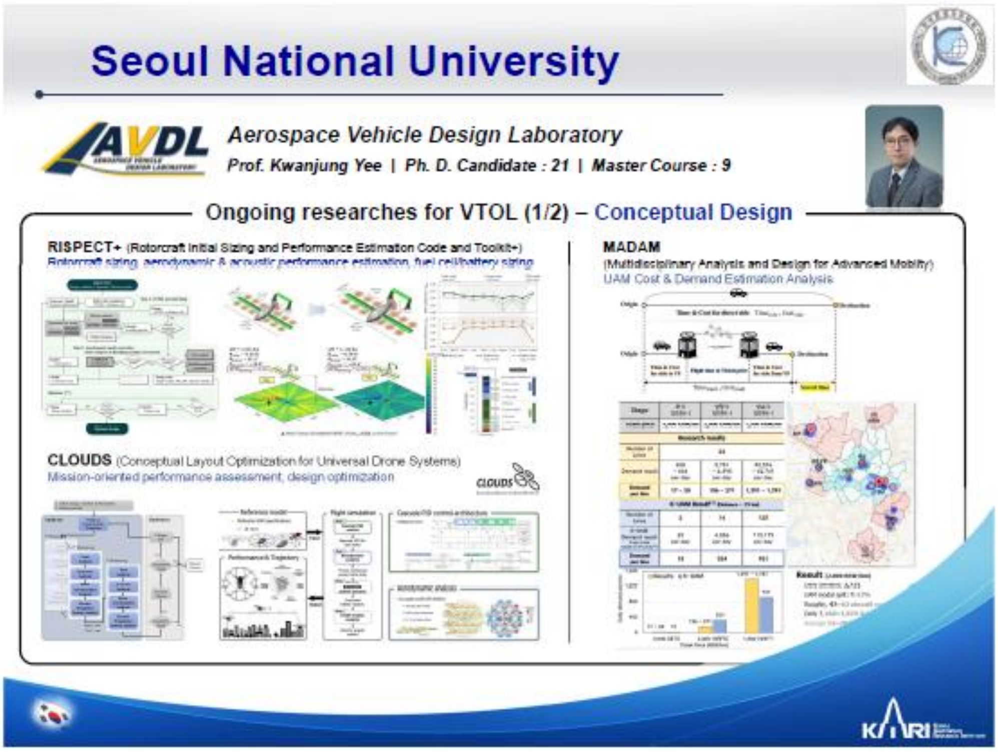
Contents
1.Overview
2.Universities
3.Industries
4.Institutes
5.Conclusion

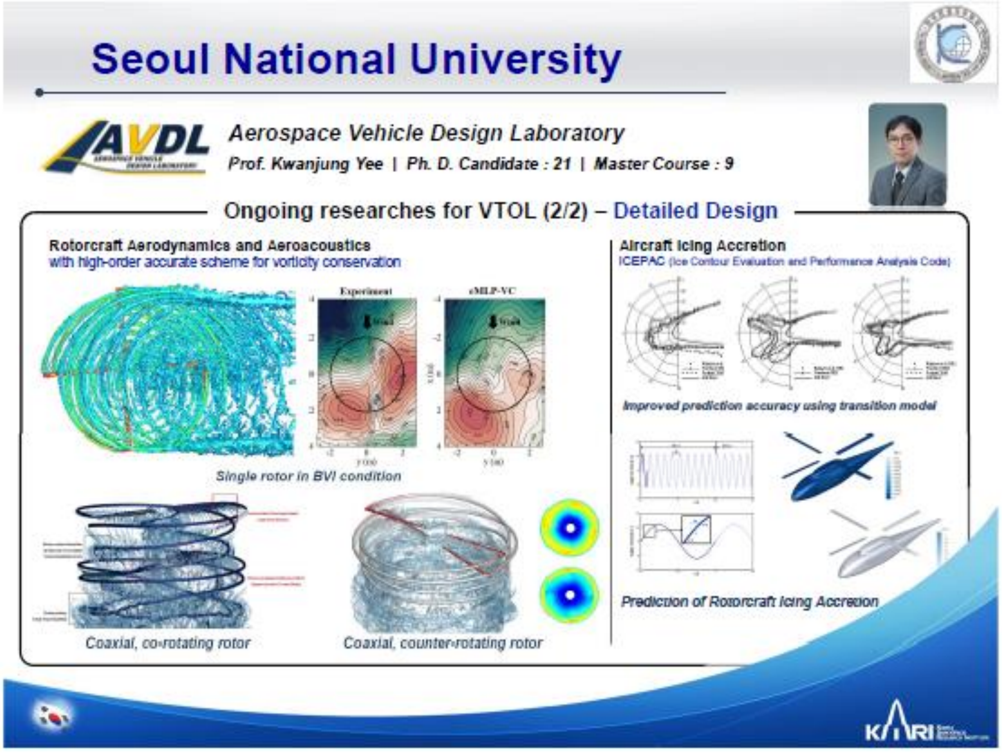
I. Overview

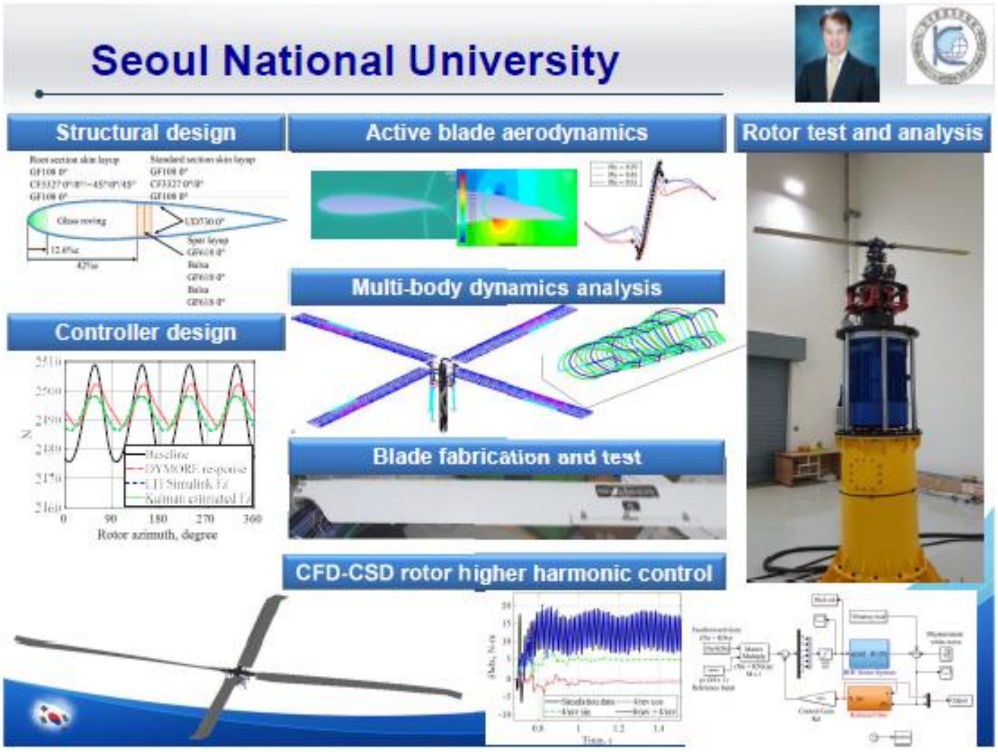
Overview

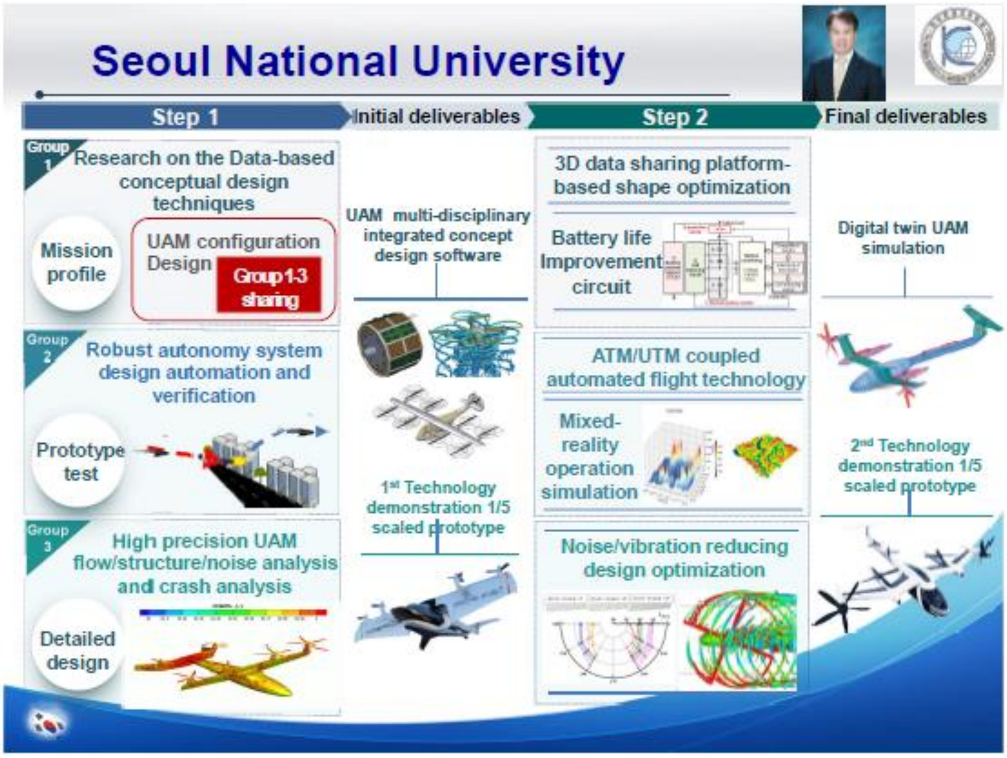
- Korea Government have launched several national program in last 5 years.
  - In civil field : eVTOL Aircraft System Technology Development, unmanned eVTOL for AAM
  - In military field : Light Armed Helicopter, Marine Attack Helicopter, Unmanned VTOL for Observation and Delivery Service
- Industry, Institute and University have worked together to reach the national R&D target for the future market according to each capability
  - Industry : System Integration and Hardware Development
  - Institute : Core Technologies Research & Development
  - University : Basic Technologies Research & Development
- Next Slides shows the each activities of University, Industry and Institutes related to VTOL Technologies

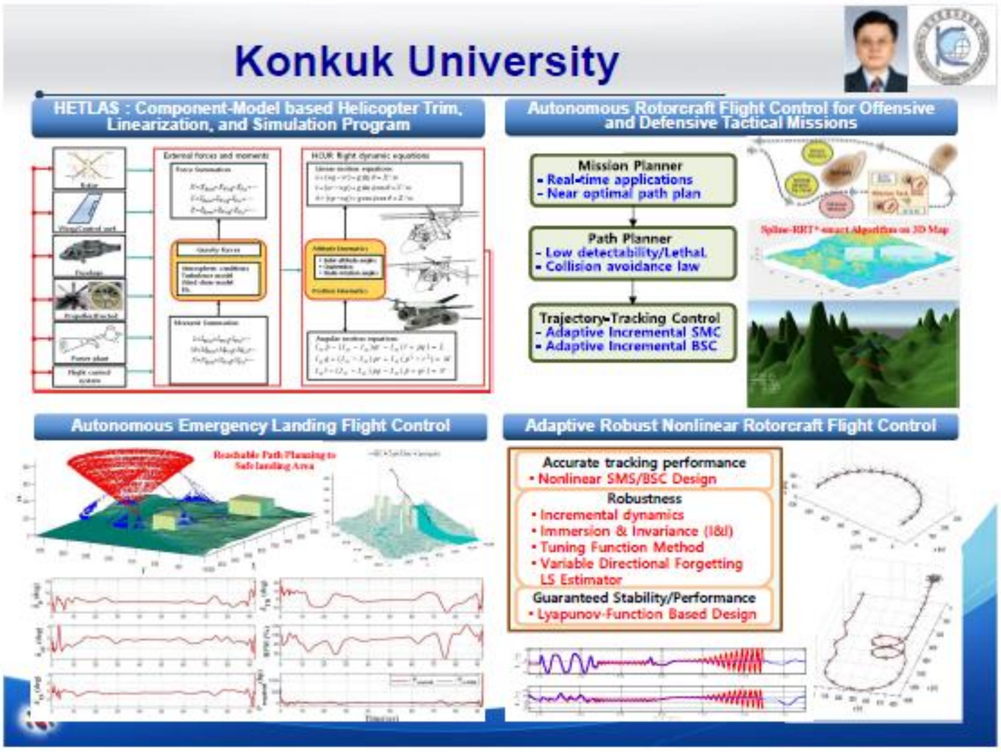

II. Universities

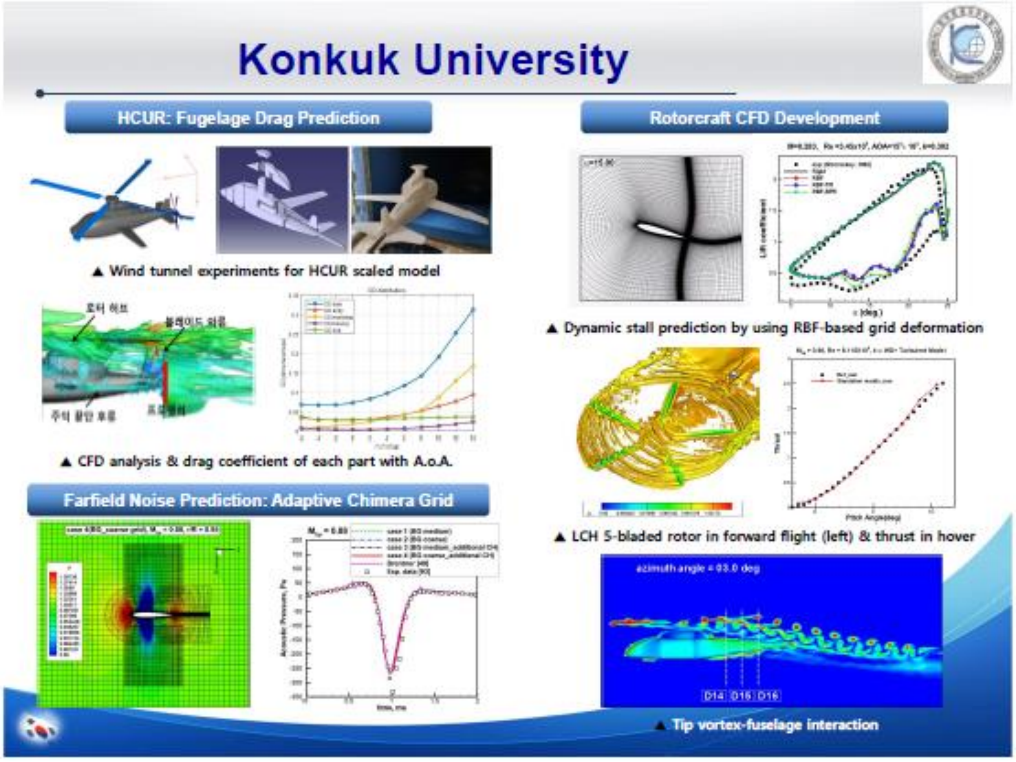

Seoul National University
AVDL
Aerospace Vehicle Design Laboratory
Prof. Kwanjung Yee | Ph. D. Candidate : 21 | Master Course : 9
Ongoing researches for VTOL (1/2) – Conceptual Design
RISPECT+ (Rotorcraft Initial Sizing and Performance Estimation Code and Toolkit+)
Rotorcraft sizing, aerodynamic & acoustic performance estimation, fuel cell/battery sizing
CLOUDS (Conceptual Layout Optimization for Universal Drone Systems)
Mission-oriented performance assessment, design optimization
CLOUDS
MADAM
(Multidisciplinary Analysis and Design for Advanced Mobility)
UAM Cost & Demand Estimation Analysis
KARI

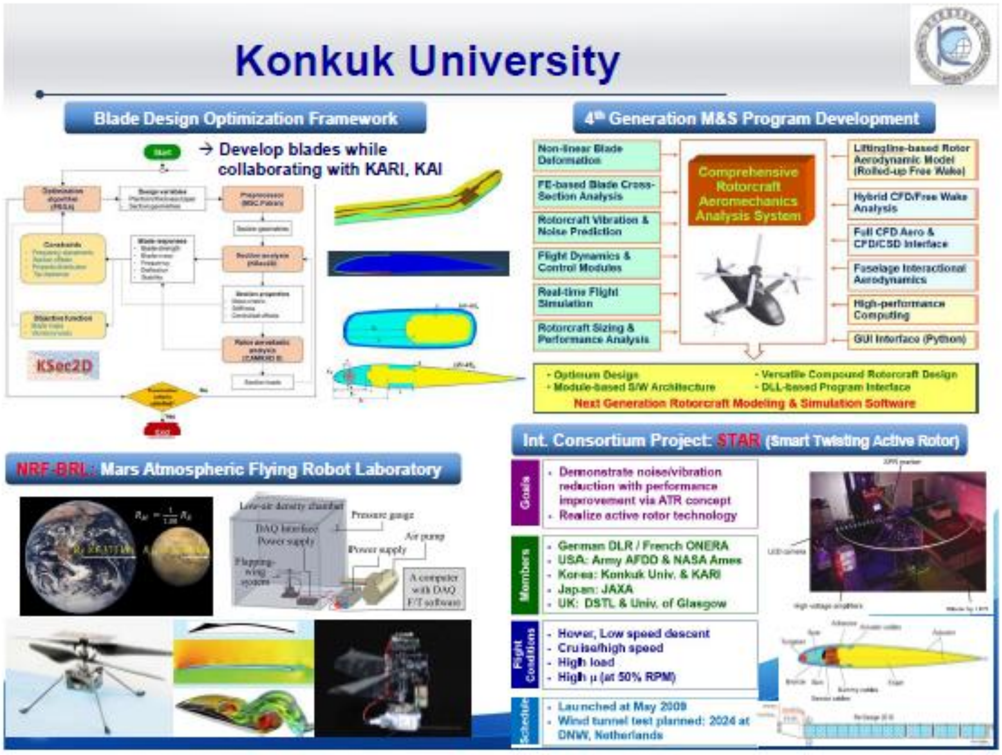

Seoul National University
AVDL
Aerospace Vehicle Design Laboratory
Prof. Kwanjung Yee | Ph. D. Candidate : 21 | Master Course : 9
Ongoing researches for VTOL (2/2) – Detailed Design
Rotorcraft Aerodynamics and Aeroacoustics
with high-order accurate scheme for vorticity conservation
Experiment
Single rotor in BVI condition
Coaxial, co-rotating rotor
Coaxial, counter-rotating rotor
Aircraft Icing Accretion
ICEPAC (Ice Contour Evaluation and Performance Analysis Code)
Improved prediction accuracy using transition model
Prediction of Rotorcraft Icing Accretion
KARI


Seoul National University
Structural design
Active blade aerodynamics
Rotor test and analysis
Multi-body dynamics analysis
Controller design
Rotor azimuth, degree
Blade fabrication and test
CFD-CSD rotor higher harmonic control


Seoul National University
Step 1
Initial deliverables
Step 2
Final deliverables
Group 1
Research on the Data-based conceptual design techniques
Mission profile
UAM configuration Design
Group1-3 sharing
UAM multi-disciplinary integrated concept design software
3D data sharing platform-based shape optimization
Battery life Improvement circuit
Digital twin UAM simulation
Group 2
Robust autonomy system design automation and verification
Prototype test
ATM/UTM coupled automated flight technology
Mixed-reality operation simulation
1st Technology demonstration 1/5 scaled prototype
2nd Technology demonstration 1/5 scaled prototype
Group 3
High precision UAM flow/structure/noise analysis and crash analysis
Detailed design
Noise/vibration reducing design optimization


Konkuk University
HETLAS : Component-Model based Helicopter Trim, Linearization, and Simulation Program
Autonomous Rotorcraft Flight Control for Offensive and Defensive Tactical Missions
Mission Planner
- Real-time applications
- Near optimal path plan
Path Planner
- Low detectability/Lethal
- Collision avoidance law
Trajectory-Tracking Control
- Adaptive Incremental SMC
- Adaptive Incremental BSC
Autonomous Emergency Landing Flight Control
Reachable Path Planning to Safe landing Area
Adaptive Robust Nonlinear Rotorcraft Flight Control
Accurate tracking performance
• Nonlinear SMS/BSC Design
Robustness
• Incremental dynamics
• Immersion & Invariance (I&I)
• Tuning Function Method
• Variable Directional Forgetting LS Estimator
Guaranteed Stability/Performance
• Lyapunov-Function Based Design


Konkuk University
HCUR: Fugelage Drag Prediction
▲ Wind tunnel experiments for HCUR scaled model
▲ CFD analysis & drag coefficient of each part with A.o.A.
Farfield Noise Prediction: Adaptive Chimera Grid
Rotorcraft CFD Development
▲ Dynamic stall prediction by using RBF-based grid deformation
▲ LCH 5-bladed rotor in forward flight (left) & thrust in hover
D14 D15 D16
▲ Tip vortex-fuselage interaction

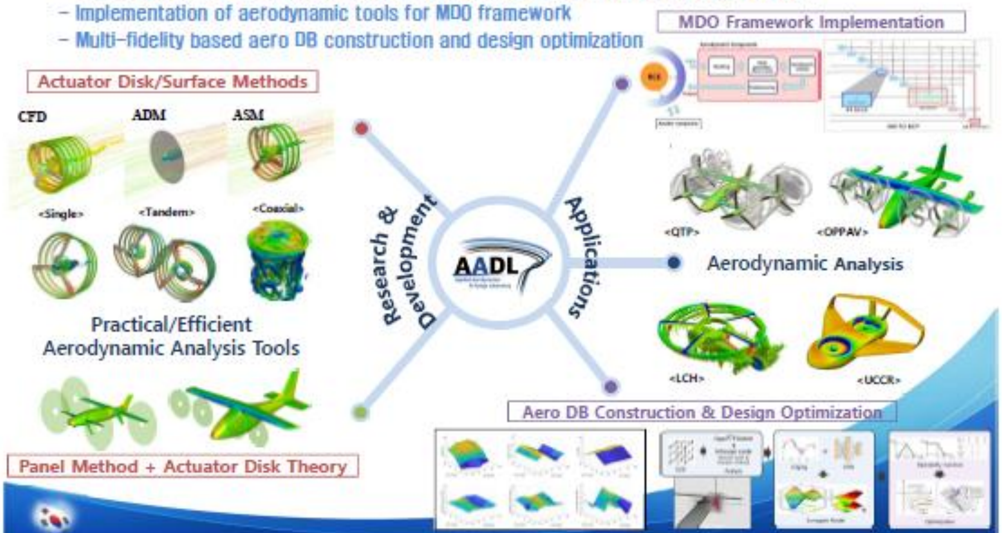

Konkuk University
Blade Design Optimization Framework
→ Develop blades while collaborating with KARI, KAI
KSec2D
4th Generation M&S Program Development
Non-linear Blade Deformation
FE-based Blade Cross-Section Analysis
Rotorcraft Vibration & Noise Prediction
Flight Dynamics & Control Modules
Real-time Flight Simulation
Rotorcraft Sizing & Performance Analysis
Comprehensive Rotorcraft Aeromechanics Analysis System
Liftingline-based Rotor Aerodynamic Model (Rolled-up Free Wake)
Hybrid CFD/Free Wake Analysis
Full CFD Aero & CFD/CSD Interface
Fuselage Interactional Aerodynamics
High-performance Computing
GUI Interface (Python)
· Optimum Design
· Module-based S/W Architecture
· Versatile Compound Rotorcraft Design
· DLL-based Program Interface
Next Generation Rotorcraft Modeling & Simulation Software
NRF-BRL: Mars Atmospheric Flying Robot Laboratory
Int. Consortium Project: STAR (Smart Twisting Active Rotor)
Goals
· Demonstrate noise/vibration reduction with performance improvement via ATR concept
· Realize active rotor technology
Members
· German DLR / French ONERA
· USA: Army AFDD & NASA Ames
· Korea: Konkuk Univ. & KARI
· Japan: JAXA
· UK: DSTL & Univ. of Glasgow
Flight Conditions
· Hover, Low speed descent
· Cruise/high speed
· High load
· High μ (at 50% RPM)
Schedule
· Launched at May 2009
· Wind tunnel test planned: 2024 at DNW, Netherlands

Pusan National University

Professor : Donghun Park & Sejong Oh (Emeritus prof.)

✧ Applied Aerodynamics and Design Lab. (AADL)

- Development of practical & efficient aerodynamic analysis tools (ADM / ASM / Panel)
- Implementation of aerodynamic tools for MDO framework
- Multi-fidelity based aero DB construction and design optimization



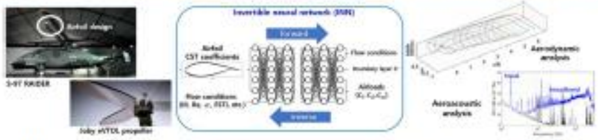
Pusan National University

Assistant professor : Yong Su Jung

✧ Computational Aerodynamics and Rotorcraft Lab (CARL)

◆ CFD Trained Invertible Neural Networks and Machine Learning for Rotor Blade Airfoil Design (2022~2024)

- Development of forward and inverse machine learning models that are trained using RANS simulations

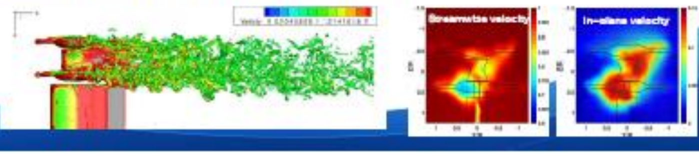


◆ Line-based Unstructured Grid CFD Techniques for Rotorcraft Applications

- Automated mesh refinement capability for 2-D Hamiltonian solver (2022~2024)
- Improvements on a laminar-turbulent boundary layer transition model

◆ Interactional Aerodynamic/Aeroacoustics for Advanced Rotorcraft Configurations

- Coaxial rotor hub flow simulations using hybrid RANS-LES
- Aeroacoustic simulations for a wingtip-mounted propeller



Chungnam National University

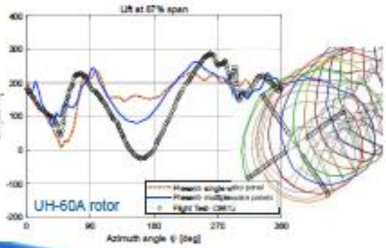
Professor Jae-Sang Park

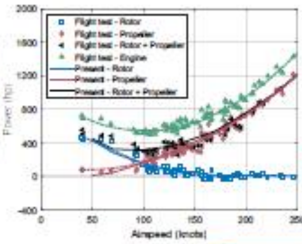
- Ph.D from School of Mechanical and Aerospace Eng., Seoul National University, 2006
- Professor in Dept. of Aerospace Eng., Chungnam National University, 2013 ~ Present
- Research interests : Rotor aeromechanics analyses, Active vibration controls, Conceptual design

▪ **Rotor aeromechanics analyses**

- Rotorcraft comprehensive analysis tools : CAMRAD II and DYMORE II
- Conventional helicopters, Lift-offset compound helicopters, Tiltrotor aircraft

X2 Technology Demonstrator



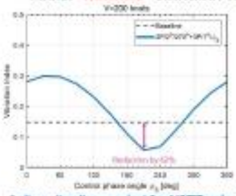


X2TD Lift-offset coaxial rotor

Chungnam National University

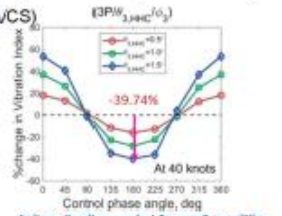
▪ **Rotorcraft active vibration controls**

- Active rotor vibration controls using Individual Blade pitch Control (IBC) or Higher Harmonic pitch Control (HHC)
- Active airframe vibration controls using Active Vibration Control System (AVCS)



Active vibration control for X2TD rotor using Individual Blade pitch Control

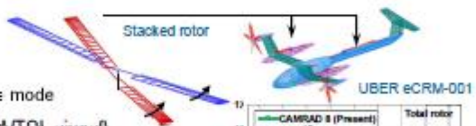
Active vibration control system (AVCS) for small-scaled compound helicopter model



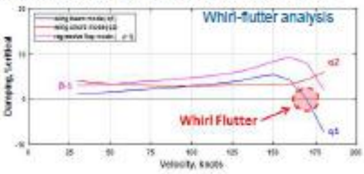
Active vibration control for medium utility helicopter using Higher Harmonic pitch Control

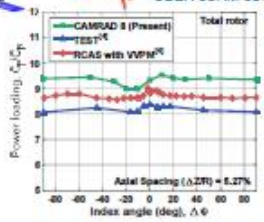
▪ **Tiltrotor and eVTOL stacked rotor**

- Whirl-flutter analyses for tiltrotor aircraft in airplane mode
- Hover performance analyses for stacked rotor of eVTOL aircraft



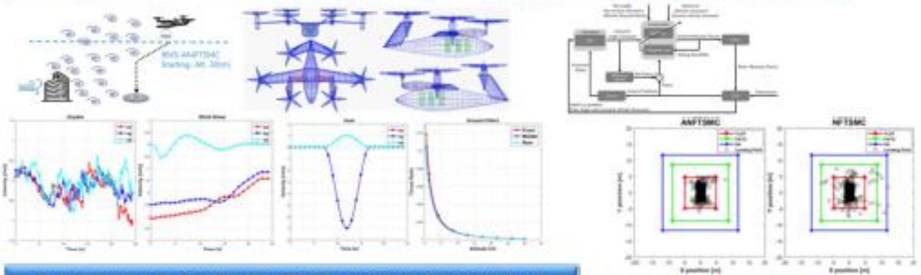
TiltRotor Aeroelastic Stability Testbad (TRAST, US)



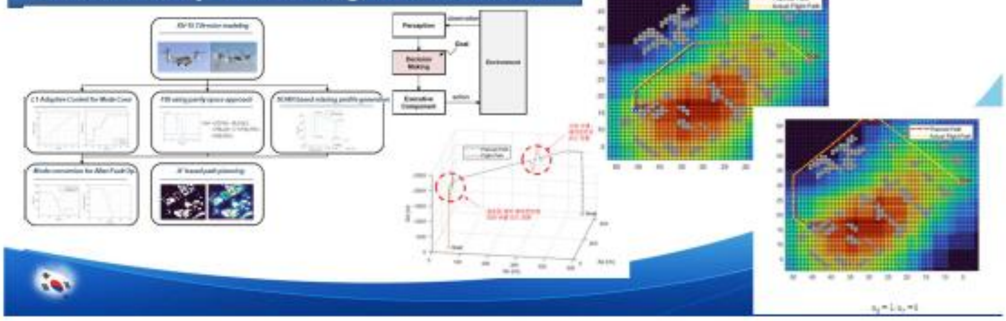


Inha University

Vision-Based Automatic Landing System for UAM Considering Building Wind



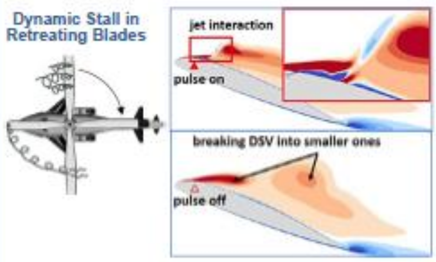
Autonomous System with Cognitive Architecture



GIST (Gwangju Institute of Science and Technology)

Dynamic Stall Control

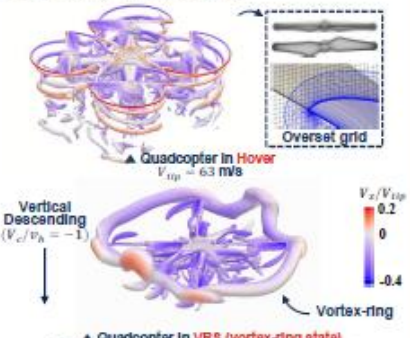
- Dynamic stall control with impulsive jets
- Impulsive jet
  - Sonic jet for 1 msec
  - Generated from combustion-powered actuation
  - Breaking DSV into smaller vortices
- Control benefits
  - Moment peak (negative) reduction by 70%
  - Lift enhancement by 20%



[Kim, T. and Jee, S., 2023, Comp & Fluids]

Multi-Copter Aerodynamics

- Full Navier-Stokes Solver with overset grid
  - OpenFOAM with SA-RC RANS
  - CFD is validated for a hovering quadcopter
- VRS : vortex-ring state
  - Must-to-avoid condition in descending
  - Well captured in current CFD



▲ Quadcopter in VRS (vortex-ring state)
Descending velocity $V_c = -5.5$ m/s $= -0.09\,V_{tip}$

[Park, Y. M. and Jee, S., 2023, AIAA Aviation]

theory.gist.ac.kr

GIST (Gwangju Institute of Science and Technology)

Multi-UAV Control

▲ Multi-UAV Control with UWB
- NO GPS for tagged UAV
- Positioning through RF-based UWB (ultra-wide band) with autonomous anchored UAVs
- Decentralized position control with stable inter-vehicle communication

dcas.gist.ac.kr
Distributed Control and Autonomous System Lab

Collision Avoidance Control

biorobotics.gist.ac.kr

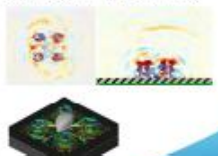
Gyeongsang National University (1 / 2)

❖ Biography
- Hakjin Lee, Ph.D. (hlee@gnu.ac.kr)
  - Assistant Professor, School of Mechanical and Aerospace Engineering, Gyeongsang National University
  - Director, Rotorcraft Aerodynamics and Noise Simulation (RANS) Lab.
- Education
  - Ph.D. in Aerospace Engineering, Korea Advanced Institute of Science and Technology (KAIST), 2019
  - M.S. in Aerospace Engineering, Korea Advanced Institute of Science and Technology (KAIST), 2014
  - B.S. in Aerospace Engineering, Korea Aerospace University, 2012
- Research Interests
  - Rotor Aerodynamic, Aeroacoustics
  - Computational Fluid Dynamics (CFD), Computational Aeroacoustics (CAA), Vortex Methods
  - Rotorcraft, Helicopter, Urban Air Mobility (UAM), Drone, Wind Turbine

❖ Research topic I
- Aeroacoustic analysis of urban air mobility
  - Investigate the interactional aerodynamics and aeroacoustics of UAM
  - Simulate the co-axial multi-rotor eVTOL vehicle in ground effects

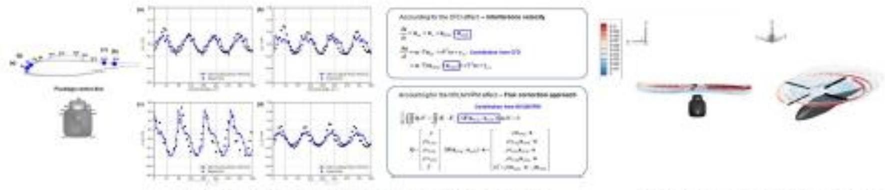
Comparison of isolated rotor and rotor-conical airframe

Acoustic dilatation field of co-axial eVTOL



Gyeongsang National University (2 / 2)

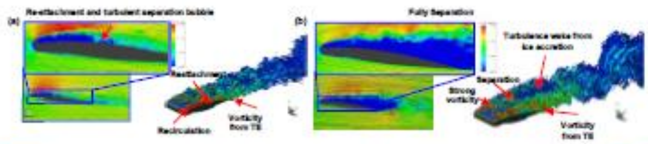
- Research topic II
  - **Comprehensive analysis of rotorcraft**
    - Hybrid Lagrangian-Eulerian approach for simulating the complex rotorcraft
    - Provide an efficient and accurate aerodynamic analysis solution, which supports the aeroacoustic design of rotorcraft



Fundamental formulation and validation results of NVLM/VPM/CFD simulation

NVLM/VPM/CFD simulation of complete rotorcraft

- Research topic III
  - **Flow physics and aeroacoustics of iced airfoil and rotor blade**
    - Analyze the expanding process of separation bubble and noise generation of an iced airfoil



Instantaneous x-velocity contour and λ_2 iso-surface: (a) 0 deg. (b) 8 deg.

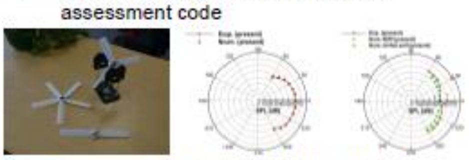
Acoustic dilatation field of iced airfoil

Hanseo University

- Research Area: Aerodynamics
  - Development of a mid-fidelity aerodynamic solver based on vortex methods
  - High-fidelity CFD computation for rotorcrafts

CFD computation for a tandem UAM helicopter

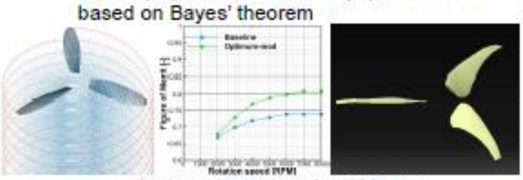
- Research Area: Aeroacoustics
  - Development of a noise-prediction code for rotorcrafts (tonal/broadband/body-scattering)
  - Development of a community noise assessment code



Rotor noise prediction for a 3-bladed UAV rotor

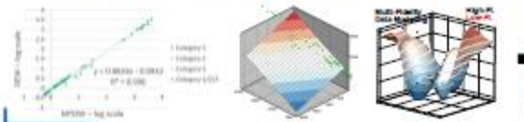
Hanseo University

- **Research Area: Design Optimization**
  - Development of machine-/deep-learning based surrogate models
  - Aleatory/epistemic uncertainty quantification based on Bayes' theorem

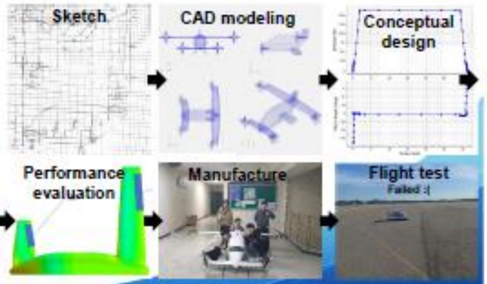


Design optimization of a sUAS rotor

- **Research Area: System Design**
  - Data modelling of aircraft performances for conceptual designs
  - Conceptual design of aircrafts
  - Manufacture and flight test of designed aircrafts



Data modelling for small-scale UAM vehicles

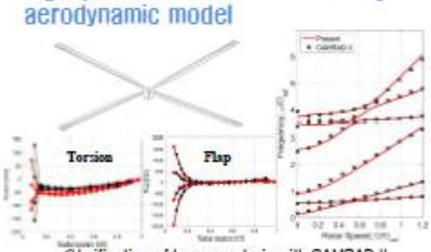


Design, manufacture, and flight test of a tilt-rotor UAM vehicle

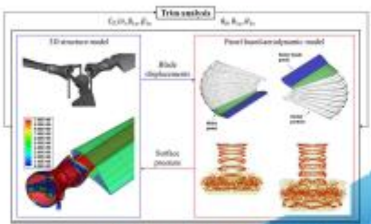
Jeonbuk National University

❖ **Development of Vibration Source Active Control Device SW for Medium Helicopter Vibration Reduction (2022~2024)**
- Nonlinear beam analysis coupled with aerodynamic model
- Load analysis and verification with CAMRAD II

❖ **Development of rigid coaxial rotor system design/manufacturing technology (2022~2026)**
- High-precision rotor structural dynamics via 3D FEM and coupling with aerodynamic model



<Verification of beam analysis with CAMRAD II for HHC application>



<Aeromechanical load/vibration analysis for coaxial rotor system>


III. Industries


Korea Aerospace Industries
A Professional Integrated Development for Rotary Wing
KUH-1
Military Helicopter
"The Excellent Mission Profiler"
• Specification
- Dimensions : 3.0m × 19.0m × 5.0m
- Power Plant : 1,855 shp × 2
- Max. Speed : 145 kt
- 18 passengers
• State-of-the-art Equipment
• Excellent performance in various terrains, harsh conditions both day/night and any adverse weather conditions
KUH Variants
Police/Medical/Etc. Helicopter
"Contribution to Safety"
• Derivatives Expanding Domestic and International Civil and Parapublic based on KUH-1.
• Various missions like search and rescue, patient transportation and fire-fighting.
LAH / LCH
Light Armed/Civil Helicopter
"Enhancement of the Armed Forces"
• Specification
- Dimensions : 3.9m × 14.3m × 4.3m
- Power Plant : 1,032 shp × 2
- 2 passengers
• LAH aims to develop an advanced armed helicopter suitable for modern battlefields.
- Equipped with modern avionics, weapons(Turret Gun, AGM, Rocket), fire-control systems.

Korea Aerospace Industries

Focal Strategy Programs

MAH / MCH	LAH Variants	New Generation
		
Marine Attack Helicopter Mine Countermeasure Helicopter	MUMT(Man-Unmanned Teaming)	High Performance Helicopter

Korean Air

Target Gross Weight	000 kg
Target Payload	00 kg
Overall Length	4 m
Prop Radius	1.5 m
Endurance	0 hrs
Max Speed	190 km/h

❖ **Program Overview**
- KAL R&D program (Model Name : KUS-VS)
- 2021. 1 ~ 2023. 8 (32 months)

❖ **KUS-VS Characteristics**
- VTOL UAV for military propose
- Electric & ICE Hybrid propulsion system
- Long Range EO/IR/LRF Camera payload
- Rapid deploy and ground transportation
- STANAG 4586 Interoperability
- Military Airworthiness Ready

❖ **Program Milestone**
- '21.1Q : Scale model flight
- '21.2Q : Electric proplusion system test
- '22.4Q : New OML release
- '23.3Q : Design complete

Korean Air

Gross Weight	000 kg
Payload	00 kg
Overall Length	6.4 m
Main Rotor Diameter	7.2 m
Max Endurance	0 hrs
Cruise Speed	100 km/h

❖ **Program Overview**
- Government R&D program (Model Name : KUS-VM)
- 2023. 8 ~ 2028. 7 (60 months)

❖ **KUS-VM Characteristics**
- VTOL UAV for Navy and Marine Corps
- Long Range EO/IR and SAR/ISAR payload
- Autonomous take-off and landing on Destroyer class ship
- Military Airworthiness Ready

❖ **Program Milestone**
- '23.3Q : Program start
- '24.4Q : CDR
- '25.4Q : Aircraft Roll out
- '28.2Q : System development Complete

LIG Nex1

Overview

Development of MTOW 200kg Multi-purpose Unmanned Helicopter(Cargo/ISR)

Program Type	Civil-Military Technology Development	Period	'17.12 ~ '21.11
Prime Company	Sung-woo Eng.	Budget	13,000,000 USD
Contractor	ADD ICMTC (Institute of Civil Military Technology Cooperation)		

Appearance

Progress

- '17.12 : Agreement and Program Start
- '18.04 : SRR (System Requirement Review)
- '18.11 : PDR (Preliminary Design Review)
- '19.02 : CDR (Critical Design Review)
- '19.10 : TRR#1 (Test Readiness Review)
- '20.02 : FFRR (First Flight Readiness Review)
- '20.06 : TRR#2 (Test Readiness Review)
- '21.11 : The program ends

Features

- MTOW : 200kg+ (Payload : Max. 60kg)
- Max. Speed : 150km/h+
- Operational Altitude : 3km+
- Endurance(Payload) : 6hrs(25kg) / 3hrs(60kg)
- Operational Range : 50km+
- Payload : EO/IR

LIG Nex1

Overview

Development of a Army Small UAV System for Reconnaissance and Attack

Program Type	Rapid Demonstration Acquisition Project	Period	'20.12 ~ '22.09
Prime Company	LIGNex1	Budget	3,900,000 USD
Contractor	DAPA (Defense Acquisition Program Administration)		

Appearance

Progress

- '20.12 : Contract
- '21.11 : Delivery Completed(ROKA, 18ea)
- '22.09 : ROKA Demonstration Support Report Submitted

Features

- Loitering munition for BN reconnaissance & attack missions
- Operational Range : 8km+, Altitude : 300m+, Time : 30min+
- Flight Speed : 90km/h, Impact Speed : 140km/h
- MTOW : 15.0kg
- IPX3 waterproof, Anti Jamming, KCMVP Communication Security

LIG Nex1

Overview

Hybrid Engine based Payload 40kg Multi-copter Cargo Drone Development for Civil-Military dual use

Program Type	Civil-Military Dual-use Technology Development	Period	'20.11 ~ '23.11
Prime Company	LIGNex1	Budget	4,600,000 USD
Contractor	ADD ICMTC (Institute of Civil Military Technology Cooperation)		

Appearance

Progress

- '20.11 : Commencement of the agreement
- '20.12 : Kick-Off Meeting
- '21.09 : PDR(Preliminary Design Review)
- '22.05 : CDR(Critical Design Review)
- '23.04 : TRR(Test Readiness Review)
- '23.06 : FFRR(First Flight Readiness Review)
- '23.10 : Final Evaluation
- '23.11 : The program ends

Features

- Maximum Payload Weight : 40kg+
- Operational Range : 10km+
- Operational Time : 60min+
- Operational Altitude : 400m+
- Maximum Flight Speed : 50km/h+
- Powertrain : Engine Battery Hybrid

LIG Nex1

Overview

Payload 200kg Cargo Drone Technology Development based on Hydrogen Fuel Cells

Program Type	National R&D Program (MOTIE)	Period	'21.06 – '25.12
Prime Company	LIGNex1	Budget	36,000,000 USD
Contractor	Korea Evaluation Institute of Industrial Technology(KEIT)		

Appearance

Progress

- '21.06 : Agreement
- '21.07 : Kick Off Meeting
- '21.10 : SRR/SFR(System Requirement/Functional Review)
- '22.11 : PDR(Preliminary Design Review)
- '23.09 : CDR(Critical Design Review)
- '23.12 : Mid-Term Evaluation
- '25.01 : FFRR(First Flight Readiness Review)
- '25.09 : Final Evaluation
- '25.12 : The program ends

Features

- Maximum Payload Weight : 200kg+
- Operational Range : 50km+
- Operational Time : 1hrs+
- Maximum Flight Speed : 100km/h+
- Powertrain: "Hydrogen fuel + Battery" Hybrid

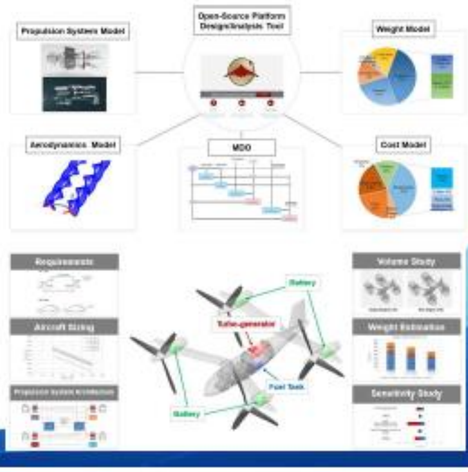
Hanwha Systems

✣ Overair Butterfly

- Capacity: 1 pilot + 5 pax
- Rotor system: 4 tilt rotors with individual blade control (IBC) system
- Full-scale propulsion system test program completed in Fall 2022

✣ Advanced Research on Hybrid-Electric VTOL Aircraft

- Feasibility study on gas turbine hybrid-electric VTOL aircraft



Hanwha Systems

❖ **Flight Control System of Optionally Piloted PAV (OPPAV)**

- OPPAV Flight Control System Dev. Project (Apr. 2019 – Dec. 2023)
- Work scope:
  - FLCC SW(OFP) Design and Implementation
  - OPPAV HILS Configuration Setup
  - FCS System Integration Test (HILS & RIG)
  - OPPAV Ground/Flight Test

❖ **eVTOL Aircraft Flight Simulator**

- UAM VIPP (Virtual Integrated Operation Platform) Project (Apr. 2022 – Dec. 2026)
- Work scope:
  - Development of fixed-base and motion-platform flight training devices for three different types of eVTOL aircrafts

IV. Institutes

Korea Aerospace Research Institute

1.OPPAV

2.High-Speed Rotor System

3.30kW-H_2 Fuel Cell Unmanned Helicopter

4.Low Noise Prop-Rotor for UAM eVTOL

1. OPPAV(Optionally Piloted Personal Air Vehicle) eVTOL

- **Optionally piloted eVTOL technology demonstrator is being developed (2019~2023)**
  - One seater class. (Vc > 200kph, Range > 60km)
  - 8 electric motors, full electric using Li-Ion, 4 tilt props and 4 fixed lift props
  - Airworthiness standard draft is being developed in parallel
  - Wind tunnel testing is completed, the first flight is planned in Jan-2023

<Wind Tunnel Test of OPPAV Scaled Powered Model in KARI-LSWT>

<KARI OPPAV Concept>

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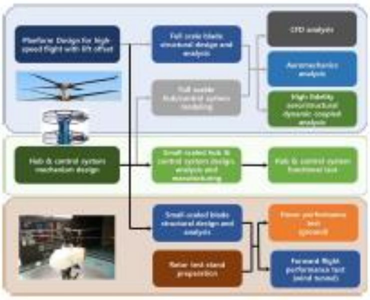
2. Rotor System for High-Speed Forward Flight

- ❖ **Rigid Coaxial Rotor System Development for High Speed Long Range Utility Helicopter**
  . 2022. 12. ~ 2026.12 (Defense Acquisition Program Administration)
  . Airspeed > 000 knot, High efficiency (FM > 0.00, L/D_e > 00)
  - Design and analysis of low drag rigid coaxial rotor planform with lift offset
  - Rigid composite blade design and analysis
  - Efficient hub control system design and analysis
  - Small-scaled model design, analysis, fabrication and ground & wind tunnel test

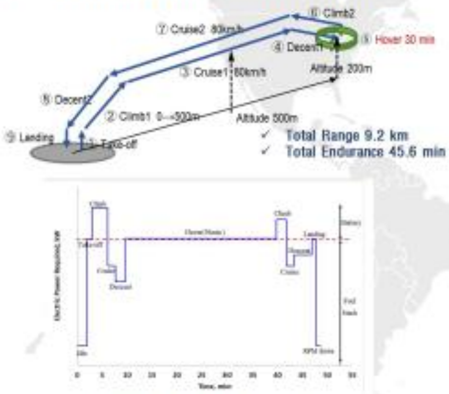


Reference model

3. 30kW-H_2 Fuel Cell Unmanned Helicopter

- ❖ **Net power 30kW class fuel cell power pack system for a unmanned helicopter with 200kg class maximum takeoff weight (2021~2025)**
  - Rotor type : 2 bladed-coaxial rotors with 2.18m of rotor radius
  - Rotor RPM : 580RPM
  - Weight : 250kg
  - Propulsion system : Electric motor powered by primary fuel cell and battery

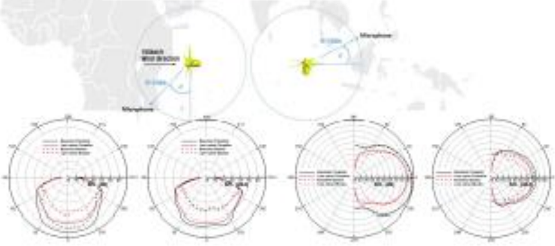
<Coaxial rotor with fuel cell>



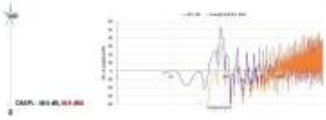
<Mission profile and power sharing>

4. Low Noise Prop-Rotor for UAM eVTOL

❖ Low noise prop rotor (2020~2023)
- Five bladed prop rotor with 1.3 meter of radius
- Maximum thrust 500kgf per prop rotor for Five seater class UAM
- Noise level 64dBA away from 150meter in forward flight
- Figure of Merit 0.7 above



<Analysis of noise level in forward flight and hover>



<Noise level measurement of prop rotor>

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V. Conclusion

V. Conclusion

- **In Civil Side, eVTOL Aircraft System Technologies were focused on AAM(UAM, RAM) Application**
  - Passenger Drone, Parcel Delivery Service, etc
  - KARI, Hanwha Systems, Hyundai Motors, KAI, Vessel Aerospace, etc.
- **In Military Side(Manned) VTOL System Technologies have been focused on Army' s Light Armed Helicopter and Marine Attack Helicopter**
  - LAH Helicopter Production Start(2023~)
  - Marine Attack Helicopter Development Start (2022~)
  - KAI
- **In Military Side(Unmanned) VTOL System Technologies have been focused on Army' s Observation and Scout, Delivery Service**
  - KAI, KAL, LIG Nex1,Hanwha Systems, Vessel Aerospace

Thank you!

Aerospace Multidisciplinary Design Laboratory AMDL

Coupled Adjoint-based Rotor Design using a Fluid Structure Interaction in Time Spectral Form

Seongim Choi[1], Hyunsoon Kim[2], and Rachit Prasad[2]

Department of Mechanical Engineering
Gwangju Institute of Science and Technology (GIST)
Virginia Polytechnic Institute and State University

1

Contents

I. Introduction

II. Fluid-Structure Interaction in Time Spectral Form

III. Adjoint Sensitivity for Time Spectral Form

IV. Sensitivity Analysis Results

V. Conclusions

2

Introduction: Motivation

- Motivation
  - The system involving **multi-physics** is difficult to analyze with high fidelity analysis.
  - For example, difficulties associated with simulation of helicopter flight
    - **Aerodynamic challenges**: Complexity of unsteady and vortical air flows
    - **Structural dynamic** challenges: Long and flexible rotor blades
    - **Coupled physics** of aerodynamics and structures

- Objective
  - *Develop an accurate but efficient analysis and design method for rotor blade.*

Source: [illegible]

3

Source: [illegible]

Introduction: Literature Review

- Literature Review for Rotor Design
  - A comprehensive rotor design code
    - CAMRAD (NASA Ames Research Center / U.S. Army, 1980)
      - Lifting-line theory, Lifting-surface theory
    - CAMRADII (Johnson Aeronautics,1994)
    - UMARC (University of Maryland, 1990)
      - FEM formulation + Quasi-steady 2-D strip theory
  - CFD/CA coupling
    - CAMRAD II, RCAS and UMARC started to include main rotor 3D-CFD coupling, (in 2000s)
    - Hybrid solver: OVERFLOW + CHARM (by CDI, 2016)

Partner	Partner label	CFD Code	CSD Code
U.S. Army Aero-flightdynamics Dir.	AFDD-1	OVERFLOW	CAMRAD II
U.S. Army Aero-flightdynamics Dir.	AFDD-2	NSU3D/SAMARC	RCAS
NASA-Langley	NL-1	OVERFLOW	CAMRAD II
NASA-Langley	NL-2	FUN3D	CAMRAD II
Georgia Institute of Technology	GIT-1	FUN3D	DYMORE4
Georgia Institute of Technology	GIT-2	GENCAS	DYMORE2
Konkuk University	KU	KFLOW	CAMRAD II
University of Maryland	UM	TURNS	UMARC
German Aerospace Center	DLR	N/A	S4

Smith, Marilyn J., et al. "An assessment of CFD/CSD prediction state-of-the-art using the HART II international workshop data," *68th Annual Forum of the American Helicopter Society*, Ft. Worth, TX, 2012.

4

Introduction: Contributions

- Literature Review
  - Adjoint-based shape optimization for **static** aeroelastic problem
    - Kenway, Kennedy and Martins (U.Mich, 2014)
  - **Time Accurate approach** with unsteady adjoint-based shape optimization of rotor (Dynamic FSI problem)
    - Mishra, Mani and Mavriplis (Wyoming University, 2014)

- <u>**Contributions of th present study**</u>
  - **Time-Spectral form** of fluid and structural equations of motion (steady form of governing equations)
  - Steady adjoint formulation for **unsteady**, dynamic problems in time-spectral form.
  - Fluid-structure interface (FSI) and **coupled adjoint solution**

1. Kenway, Gaetan KW, Graeme J. Kennedy, and Joaquim RRA Martins. "Scalable parallel approach for high-fidelity steady-state aeroelastic analysis and adjoint derivative computations." *AIAA journal* 52.5 (2014): 935-951.
2. Mishra, Asitav, et al. "Time-dependent adjoint-based aerodynamic shape optimization applied to helicopter rotors." *Rx* 3 (2014): 2.

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I. **Introduction**

II. **Fluid-Structure Interaction in Time Spectral Form**

III. **Adjoint Sensitivity for Time Spectral Form**

IV. **Sensitivity Analysis Results**

I. **Conclusions**

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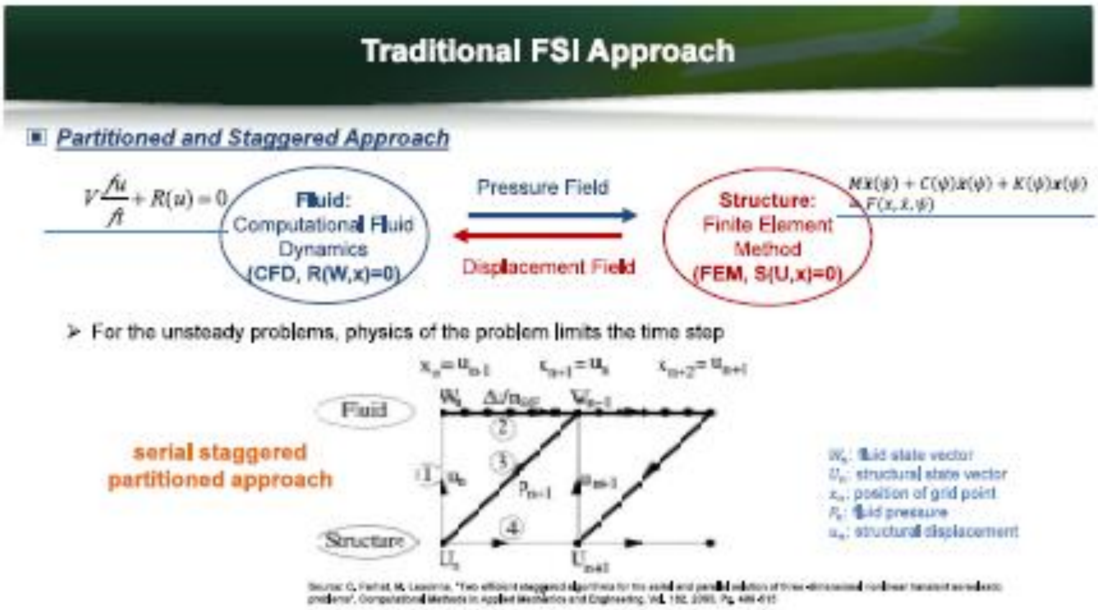
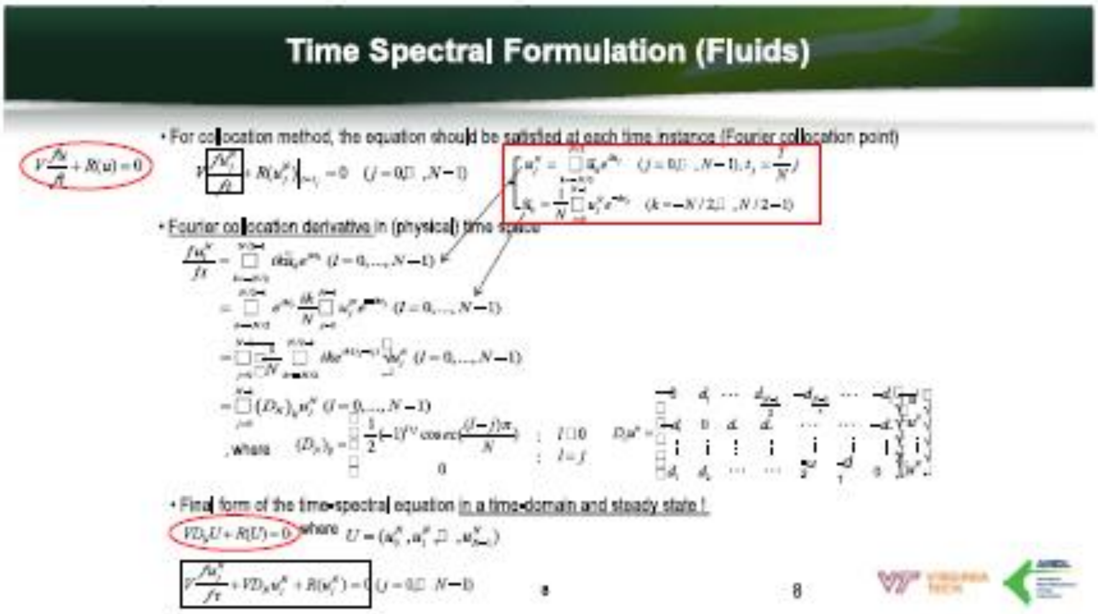

Traditional FSI Approach
Partitioned and Staggered Approach
Fluid:
Computational Fluid
Dynamics
(CFD, R(W,x)=0)
Pressure Field
Displacement Field
Structure:
Finite Element
Method
(FEM, S(U,x)=0)
For the unsteady problems, physics of the problem limits the time step
serial staggered
partitioned approach
Fluid
Structure
W_n: fluid state vector
U_n: structural state vector
x_n: position of grid point
P_n: fluid pressure
u_n: structural displacement


Time Spectral Formulation (Fluids)
For collocation method, the equation should be satisfied at each time instance (Fourier collocation point)
Fourier collocation derivative in (physical) time space
where
Final form of the time-spectral equation in a time-domain and steady state !
8

Time Spectral Formulation (Structures)

- Dynamic Structural Analysis
  - Governing equation

$$M\ddot{x}(\psi) + C(\psi)\dot{x}(\psi) + K(\psi)x(\psi) = F(x, \dot{x}, \psi)$$

  - First order ODE form

x: nodal displacements
ψ: azimuth angle (0 ° ~ 360°)

$$\dot{y}(\psi) = Ay(\psi) + Bf(\psi)$$

where, $y(\psi) = \begin{bmatrix} x(\psi) \\ \dot{x}(\psi) \end{bmatrix}$, $f(\psi) = \begin{Bmatrix} 0 \\ F \end{Bmatrix}$, $A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}$, and $B = \begin{Bmatrix} 0 \\ M^{-1} \end{Bmatrix}$

9

VIRGINIA TECH.

Time Spectral Formulation (Structures)

- Dynamic Structural Analysis using Spectral Formulation
  - State-vector form equation

$$\dot{y}(\psi) = Ay(\psi) + Bf(\psi)$$

Spectral Method

solution approximation	error minimization
- Trigonometric (Fourier)	- Galerkin
- Chebychev	- Collocation
- Legendre	- Tau

  - Assuming the solution with a Fourier series

$$y(t) = \hat{y_0} + \sum_{n=1}^{N_H} (\hat{y_{cn}} \cos \omega n t + \hat{y_{sn}} \sin \omega n t)$$

  - The time derivative can be converted into a Matrix Vector product. It can be solved by applying pseudo-time stepping

$$\frac{\partial y_{TS}}{\partial \tau} + D_N y_{TS} - A y_{TS} - B f_{TS} = 0$$

τ: pseudo time

where, $y_{TS} = \begin{pmatrix} y(\psi_0 + \Delta\psi) \\ y(\psi_0 + 2\Delta\psi) \\ \vdots \\ y(\psi_0 + 2\pi) \end{pmatrix}$ $f_{TS} = \begin{pmatrix} f(\psi_0 + \Delta\psi) \\ f(\psi_0 + 2\Delta\psi) \\ \vdots \\ f(\psi_0 + 2\pi) \end{pmatrix}$

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Proposed FSI in Time-Spectral Formulation

- Time Spectral form of Governing Equations

Pressure Field →

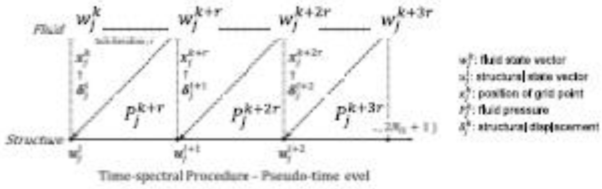
← Displacement Field

Fluid Equation

$$V\frac{\partial w_{ts}}{\partial \tau} + V\omega D w_{ts} + R(w_{ts}) = 0$$

Structural Equation

$$\frac{\partial y_{ts}}{\partial \tau} + \omega D y_{ts} - A y_{ts} - B f_{ts} = 0$$



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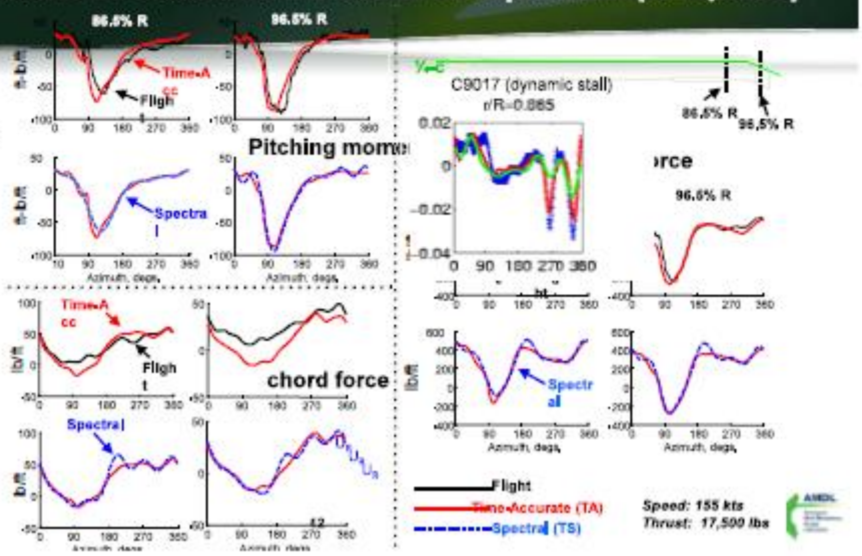
TS FSI Validation: Sectional Airloads Comparison (CFD/CSD)

UH-60A
C8534
with 7 harmonics



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III. Adjoint Sensitivity for Time Spectral Form

IV. Sensitivity Analysis Results

I. Conclusions

Sensitivities and Design

- Approach: **Sensitivity Analysis for unsteady problems.**
  - Shape Optimization requires gradient with respect to a large number of design variables.

Finite Difference Method (FDM) → With N design variables **N+1** Aeroelastic Simulations

$$f'(x) \approx \frac{f(x+\Delta x)-f(x)}{\Delta x}$$

  - Adjoint Method is extremely handy in such cases

Adjoint Method → 1 Aeroelastic Solution + 1 Adjoint Solution

$$\left(\frac{\partial R}{\partial w}\right)^T \lambda = -\frac{\partial I}{\partial w}$$

  - Disadvantage: For unsteady problems, physics residuals and adjoint variables need to be stored at each phy sical time step→ Memory and time intensive.

Coupled Adjoint for Coupled Sensitivity Analysis

- Coupled Adjoint Analysis
  - Gradient computation using adjoint method for a coupled FSI problem
  - Objective function: $I = I(w, y, x, b)$

w: fluid state variables
y: structural state variables
x: mesh state variables
b: design variables

  - Total derivative of objective function w.r.t design variables

$$\frac{dI}{db} = \frac{\partial I}{\partial b} + \frac{\partial I}{\partial w}\frac{\partial w}{\partial b} + \frac{\partial I}{\partial y}\frac{\partial y}{\partial b} + \frac{\partial I}{\partial x}\frac{\partial x}{\partial b}$$

  - State equations for fluid and structural system and their derivatives w.r.t design variables

Fluid: $R(w, y, x, b) = 0 \rightarrow \frac{dR}{db} = \frac{\partial R}{\partial b} + \frac{\partial R}{\partial w}\frac{\partial w}{\partial b} + \frac{\partial R}{\partial y}\frac{\partial y}{\partial b} + \frac{\partial R}{\partial x}\frac{\partial x}{\partial b} = 0$

Structure: $S(w, y, x, b) = 0 \rightarrow \frac{dS}{db} = \frac{\partial S}{\partial b} + \frac{\partial S}{\partial w}\frac{\partial w}{\partial b} + \frac{\partial S}{\partial y}\frac{\partial y}{\partial b} + \frac{\partial S}{\partial x}\frac{\partial x}{\partial b} = 0$

  - As the residual derivatives are zero, they can be multiplied with an adjoint vector and added to the objective function derivative.

$$\frac{dI}{db} = \frac{\partial I}{\partial b} + \frac{\partial I}{\partial w}\frac{\partial w}{\partial b} + \frac{\partial I}{\partial y}\frac{\partial y}{\partial b} + \frac{\partial I}{\partial x}\frac{\partial x}{\partial b} + \lambda^T \underbrace{\left(\frac{\partial R}{\partial b} + \frac{\partial R}{\partial w}\frac{\partial w}{\partial b} + \frac{\partial R}{\partial y}\frac{\partial y}{\partial b} + \frac{\partial R}{\partial x}\frac{\partial x}{\partial b}\right)}_{= \text{Zero}} + \phi^T \underbrace{\left(\frac{\partial S}{\partial b} + \frac{\partial S}{\partial w}\frac{\partial w}{\partial b} + \frac{\partial S}{\partial y}\frac{\partial y}{\partial b} + \frac{\partial S}{\partial x}\frac{\partial x}{\partial b}\right)}_{= \text{Zero}}$$

λ: adjoint vector for flow state
ϕ: adjoint vector for structural state

Coupled Adjoint for Coupled Sensitivity Analysis

- Coupled Adjoint Analysis
  - Rearranging the terms

$$\frac{dI}{db} = \frac{\partial I}{\partial b} + \lambda^T\frac{\partial R}{\partial b} + \phi^T\frac{\partial S}{\partial b} + \underbrace{\left[\frac{\partial I}{\partial w} + \lambda^T\frac{\partial R}{\partial w} + \phi^T\frac{\partial S}{\partial w}\right]}_{= \text{Zero}}\frac{\partial w}{\partial b} + \underbrace{\left[\left(\frac{\partial I}{\partial y} + \lambda^T\frac{\partial R}{\partial y} + \phi^T\frac{\partial S}{\partial y}\right)\right]}_{= \text{Zer}}\frac{\partial y}{\partial b}$$

R: fluid residuals
S: Structural residuals
w: fluid state variables
y: structural state variables
x: mesh state variables
b: design variables

  - The arbitrary adjoint vector can be chosen to be independent of the derivative of state variables w.r.t. the design variables.
  - The adjoint equation to be solved

$$\boxed{\begin{bmatrix} \frac{\partial R}{\partial w} & \frac{\partial R}{\partial y} \\ \frac{\partial S}{\partial w} & \frac{\partial S}{\partial y} \end{bmatrix}^T \boxed{\begin{Bmatrix} \lambda \\ \phi \end{Bmatrix}} = -\begin{bmatrix} \frac{\partial I}{\partial w} \\ \frac{\partial I}{\partial y} \end{bmatrix}}$$

  - Total derivative of objective function w.r.t. design variables is

$$\frac{dI}{db} = \frac{\partial I}{\partial b} + \frac{\partial I}{\partial w}\frac{\partial w}{\partial b} + \frac{\partial I}{\partial y}\frac{\partial y}{\partial b} = \frac{\partial I}{\partial b} + \lambda^T\frac{\partial R}{\partial b} + \phi^T\frac{\partial S}{\partial b}$$

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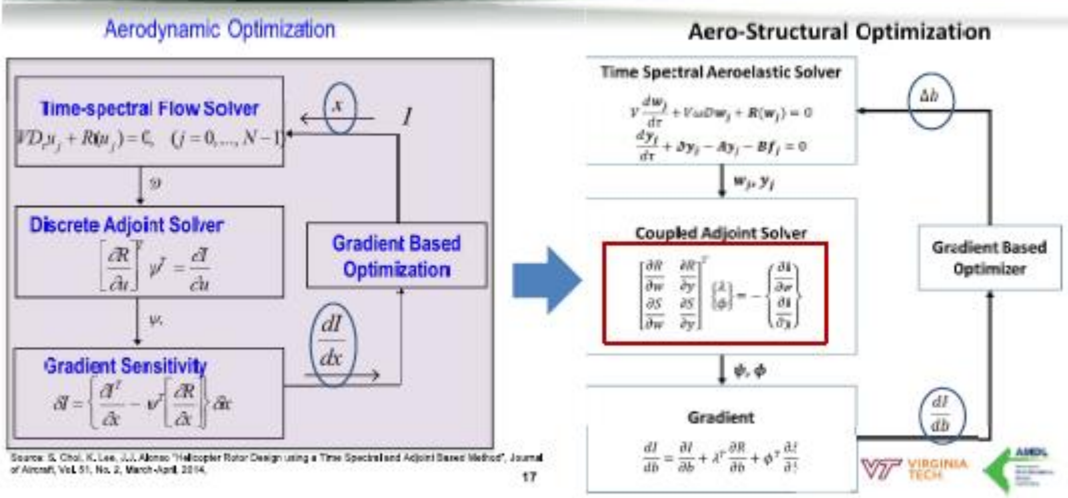
Design Framework



Aero-Only Design at Forward Flight (Flight 8534 of UH-60A)

Design condition:

- At each iteration, new control angles and aeroelastic deformation should be provided from the Comprehensive Analysis
- Simplifications for "aerodynamic design"
  - constant aeroelastic deformation, and constant shaft angle.
  - only two constraints.

- Objective function : reduce Torque (C_Q).
- Constraint 1 : same Thrust (C_T).
- Constraint 2 : same or less Drag Force (C_D).

- A total of 4 harmonics (9 time instances) are used
- Using NPSOL (Nonlinear Programming SOLver).

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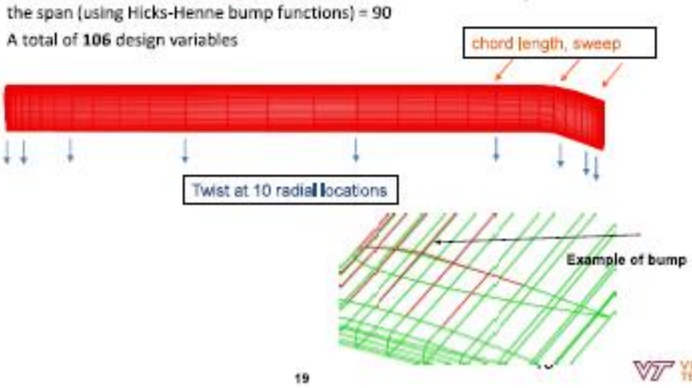
Design variables

- Chord length and position of leading edge / sweep at 84.7% and 94.2%, 100% = 6
- Twist angle at the 10 span locations = 10
- Airfoil camber/thickness changes at 10 locations around airfoil along 9 sections on the span (using Hicks-Henne bump functions) = 90
- A total of **106** design variables



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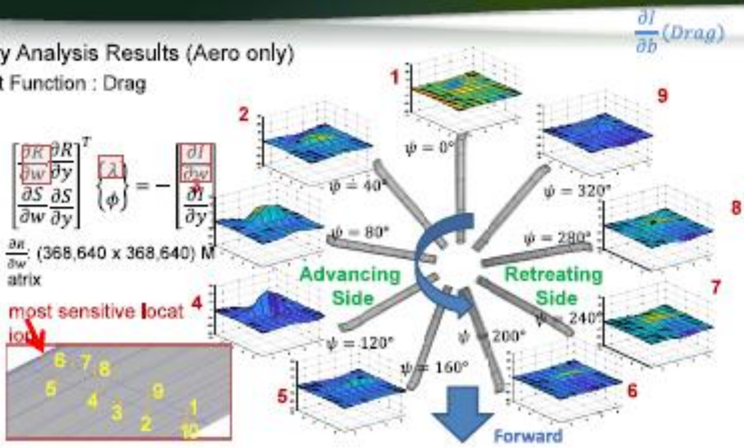
Sensitivity Analysis Results

- Sensitivity Analysis Results (Aero only)
  - Object Function : Drag

$$\begin{bmatrix} \frac{\partial R}{\partial w} & \frac{\partial R}{\partial y} \\ \frac{\partial S}{\partial w} & \frac{\partial S}{\partial y} \end{bmatrix}^T \begin{Bmatrix} \lambda \\ \phi \end{Bmatrix} = - \begin{bmatrix} \frac{\partial I}{\partial w} \\ \frac{\partial I}{\partial y} \end{bmatrix}$$

$\frac{\partial R}{\partial w}$: (368,640 x 368,640) Matrix



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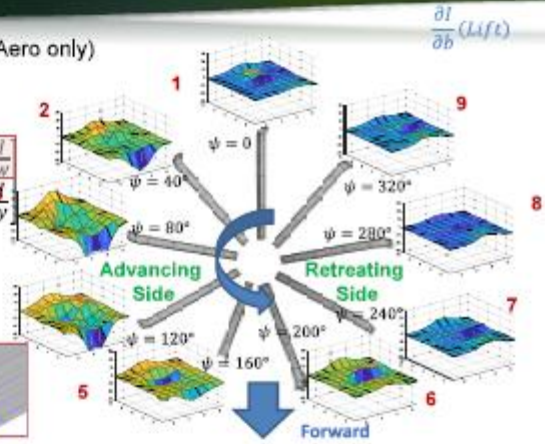
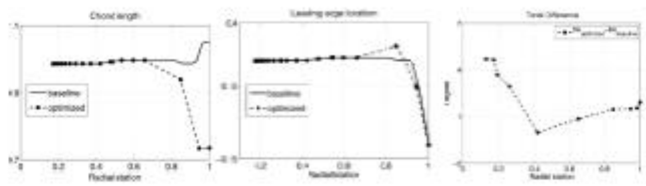
Sensitivity Analysis Results

- Sensitivity Analysis Results (Aero only)
  - Object Function : Lift

$$\begin{bmatrix} \frac{\partial R}{\partial w} & \frac{\partial R}{\partial y} \\ \frac{\partial S}{\partial w} & \frac{\partial S}{\partial y} \end{bmatrix}^T \begin{Bmatrix} \lambda \\ \phi \end{Bmatrix} = - \begin{bmatrix} \frac{\partial I}{\partial w} \\ \frac{\partial I}{\partial y} \end{bmatrix}$$



Optimized Results



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CFD/CSD Coupled Validation

- After 5 [illegible]

CFD : Time-accurate, Navier-Stokes computation

CSD : UMARC (3 degree trim - thrust, rolling, pitching M constrained, shaft angle fixed)

Aero-optimization validation

7.4% reduction in torque.

almost constant in thrust.

but 30% increase in rolling M.

15% increase in pitching M.

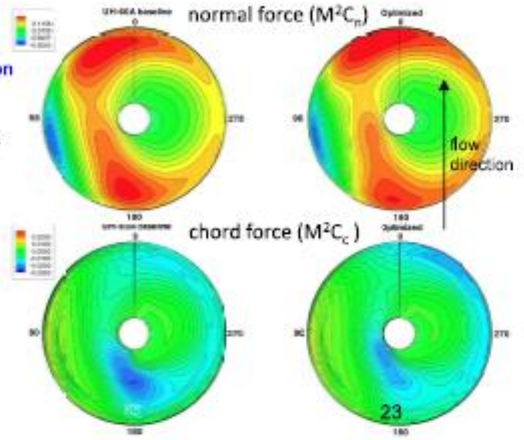
CFD/CSD coupled

5% decrease in torque.

Constant in thrust.

3% increase in rolling M.

2% increase in pitching M.



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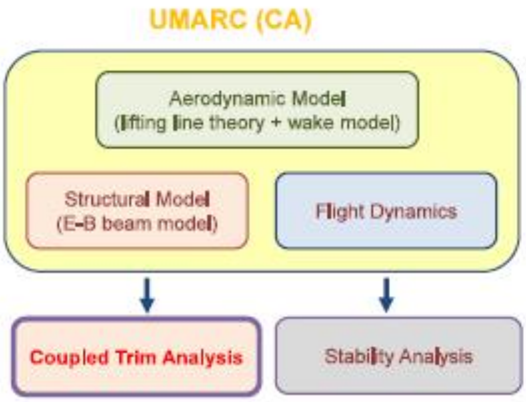
I. **Conclusions**

Computational Modelling: Comprehensive Analysis (CA)

▣ UMARC : University of Maryland Advanced Rotorcraft Code [Ref.6]



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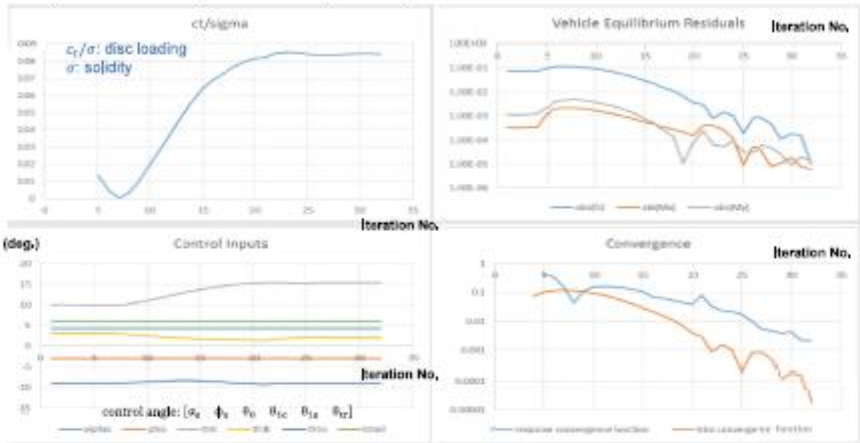
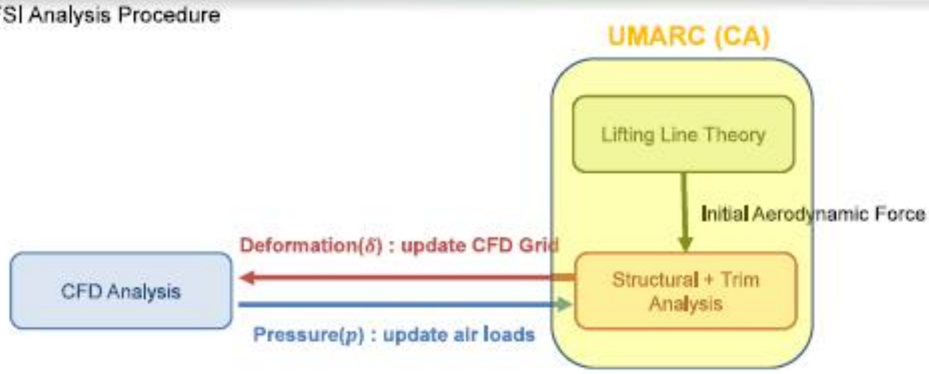
Computational Modelling: Structures

▣ Coupled Trim Analysis Results (UMARC)



Computational Modelling: Loosely Coupled FSI Analysis

■ FSI Analysis Procedure



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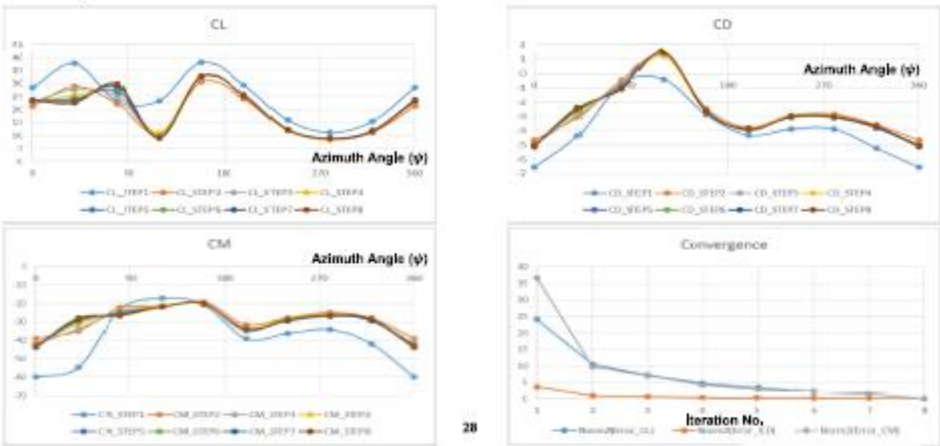
Computational Modelling: Loosely Coupled FSI Analysis

■ FSI Analysis Results



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Sensitivity Analysis Results

- Coupled Sensitivity Analysis: Aero + Structure

Aerodynamic Jacobian

$$
\begin{array}{cc}
 & \begin{array}{cc} (368{,}640) & (3{,}348) \end{array} \\
\begin{array}{c} (368{,}640) \\ (3{,}348) \end{array} & \begin{bmatrix} \dfrac{\partial R}{\partial w} & \dfrac{\partial R}{\partial y} \\ \dfrac{\partial S}{\partial w} & \dfrac{\partial S}{\partial y} \end{bmatrix}^T
\end{array}
\begin{Bmatrix} \lambda \\ \phi \end{Bmatrix} = - \begin{bmatrix} \dfrac{\partial I}{\partial w} \\ \dfrac{\partial I}{\partial y} \end{bmatrix}
$$

Coupled Cross Jacobians   Structural Jacobian

- ✓ $\frac{\partial R}{\partial w}, \frac{\partial S}{\partial y}$ and $\frac{\partial S}{\partial w}$ are sparse matrices, $\frac{\partial R}{\partial y}$ is densely populated matrix
- ✓ Due to the large size of the adjoint matrix, GMRES, a Krylov subspace solver has been used to solve the system,
- ✓ This has been implemented using PETSC, a suite of scalable and parallel routines for the solution of large scale PDEs.
- ✓ The above system takes around ~1500 iterations with 600 restart iterations to converge

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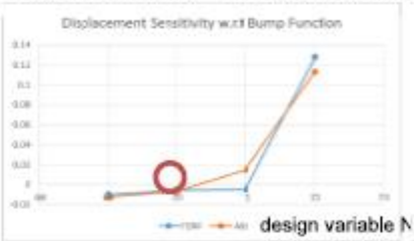
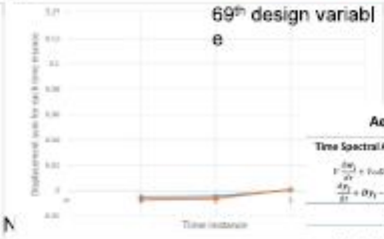
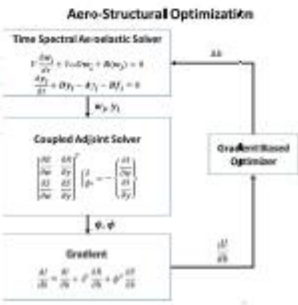
Sensitivity Analysis Results

- Coupled Sensitivity Analysis: Aero + Structure

  I (objective function) = Sum of all displacement







- Future Design

  I (objective function) = torque

  C (constraints) = moments and thrust

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Conclusion

- Time spectral and adjoint-based method is effective for the design involving multiphysics problems.
- An accurate but efficient coupled sensitivity analysis method for rotor design is developed.
- Aerodynamics only and Coupled sensitivity analysis is performed and validated by comparing with FDM results.
- Fluid-Structure coupled adjoint-based sensitivity analysis will be used to optimize the shape of rotor blade.

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Aerospace Multidisciplinary Design Laboratory AMDL

Thank you for your attention !

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Adjoint based Sensitivity Analysis

- Coupled Adjoint Analysis
  - Gradient computation using adjoint method for a coupled FSI problem
  - Objective function: $I = I(w, y, x, b)$
  - Total derivative of objective function w.r.t design variables

$$\frac{dI}{db} = \frac{\partial I}{\partial b} + \frac{\partial I}{\partial w}\frac{\partial w}{\partial b} + \frac{\partial I}{\partial y}\frac{\partial y}{\partial b} + \frac{\partial I}{\partial x}\frac{\partial x}{\partial b}$$

$\boldsymbol{w}$: fluid state variables
$\boldsymbol{y}$: structural state variables
$\boldsymbol{x}$: mesh state variables
$\boldsymbol{b}$: design variables

  - State equations for fluid and structural system and their derivatives w.r.t design variables

Fluid: $R(w, y, x, b) = 0 \rightarrow \frac{dR}{db} = \frac{\partial R}{\partial b} + \frac{\partial R}{\partial w}\frac{\partial w}{\partial b} + \frac{\partial R}{\partial y}\frac{\partial y}{\partial b} + \frac{\partial R}{\partial x}\frac{\partial x}{\partial b} = 0$

Structure: $S(w, y, x, b) = 0 \rightarrow \frac{dS}{db} = \frac{\partial S}{\partial b} + \frac{\partial S}{\partial w}\frac{\partial w}{\partial b} + \frac{\partial S}{\partial y}\frac{\partial y}{\partial b} + \frac{\partial S}{\partial x}\frac{\partial x}{\partial b} = 0$

  - As the residual derivatives are zero, they can be multiplied with an adjoint vector and added to the objective function derivative.

$$\frac{dI}{db} = \frac{\partial I}{\partial b} + \frac{\partial I}{\partial w}\frac{\partial w}{\partial b} + \frac{\partial I}{\partial y}\frac{\partial y}{\partial b} + \frac{\partial I}{\partial x}\frac{\partial x}{\partial b} + \lambda^T \underbrace{\boxed{\left(\frac{\partial R}{\partial b} + \frac{\partial R}{\partial w}\frac{\partial w}{\partial b} + \frac{\partial R}{\partial y}\frac{\partial y}{\partial b} + \frac{\partial R}{\partial x}\frac{\partial x}{\partial b}\right)}}_{= \text{Zero}} + \phi^T \underbrace{\boxed{\left(\frac{\partial S}{\partial b} + \frac{\partial S}{\partial w}\frac{\partial w}{\partial b} + \frac{\partial S}{\partial y}\frac{\partial y}{\partial b} + \frac{\partial S}{\partial x}\frac{\partial x}{\partial b}\right)}}_{= \text{Zero}}$$

$\boldsymbol{\lambda}$: adjoint vector for flow state
$\boldsymbol{\phi}$: adjoint vector for structural state

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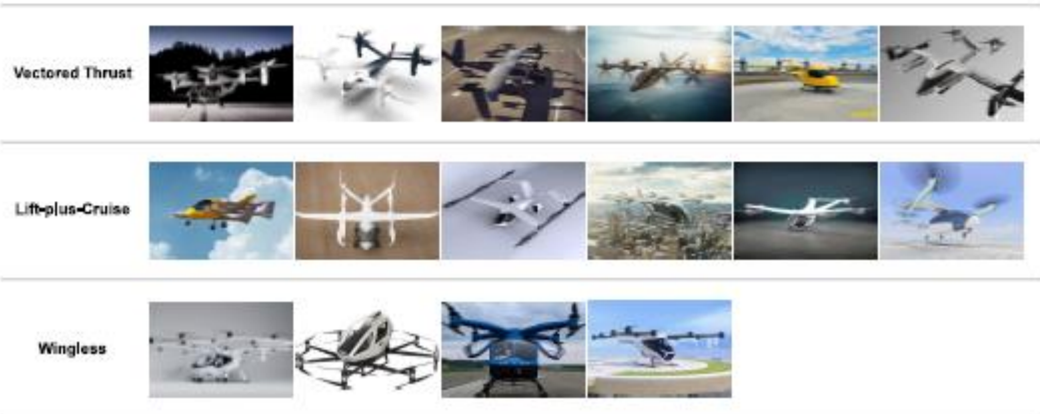
Development of UAM Vehicle in Hanwha

Sehwan Park
Hanwha Systems

Feb 10, 2023
Yeosu, Korea

UAM eVTOL Vehicles

Hanwha Systems



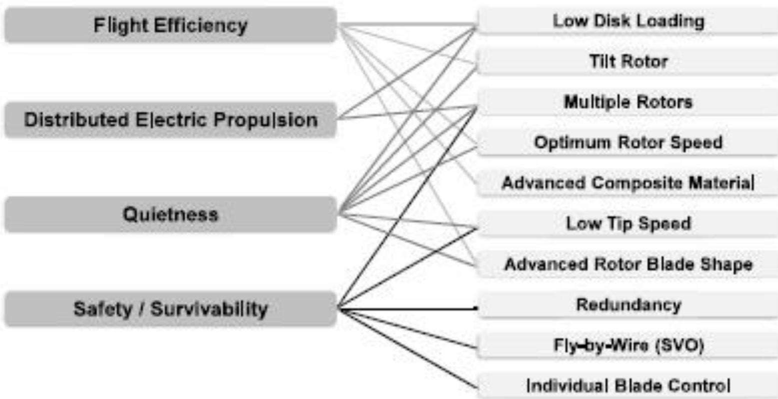
Butterfly

Hanwha–Overair Joint Development

- Payload: 1 pilot + 5 pax (1,100 lb)
- Range: 100+ mile
- Speed: max cruise 200 mph, cruise 150 mph
- Noise: 55 dBA (hover @ 100m), 30 dBA (cruise @ 500m)

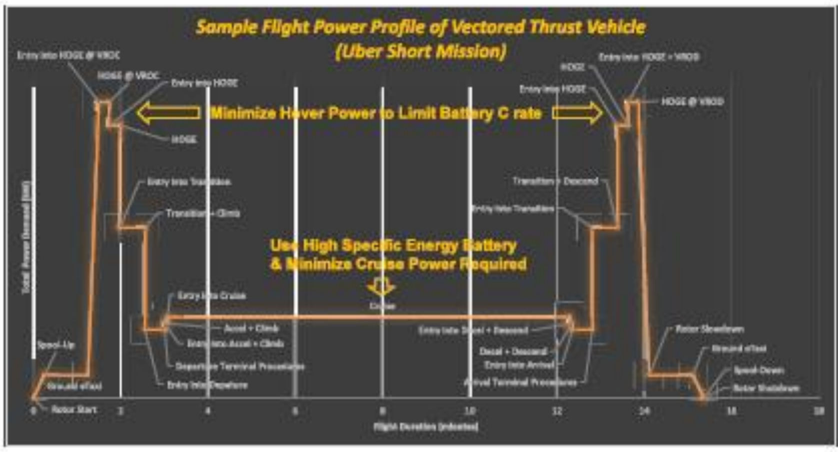
Butterfly | Design Philosophy

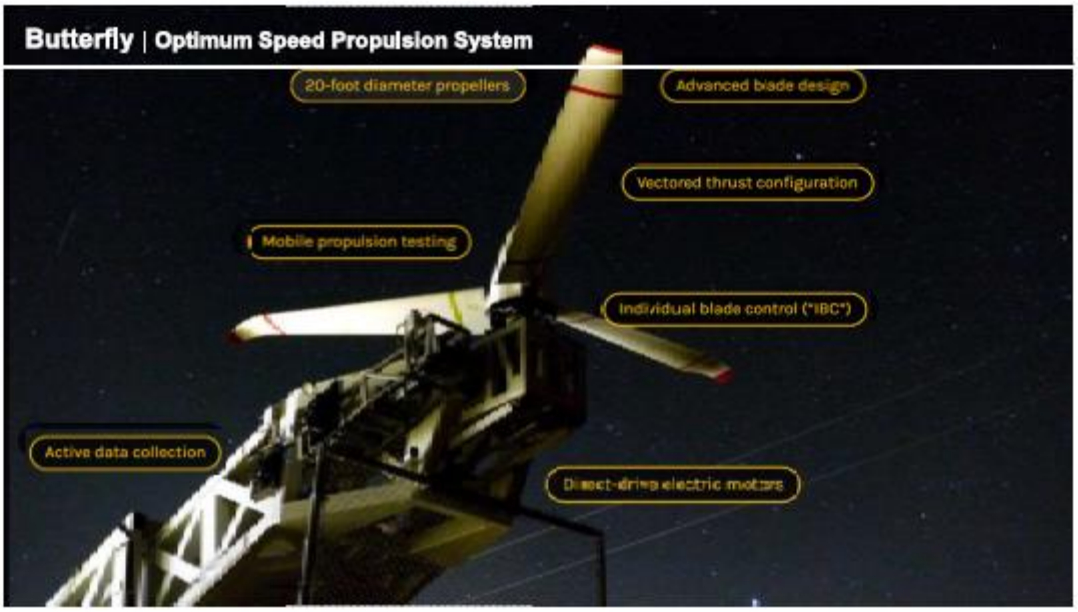
Design Goal: Fly Longer, Faster, Safe and Quiet with Lower Cost

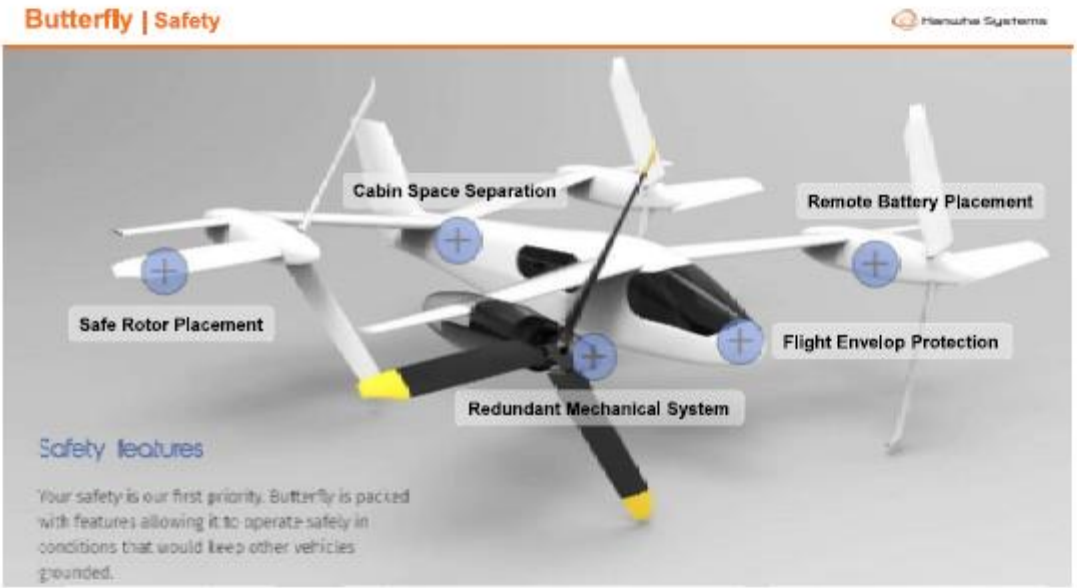


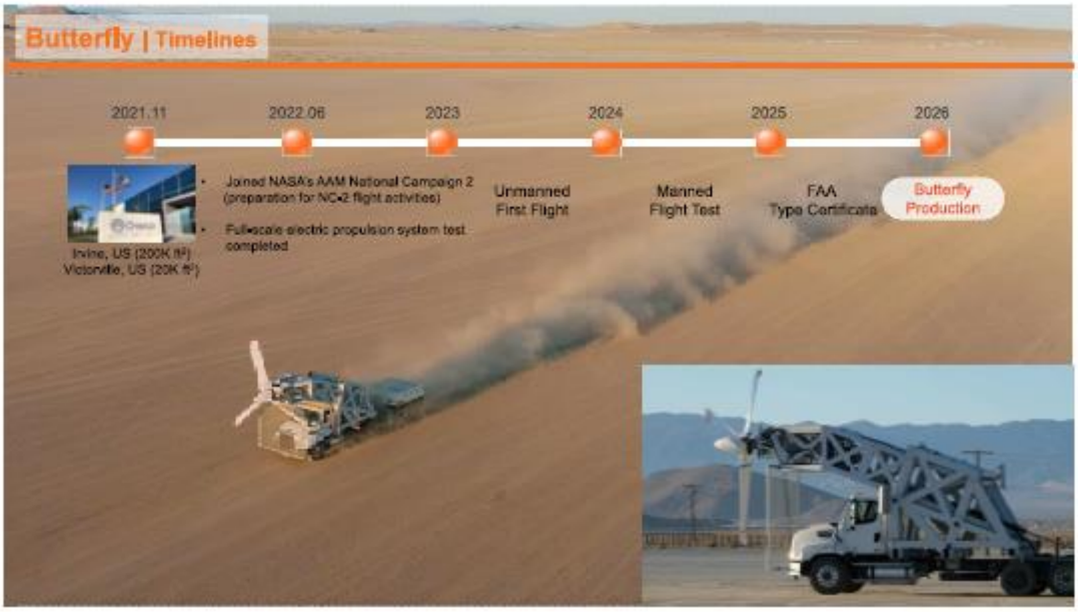
Butterfly | Flight Efficiency in Hover and Cruise

Maximum Hover and Cruise Efficiency is Required






Butterfly | Safety
Hanwha Systems
Cabin Space Separation
Remote Battery Placement
Safe Rotor Placement
Flight Envelop Protection
Redundant Mechanical System
Safety features
Your safety is our first priority. Butterfly is packed with features allowing it to operate safely in conditions that would keep other vehicles grounded.


Butterfly | Timelines
2021.11
2022.06
2023
2024
2025
2026
Irvine, US (200K ft²)
Victorville, US (20K ft²)
• Joined NASA's AAM National Campaign 2 (preparation for NC-2 flight activities)
• Full-scale electric propulsion system test completed
Unmanned First Flight
Manned Flight Test
FAA Type Certificate
Butterfly Production

eVTOL Flight Control System

OPPAV Flight Control System Development Project (Apr. 2019 – Dec. 2023)

- FLCC SW(OFP) Design and Implementation
- OPPAV HILS Configuration Setup
- FCS System Integration Test (HILS & RIG)
- OPPAV Ground/Flight Test

eVTOL Flight Training System

eVTOL Flight Simulator Development Project (Apr. 2022 – Dec. 2025)

- Fixed-base and motion-platform flight training devices for three different types of eVTOL vehicle (Vectored Thrust, Lift-plus-Cruise, and Wingless Multicopter)
- eVTOL Vehicle Design & AeroDB Generation
- Flight Control Law & SVO
- Flying & Handling Quality Assessment
- Pilot Training Program

UAM Virtual Integrated Operation Platform Project

Fixed-base Flight Simulator

Motion-platform Flight Simulator

Vectored Thrust Lift-plus-Cruise Wingless

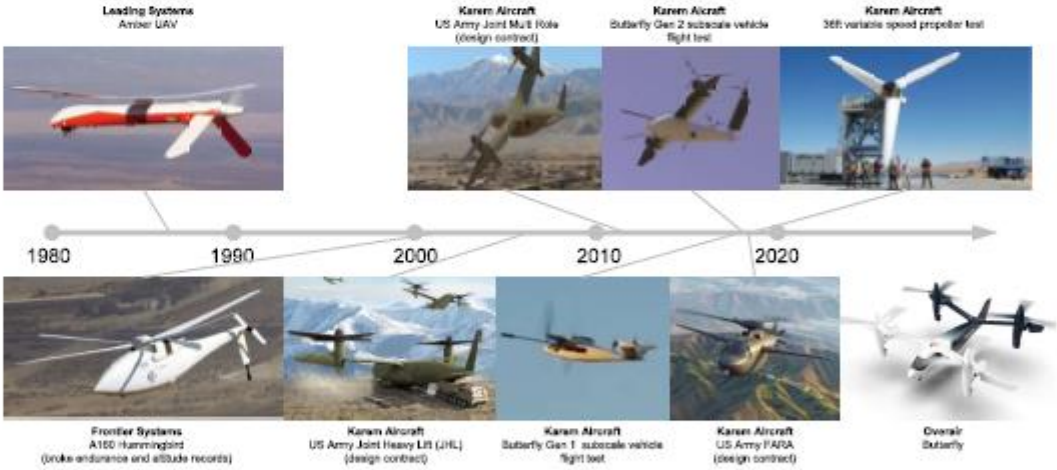
Hybrid–Electric VTOL Aircraft

Hanwha Systems

Advanced Research on Hybrid–Electric VTOL Aircraft

Appendix | Introduction to Karem Aircraft & Overair

Hanwha Systems

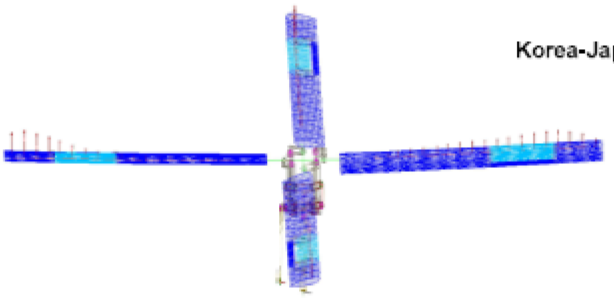


Seoul National University
Active Aeroelasticity and Rotorcraft Lab.

Hover Test of SNU Active Trailing Edge Flap for Rotor Vibration Reduction

SangJoon Shin

Seoul National University



Korea-Japan Joint Workshop on Rotorcraft
Yeosu, Republic of Korea

Session II Analysis & Test
February 10th 2023
13:00 – 13:20

Seoul National University
Active Aeroelasticity and Rotorcraft Lab.

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Ⅰ. Introduction

Ⅱ. Hover Test Preparation

Ⅲ. Pre-test Prediction

Ⅳ. Conclusion

Introduction

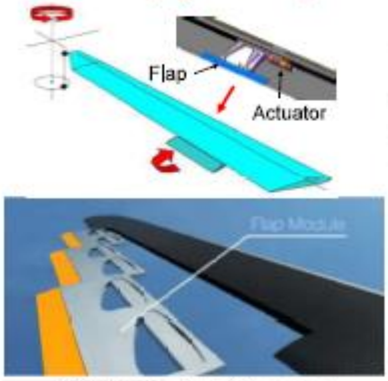
Seoul National University
Active Aeroelasticity and Rotorcraft Lab.

❖ Rotor blade with a trailing-edge flap

➢ **Rotor vibration and noise control by active flap blades**

- Active rotor – numerous studies have been done*, and recently by DLR, JAXA, NUAA, SNU, …
  - Mechanism structural design, fluid dynamics, control, and wind-tunnel test

✓ **Underlying structural dynamics and aerodynamic features yet to be extracted**



▲ Trailing-edge flap blade concept

▲ SMART rotor whirl stand test

▲ Sikorsky wind tunnel test

*Friedmann, P. P., "On-Blade Control of Rotor Vibration, Noise, and Performance: Just Around the Corner? The 33rd Alexander Nikolsky Honorary Lecture," American Helicopter Society 69th Annual Forum, Phoenix, AZ, May 2013.

3

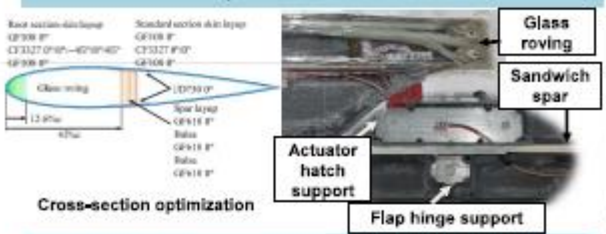
Introduction

Seoul National University
Active Aeroelasticity and Rotorcraft Lab.

❖ SNUF (SNU Flap-blade) research objectives

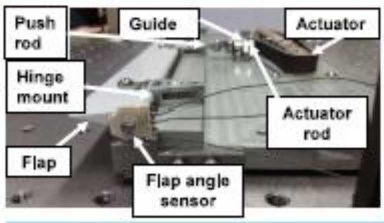
➢ **Baseline multi-disciplinary investigation**

Composite blade structures

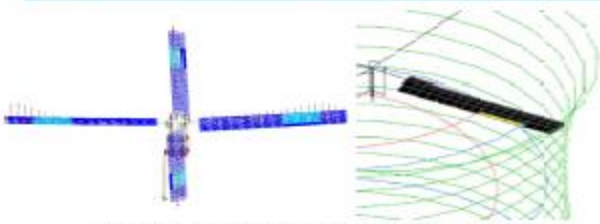


Cross-section optimization

Flap driving mechanism

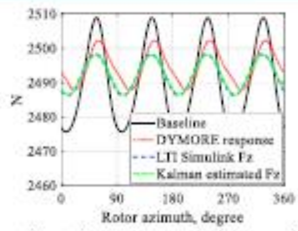


Multi-body comprehensive rotor aeromechanics



Mid-fidelity aeromechanics analysis with full flap rotor

Active rotor controls



Closed-loop vibratory load control

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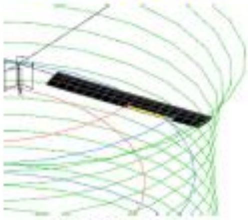
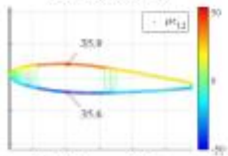
Introduction

❖ **Hover test overview**

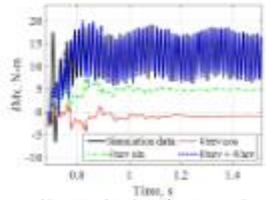
- Active flap blade **aeromechanics**, **composite blade integrity correlation**
- **Low-latency harmonic signal processing** for higher harmonic control
- **Time-periodic and multi-blade nature** w/ different collective
- **Hub load dynamics** w/ different **flap actuation mode**



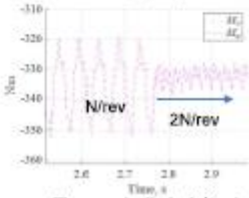
Aeromechanics



Composite blade analysis correlation



Harmonic signal processing



Time-periodic hub load

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Seoul National University
Active Aeroelasticity and Rotorcraft Lab.

I. Introduction

II. Hover Test Preparation

III. Pre-test Prediction

IV. Conclusion

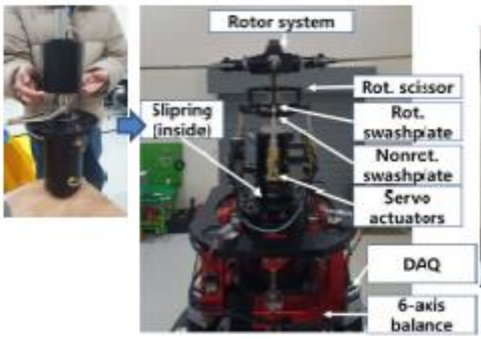
Test Preparation

Seoul National University
Active Aeroelasticity and Rotorcraft Lab.

❖ Hover test stand fabrication

➢ **Seoul National University Rotor Test System (SNURTS)**

- Siheung Campus test center: 9X12 m, 240 kW electric power capacity
- Collaboration w/ Chungnam National University: design/fabrication of the test stand
- 55kW AC motor direct drive, max. 2,000 RPM
- 6-axis balance: max. 2,000kgf thrust, 160kgf-m torque



▲ SNURTS components

▲ SNURTS control room

▲ SNURTS installed

Test Preparation

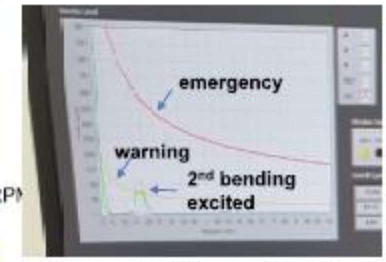
Seoul National University
Active Aeroelasticity and Rotorcraft Lab.

❖ Test stand fundamental mode identification

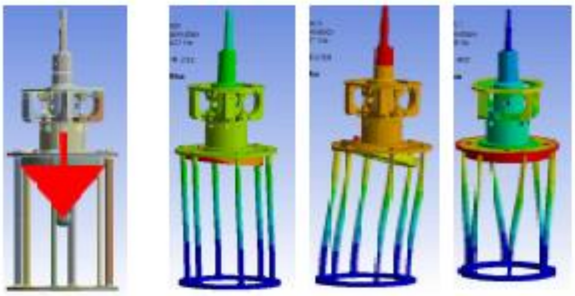
➢ **Impact test and correlation**

- Test stand structural analysis by ANSYS

  - Contact normal stiffness adjusted to match test results
- Major resonant speed identified: 300, 900RPM
- ISO-1940: satisfactory vibration level @ 1,100~1,300 RPM

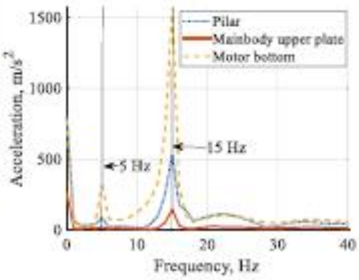


▲ Test stand vibration level at 1,120 RPM



Concentrated motor mass | 1st bending 4.8 Hz | 2nd bending 15 Hz | 1st torsion 22 Hz

▲ 3D FEM modal analysis correlation



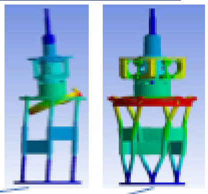
▲ Impact test result

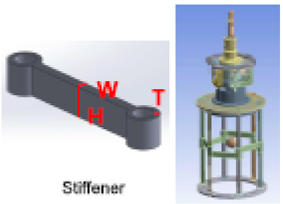
Test Preparation

❖ Test stand fundamental mode identification

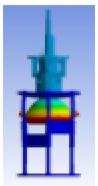
➢ Mode control by the stiffener

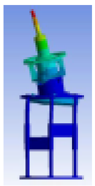
- Bending and torsion modes of the stand may be adjusted
- Bearing tower is structurally isolated with the test stand
- k/rev : 1300, 2600, 3900, 5200 … RPM avoided





Stiffener





▲ Isolated bearing tower mode

W mm	H mm	T mm	N	Support pillar 1st bending RPM (Hz)	Support pillar 2nd bending RPM (Hz)	Bearing tower 1st axial RPM (Hz)	Stand 1st torsion RPM (Hz)	Bearing tower 1st bending RPM (Hz)	Stand 2nd torsion RPM (Hz)
Baseline				295 (4.92)	924 (15.4)	1,532 (25.5)	1,320 (22)	4,022 (67.0)	5,120 (85.3)
20	60	10	3	336 (5.60)	1,059 (17.7)	-	1,448 (24.1)	-	-
20	60	10	6	362 (6.04)	1,227 (20.5)	1,538 (25.6)	1,558 (26.0)	4,084 (68.1)	5,358 (89.3)
20	120	10	6	383 (6.39)	1,474 (24.6)	1,538 (25.6)	1,714 (28.6)	4,154 (69.2)	5,580 (93.0)
20	150	10	6	388 (6.47)	1,560 (26)	1,539 (25.7)	1,776 (29.6)	4,188 (69.8)	5,706 (95.1)
20	180	10	6	392 (6.53)	1,638 (27.3)	1,540 (25.7)	1,830 (30.5)	4,218 (70.3)	5,874 (97.9)

▲ Stiffener parametric examination

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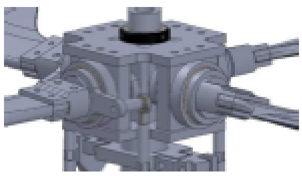
Seoul National University
Active Aeroelasticity and Rotorcraft Lab.

Test Preparation

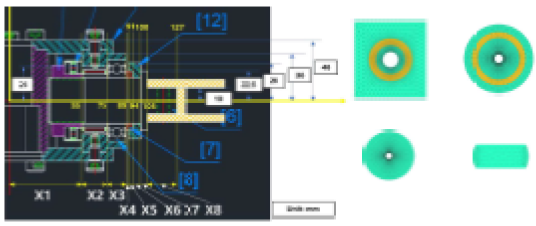
❖ Rigid 4-blade SNUF rotor hub

➢ Blade and grip structural integrity evaluation

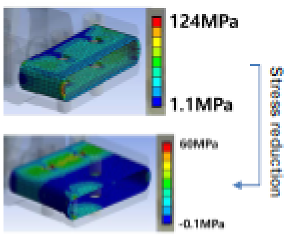
- Hingeless hub: grip structural analysis
- Rotor load from analysis: 39kN → applied load factor 1.5: 58kN centrifugal load
- Safety margin > 2



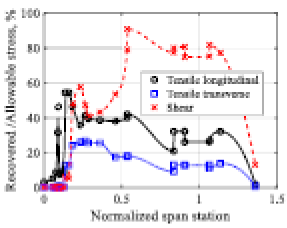
▲ SNURTS rigid hub



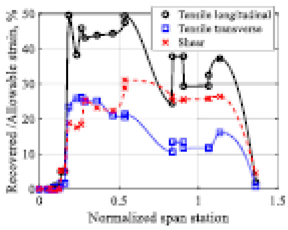
▲ VABS cross sectional modeling



▲ Grip M6-bolt reinforcement



▲ Stress recovery



▲ Strain recovery

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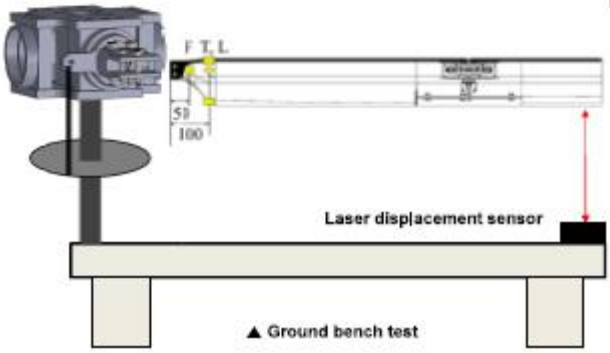
Test Preparation

❖ SNUF blade ground-test

➢ **Ground bench test (scheduled ~March 23')**

- Strain gauge calibration by the tip displacement (flap, lag, torsion)
  - Tip displacement measure sensor for the test stand
- Measurement and control program test
- Actuator inner-loop position control test

▲ SNUF blade ground test



▲ Ground bench test

▲ Fabricated grip and SNUF rotor hub assembly

Test Preparation

Seoul National University
Active Aeroelasticity and Rotorcraft Lab.

❖ SNURTS evaluation

➢ **Reference OLS rotor from NASA test***

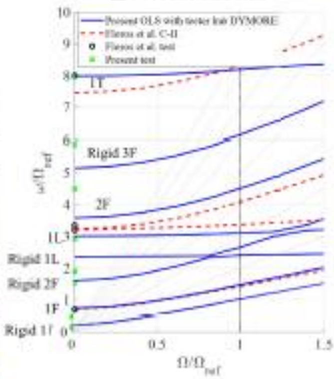
- 2-m diameter, NACA0012, no twist, no taper
- To evaluate the functionality of SNURTS
- Validate against the present prediction

▲ Present OLS hub

▲ Present DYMORE configuration of the SNURTS-OLS rotor

▲ Blade modal test

▲ Rotor hub modal test



▲ Fan plot from the present hub test result

*Floros, M. W., Gold, N. P., and Johnson, W., "An Exploratory Aerodynamic Limits Test with Analytical Correlation", American Helicopter Society 4th Decennial Specialists' Conference, Jan 2004.

Test Preparation

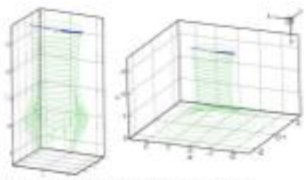
Seoul National University
Active Aeroelasticity and Rotorcraft Lab.

❖ OLS rotor hover test

➢ Collective pitch sweep test

- Test repeated 3 times and one open-door test
- Sufficient ground height for OLS rotor
- Functionality of SNURTS verified (run, collective, stop command)

▲ Closed-door test (@ free run stop)



▲ Ground effect wake analysis

→ No ground effect

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Test Preparation

Seoul National University
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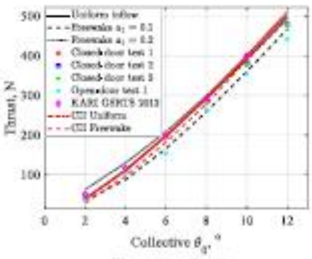
❖ OLS rotor hover test

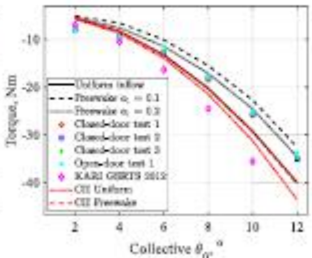
➢ Collective pitch sweep test

- 98% ↑ reproducibility for the measured thrust and torque
- Measured unrealistic figure of merit: 2012 KARI test as a reference
- Present momentum theory inflow analysis gives good correlation to the reference test
- Free-wake viscous influence should be carefully correlated
- Balance designed for SNUF rotor 400 N-m rated torque

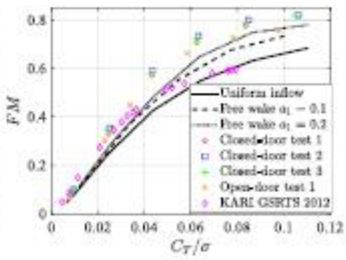
  → torque resolution unmatched for max torque 40 N-m OLS rotor



▲ Thrust-collective



▲ Torque-collective



▲ Figure of merit

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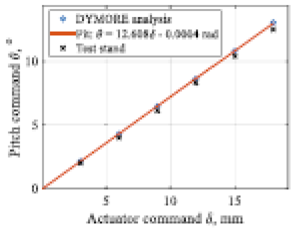
Pre-test Prediction

Seoul National University
Active Aeroelasticity and Rotorcraft Lab.

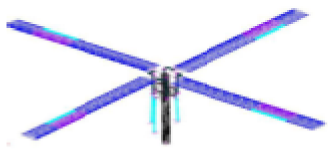
❖ Correlation against the comprehensive analysis

➢ **Multi-body dynamic analysis: DYMORE and CAMRAD-II**

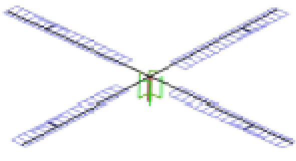
- Incorporate SNURTS pitch link, servo actuators, shaft, trailing-edge flaps
- Code-to-code comparison and evaluation
- Time-marching free-wake analysis with the multiple-trailer wake
- DYMORE-Simulink coupled simulation for the control



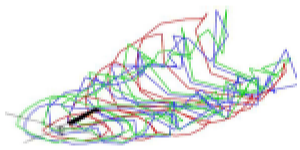
▲ Servo-pitch test and prediction



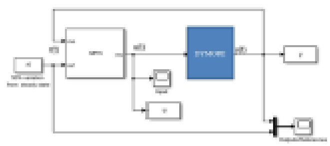
▲ SNUF DYMORE configuration



▲ SNUF CAMRAD-II configuration



▲ Free-wake analysis



▲ DYMORE-Simulink coupled simulation

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Pre-test Prediction

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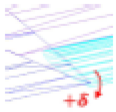
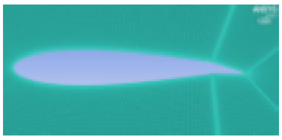
❖ Additional accuracy for the lifting-line theory

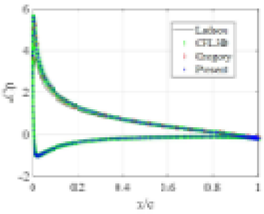


➢ C81 table for an airfoil w/ a flap

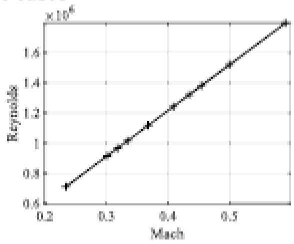
- Improved aerodynamic load prediction at the flap station
- RANS (k-ω SST) by using FLUENT, matched y+=1 for all the cases
- Advance ratio μ = 0 ~ 0.16 → Mach 0.3~0.5



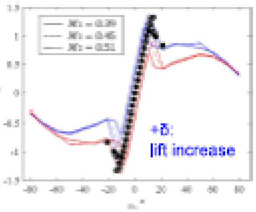
▲ CFD grid of NACA0015 15% flap



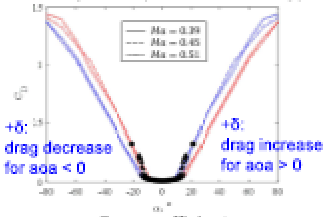
▲ Present CFD grid accuracy comparison (NACA0012, no flap)



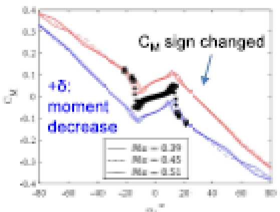
▲ Present rotor operating condition



▲ Lift coefficient



▲ Drag coefficient



▲ Moment coefficient

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Pre-test Prediction

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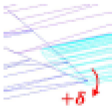
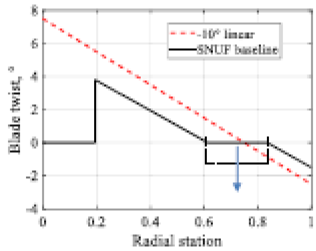
❖ Hover test prediction

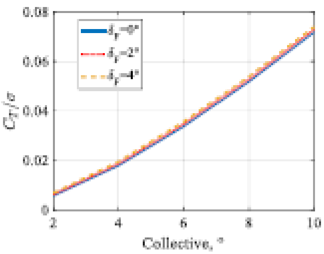


➢ Flap rotor test

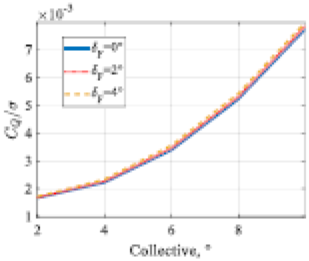
- Baseline rotor performance
- Far wake 5 ages, 2˚ azimuth, 10˚ spatial step
- Flap deflection (steady and harmonic)
- Nonlinear blade twist achieved by the steady flap deflection (2˚, 4˚, 6˚, 8˚, 10˚)
- Positive flap deflection:
  thrust and torque slightly increase, no FM variation



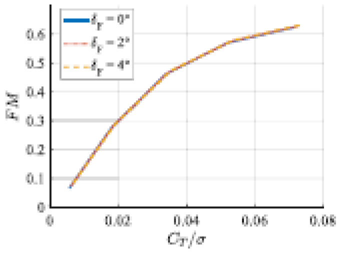
▲ SNUF blade effective twist due to the steady flap deflection



▲ Blade loading vs collective



▲ C_Q/σ vs collective



▲ Steady flap sweep F.M.

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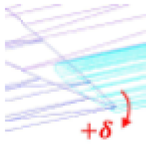
Pre-test Prediction

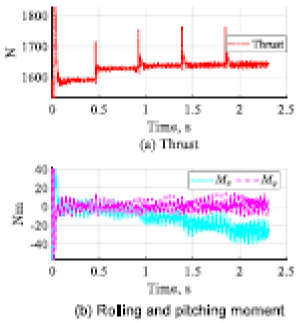


❖ Wind-tunnel test prediction

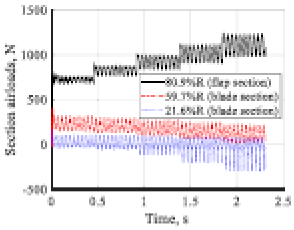
➢ **Isolated rotor in the forward flight, fixed collective**

- Wind-tunnel speed 30 m/s ($\mu = 0.162$), shaft angle $\alpha_s = -6°$
- Steady collective mode flap deflection sweep (2°, 4°, 6°, 8°, 10°)
- Thrust increased most when 0° → 2°
- Control authorities: rolling moment > pitching moment
- **Flapped section pitching moment drives the entire blade to the opposite AOA**
- A soft in-plane blade responds in a 'control reversal' mode

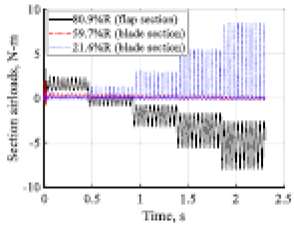
→ Additional control phase lead or lag will be induced



▲ Propulsive loads control authorities



▲ Sectional lift



▲ Sectional pitching moment

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Active Aeroelasticity and Rotorcraft Lab.

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Conclusion

❖ Conclusion and test schedule

➢ **Conclusion**

- SNUF blade design: blade structural design, test and analysis
- SNURTS preparation: 3m-diameter 75HP class Mach-scaled rotor test stand

➢ **Test schedule and future works**

- **Hover test schedule: April ~ May 2023**
- SNUF baseline rotor test (passive flap)
  - RPM: 1,100 ~ 1,300 RPM
  - Collective sweep: 2°~12°
- 1- active flap actuation test
- 4- active flap actuation test
- Future work: 5-hole fast response probe for wake measurement
- Wind-tunnel tests on ROKAFA

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Seoul National University
Active Aeroelasticity and Rotorcraft Lab.

Thank you

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A Study on the Performance Improvement of Dual Tiltrotor ;
Switch to Hydrogen Fuel Cell

NARMA
New AeRo Mission Accomplishment

Kijung Kwon, CEO

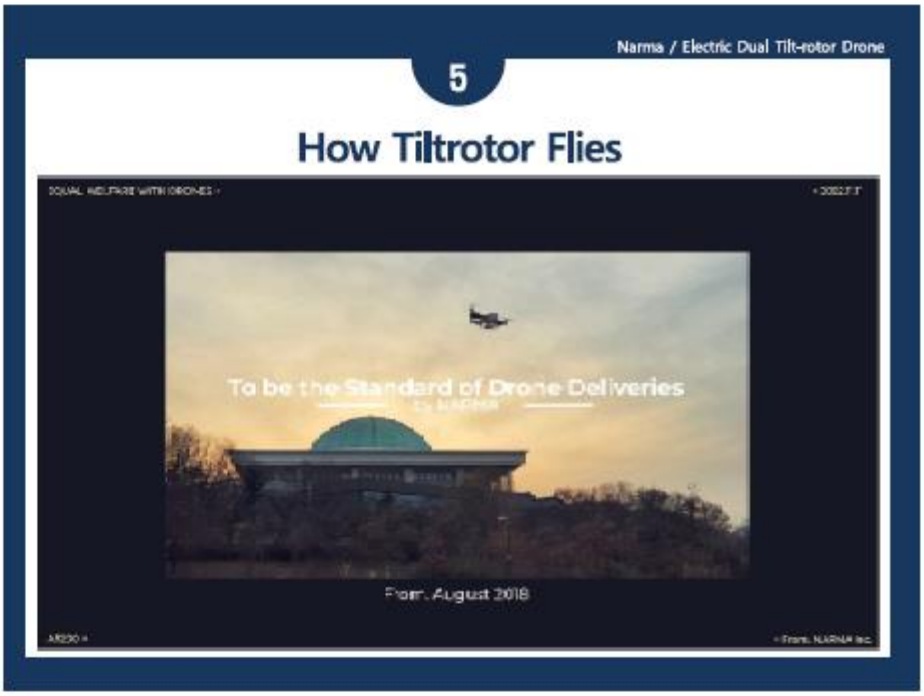
Narma / Electric Dual Tilt-rotor Drone

4

Dual Tilt-rotor

- Narma has the **world 1st and only electric** dual tilt-rotor technology.
- Spin-off company of **KARI**(Korea Aerospace Research Institute)

Photo Bell



Narma / Electric Dual Tilt-rotor Drone
5
How Tiltrotor Flies
To be the Standard of Drone Deliveries
From. August 2018

Narma / Electric Dual Tilt-rotor Drone
6
Core Value
Highest Wind Resistance
Tilt-prop
(Others)
Tilt-rotor
(Narma)
Wind gust 12m/s
Wind gust 15m/s
Annual usage : 200 vs 250 days

Narma / Electric Dual Tilt-rotor Drone

7

Best for

- **Drone Delivery**

*range : 13 miles

- **Surveillance from Ships**

*range : 20 miles

Narma / Electric Dual Tilt-rotor Drone

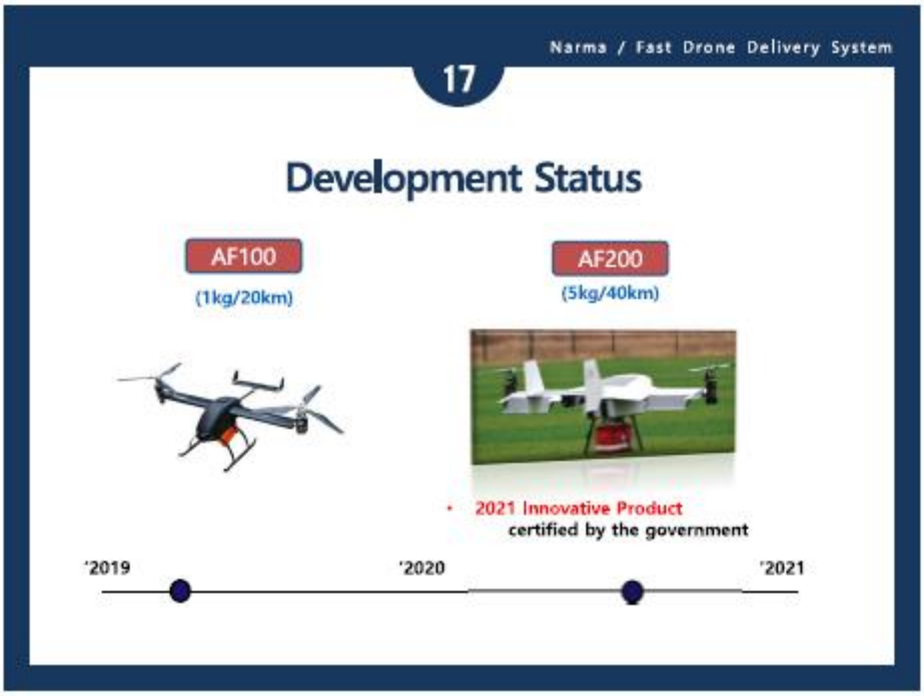
8

Delivery

[Last Friday in NeoCity, FL)]

[Yesterday in Sarasota, FL)]


Narma / Electric Dual Tilt-rotor Drone
9
Core Value - KIOSK
Ease of use (Patent in KR & US)
Previous
vs.
Now
Controller
Ground Control Station
KIOSK
(Ground Control System)
US Patent


Narma / Fast Drone Delivery System
17
Development Status
AF100
(1kg/20km)
AF200
(5kg/40km)
2021 Innovative Product
certified by the government
'2019
'2020
'2021

Narma / Electric Dual Tilt-rotor Drone

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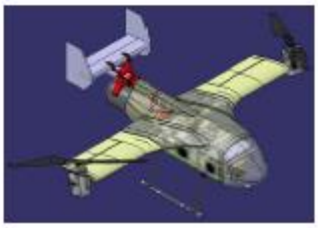
Hydrogen Fuel Cell

L x W x H	1675x1850x567mm
Weight(Empty)	12kg
MTOW	20.5kg (5L liquefied hydrogen) 21.5kg (9L compressed hydrogen)
Payload	3.5kg
Flight Time	2.5h(Liquifed), 1.5h(Compressed)



Narma / Electric Dual Tilt-rotor Drone

18

Hydrogen Fuel Cell

☐ **Using Li-ion battery**

18

Hydrogen Fuel Cell

☐ **In 2023**

- Taean UV Land test site
- 2h/150km
- Test certification

Narma / Kijung Kwon. CEO

3-2

Korea-Japan Joint Workshop on Rotorcraft
Feb. 10, 2023

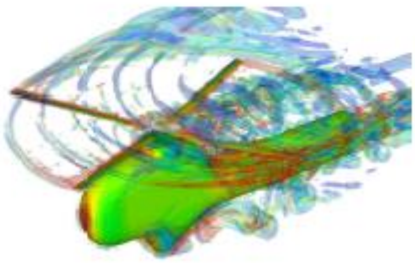
Rotorcraft Aeromechanics Research Activities at Konkuk University

Prof. Sung Nam Jung
Konkuk University, Seoul, Republic of Korea

02/09/2023

Part I

Introduction to Konkuk IRT Group



KU

Intelligent Rotorcraft Structures Lab

Konkuk University (KU)

❖ Dept. of Aerospace Eng.

- Established in Mar. 1990
- Currently 12 faculty members
- About 160 undergraduate students & 70 graduate students enrolled
- Home of BK21 ST-IT fusion program sponsored by MOE (2006 – 2013)

Subsonic wind tunnel

High speed shock tube (M = 2.5)

• Konkuk University (KU):

- Founded in 1946; One of the leading private universities in Korea
- Located in the northeastern region of Seoul
- About 25k students enrolled, including 3k graduate students
- Over 700 faculty members

KU

Intelligent Rotorcraft Structures Lab

KU Int. Rotorcraft Technology (IRT) Group

❖ IRT group members of Int. R&D Hub program sponsored by KRF (2006 – 2013)

> All IRT members joined on or after BK-21

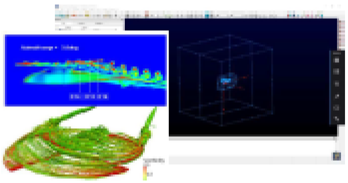
KU

Intelligent Rotorcraft Structures Lab

KU Int. Rotorcraft Technology (IRT) Group Activities

❖ Major research activites of KU IRT group

- Home of national BK21 & IRH programs sponsored by NRF Korea (2006- 2013)
- German DLR - Konkuk MoU research (2008 - 2013)
- Active participants of Int. HART II Workshop (2008 - 2012)
- One of STAR (Smart Twisting Active Rotor) int. consortium project members (since 2008)
- Founding member of international meetings such as Rotor Korea (2007, 2008) and ARF
- Development of various rotorcraft software tools: KFLOW, HETLAS, Ksec2D, etc.
- Establishment of high precision numerical schemes such as CFD/CSD coupling for HART I/II validation



3D compressible RANS flow solver KFLOW

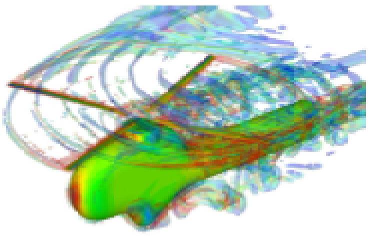
Rotorcraft flight dynamics simulation S/W HETLAS

2D FE cross-sectional analysis S/W Ksec2D

Intelligent Rotorcraft Structures Lab

Part II

Summary of Rotorcraft Aeromechanics Research Outcomes at KU



Intelligent Rotorcraft Structures Lab

HART I Blade Property Test

Motivation:

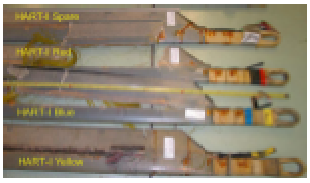
- HART I rotor test conducted in 1994
- No systematic measured blade property data available so far
- All blades damaged at a follow-on test

Approaches:

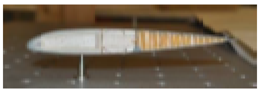
- In collaboration with NASA, DLR, KU
- Use the original blade set tested in DNW (1994)
- Well-established test techniques employed
- Destructive-type of test techniques adopted

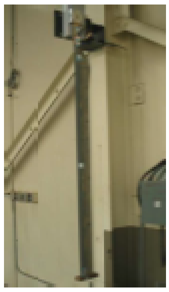
Outcomes:

- Property table completed for HART I blades and documented as NASA tech report (NASA/CR-2012-216039)
- Property data released in JAHS 2013

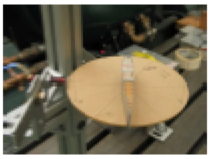


HART I blades used for structural test





Mirror method for flap bending



Trifillar pendulum for section MOI

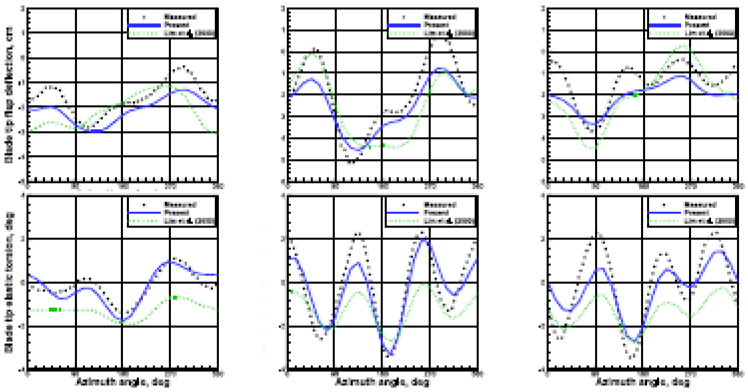
3 point bending for chord stiffness

Intelligent Rotorcraft Structures Lab

Result: HART I Blade Property Test

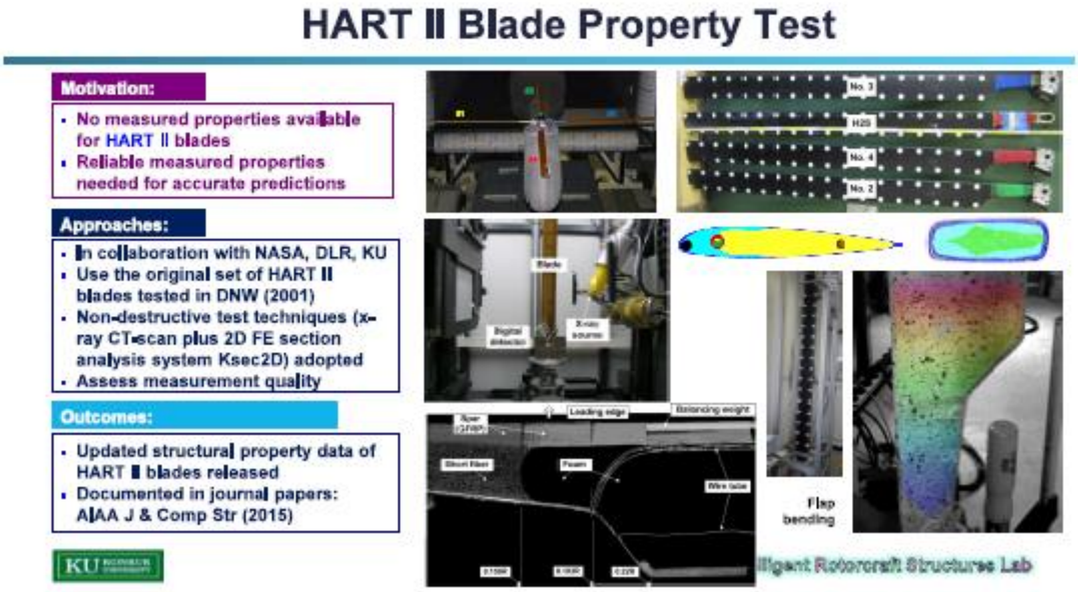
Elastic flap motion:

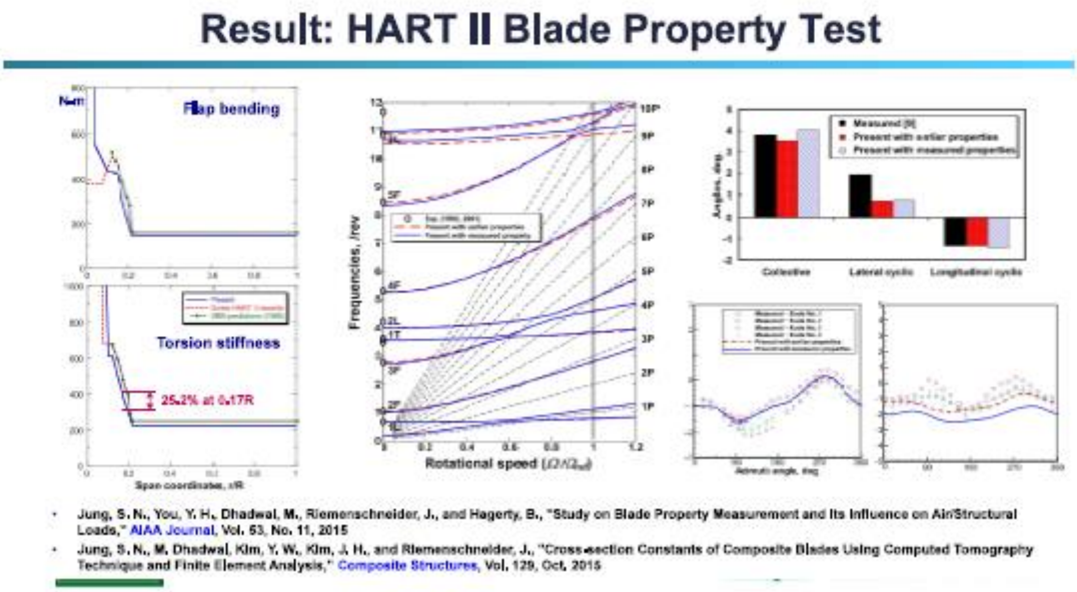
Elastic torsion motion:



(a) BL (b) MN (c) MV

- Jung, S. N., You, Y. H., Lau, B., Johnson, W., and Lim, J. W., "Evaluation of Rotor Structural and Aerodynamic Loads Using Measured Blade Properties," Journal of the American Helicopter Society, Vol. 58, No. 4, Oct. 2013
- Jung, S. N., and Lau, B., "Determination of HART I Rotor Blade Structural Properties by Laboratory Testing," NASA CR-2012-216039, Aug. 2012.


HART II Blade Property Test
Motivation:
No measured properties available for HART II blades
Reliable measured properties needed for accurate predictions
Approaches:
In collaboration with NASA, DLR, KU
Use the original set of HART II blades tested in DNW (2001)
Non-destructive test techniques (x-ray CT-scan plus 2D FE section analysis system Ksec2D) adopted
Assess measurement quality
Outcomes:
Updated structural property data of HART II blades released
Documented in journal papers: AIAA J & Comp Str (2015)
No. 3
H20
No. 4
No. 2
Blade
Digital detector
X-ray source
Leading edge
Balancing weight
Short fiber
Foam
Wire tube
Flap bending
lligent Rotorcraft Structures Lab

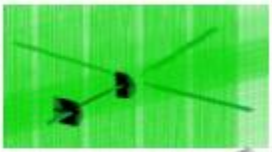

Result: HART II Blade Property Test
Flap bending
Torsion stiffness
25.2% at 0.17R
Span coordinates, r/R
Frequencies, /rev
Rotational speed
Angles, deg
Collective
Lateral cyclic
Longitudinal cyclic
Azimuth angle, deg
Jung, S. N., You, Y. H., Dhadwal, M., Riemenschneider, J., and Hagerty, B., "Study on Blade Property Measurement and Its Influence on Air/Structural Loads," AIAA Journal, Vol. 53, No. 11, 2015
Jung, S. N., M. Dhadwal, Kim, Y. W., Kim, J. H., and Riemenschneider, J., "Cross-section Constants of Composite Blades Using Computed Tomography Technique and Finite Element Analysis," Composite Structures, Vol. 129, Oct. 2015

Validation of HART I Rotor

Summary:
- HART I test performed at DNW in 1994
- First international joint effort to apply HHC technology to reduce rotor noise/vibration
- Measured blade properties available due to the recent measurement campaign

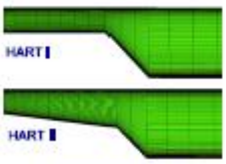
Approaches:
- Modern CFD/CSD coupling used
- Both isolated rotor & rotor-fuselage models used
- In CFD, up-to-date space/time marching schemes adopted for high precision results

Findings:
- CFD/CSD coupled airloads results showed excellent correlation with the test data
- BVI characteristic of HART I data captured precisely
- Structural loads correlation showed slight improvements

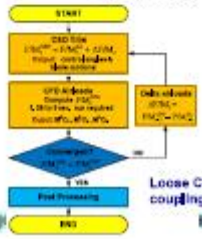



	HART I	HART II
No. of air stations	3 (0.75, 0.87, 0.97R)	1 (0.87R)
No. of strain gages	34 → 32!	6

Isolated rotor: 20.9M cells
Rotor-fuselage: 37.5M cells



Shank models

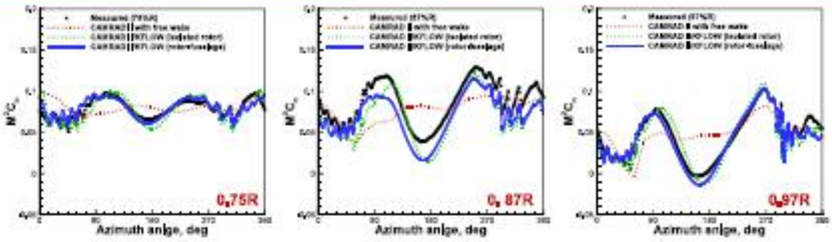


Loose CFD/CSD coupling algorithm

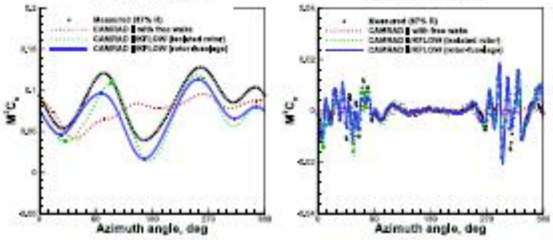
KU

Validation of HART I Test Data

Section airloads:

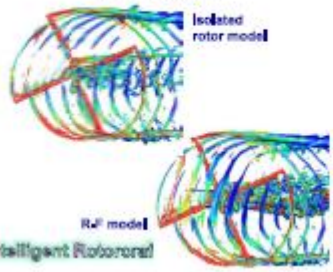


Harmonic analysis on M^2C_n (at 0.87R):



Low harmonic (0 to 10P)

High harmonic (11P and higher)

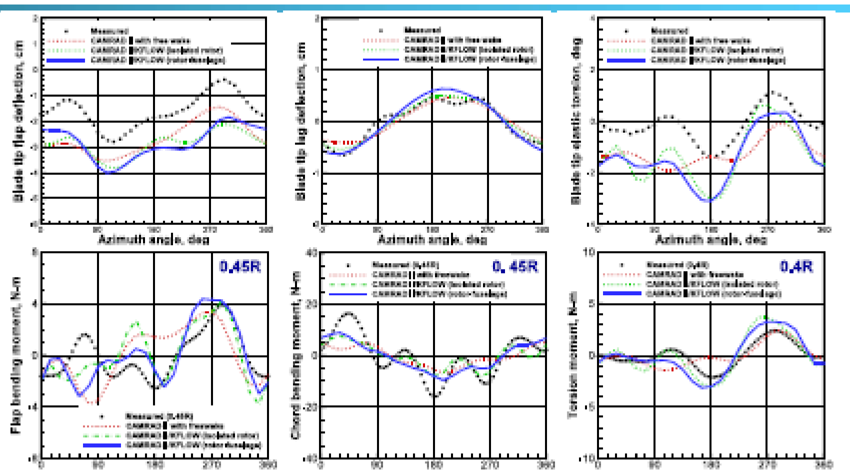


KU

Validation of HART I Test Data

Blade tip motions:

Blade structural loads:



- "Improved Rotor Aeromechanics Predictions using a Fluid-Structure Interaction Approach," Aerospace Science and Technology, Vol. 73, No. 2, Feb. 2018
- "Data Transfer Schemes in Rotorcraft Fluid-Structure Interaction Predictions," International Journal of Aerospace Engineering, Vol. 2018, Mar. 2018
- "Comprehensive Aeromechanics Predictions on Air and Structural Loads of HART I Rotor," Int. J. of Aeronautical and Space Sciences, Vol. 18, No. 1, 2017

Validation of HART II Rotor

Motivation:

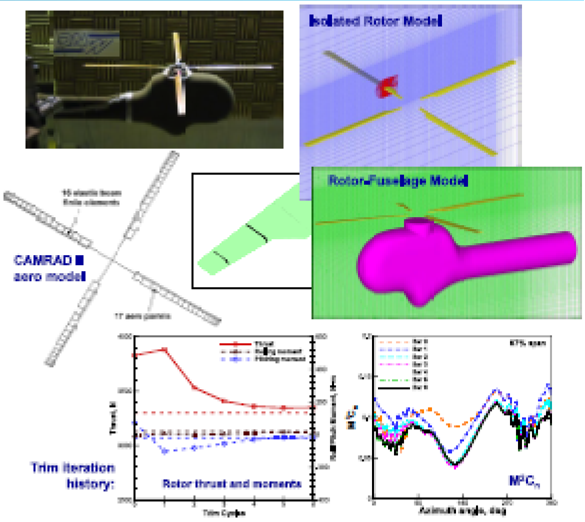
- HART II test performed at DNW in 2001
- Wind tunnel test data open to public in 2006
- High resolution test data used to demonstrate the prediction capability

Approaches:

- Step-by-step approaches taken for the validation of measured data
  1) CSD approach: CAMRAD II alone or with prescribed (CFD or measured) airloads
  2) CFD approach: KFLOW with measured blade motions
  3) Loose CFD/CSD coupled approach

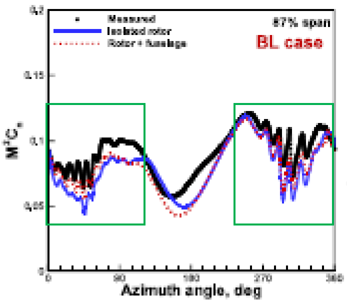
Outcomes:

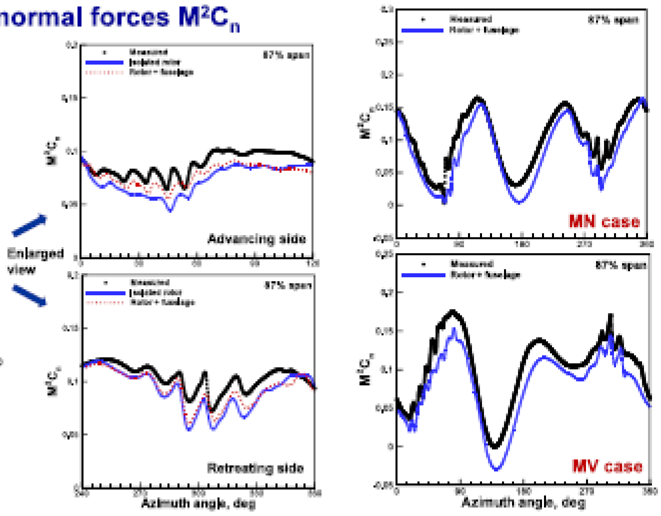
- Code-to-code validation proved efficient for improved correlation of HART II data
- Mechanism of BVI noise reduction via HHC inputs explained
- Loose CFD/CSD coupling algorithm shown to be highly reliable for aeromechanics predictions



Validation of Section Airloads

❖ Validation of section normal forces M^2C_n





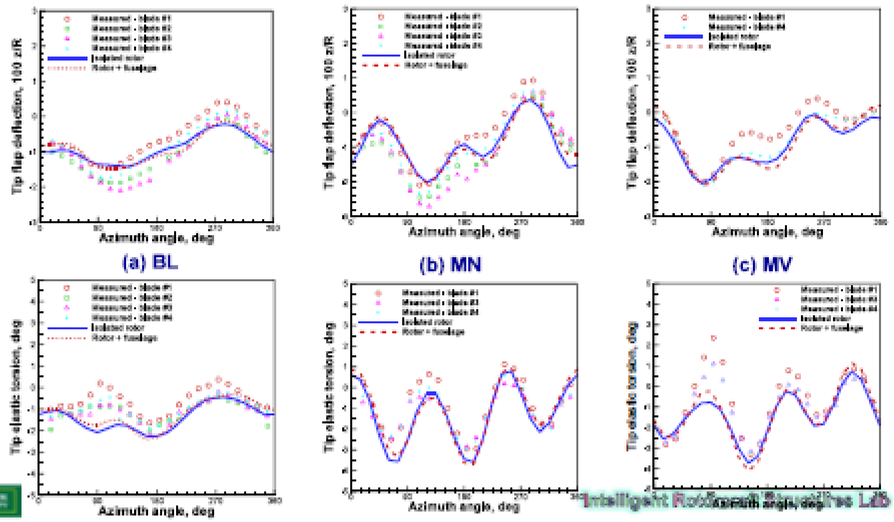
➢ Good correlation (BVI peaks, phase) obtained, particularly with R-F model

KU KONKUK UNIVERSITY

Validation of Blade Elastic Motions

Flap motion:

Torsion motion:



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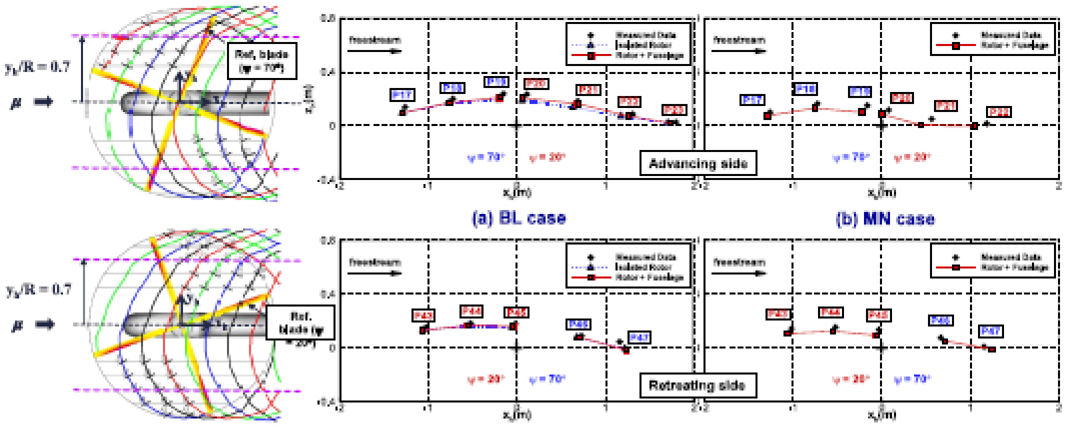
Intelligent Rotorcraft Structures Lab

Validation of Tip Vortex Trajectories



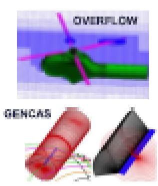
- "Modern Computational Fluid Dynamics/Structural Dynamics Simulation for a Helicopter in Descent," Journal of Aircraft, Vol. 50, No. 5, 2013
- "Loose Fluid-Structure Coupled Approach for a Rotor in Descent Incorporating Fuselage Effects," Journal of Aircraft, Vol. 50, No. 4, 2013
- "Correlation of Aeroelastic Responses and Structural Loads for a Rotor in Descending Flight," Journal of Aircraft, Vol. 49, No. 2, 2012
- "Comprehensive Code Validation on Airloads and Aeroelastic Responses of the HART II Rotor," Int. J. of Aeronautical and Space Sciences, Vol. 11, No. 2, 2010

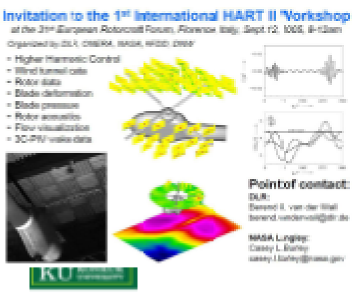
International HART II Workshop

- 1st Int. HART II Workshop started: Sept. 2005
- HART II test data opened to public: 3 test points in descending flight
  - Test data points: BL, MN, MV (at μ = 0.15)
  - Data released: Blade motions, Airloads, Rotor trim, Acoustics, PIV wake, Flow visualization for descending flight
- Workshop held biannually at AHS & ERF until 2012

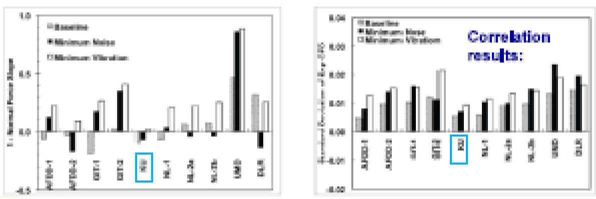
Participating organizations for joint workshop:

Partner	Partner label	CFD code	CSD code
US Army Aero-flightdynamics Dir.	AFDD-1	OVERFLOW	CAMRAD II
US Army Aero-flightdynamics Dir.	AFDD-2	HELIOS	RCAS
NASA Langley	NL-1	OVERFLOW	CAMRAD II
NASA Langley	NL-2	FUN3D	CAMRAD II
Georgia Institute of Technology	GIT-1	FUN3D	DYMORE4
Georgia Institute of Technology	GIT-2	GENCAS	DYMORE2
Konkuk University	KU	KFLOW	CAMRAD II
University of Maryland	UMD	TURNS	UMARC
German Aerospace Center	DLR	N/A	S4





HART II Workshop Database
ftp://HART-II@ftp.dlr.de
Password: HART-II



Joint workshop held in AHS Forum, Fort Worth, TX, May 1-3, 2012

DLR-KU MoU Research

Goals:

- To establish an int. collaboration
- To broaden the technology base by increasing fundamental knowledge on helicopter aeromechanics area

Summary:

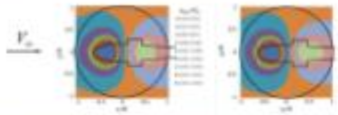
- MoU began in Apr, 2008 for 6 years
- Consisted of 2+ tasks: rotor aeromechanics, dynamic stall, and information exchange (rotary UAV)
- Meetings held twice per year at the other organization
- Points of contact: Sung N. Jung (KU), Berend G. van der Wall (DLR)

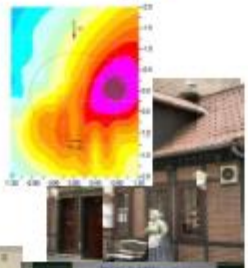
Outcomes:

- S4-KFLOW coupling attempted
- Bound meeting minutes (11 meeting volumes)
- 1 journal papers and 7 conference papers

Task	Area
Task I - 1	Aeromechanics on: Various Rotorcraft Activities
Task I - 2	Aeromechanics on: STAR/HART Blades
Task II	Dynamic Stall: CFD prediction and validation
Potential Task	UAV Activities or other areas (e.g., FBW) KARI Rotorcraft Activities

Konkuk/DLR MoU on Helicopter Aeromechanics
7th semi-annual Meeting
Sept. 8-9, 2011





STAR (Smart Twisting Active Rotor) Int. Consortium Project

Goals

- Reduce noise/vibration with improved performance via ATR concept (post-decessor of HART II)
- Realize active rotor technology

Members

- German DLR / French ONERA
- US Army AFDD & NASA Ames
- Korea Konkuk Univ. & KARI
- Japan JAXA
- UK DSTL & Univ. of Glasgow

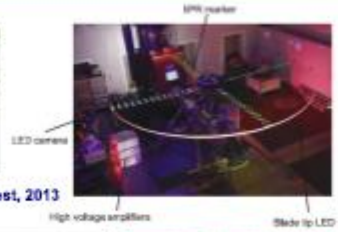
Flight Conditions

- Hover, Low speed descent
- Cruise/high speed
- High load, High μ (at 50% RPM)
- Speed/thrust/phase sweep

Schedule

- Phase I: Launched at May 2009
- Phase II: Resumed in 2018
- Wind tunnel test planned: Sept. 2024 at DNW, Netherlands

STAR hover test, 2013

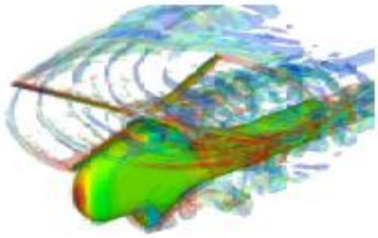


- Ahn, J. H., Hwang, H. J., Jang, S., Jung, S. N., Kalow, S., and Keimer, R., "X-ray Computed Tomography Method for Macroscopic Structural Property Evaluation of Active Twist Composite Blades," Aerospace, Vol. 8, Nov. 2021

Q & A

Thank you!

Contact: snjung@konkuk.ac.kr



Korea-Japan Joint Workshop on Rotorcraft 2023

KARI MDAO System Development Plan and Status for the Hybrid eVTOL Aircraft Design

February 10, 2023

Seung-Kil Paek

Korea Aerospace Research Institute

Background

- **Interests in UAM(Urban Air Mobility) or AAM(Advanced Air Mobility) is in full swing.**
  - The Vertical Flight Society (US) counts almost 700 entrants in the AAM industry with new ones added on a weekly basis

- **KARI(Korea Aerospace Research Institute) should provide the Korean industry with the core technology for those types of aircrafts as a Korean government funded research institute since 1989.**
  - Developing also an eVTOL aircraft a.k.a. OPPAV[1]
  - Developing MDAO[2] technology on eVTOL aircraft through an internal project since 2019.
    - Started a new five-year-long internal project to develop a MDAO system.

[1]OPPAV : Optionally Piloted Personal Air Vehicle, 2019 ~ 2023
[2]MDAO : Multi-disciplinary analyses and optimization

KARI MDAO System Development Plan and Status 1

Previous Researches

- **There have been various MDAO Frameworks, related software and digital contents:**
  - CEASIOM(CEASIOMpy), pyMDO, OpenMDAO, 3DOPT, MDOPT, CPACS, RCE, and etc.

- **DLR (Germany) started the development of the aircraft design environment from 2005.**

- **DLR created the open-sourced CPACS as a common namespace.**
  - a standard for exchanging aircraft design information among aviation-related institutions of DLR.

- **DLR developed the open-sourced RCE as a process integration framework**
  - It supports collaborative and distributed work.

Previous Researches

- **A collaborative MDAO system**
  - the design tools implemented by each discipline specialist are operated in independent software environments
  - their outputs are shared by design tools in other fields

- **DLR has been conducting collaborative optimization design research in a distributed environment early on.**

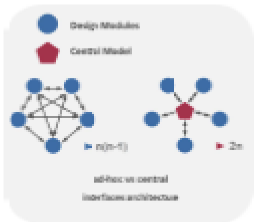
- **In the AGILE project,**
  - AGILE : Aircraft 3rd Generation MDO for Innovative Collaboration of Heterogeneous Teams of Experts
    - from 2015 to 2018, part of the Horizon 2020 program.
  - DLR has reached the level of designing an aircraft by implementing interworking between processes distributed across three continents, 19 institutions, and heterogeneous platforms

KARI MDAO System Development Plan

- **Software structure**
  - Collaborative software structure will be used:
  - The independent analysis method established by using the most familiar software tools such as Excel, script, commercial S/W, and in-house software, in the most appropriate operating environment by each discipline expert will be combined as a process.
  - The concept of establishing a process is not to create a new tool, but to transform an existing tool into a form that can be shared as much as possible on the network
  - In Korea, optimal design researches under such a collaborative system have hardly been conducted.
    - Hence this research will be a big challenge.

KARI MDAO System Development Plan

- **Central Data Model**
  - Central data model will be used to minimize the interfaces.
  - Communication between different disciplines is achieved through design parameters.
  - In KARI, these design variables were independently defined and there was no common parameter pool until now.
  - In this project, CPACS[1] is used to control design variables in all disciplines as much as possible
  - Using CPACS, is like forcing people with different mother tongues to use only one foreign language!
    - Big challenge
  - CPACS is mainly used for conventional fixed wing aircrafts with jet fan engines until now.
    - It needs much enhancements so that it can be used for UAM aircraft design

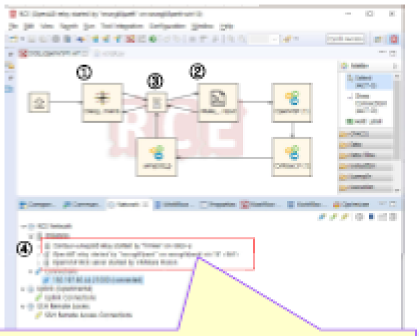


Courtesy of https://github.com/DLR-SL/CPACS

[1]CPACS : Common Parametric Aircraft Configuration Schema. A data definition for the air transportation system. Opensource digital content hosted in github.

KARI MDAO System Development Plan

- **Process Integration**
  - KARI had used ModelCenter® for the process integration
    - Kang, H.-J, "Design optimization of QTP-UAV prop-rotor blade using ModelCenter®", *Journal of Aerospace System Engineering*, Vol. 11, No. 4, pp. 36—43, 2017.
  - Recently, RCE, an open-source replacement have been tested instead.
  - The user experience with RCE was satisfactory.
  - RCE will be used for this project.



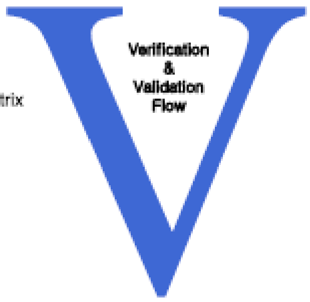
Three engineering tools was integrated:

- an aircraft geometry creating tool using OpenVSP and Rhino®
- a commercial mesh generation tool CENTAUR®
- an inhouse CFD solver to make geometry design study

KARI MDAO System Development Plan

- **2022 : MDO System Requirements & System Architecture Design**
  - Define the requirements for the MDAO system
  - Define the tool list to be integrated in the MDAO system
  - Define the interface using the central data model.
  - Define the workflow of the MDAO system as XDSM[1] format
- **2023 :**
  - Verification of System Architecture
  - Development of tools and discipline workflows
- **2024 : Verification of each discipline workflow**
- **2025 : Verification of the integrated workflow**
- **2026 : Verification of the optimal design capability**

[1]XDSM : Extended Design Structure Matrix



- **Based on system engineering methodology for software development.**
  - Project management with Redmine software
  - Configuration control with Git software

Concept Design Study from 2022 to 2023

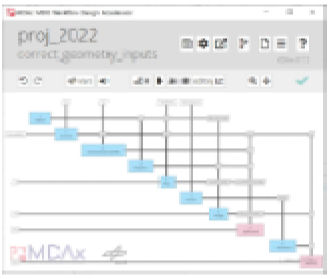
- **KARI is making a concept design of a 6 seated UAM aircraft:**
  - Define the top-level requirement and analysis standard
    - the follow-up study of the OPPAV aircraft
  - Decide the design variables, analysis cases, and major performance objectives
  - Establish an optimal design problem
  - Create a concept design.

Preliminary Design Study from 2024 to 2026

- **2024 :**
  - Build a surrogate model for each discipline workflow
  - The collected surrogate models are integrated into the total workflow.
  - The work will be used for optimal design study
  - The optimal design will be reviewed.
- **2025 :**
  - The discipline workflows will be integrated altogether.
  - DOE using the integrated workflow will be made.
  - Optimal solution using DOE results
- **2026**
  - Direct optimization with the integrated workflow

MDAO System Design Tool

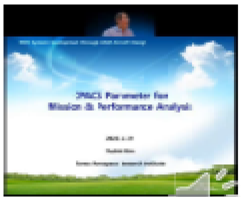
- **For the design of the MDAO system, such as the input/output definition of each component and the workflow design combining each component, tools are needed:**
  - KADMOS
    - An open source python package based on the data schema called CMDOWS
    - Little documentation and not easy to start
  - MDAx : MDO Workflow Design Accelerator
    - A web-based GUI application by DLR
    - An easy-to-use substitute of KADMOS
    - more promising than KADMOS.



KARI-DLR Collaboration for System Design

- **KARI have been studying the usability of various DLR software tools:**
  - RCE, TiGL, TiXI, VAMPzero, CPACS and MDAx
- **KARI-DLR cooperation was proposed by KARI in 2020 and welcomed by DLR.**
  - Enhancement of DLR tools through the test and evaluation
  - Discussions were made to materialize the cooperation through 2021.
  - An online meeting was made between the aeronautics research directorate of KARI and the institute of system architecture in aeronautics of DLR in March 2022 to discuss the practical cooperation.

- **Online workshops have been held four times through the video conferencing**
  - from May 2022 to Aug 2022
  - CPACS and TiGL Tutorial and Q&A
  - Hands-on exercises using MDAx via the web "as-a-service"
  - KARI work procedures for flight control, mission analysis, and geometry generation
  - Totally 43 people from KARI side attended the workshops.



MDAO System Design Status

- **MDO System Requirement Documentation**

Internal Workshops

- **MDO System design needs the cooperation between the experts on physical models constituting the system.**
- **Intensive discussions and brain storming were needed in a short time.**
- **Six internal workshops were made in 2022.**
  - February : eVTOL concept design seminar
  - March : 1st optimal design problem definition
  - May : CPACS-RCE basics and 1st N2 chart build
  - July : 2nd N2 chart build
  - August : 2nd optimal design problem definition
  - September : MDO system design

MDAO System Design Status

- **MDO System Requirement – Top Level Requirements**
  - Six top level requirements
    - Preliminary design for 5 seated hybrid eVTOL aircrafts
    - CPACS as central data model
    - RCE as the process integrator
    - Each Component to be able to separate execution
    - Interoperable components
    - System engineering to be followed

MDAO System Design Status

- **MDO System Requirement – High Level Requirement**
  - Five functional requirements
  - Six environment requirements
  - One Performance requirement

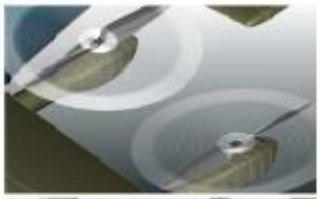
MDAO System Design Status

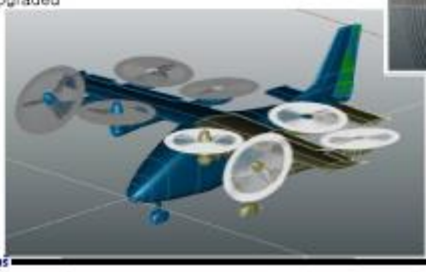
- **MDO System Requirement – Use Cases and Test Cases**
  - Five use cases
    - One execution of a specific component
    - Design of Experiment (Multiple executions) using a specific component
    - Design of Experiment (Multiple executions) using plural components
    - Optimization using plural components
    - Optimization using all components

MDAO System Design Status

- **Major tools to be integrated into the MDAO system:**
  - Geometry : inhouse software using CPACS, TiXI, TiGL, Python
  - Aerodynamics* :
    - Athena Vortex Lattice (AVL) code
    - Inhouse source doublet panel method + actuator disk theory
    - OpenFOAM + actuator disk model
  - Flight control : inhouse flight model, MATLAB, CONDUIT
  - Mission performance and Prop* : inhouse software, CAMRAD II
  - Noise* : inhouse software
  - Structure* : inhouse FE modeler, MSC/NASTRAN, Hypersizer
  - Hybrid electric propulsion* : inhouse software in MATLAB and SIMULINK

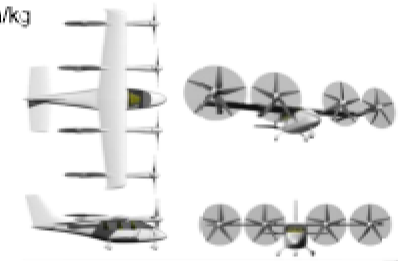
*Need to be developed or upgraded



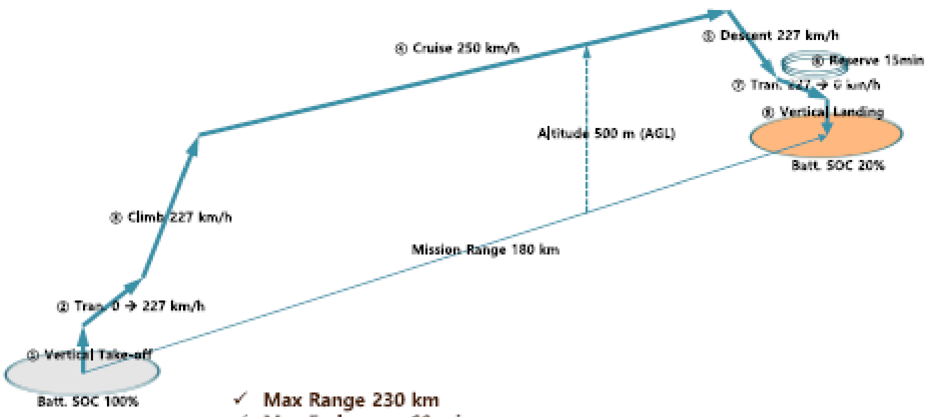


Requirements for a UAM Design

- **TLAR**
  - Payload : more than 550 kg (1 pilot and 5 passengers)
  - Cruise speed : more than 250 km/h
  - Maximum speed : more than 300 km/h
  - Maximum range : more than 200 km
  - Maximum endurance : more than 60 minutes
  - Maximum altitude : 2 km
  - Noise : less than 65dBA at T/O and Landing (100 m distant and at 100 m altitude)
- **Assumption**
  - Battery Pack Energy Density : more than 250 Wh/kg



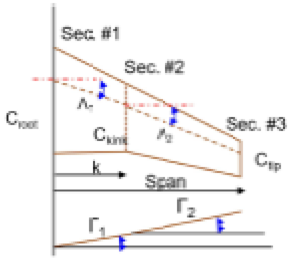
Mission Profile



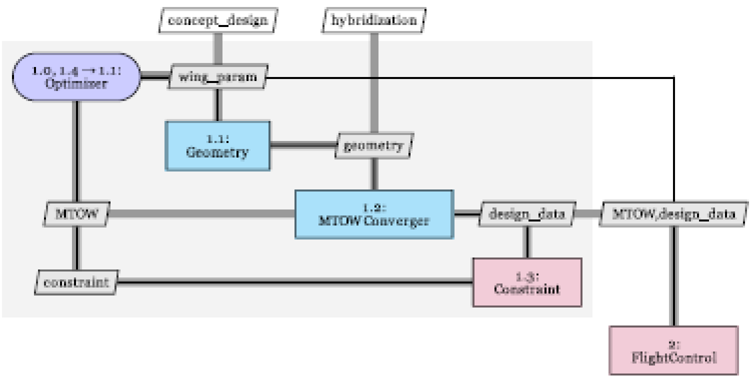
✓ Max Range 230 km
✓ Max Endurance 60 min

Optimization Problem

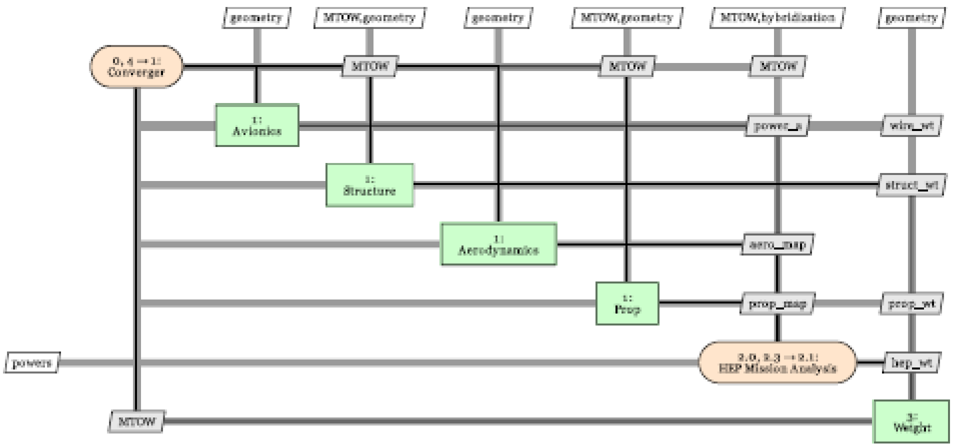
- **Design Parameters**
  - k, b : the kink position and span of the main wing
  - $C_{root}, C_{kink}, C_{tip}$: the chord lengths of the root, kink, and tip sections of the main wing
  - Λ_1, Λ_2: the sweep angles of the root and kink sections of the main wing
  - θ_1, θ_2 : the twist angles of the kink and tip sections of the main wing
  - Γ_1, Γ_2 : the dihedral angles of the root and kink sections of the main wing
  - Hybridization factor
- **Objective**
  - Minimize the maximum take-off weight



Optimization Problem

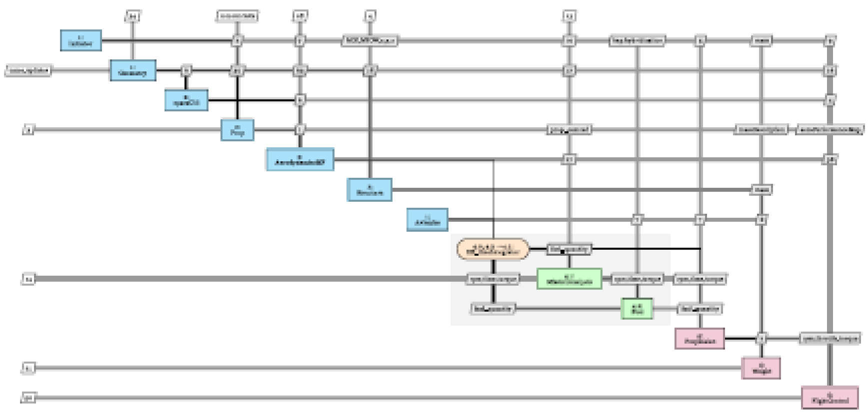


Optimization Problem – MTOW Converger



MDAO System Design Status - XDSM

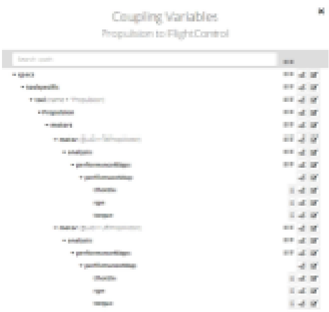
- Draft XDSM chart

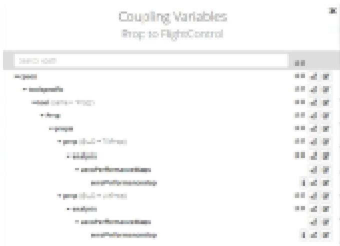


cpacsUtil : from CPACS to higher level parameter

MDAO System Design Status - CPACS

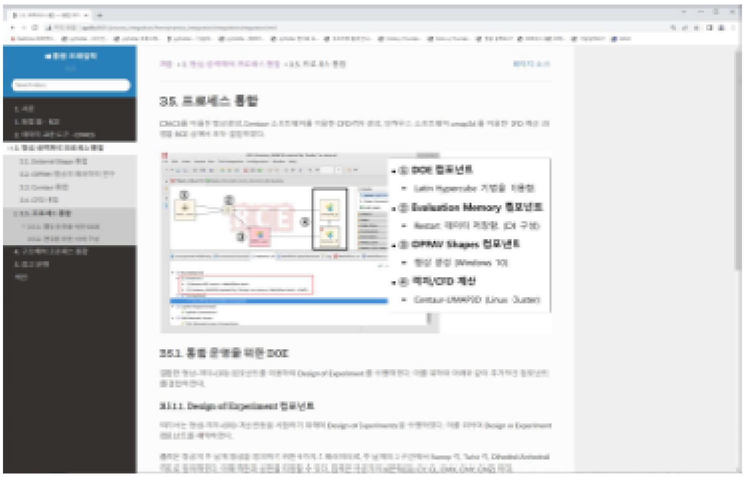
- **Enhancement being devised**
  - Elements for UAM specific systems
  - Performance Map for Propellers and Motors





User Manual

- **User manual is being made**



Initial Sizing

- **Concept Design Tool**
  - Based on SUAVE(an open source concept design tool by Stanford Univ)
  - Devised a component for the Lift-Tilt configuration

Initial Sizing

- **The first sizing**
  - Based on OPPAV, one-seated vehicle, the sizing was made with the six-seater requirement.

Conclusion

- **The KARI plan, from 2022 to 2026, on the overall MDAO system development was explained**
- **KARI-DLR cooperations until now were explained.**
- **MDAO system design and concept design in 2022 were explained**
  - Requirements
  - System design
  - Interfaces
  - Component workflows

3-6

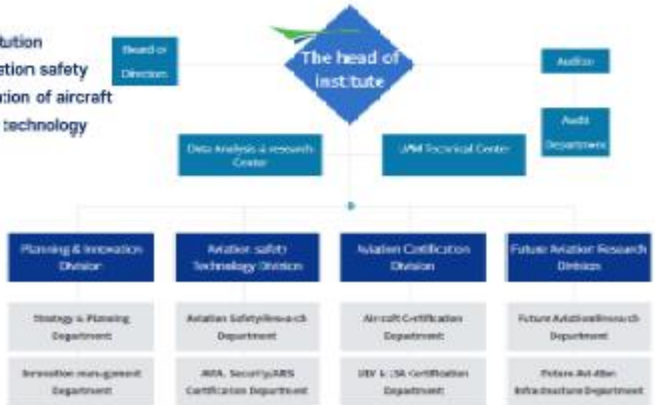

Republic of Korea's
UAM Policy and Aircraft Certification
Feb, 2023
UAM Technical Center
Korea Institute of Aviation Safety Technology
KIAST Korea Institute of Aviation Safety Technology


Part 1
Overview

Introduction of KIAST (Korea Institute of Aviation Safety Technology)

Overview

- Established in 2013 as a special institution
- Public organization specialized in aviation safety
- Dedicated to aviation safety certification of aircraft
- Research and development of safety technology



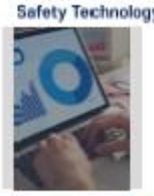
Introduction of KIAST (Korea Institute of Aviation Safety Technology)

Major activities of KIAST

Aircraft Certification

Safety Certification

Safety Technology R&D



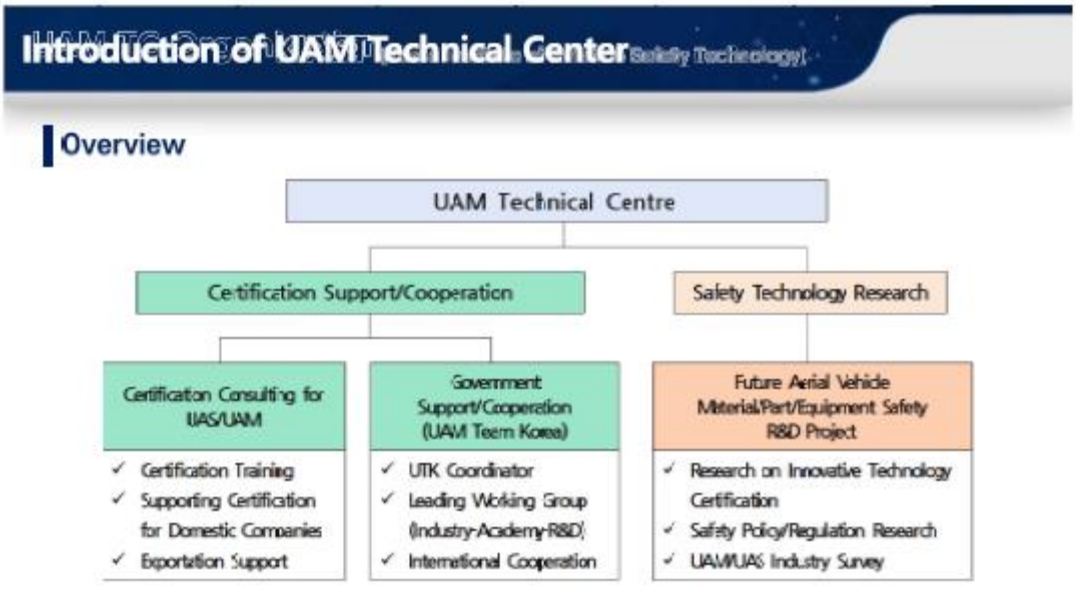
Aviation Security

Drone Safety Evaluation

UTM Development

Drone Industry Support

Navigational Aid


Introduction of UAM Technical Center
Overview
UAM Technical Centre
Certification Support/Cooperation
Safety Technology Research
Certification Consulting for UAS/UAM
✓ Certification Training
✓ Supporting Certification for Domestic Companies
✓ Exportation Support
Government Support/Cooperation (UAM Team Korea)
✓ UTK Coordinator
✓ Leading Working Group (Industry-Academy-R&D)
✓ International Cooperation
Future Aerial Vehicle Material/Part/Equipment Safety R&D Project
✓ Research on Innovative Technology Certification
✓ Safety Policy/Regulation Research
✓ UAM/UAS Industry Survey


Part 2
K-UAM Roadmap

Introduction of K-UAM Roadmap

K-UAM Roadmap 1.0 based on a phased approach

1st Stage — 1. Preliminary Phase ('20~'24)
- Issue/Task identification
- Regulatory revision
- Test and demonstration

2nd Stage — 2. Early Phase ('25~'29)
- A few commercial routes
- Hubs around city
- Multimodal transportation

3rd Stage — 3. Growing Phase ('30~'35)
- More commercial routes
- City based hub operation
- Business turn to profit

4th Stage — 4. Mature Phase ('35~)
- Widespread UAM Service
- Intercity routes
- Autonomous operation

Introduction of K-UAM Roadmap

K-UAM ConOps 1.0

- ✓ Official release in Sep 2021
- ✓ Drafted by UAM Team Korea
- ✓ Corridor and monitoring system adopted
- ✓ Nominal and Off-nominal situations defined

Introduction of K-UAM Roadmap
K-UAM Grand Challenge
✓ Official announcement in Feb 2022
✓ A total of 55 applications submitted
✓ Aircraft/Operator, Traffic Management, Vertiport
✓ Selection of participants in November
Example route for initial service
Source http://en.kuam-go.kr/

Part 3
UAM Flight Demonstration Project

UAM Flight Demonstration Project

Flight Demonstration Project since 2020

2020

UAM Seoul Demonstration
Han River, Seoul

2021

UAM Airport Demonstration
Gimpo/Incheon Airports

2022

UAM/Vertiport Demonstration
Gimpo Ara-Marina

UAM Flight Demonstration Project

2022 Demonstration – Venue Configuration

1F Exhibits for Vertiport Experience
(Security check, biometrics, reservation platform)

3F UAM Takeoff and landing pad
(OPPAV, VOLTLINE, V-SPACE)

Vertiport model(KAC) / UAM reservation platform (SKT&Tmap Mobility)
Smart Check-in System(Hanwha System) / Security Check(ROHDE & SCHWARZ)

Vehicle : OPPAV, VOLTLINE, V-SPACE


UAM Flight Demonstration Project
Vehicle for Flight Demonstration
V-SPACE
VOLTLINE


Part 4
UAM Aircraft Certification

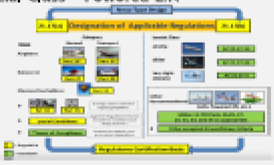
UAM Aircraft Certification

UAM Aircraft Certification – USA vs Europe

- Different frames between the USA and Europe
  - ✓ USA) Special Class – Powered Lift, CFR 14 Part 21.17(b)
  - ✓ Europe) Special Condtion for Small-Category VTOL Aircraft(SC-VTOL)

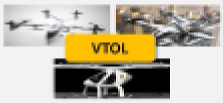
US, FAA)

- (Part 23/27) + Special Condition
  ➔ Special Class – Powered Lift



Euroup, EASA)

- Interim standard for Small-Category VTOL (SC-VTOL, '19.6)
- Interim standard for Propulsion System (SC-E-19, '20.1)



UAM Aircraft Certification

Korea's UAM Aircraft Certification Direction

- Promoting integration of UAM aircraft within the current aircraft certification system
  - ✓ Establish an internationally equivalent certification system in a timely/simultaneously
    - Cooperation with international associations and foreign airworthiness authorities for harmonization of certification systems between countries (FAA, EASA, JAPAN, ASTM, EUROCAE, etc)
  - ✓ Establish a certification system suitable for the domestic situation
    - Considering aviation safety policies and aspects of revitalizing the domestic UAM industry, setting certification directions suitable for the domestic operating environment and actual situation
    - MOLIT is in the process of establishing regulation for UAM aircraft certification
  - ✓ For the successful commercialization of UAM, research and system establishment not only of aircraft but also of the entire ecosystem
    - In addition to aircraft certification, it is necessary to establish standards and related regulations for personnel licensing, operation and facilities, etc.

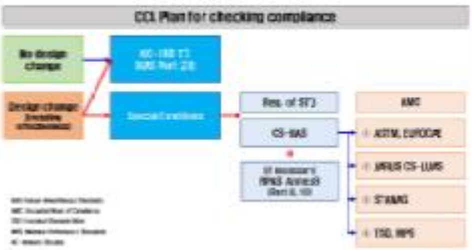
Part 5

R&D Project on UAS/UAM

R&D Project on UAS/UAM

CTsUA R&D Project

- ✓ Development of certification technology of UAS via modification of existing type certified KC-100 airplane into unmanned configuration



▣ Current Status

- ✓ Part 23 + Special Condition
- ✓ CCL finalized
- ✓ Test Readiness Review Completed

R&D Project on UAS/UAM

OPPAV R&D Project

▣ OPPAV Project Overview
- ✓ Development of verification technology for OPPAV
- ✓ Research on a new framework for safe operation of VTOL
- ✓ Aircraft certification, airspace integration, pilot/operator license
- ✓ First flight of full-scale aircraft scheduled in late 2022

▣ Optionally Piloted Personal Air Vehicle (OPPAV)
- ✓ Development of 8-proprotor eVTOL aircraft by KARI
- ✓ 4 front rotors tilt for lift/thrust, 4 rear rotors fixed for lift
- ✓ Certification basis and MOC for OPPAV by KIAST
- ✓ Supplementary guidance material for key technologies

Thank you

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Director of UAM Technical Center, KIAST, Korea
leesk@kiast.or.kr

将来回転翼機研究会・回転翼解析技術交流会

No.	氏名	所属	タイトル
JHS-TM-2022-001	砂田　茂	名古屋大学	rFlow3Dを中心としたJAXAとの共同研究について
JHS-TM-2022-002	弓野　拓海	東京農工大学	高速前進飛行における二重反転ロータの振動低減手法の検討
JHS-TM-2022-003	濵本　佑典	金沢工業大学	主翼を有するシングルロータ機の前進飛行時とタンデムロータ機のホバ時の空力特性
JHS-TM-2022-004	坂爪　竣哉	横浜国立大学	低レイノルズ数領域における平板翼ロータのホバリング解析
JHS-TM-2022-005	吉川　昂汰	工学院大学	火星ヘリコプタ『HAMILTON』に関する数値解析および計測実験
JHS-TM-2022-006	Jianwei Sun	千葉大学	PIV Measurements and Computational Study of a Drone Propeller
JHS-TM-2022-007	有田　俊作	防衛大学校	ロータの影響を受けるプロペラの振動計測
JHS-TM-2022-008	保江	JAXA	非構造流体解析ソルバFaSTAR-Moveの回転翼解析事例および最新機能紹介
JHS-TM-2022-009	木村	JAXA	自動格子生成ツールrGridの機能紹介
JHS-TM-2022-010	菅原	JAXA	回転翼統合解析ツールの最新機能紹介（rBET/RMT, rFlow3D, rNoise）

JHS-TM-2022-001

rFlow3D を中心とした JAXA との共同研究について

名古屋大学
砂田　茂

今のドローン

回転数を変化させて飛行

従来の航空工学

翼と流れの成す角度を変化させて飛行

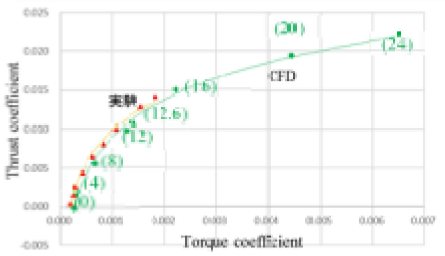
回転翼

回転翼の下方にあるフィンも

1988年，名古屋大学（鈴木正之名誉教授，丹羽昌平講師（当時），杉浦一郎名誉教授）と日立造船㈱との共同研究によって開発されたもの

名大博物館

Collective Pitchによる飛行するドローン



高い信頼性
自信を持って論文を作成可能

「マルチロータ機におけるロボット工学と航空工学の融合」
日本ロボット学会論文集

<u>ＪＡＸＡ　泉　耕二氏の分析</u>

（1）これからの日本で伸びる交通手段：
首都圏の「地下鉄」、郊外の中･長距離では「航空機」

地下と空中利用の「３次元的移動手段」

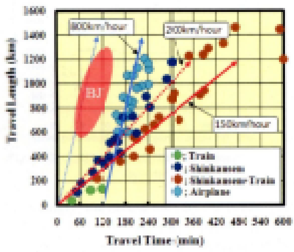
Ref. 「ＪＡＸＡの航空と世界の動き」：ながれ　25 (2006) pp.525-532.

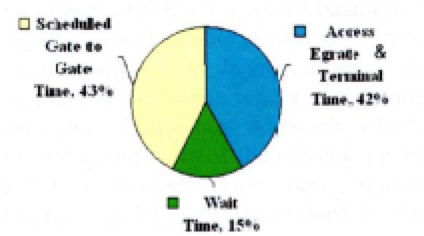
ＪＡＸＡ　泉　耕二氏の分析

（2）乗り換え時間、待ち時間＝ムダ時間

Personal 化、Door To Door の移動手段

Ref. ‘The Potential for an air taxi business in Japan’s skies’, ICAS 2010





空飛ぶクルマの意義

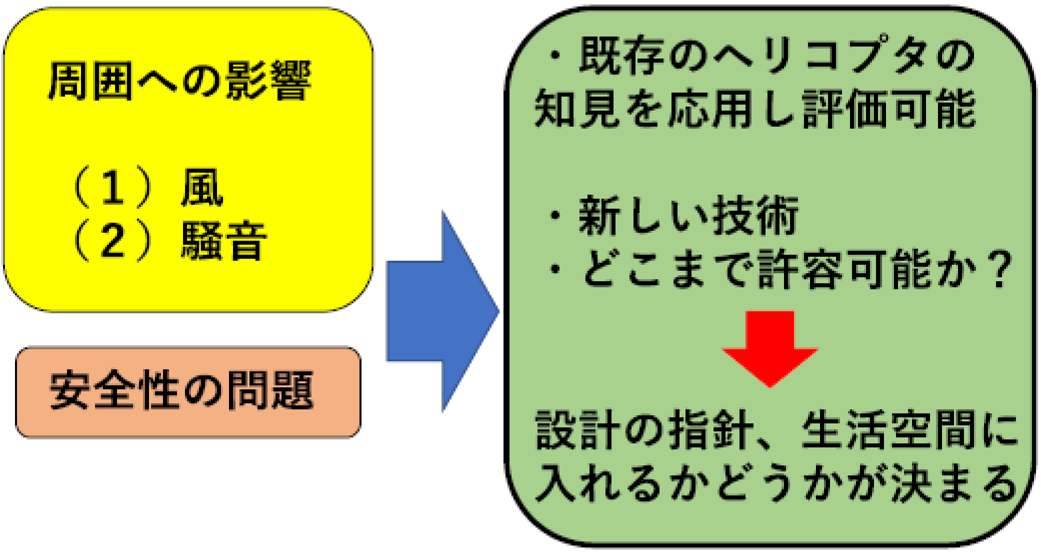
〇2次元から3次元の移動へ

〇Personal

〇Door To Door

〇トータルの移動時間の短縮

〇ストレス軽減



2重反転ロータを有する空飛ぶクルマのロータの設計法の検討
空力性能（rFlow3D）と騒音（rNoise）詳細は4月の航空宇宙学会年会にて

表1　3種類のロータで共通の諸元

ロータ半径, R [m]	0.75
合計ブレード枚数, b	6
鉛直方向発生空気力, L [N]	981
C_T/σ（上下段のブレードの合計推力でC_Tを，2段の全ブレードでσを定義）	0.11
上下ロータ間距離, h [m]	0.225
ブレードカットアウト[m]	0.15
平面形	矩形
捩じり下げ [deg]	8（線形）
翼型	NACA4412

表2 3種類のロータで異なる諸元

項目/ロータ番号	1	2	3
ホバ時の翼端マッハ数, M_{tip}	0.3	0.45	0.6
コード長，c [m]	0.155	0.0689	0.0388
回転角速度，Ω [rad/s]	136	204	272
アスペクト比, AR	4.84	10.9	19.4
h/c	1.45	3.27	5.81
ホバ時の翼端レイノルズ数, Re_{tip}	1.08×10^6	7.23×10^5	5.42×10^5

ロータ半径, R [m]	0.75
合計ブレード枚数, b	6
鉛直方向発生空気力, L [N]	981
C_T/σ （上下段のブレードの合計推力でC_Tを，2段の全ブレードでσを定義）	0.11
~~上下ロータ間距離, h [m]~~	~~0.225~~
ブレードカットアウト[m]	0.15
平面形	矩形
捩じり下げ [deg]	8（線形）
翼型	NACA4412

表2 3種類のロータで異なる諸元

項目/ロータ番号	ロータ2	シングルロータ
ホバ時の翼端マッハ数, M_{tip}	0.45	
コード長, c [m]	0.0689	
回転角速度, Ω [rad/s]	204	
アスペクト比, AR	10.9	
h/c	3.27	
ホバ時の翼端レイノルズ数, Re_{tip}	7.23×10^5	

結果１　ホバリング

	ロータ1	ロータ2	6ブレードのシングルロータ	ロータ3
75%Rでの(θ_u, θ_l) [deg]	$\binom{16.2,}{17.0}$	$\binom{11.3,}{12.0}$	12.6	$\binom{8.7,}{9.1}$
FOM	0.76	0.78	0.71	0.76
地上での平均音圧[dB]	57.8	59.6	42.8	62.3

高AR　低Re　高M

2重反転、高Mは騒音の点で劣る

結果２　前進飛行

	ロータ2	シングルロータ
75%Rでの(θ_u, θ_l) [deg]	(9.37, 9.92)	11.1
無次元振動数 $k=\Omega c/2V$	0.25	
L/D_E	2.37	1.95
平均音圧 [dB]	66.4	51.1

・2重反転、高Mは騒音の点で劣る

・サイクリックピッチが入らない：1周期中の流入速度に加え迎角も大きく変化。非定常空気力の関与が増の可能性

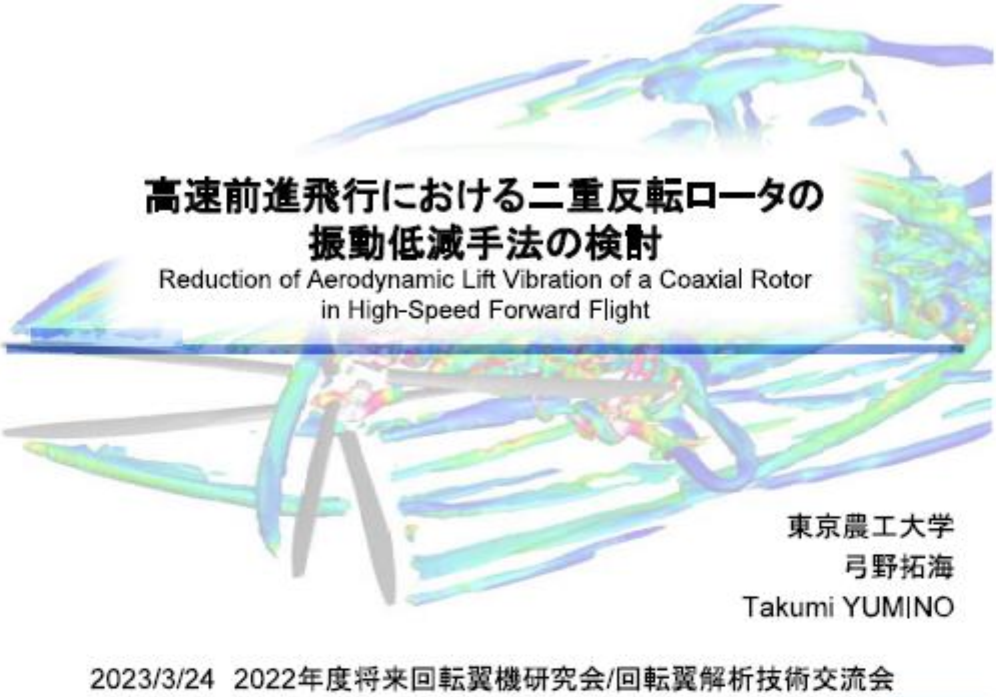
空力性能（rFlow3D）と騒音（rNoise）

高い信頼性

⬇

空飛ぶクルマを初めとした
新しい回転翼の使用状況の分析に適用可能


ありがとうございました


高速前進飛行における二重反転ロータの
振動低減手法の検討
Reduction of Aerodynamic Lift Vibration of a Coaxial Rotor
in High-Speed Forward Flight
東京農工大学
弓野拓海
Takumi YUMINO
2023/3/24 2022年度将来回転翼機研究会/回転翼解析技術交流会


研究背景
コンパウンド・ヘリコプタ：高速ヘリの機体コンセプト
（揚力発生機構 + 推進力発生機構）
コンパウンド・ヘリコプタ
現行ヘリコプタ
150 kt
シングルロータ
救命率
向上
250 kt
二重反転ロータ + 推進プロペラ
(s-97 raider, U.S, Army)
270 kt
シングルロータ, 固定翼 + 推進プロペラ
(Concept of High-Speed Rotorcraft, JAXA)
1/8

研究背景

高速飛行時、**逆流領域**が生じる

〇現行ヘリ

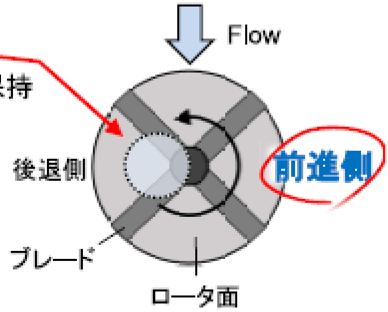
→ 前進側の揚力を抑制＆モーメント・バランス保持

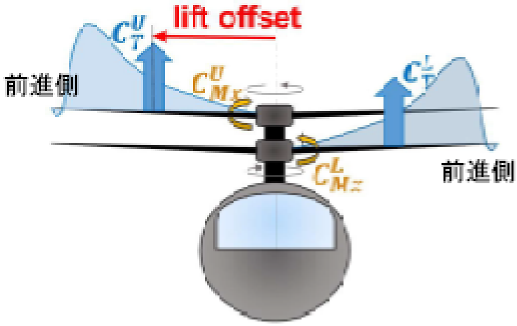
→ 全体として揚力不足

〇高速ヘリ（二重反転ロータ＋推進プロペラ）

→ 前進側の揚力を活用（Lift offset, *LO*）

→ **高速飛行可能！**





$$LO = \frac{|C_{M_x}^U| + |C_{M_x}^L|}{C_T^U + C_T^L} = \frac{|r_T|}{R}$$

C_T：推力係数

C_{M_x}：ローリング・モーメント係数

r_T：ロータ面の推力中心半径位置[m]

R：ロータ半径[m]

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研究目的

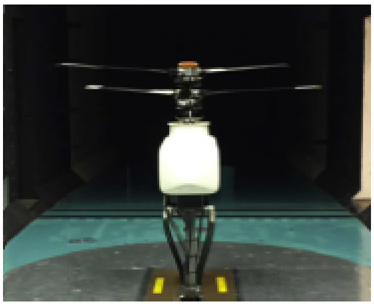
◆ 二重反転ロータの課題

〇 揚力を得やすい

✕ 振動、騒音が課題

CFDを用いて振動を低減させる手法の検討

◆ 振動の原因：推力変動



2枚ブレード

Cameronらの風洞試験[1]
性能の調査

早見らの解析[2]
Lift offsetによる低減効果を明らかに

This presentation

4枚ブレードでの計算妥当性の検証

[1]Cameron., et al., "Performance and Loads of a Model Coaxial Rotor Part I: Wind Tunnel Testing"

[2] Hayami, K., Sugawara, H., Yumino, T., Tanabe, Y., Kameda, M.,et al.,"CFD Analysis on the performance of a coaxial rotor with lift offset at high advance ratio", Aerospace Science and Technology, in press, 2023

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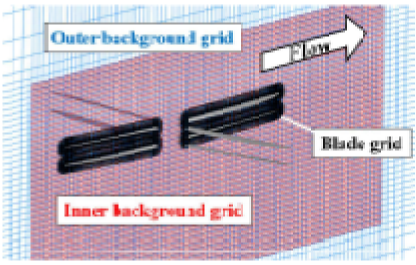
CFDソルバ・計算モデル

◆回転翼用CFDソルバ：**rFlow3D**

✓3次元圧縮性流体ソルバ

✓移動重合格子法

✓JAXAスーパーコンピュータJSS3上で実行



◆Sikorsky社X2TD[2]のロータ形状($N_b = 4$)

N_b；1ロータ当たりのブレード枚数

X2TD

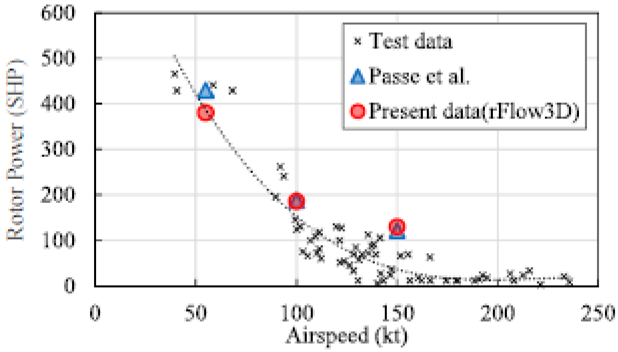
[2]Walsh, D., et al., "High Airspeed Testing of the Sikorsky X2 Technology Demonstrator"

ロータ諸元

ロータ半径	4.023 m
ロータ間間隔	0.457 m
プリ・コーニング角	2°
回転方向	上側ロータ反時計回り

妥当性検証結果

◆ロータ・パワーの比較



飛行試験
&
Passeらによる
解析結果と
概ね一致

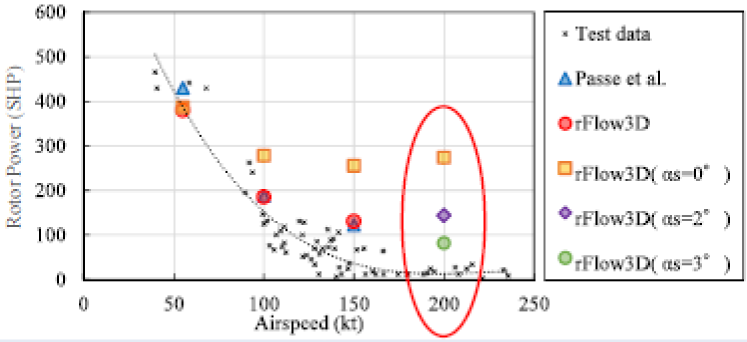
150 ktやや過大評価

機体姿勢角の
違いによるもの

前進速度 [kt] **(前進率 μ)**	**55** ($\mu = 0.15$)	**100** ($\mu = 0.27$)	**150** ($\mu = 0.41$)
合計推力係数 $\sum C_T$	0.0115	0.0113	0.0100
機体姿勢角 i [°] **(一様流角度)**	-0.44（前傾）	2.43（後傾）	2.10（後傾）

妥当性検証結果

◆機体姿勢角によるロータ・パワーの変化



目標とする速度に近い
200 ktで姿勢角0°、2°、3°
のロータ・パワーを調査

3°後傾することでおよそ1/3に
（有効迎角が大→発生揚力大）

誤差は機体姿勢角の違いによるもの

本計算の妥当性が確認できた

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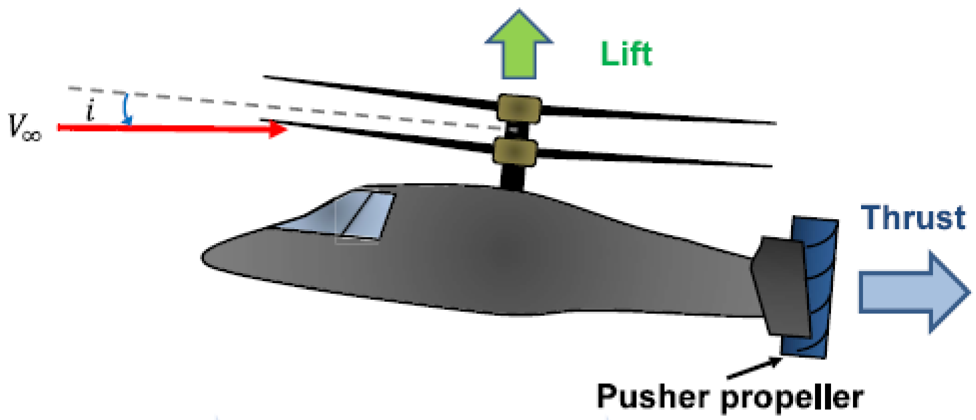
機体姿勢角とロータ・パワー



少し後傾 → ロータ面の下から
の相対風によって
有効迎角が増加 → **ロータパワー減少**

7/8

まとめ

Target

4枚ブレードでの計算妥当性検証

- 飛行試験結果、先行研究による解析結果と**概ね一致**

- 機体姿勢角によりロ—タ・パワ—は大きく変化
  →結果の差異は機体姿勢角の違いによるもの

本計算の妥当性が確認できた

2022年度将来回転翼機交流会／回転翼解析技術交流会
24 Mar. 2022, 東京

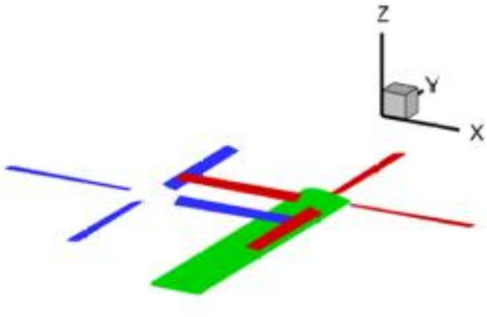
KIT 金沢工業大学

主翼を有するシングルロータ機の前進飛行時と タンデムロータ機のホバ時の空力特性

〇濵本佑典（金沢工業大学大学院）
齊藤寛泰（金沢工業大学大学院）
赤坂剛史（金沢工業大学）

発表内容（2つの機体形状）

翼付きコンパウンドヘリコプタ
の前進飛行時の空力特性



翼付きタンデムロータ型
コンパウンドヘリコプタ
のホバー時の空力特性

目次

- 背景
- 目的とアプローチ
- 解析手法と計算条件（計算格子，トリム条件，飛行条件）
- 代表的な計算結果
- まとめ

説明する機体形状

翼付きコンパウンドヘリコプタ
の前進飛行時の空力特性

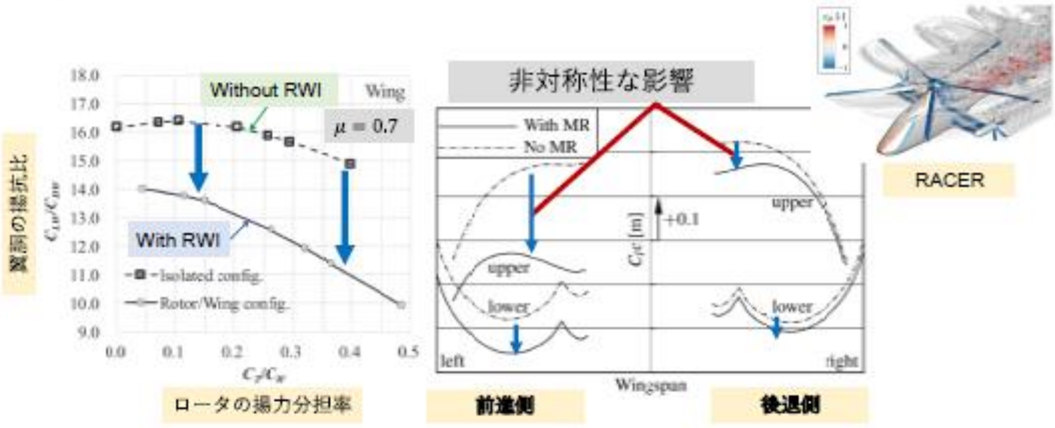
背景

JAXAのコンパウンドヘリコプタ概念図

Tanabe, Y., Sugiura, M., Kobiki, N., Sugawara, H., "A New Concept of Compound Helicopter and Flight Tests", the 2018 Asia-Pacific International Symposium on Aerospace Technology (APISAT2018), Lecture Notes in Electrical Engineering, Vol. 459, June 2019, pp. 1343–1352.

従来のヘリコプタの1.5～2倍の飛行速度に達する

背景



Sugawara, H., Tanabe, Y., Kameda, M., "Influence on Aerodynamic Performance of a Compound Helicopter by Wing Incidence Angle", Journal of the Japan Society for Aeronautical and Space Sciences, Vol. 67, No. 3, June 2019, pp. 93–101 (in Japanese).

Frey, F., Thiemeier, J., Öhrle, C., Keßler, M., and Kr'amer, E., "Aerodynamic Interactions on Airbus Helicopters' Compound Helicopter RACER in Cruise Flight", the VFS International 76th Annual Forum &Technology Display, Oct. 2020.

研究目的とアプローチ

目的

前進率の変化がロータ/翼胴間空力干渉時の翼胴の非対称な空力特性に与える影響を明らかにする

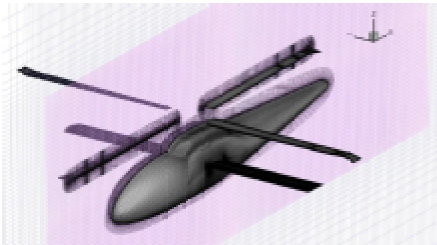
アプローチ

・CFDツールを使用
・機体重量はUH-60Aの最大離陸重量で一定
・前進率は0.1～0.7の8段階で計算
・ロータ/翼胴間空力干渉時の翼胴と空力干渉のない単体翼胴で空力特性を比較

CFDツールと解析手法

rFlow3D

- 回転翼機向けCFD解析ツール（JAXA開発）
- 移動重合格子
- トリム解析



計算格子

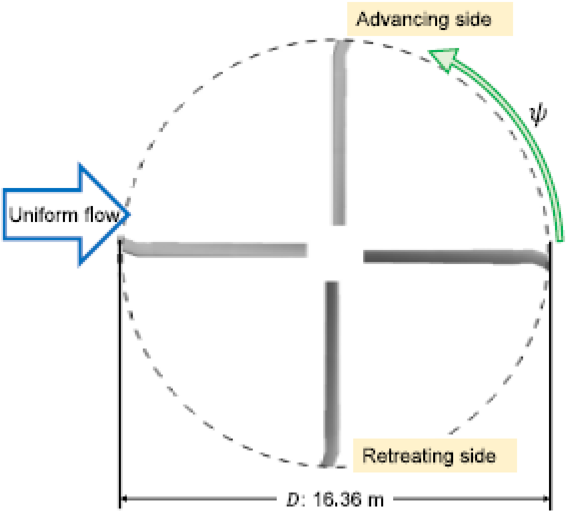
解析手法

	背景格子	ブレード / 翼胴 格子
支配方程式	3次元圧縮性N-S方程式	
空間離散化	セル節点有限体積法	セル中心有限体積法
時間積分法	4段階のRunge-Kutta法	Dual-time stepping / LU-SGS
数値流束関数	mSLAU (modified SLAU)	
再構築法	Fourth-order Compact MUSCL TVD	
粘性流束	2次精度の中心差分法	
乱流モデル	Menter k-ω SST 2003 model	

計算モデル（ロータ）

ロータ諸元

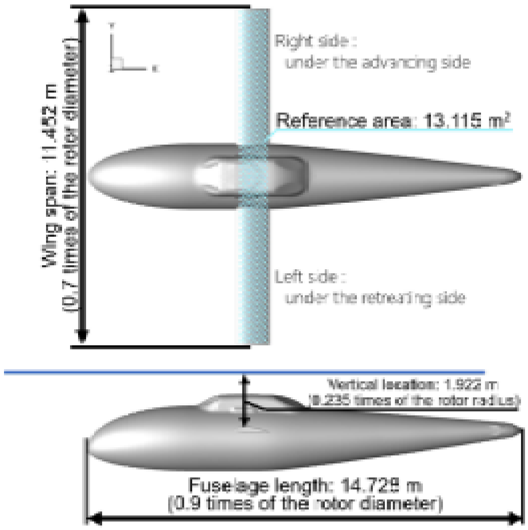
ブレード枚数	4
ロータ半径	8.18 m
ノミナルコード長	0.527 m
ソリディティ	0.082
等価ねじり下げ	-16 deg
翼型	SC1095/SC1094R8
ロータ回転方向	反時計回り



計算モデル（翼胴）

翼胴諸元

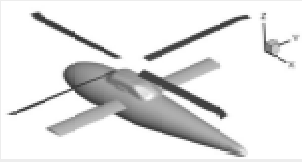
スパン長	11.452 m（b/D = 0.7）
翼面積	13.115 m^2
アスペクト比	10
平面形	矩形
翼配置	中翼（z/R = 0.235）
翼型	NACA4415
取り付け角	4.2 deg



形態とトリム条件

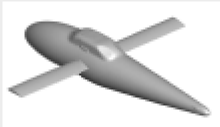
ロータ/翼胴形態

- **ロータと翼胴の合計揚力＝機体重量**
- **ロータ回転中心周りにロータの$M_X = M_Y = 0$**



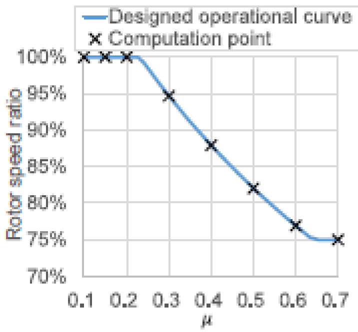
単体翼胴

- **トリム計算無し**

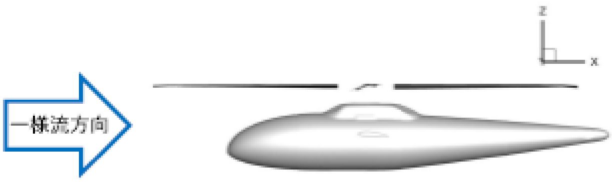


飛行条件

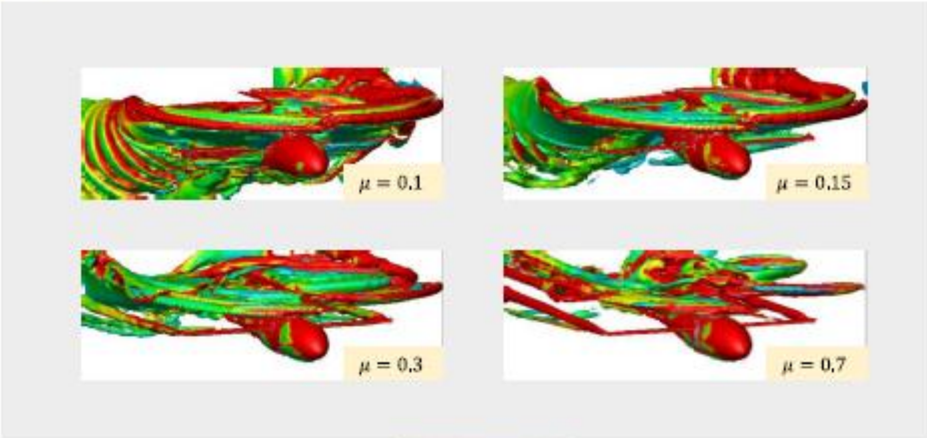
計算条件	
機体重量	97860.8 N (UH-60A 最大離陸重量)
前進率	0.1 – 0.7
ロータ回転速度	Scheduled from 75% to 100% 100% : 258 RPM
一様マッハ数	前進率とロータ回転数に従う (0.065 - 0.34)
ロータシャフト角	0 deg



ロータ回転数のスケジュール



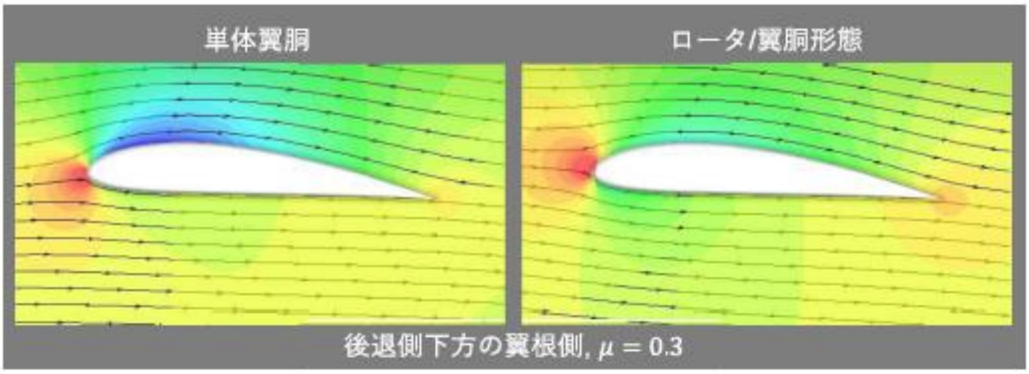
流れ場



$\mu = 0.1$
$\mu = 0.15$
$\mu = 0.3$
$\mu = 0.7$

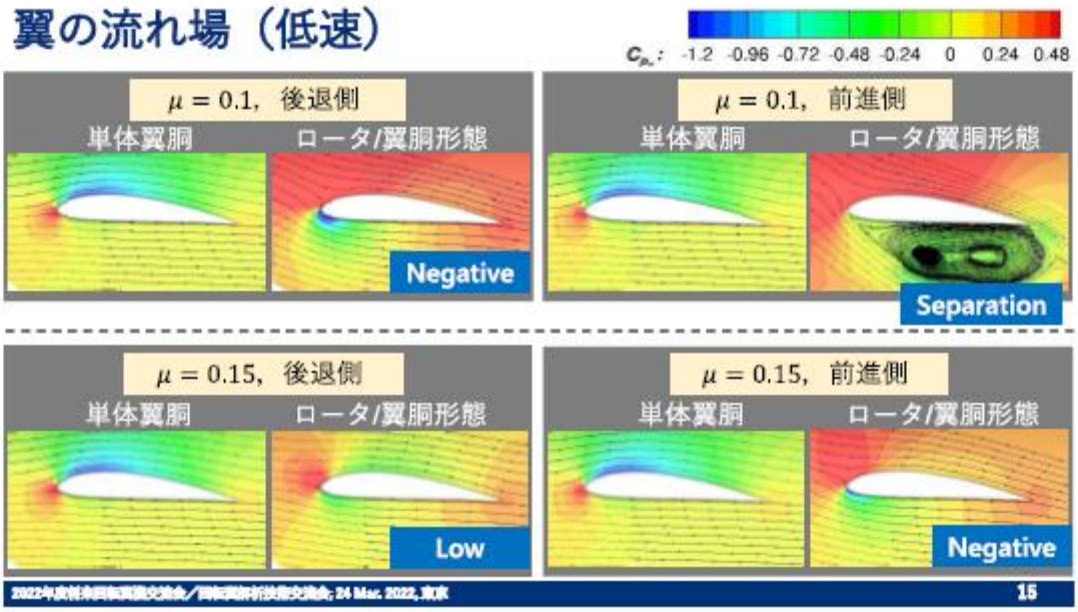
vorticity/a_∞ 0 0.02 0.04 0.06 0.08 0.1

翼の流れ場

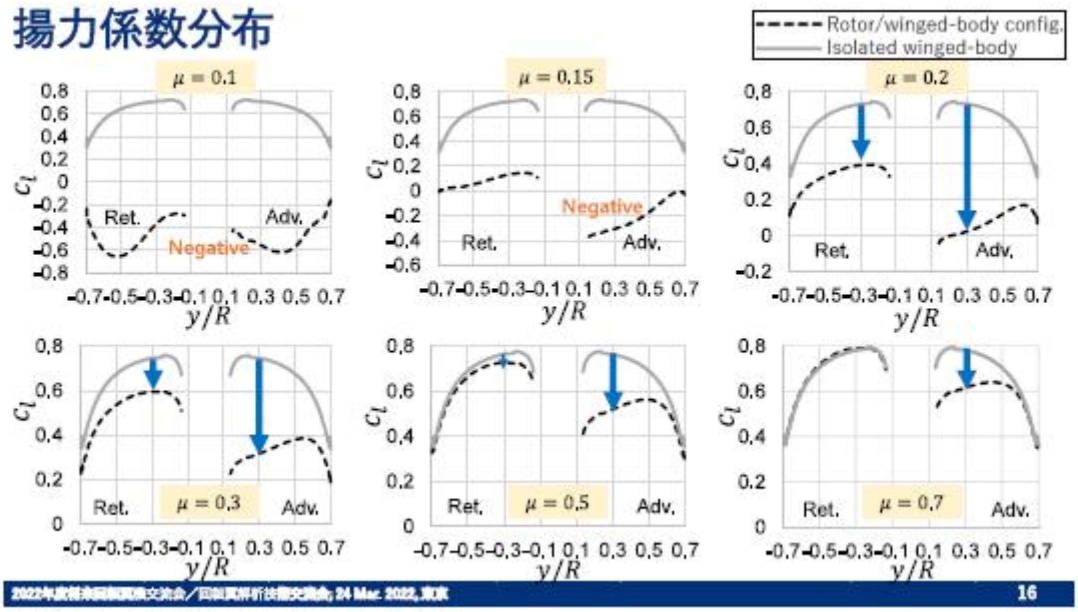


単体翼胴
ロータ/翼胴形態
後退側下方の翼根側, $\mu = 0.3$

C_{p_c}: -1.2 -0.96 -0.72 -0.48 -0.24 0 0.24 0.48

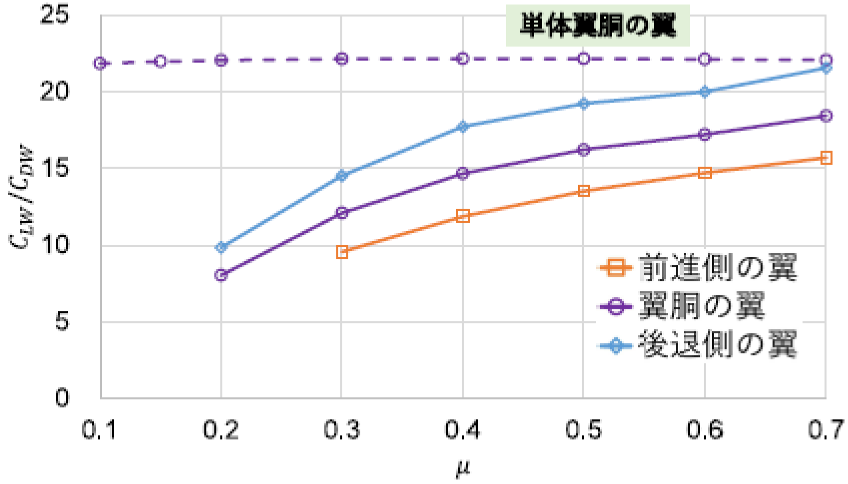


翼の流れ場（低速）
C_{p_∞}: -1.2 -0.96 -0.72 -0.48 -0.24 0 0.24 0.48
$\mu = 0.1$, 後退側
単体翼胴
ロータ/翼胴形態
Negative
$\mu = 0.1$, 前進側
単体翼胴
ロータ/翼胴形態
Separation
$\mu = 0.15$, 後退側
単体翼胴
ロータ/翼胴形態
Low
$\mu = 0.15$, 前進側
単体翼胴
ロータ/翼胴形態
Negative
15



揚力係数分布
Rotor/winged-body config.
Isolated winged-body
$\mu = 0.1$
$\mu = 0.15$
$\mu = 0.2$
$\mu = 0.3$
$\mu = 0.5$
$\mu = 0.7$
c_l
y/R
Ret.
Adv.
Negative
-0.7 -0.5 -0.3 -0.1 0.1 0.3 0.5 0.7
16

翼胴の揚抗比

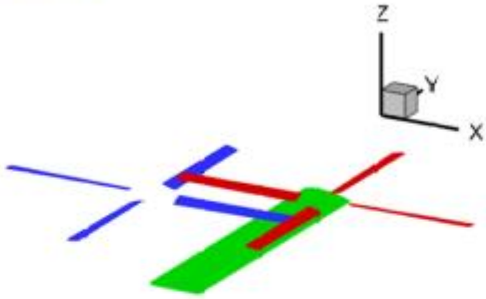


まとめ

この数値計算より次のことが明らかになった：

1. 空力干渉による翼の実効揚抗比の減少量は，前進率が増加すると小さくなる．
2. 前進側ブレード下方の翼の実効揚抗比は，前進率が増加しても減少したままである．
3. 翼の揚力係数は，後退側より前進側で，翼端より翼根で，高前進率より低前進率で，減少する．
4. 翼の揚力係数は，前進率0.1の両翼で，前進率0.15の前進側で負になる．

説明する機体形状



翼付きタンデムロータ型
コンパウンドヘリコプタ
のホバー時の空力特性

背景

NASA考案のタンデムロータ型
コンパウンドヘリコプタ

巡航速度：350 knot
乗客：120 人

Yeo, H., Johnson, W., "Aeromechanics Analysis of a Heavy Lift Slowed-Rotor Compound Helicopter", the American Helicopter Society International Vertical Lift Aircraft Design Conference, 2006.

ボーイングバートル
モデル347技術実証機

https://www.chinook-helicopter.com/history/aircraft/A_Models/65-07992/65-07992.html

研究目的とアプローチ

目的

主翼フラップによるタンデムロータ/主翼間空力干渉時のダウンロード低下効果を明らかにする

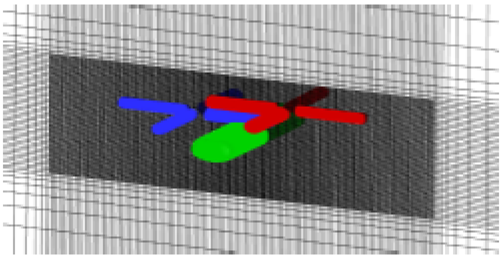
アプローチ

・CFDツールを使用
・機体重量はCH-47Bの最大離陸重量で一定
・ロータ間距離／ロータ直径は0.6
・フラップ角を0，45，60，75，90 degに変化

CFDツールと解析手法

rFlow3D

- 回転翼機向けCFD解析ツール（JAXA開発）
- 移動重合格子
- トリム解析

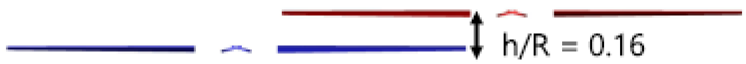


計算格子

解析手法

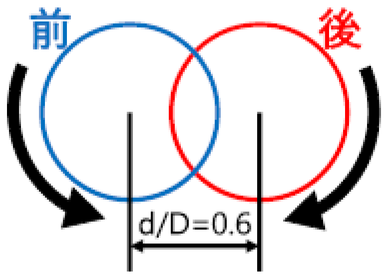
	背景格子	ブレード / 翼胴 格子
支配方程式	3次元圧縮性N-S方程式	
空間離散化	セル節点有限体積法	セル中心有限体積法
時間積分法	4段階のRunge-Kutta法	Dual-time stepping / LU-SGS
数値流束関数	mSLAU (modified SLAU)	
再構築法	Fourth-order Compact MUSCL TVD	
粘性流束	2次精度の中心差分法	
乱流モデル	Menter k-ω SST 2003 model	

計算モデル（ロータ）

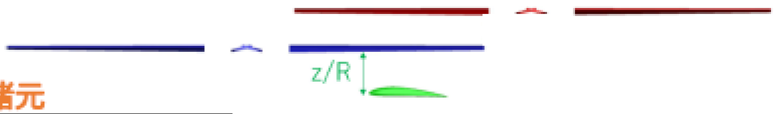


ロータ諸元

ブレード枚数	4
ロータ半径	9.145 m
ブレードコード長	0.81 m
ソリディティ	0.114
ねじり下げ	-10 deg
翼型	NACA0012
ロータ回転数	225 RPM

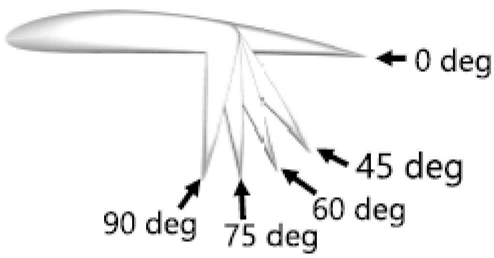


計算モデル（翼胴）



翼胴諸元

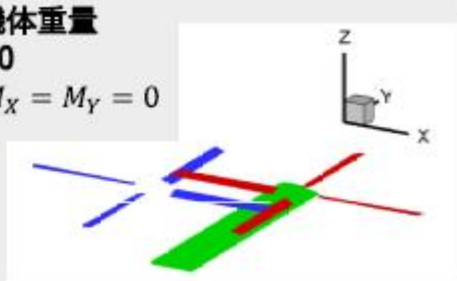
スパン長	18.29 m（$b/D = 1.0$）
翼面積	55.75 m^2
アスペクト比	6
平面形	矩形
翼配置	$z/R = 0.2$ （前方ロータ基準）
翼型	NACA4412
取り付け角	2.75 deg
フラップ翼弦長	40 %



形態とトリム条件

タンデムロータ/主翼形態

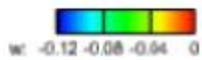
・ロータ推力 + 翼胴ダウンロード = 機体重量
・前ロータトルク + 後ロータトルク = 0
・各ロータ回転中心周りで各ロータの$M_X = M_Y = 0$

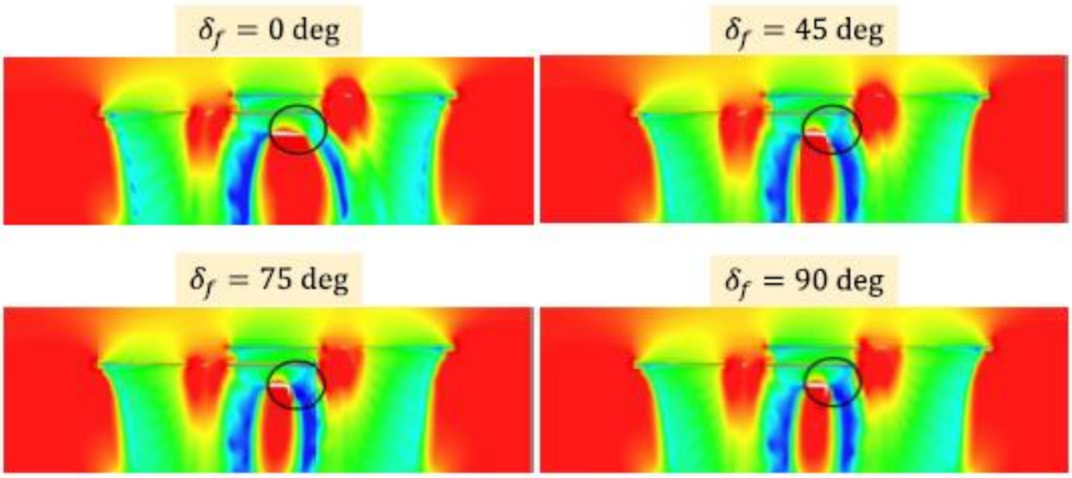


トリム計算のテクニック

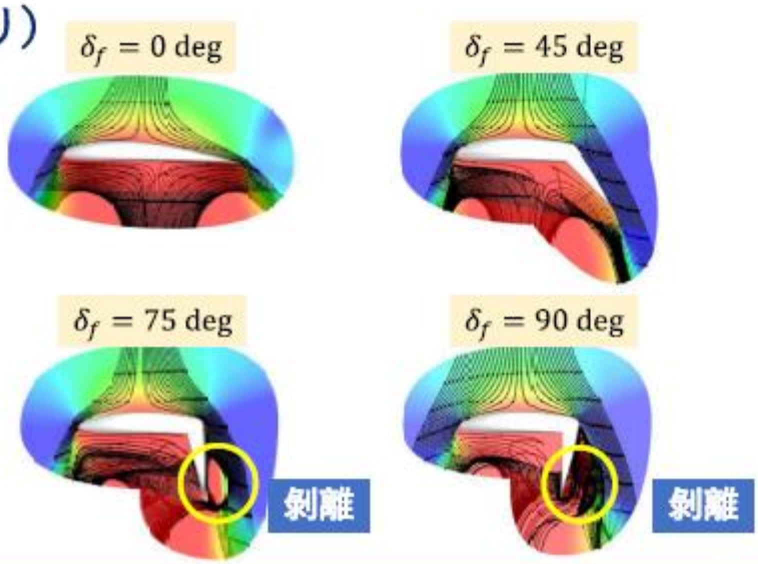
1. rFlow3Dのトリム機能
   ・ロータ推力 = 目標推力
   ・前ロータトルク + 後ロータトルク = 0
   ・各ロータ回転中心周りで各ロータの$M_X = M_Y = 0$
2. CFD結果より主翼ダウンロードを取得
3. 機体重量 - 主翼ダウンロード = 目標推力

流れ場（下向きの流速分布，y/R = 0）

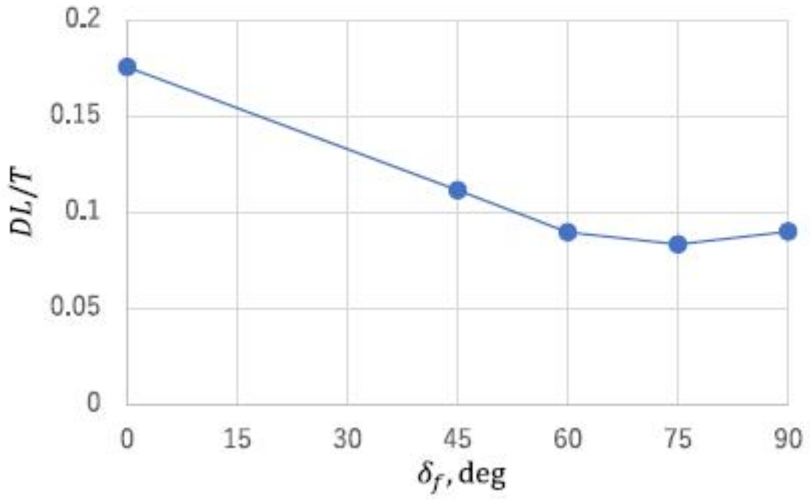




流れ場（翼周り）



ダウンロード-推力比



まとめ

この数値計算より次のことが明らかになった：

1. ダウンロードは，フラップ角が0～75 degでは，フラップ角の増加と共に減少する．
2. ダウンロードは，フラップ角が75 degの時に最小になる．
3. フラップ角75，90 degではフラップ後縁で剥離が生じている．

発表資料の元になった文献

この発表資料は次の文献を元に作成した

Hamamoto, Y., Akasaka, T., Tanabe, Y. and Sugawara, H., “The Influence of Rotor/Wing Aerodynamic Interaction of Compound Helicopter in Forward Flights on Wing-body”, 48th European Rotorcraft Forum, Sept. 2022.

齊藤寛泰, “タンデムロータ型コンパウンドヘリコプタのホバリング時におけるロータと主翼の空力干渉”, 金沢工業大学大学院修士学位論文, 金沢工業大学, 2023.

将来回転翼機研究会/回転翼解析技術交流会　2023/3/24

低レイノルズ数領域における平板翼ロータのホバリング解析

横浜国立大学　坂爪竣哉、鈴木恵太、古澤善克、北村圭一

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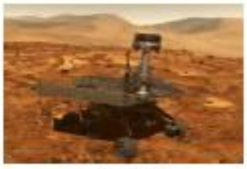
目次

- 研究事例①（低レイノルズ数領域における平板翼ロータのホバリング解析）
  - 背景・目的
  - 研究手法
  - 結果・考察
- 研究事例②
  （風洞スケール・実機スケールでのプロペラ翼端付近の圧縮性の影響）
- 研究事例③
  （プロペラ・固定翼統合モデルにおける空力干渉の数値解析）

2

計算事例①-背景・目的

・火星探査機の多様化
→用途に応じて使用される



ローバ [1]

オービタ[2]

・火星ヘリコプタの使用
→垂直離着陸が可能
　竪穴探査への利用が期待

ヘリコプタ [3]

[1]https://www.space.com/42288-nasa-keeps-hailing-mars-rover-opportunity.html
[2]https://mars.nasa.gov/mars-exploration/missions/maven/
[3]https://slashgear.jp/science/9399/

3

計算事例①-背景・目的

火星ヘリコプタ使用の条件・課題

・大気密度が地球の約1/100
→低レイノルズ数領域での飛行

・二重反転ローターの使用
→上面ロータの後流が下面ロータに干渉するなど流れ場が複雑になる

目的

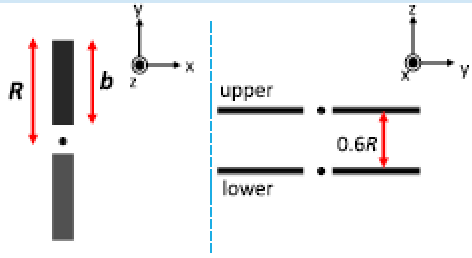
低レイノルズ数領域における二重反転ロータの空力解析
・シングルロータとの比較
・二重反転ロータの非定常性に関する調査

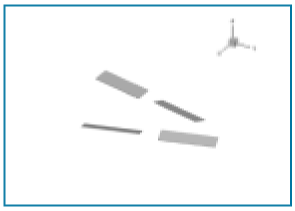
4

計算事例①-研究手法

・計算条件[4]

翼型	平板翼
アスペクト比	4
コード長c [m]	0.0295
スパン長b [m]	0.117
ロータ半径R [m]	0.137
ロータ間距離 [m]	0.0822(0.6R)
回転速度 [rpm]	500
レイノルズ数	1.1×10^4
ピッチ角[deg.]	15
翼端マッハ数	0.02108





[4]西村綾、大川真生、伊神翼、藤田昂志、永井大樹、"低レイノルズ数条件下における同軸反転ロータの アスペクト比の違いによる性能調査"、第54回流体力学講演会、2022.

計算事例①-研究手法

・計算手法

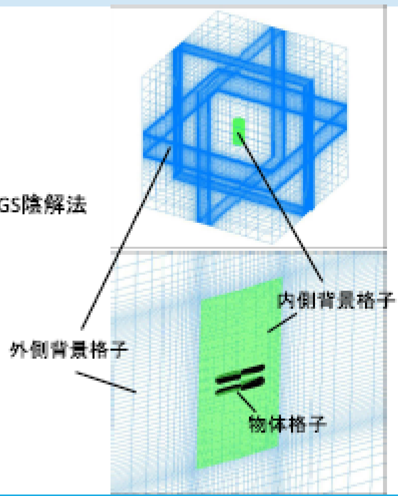
ソルバ　　　：rFlow3D
支配方程式 ：圧縮性NS方程式
乱流モデル ：なし
時間積分　 ：（外側背景格子）4段階ルンゲクッタ陽解法
　　　　　　（内側背景格子・物体格子）Dual-time stepping/LU-SGS陰解法
空間精度　 ：FCMT(Fourth Order Compact MUSCL TVD)

・計算格子

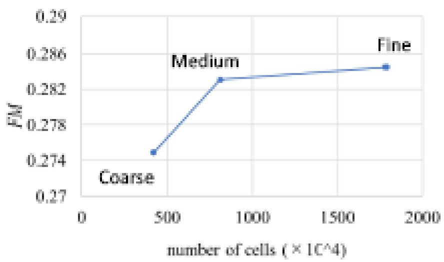
・3種類の格子を重合（物体格子、外側・内側背景格子）

・異なる格子密度について検証→密度に対する解の収束を検証

Coarse　：4,192,928 cell
Medium　：8,115,537 cell
Fine　　：17,794,159 cell



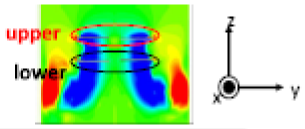
計算事例①-結果・考察

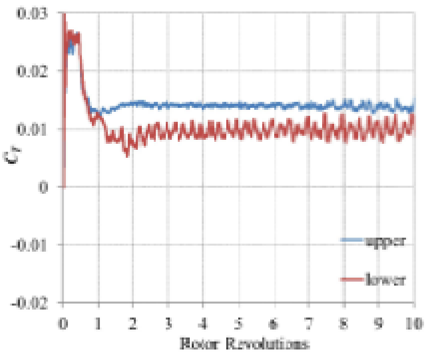


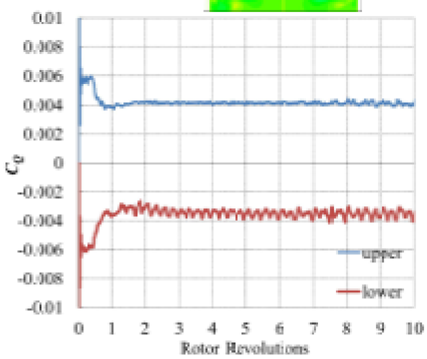
・3パターンを検証し、格子収束を確認

計算事例①-結果・考察

・二重反転ロータの結果
→upperに比べ、lowerでは大きな振動が見られる



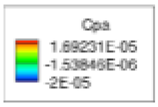


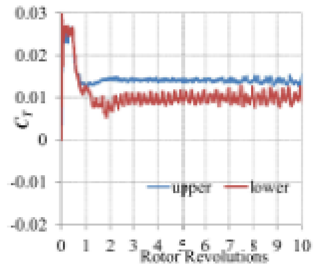


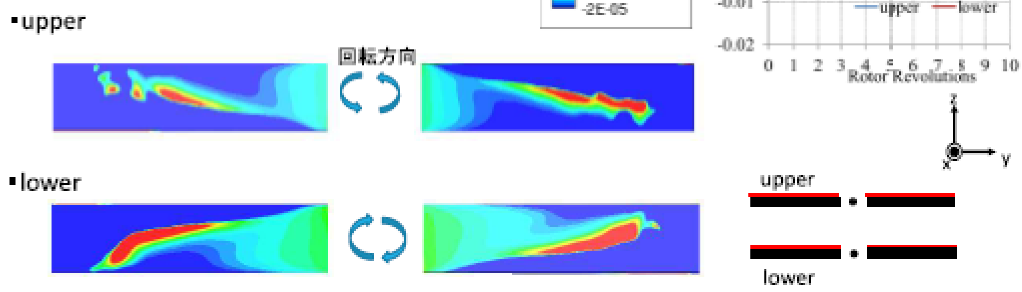
計算事例①-結果・考察

・1周分の表面圧力の変化（上面）

- ・表面圧力の時間変動：upper＜lower
- ・翼根側にも変化が見られる







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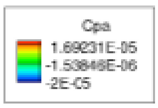
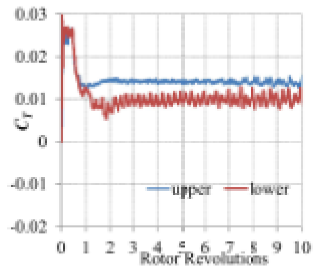
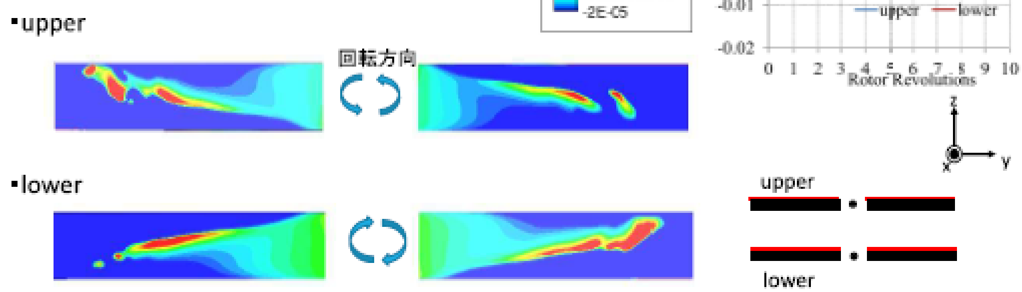
計算事例①-結果・考察

・1周分の表面圧力の変化（上面）

- ・表面圧力の時間変動：upper＜lower
- ・翼根側にも変化が見られる







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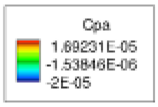
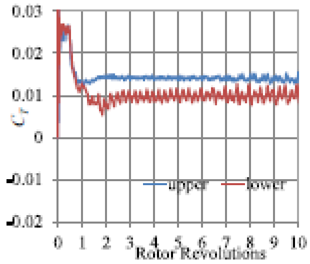
計算事例①-結果・考察

・1周分の表面圧力の変化（下面）

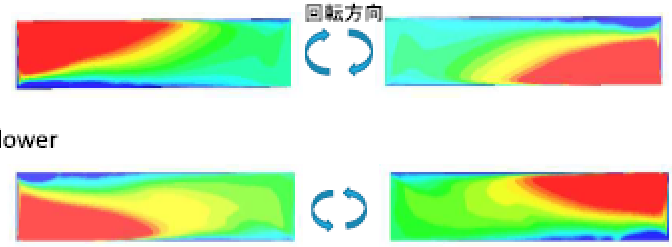
・表面圧力の時間変動：upper＜lower
・高圧領域の変化が顕著

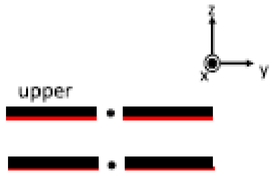




・upper

・lower





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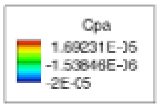
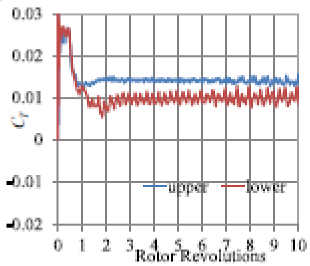
計算事例①-結果・考察

・1周分の表面圧力の変化（下面）

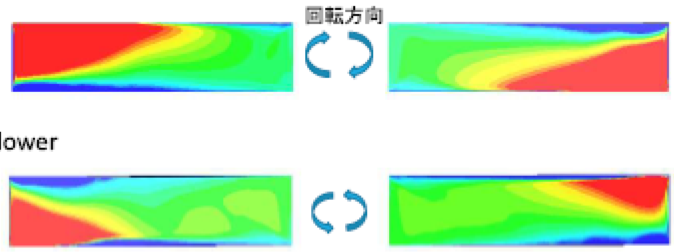
・表面圧力の時間変動：upper＜lower
・高圧領域の変化が顕著

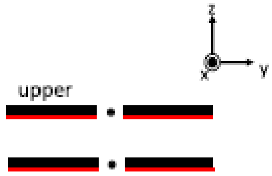




・upper

・lower





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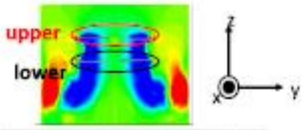
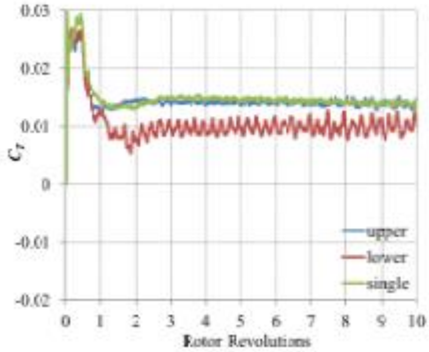
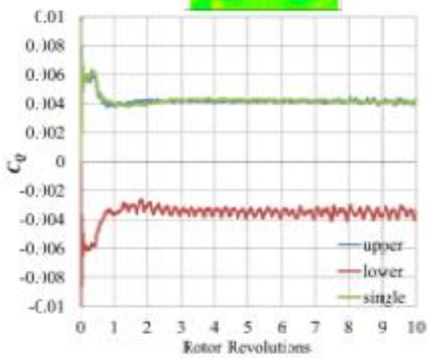
計算事例①-結果・考察

・シングルロータとの比較
→upperがおおよそ一致
→推力の上昇(lowerの影響)はほぼ見られない





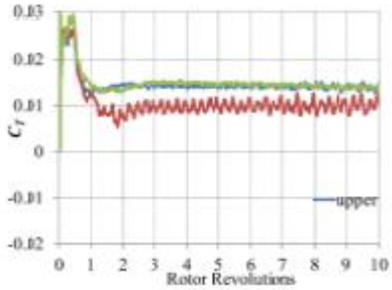


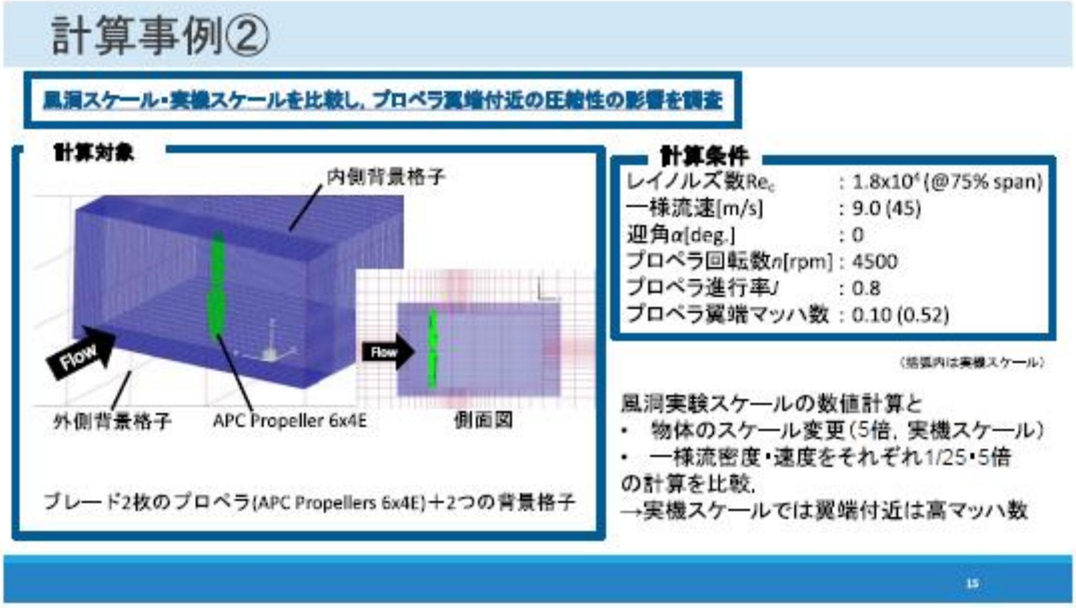
計算事例①-結果・考察

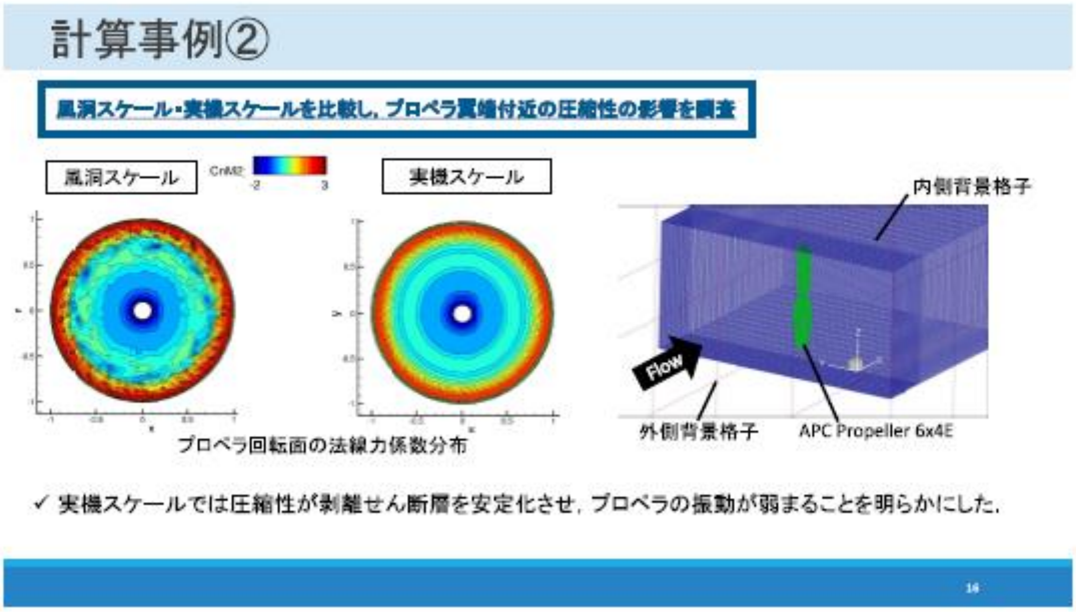
結論

・upperに比べ、lowerでは大きな振動が見られる
→・表面圧力の時間変動：upper＜lower
・特に下面側において高圧領域の変化が顕著

・推力係数はシングルロータとupperがおおよそ一致
→推力の上昇(lowerの影響)はほぼ見られない




計算事例②
風洞スケール・実機スケールを比較し，プロペラ翼端付近の圧縮性の影響を調査
計算対象
内側背景格子
Flow
Flow
外側背景格子
APC Propeller 6x4E
側面図
ブレード2枚のプロペラ(APC Propellers 6x4E)＋2つの背景格子
計算条件
レイノルズ数Re_c : 1.8x10^4 (@75% span)
一様流速[m/s] : 9.0 (45)
迎角α[deg.] : 0
プロペラ回転数n[rpm] : 4500
プロペラ進行率J : 0.8
プロペラ翼端マッハ数 : 0.10 (0.52)
（括弧内は実機スケール）
風洞実験スケールの数値計算と
• 物体のスケール変更（5倍，実機スケール）
• 一様流密度・速度をそれぞれ1/25・5倍
の計算を比較．
→実機スケールでは翼端付近は高マッハ数
15


計算事例②
風洞スケール・実機スケールを比較し，プロペラ翼端付近の圧縮性の影響を調査
風洞スケール
CnM2
-2
3
実機スケール
内側背景格子
Flow
外側背景格子
APC Propeller 6x4E
プロペラ回転面の法線力係数分布
✓ 実機スケールでは圧縮性が剥離せん断層を安定化させ，プロペラの振動が弱まることを明らかにした．
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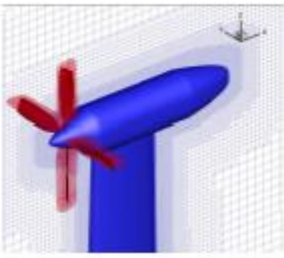
計算事例③

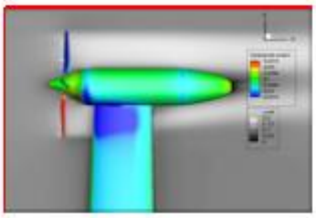
・プロペラ・固定翼統合モデルにおける空力干渉の数値解析

ソルバ:Fastar-Move

AIAA workshopで取り上げられた、プロペラ・固定翼における空力干渉を計算

(Hooker, J et al.: Overview of Low Speed Wind Tunnel Testing Conducted on a Wingtip Mounted Propeller for the Workshop for Integrated Propeller Prediction, AIAA Paper 2020-2673, 2020.)



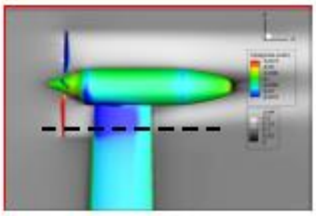


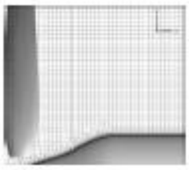
計算事例③

・プロペラ・固定翼統合モデルにおける空力干渉の数値解析

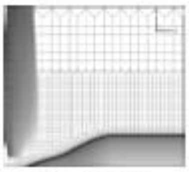
プロペラ近傍は一様な格子によって解像するべき
しかし、一様な細かい格子は<u>格子点数</u>増 <u>計算コスト</u>増

→格子点数の節約を目的とし、非一様な計算格子において同様の計算
その結果…
・プロペラ後流中の固定翼表面圧力
→どちらの格子でも良好に再現

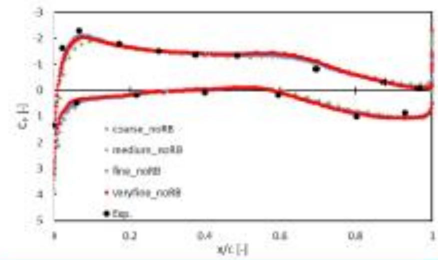




一様な格子
(Refinement Box)



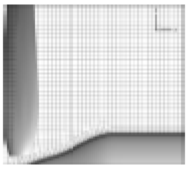
非一様な格子



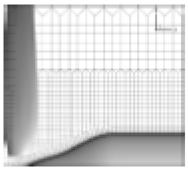
計算事例③

▪プロペラ▪固定翼統合モデルにおける空力干渉の数値解析

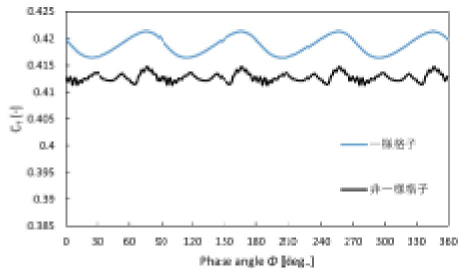
▪格子のレベルが切り替わる領域で非物理的な圧力勾配
→回転翼の空力解に振動が発生



一様な格子
(Refinement Box)



非一様な格子



火星ヘリコプタ「HAMILTON」に関する数値解析および計測実験

吉川 昂汰*, 佐藤 允*, 大山 聖†

*工学院大学, †ISAS/JAXA

2022年度将来回転翼機研究会/回転翼解析技術交流会
2023.03.24

火星縦孔・地下空洞探査

Cushing *et al*., (2015)

- 放射線が届きにくい
- 気候が比較的安定
- 液体存在の可能性

- 生命発見や痕跡の可能性
- 断層から火山活動の調査
- 有人火星探査の拠点

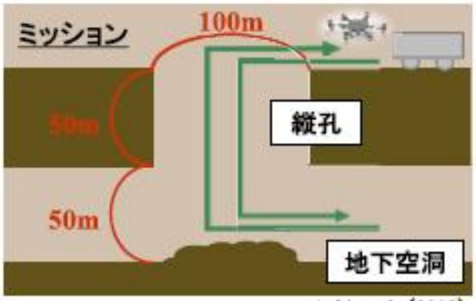
<u>ヘリコプタ型探査機を用いた探査が有望</u>

一方で，火星は地球に比較して，大気密度は約1/100，
音速は約3/4となり飛行に制約
⇒ 空力性能に関する知見の獲得が必要

火星ヘリコプタ「HAMILTON」 3

HexAcopter for Martian pIt crater expLoraTiON

Sugiura *et al.*, (2022)



Aoki *et al.*, (2018)

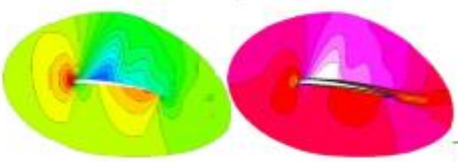
- 可変ピッチ機構
- マルチコプタ型（ヘキサロータ）
- 最適化に基づくブレード平面・断面形状

火星大気環境（低レイノルズ数・高マッハ数）における
ロータの空力特性の検証が進行

「HAMILTON」に関する既往研究 4

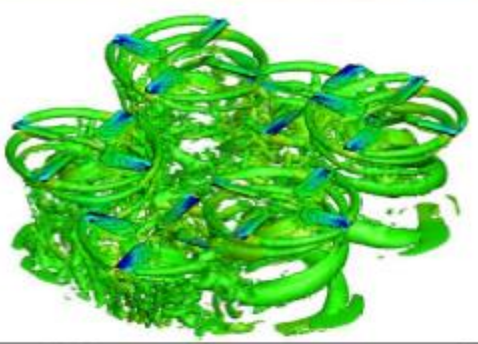
翼平面形状の最適化

Sugiura *et al.*, (2022)



空力特性に対する
翼端マッハ数効果

佐藤ら, (2021)



空力特性に対するロータ配置の影響

Kishi *et al.*, (2022)

数値解析による形状最適化および空力特性評価は進行
低*Re*数かつ高*Ma*数環境下での実験は少ない

5

研究目的・本日の内容

火星ヘリコプタの開発に向けた
低レイノルズ数かつ高マッハ数環境における
回転翼の空力特性を調べること

本日の内容

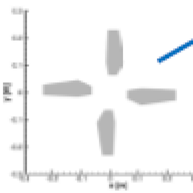
1. 数値解析と計測実験の比較
2. 圧縮性の効果が空力特性に及ぼす影響を検証

6

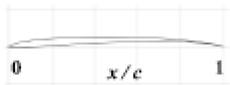
解析対象のロータ, 解析条件

解析対象のロータ

- ブレード枚数 ：4（シングルロータ）
- 半径 ：0.23 [m]
- ソリディティ ：0.2436
- 翼断面形状 ：CLF5605



Sugiura *et al.*, (2022)



Koning *et al.*, (2019)

解析条件 Koning *et al.*, (2019)

	計算条件	実験条件
温度 [K]	223.2	293.15
気体定数 [J/(kg・K)]	188.9	287
比熱比	1.289	1.403
粘性係数 [Pa・s]	1.13×10^{-5}	1.81×10^{-5}
回転数 [rpm]	7452	11000
翼端マッハ数	0.77	
レイノルズ数（翼端 0.038m）	10260	

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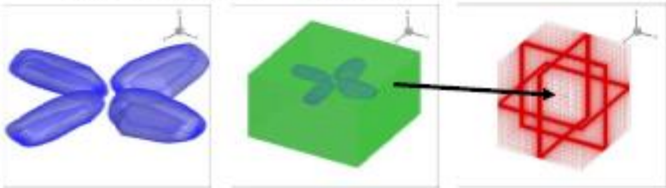
計算手法

- ソルバー　　　　：rFlow3D
- 支配方程式　　　：3次元圧縮性Navier-Stokes方程式
- 数値流束関数　　：mSLAU(Modified SLAU)
- 空間高次精度化：FCMT(Fourth order Compact MUSCL TVD)
- 乱流モデル　　　：なし
- 計算機　　　　　：JSS3(Node:1 / Core:48)
- 所要時間　　　　：約120時間(1ケースあたり)
- 計算格子：



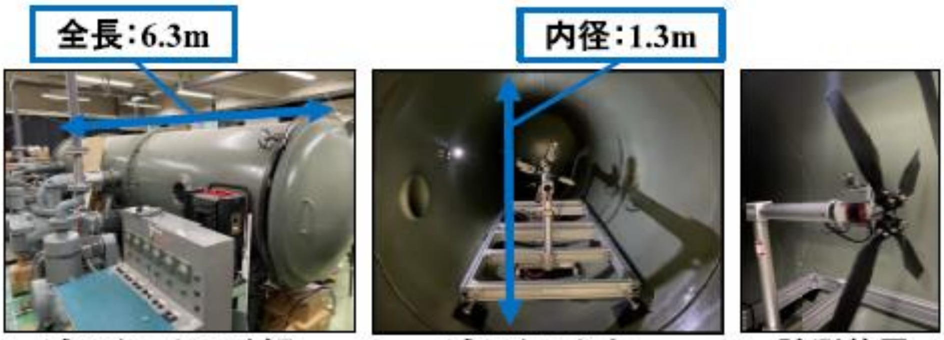
ブレード格子　　内側背景格子　　外側背景格子

ブレード	内側背景	外側背景	全格子
90万点×4	100万点	235万点	約700万点

8

実験手法

- 減圧タンク(JAXA宇宙科学研究所)
- ロータ空力性能計測装置



減圧タンクの外観　　減圧タンク内　　計測装置

<u>レイノルズ数の設定</u>

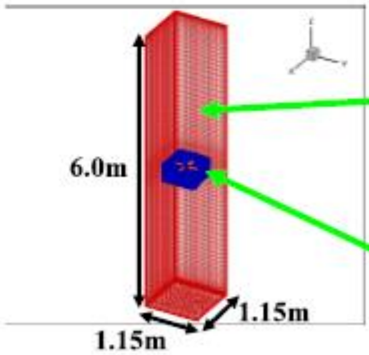
タンク内の気圧を減圧して大気密度を変化させる

9

実験とCFDの比較（閉空間について）

比較するにあたり減圧タンク内を模擬した数値解析を進行

（計算格子）



減圧タンク

ロータ

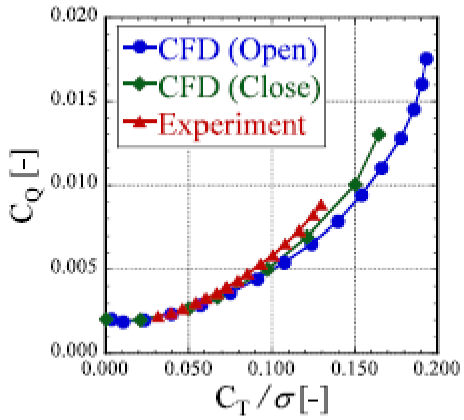
- 解析ソルバー： rFlow3D
- 計算機：JSS3（Node:1 / Core:48）
- 計算時間：約1920時間（1ケース）

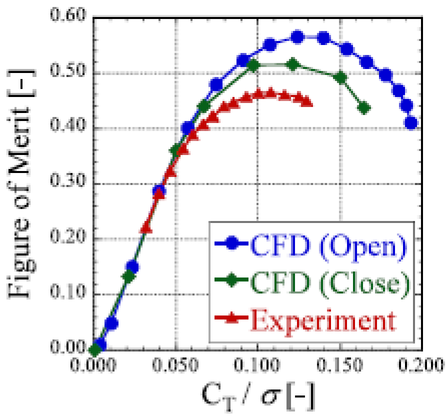
10

数値解析と計測実験の比較

11

CFDと計測実験の比較

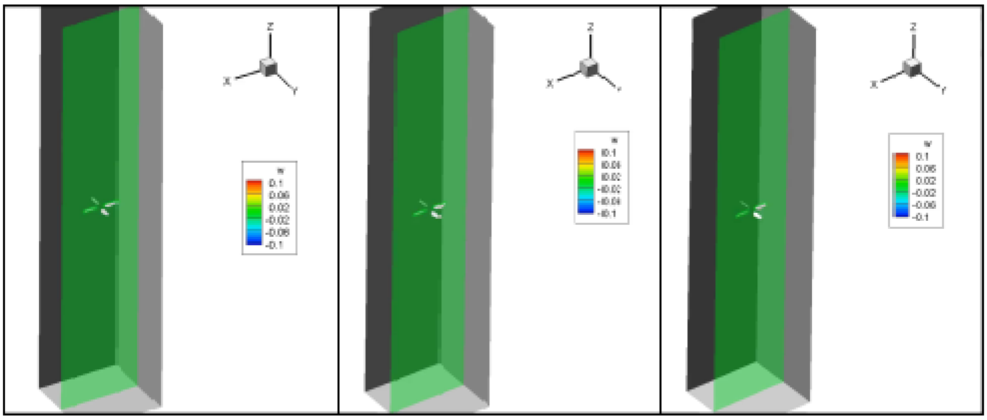




実験結果と数値解析結果のトレンドは一致
⇒ 低推力領域および高推力領域で差異

12

流れ場および速度分布のムービー



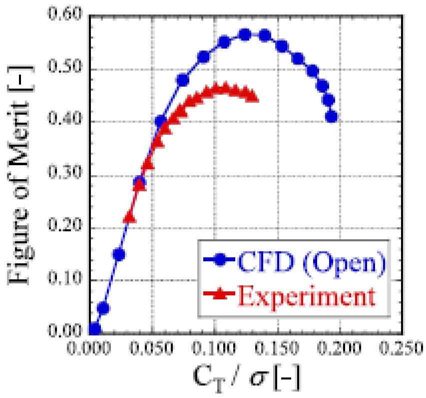
Pitch Angle = 10°　Pitch Angle = 18°　Pitch Angle = 26°

ピッチ角が大きくなるにつれて，サイドの壁面に +z 方向の流れが顕著に確認できる

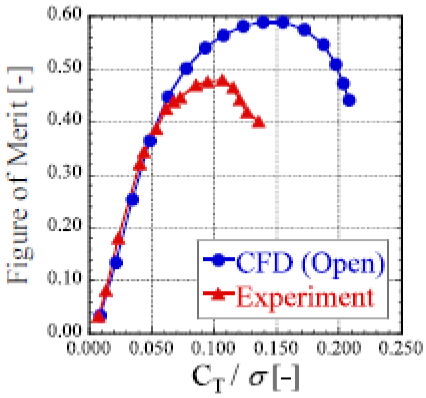
13

計測実験とCFD(閉空間)の差異

M_{tip} =0.77 (11000rpm)



M_{tip} = 0.21 (3000rpm)



M_{tip}= 0.21の条件では，低推力領域で一致
⇒ 高回転によるブレード変形の可能性

14

圧縮性の効果が空力特性に及ぼす影響を検証

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条件設定

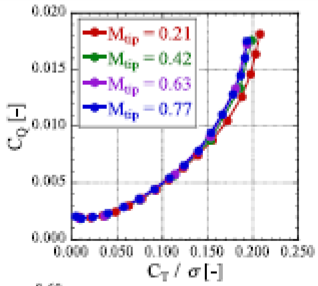
条件	
回転数 [rpm]	3000, 6000, 9000, 11000
翼端マッハ数	0.21, 0.42, 0.63, 0.77
レイノルズ数（翼端 0.038m）	10260

レイノルズ数を固定し，翼端マッハ数のみを変化させた

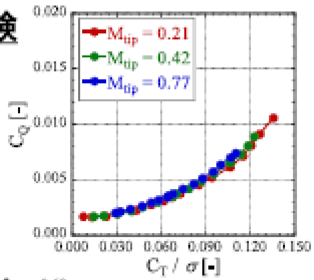
16

翼端マッハ数の変化による空力特性

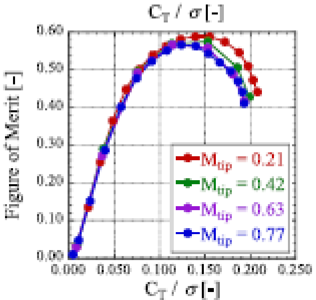
CFD（Open）



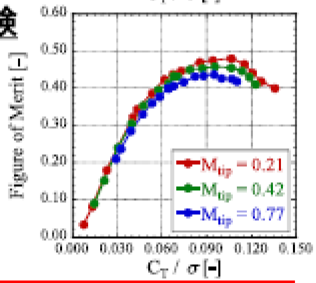
実験



CFD（Open）



実験

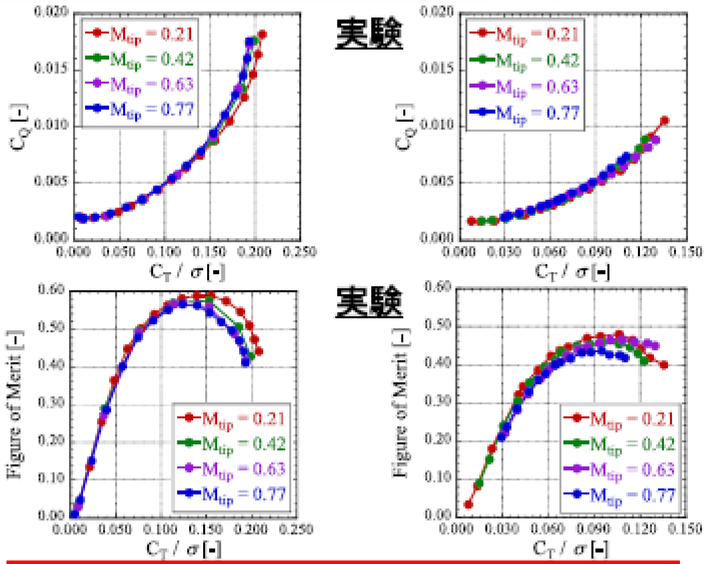


C_T/σ の増加に伴い差異が生じる

翼端マッハ数の変化による空力特性

CFD
(Open)

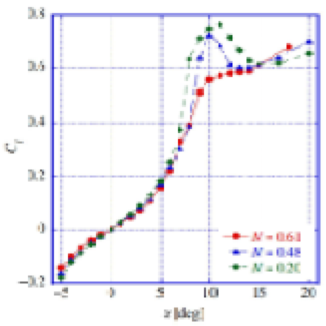
実験

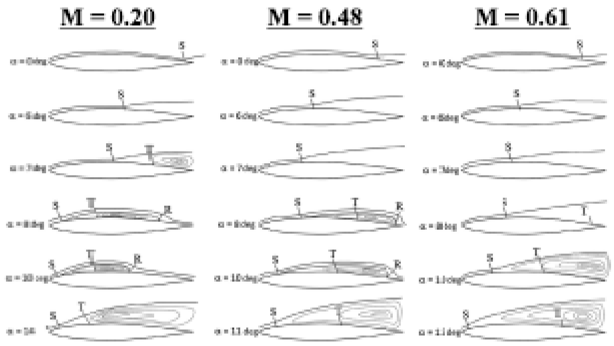


C_T/σ の増加に伴い差異が生じる

固定翼における圧縮性の効果

レイノルズ数 = 11000
(翼型:NACA 0012-34)

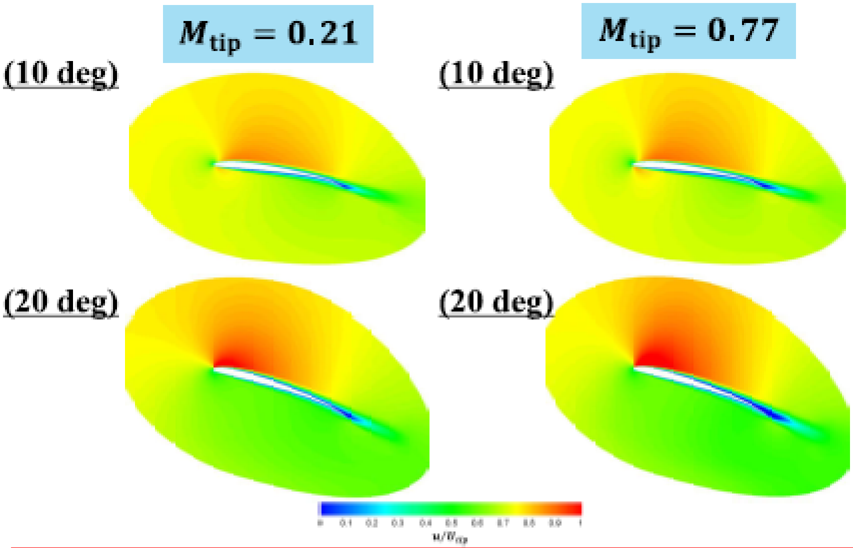




Anyoji *et al.*, (2015)

低迎角で圧縮性の効果は小さい.
8[deg.]以降剥離の再付着に起因して特性が異なる.

断面速度分布($r/R=0.75$)



8[deg.]以降剥離の再付着に起因して特性が異なる.

まとめ

<u>低レイノルズ数かつ高マッハ数環境における回転翼の空力特性を数値解析および計測実験により調べた.</u>

- 数値解析と計測実験の比較について，低C_T領域および高C_T領域おいて差異が生じた.
  - 低C_T領域は，M_{tip}増加に伴うブレードの変形が要因の1つとして考えられる.
  - 高C_T領域では，ピッチ角の増加に伴い閉空間の影響が顕著になるためである.
- 圧縮性の効果が空力特性に及ぼす影響について，C_Tの増加に伴い圧縮性の効果が大きくなる.
  - 既往研究(固定翼)と同じ傾向を示しており，今後さらなる考察が必要.

今後の展望

数値解析と計測実験の比較に関して,
- $M_{\mathrm{tip}} = 0.21$で閉空間の数値解析を行い，計測機由来の問題との切り分けを進める.

圧縮性の効果に関して,
- 数値解析の結果を用いて，流れの遷移および圧力分布を中心に考察を進める.

新たなテーマとして,
- ロータを2つを対象にロータ間干渉に関する研究を行う.

PIV Measurements and Computational Study of Aeroacoustics of a Drone Propeller

Jianwei Sun[1], Ryo Aoki[1], Koichi Yonezawa[2, 3], and Hao Liu[1, 3(*)]

1 Graduate School of Engineering, Chiba University, Japan
2 Central Research Institute of Electrical Power Industry, Japan
3 Center for Aerial Intelligent Vehicles, Chiba University, Japan

CHIBA UNIVERSITY CAIV CRIEPI Central Research Institute of Electric Power Industry JAXA

Outline

- Background and Motivation
- Objective and Methodology
- Comparison
    - Flow field
    - Acoustic performance
    - Aerodynamic performance
- Conclusion

2

Background and Motivation

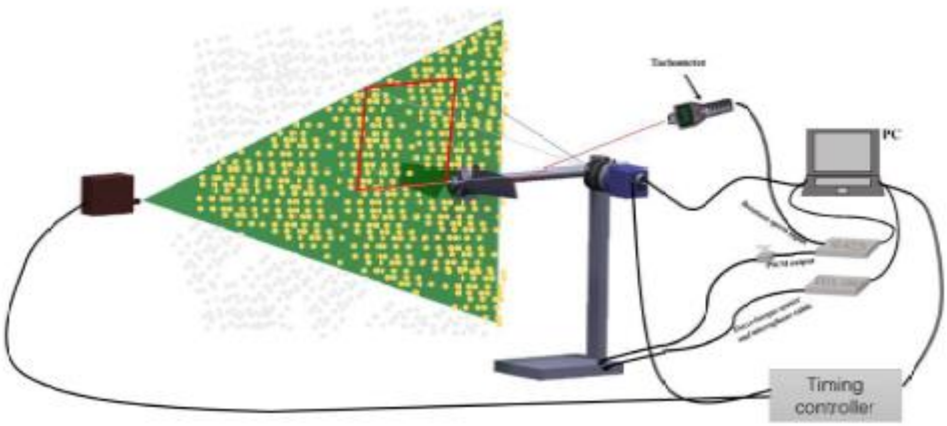
- Drone propellers rely on aerodynamic and aeroacoustic performance for optimal flight.
- Predicting these performance characteristics accurately is a significant challenge.
- Improving our ability to predict their performance will allow us to design more efficient and effective drone propellers.

Background and Motivation

Experiment	CFD simulation
Quantitative description of flow phenomena using measurement	Quantitative prediction of flow phenomena using CFD software
For a quantity at a time	For all desired quantities
High frequency resolution	High time resolution
For a limited range of problems and operating conditions	Virtual problems
uncertainty	Not 100 % reliable
Expensive and slow	Cheap(er) and fast(er)

Objective and Methodology

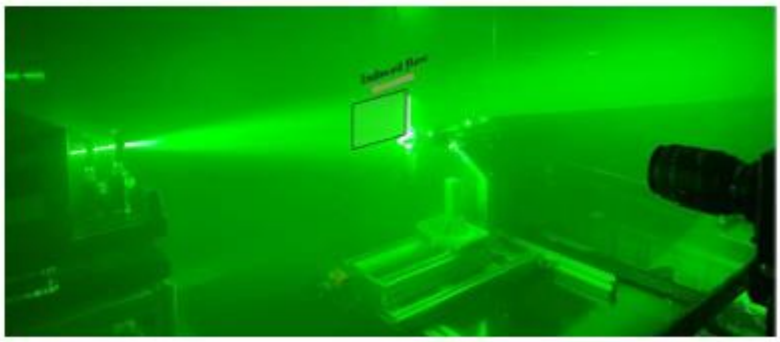
Free-run and phase-locked PIV:



5

Objective and Methodology

Free-run and phase-locked PIV:

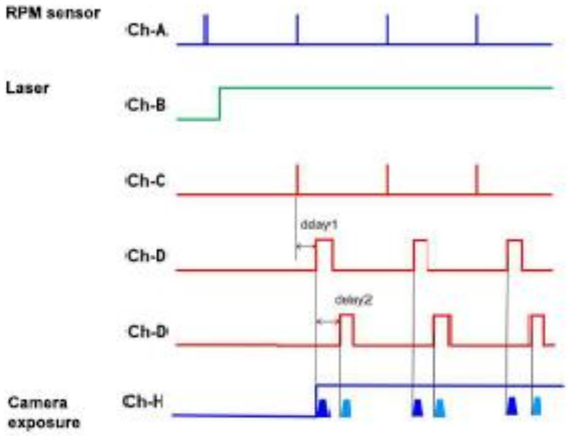


Particles on Smoke → Illuminate of laser → High-speed camera photography → Images processing

6

Objective and Methodology

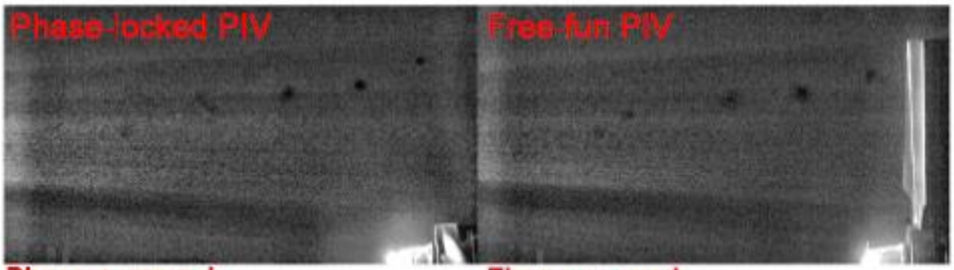
Free-run and phase-locked PIV:



7

Objective and Methodology

Free-run and phase-locked PIV :



Phase-averaged

$$\bar{v} = \frac{1}{N}\sum_{i=1}^{N} v(t_0 + i\,T)$$

Time-averaged

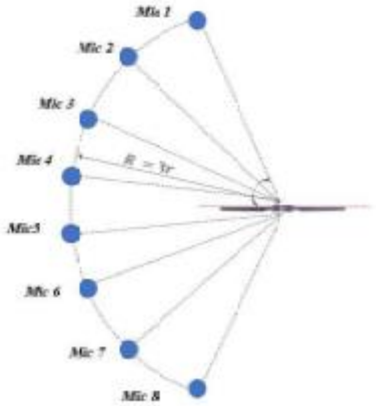
$$\hat{v} = \frac{1}{N}\sum_{i=1}^{N} v(t_0 + i\,\Delta t)$$

- Phase-averaged algorithm: Enhances the periodic component of the signal with a known period in RPS, and filters out the random component.
- Time-averaged algorithm: Filters both the periodic and random components of the signal, but retains the trend component.

8

Objective and Methodology

Hover-stand experiment in anechoic chamber:

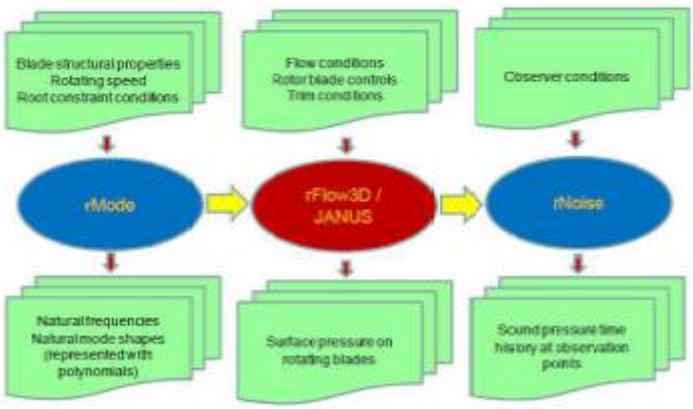


Key parameters:

Rotational speed	5400rpm
Diameter	200mm
Pitch angel	14deg
Fs(Hz) Sampling rate	50,000Hz/20,000Hz
Distance	800mm
Polar angle	75deg (mic1) & 50deg (mic2) & 25deg(mic3) & 5deg (mic4) & -5deg (mic5) & -25deg (mic 6) & -50deg (mic7) & -75deg (mic8)

Objective and Methodology

rFlow3D & rNoise:



Tanabe, et. al.(2012)

Objective and Methodology

rFlow3D & rNoise:

$$4\pi p'(\boldsymbol{x},t) = 4\pi (p'_T(\boldsymbol{x},t) + p'_L(\boldsymbol{x},t)) = \frac{\partial}{\partial t}\int_{f=0}\left[\frac{\rho_0 v_n}{r(1-M_r)} + \frac{p\cos\theta}{c\, r(1-M_r)}\right]_{ret} dS + \int_{f=0}\left[\frac{p\cos\theta}{r^2(1-M_r)}\right]_{ret} dS$$

$$4\pi p_{\mathrm{TF}}(\boldsymbol{r}_{\mathrm{ob}},t) = \frac{\partial}{\partial t}\int_{f=0}\left[\frac{\rho_0 \boldsymbol{v}_n}{r(1-M_r)}\right]_{\tau} \mathrm{d}S(\boldsymbol{r}_{\mathrm{b}})$$

Thickness noise

$$4\pi p_{\mathrm{LF}}(\boldsymbol{r}_{\mathrm{ob}},t) = \frac{1}{c_s}\frac{\partial}{\partial t}\int_{f=0}\left[\frac{p_{\mathrm{b}}\cos\theta}{r(1-M_r)}\right]_{\tau} \mathrm{d}S(\boldsymbol{r}_{\mathrm{b}})$$

Far field loading noise

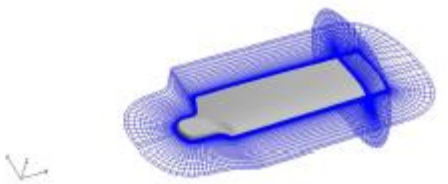
$$4\pi p_{\mathrm{LN}}(\boldsymbol{r}_{\mathrm{ob}},t) = \int_{f=0}\left[\frac{p_{\mathrm{b}}\cos\theta}{r^2(1-M_r)}\right]_{\tau} \mathrm{d}S(\boldsymbol{r}_{\mathrm{b}})$$

Near field loading noise

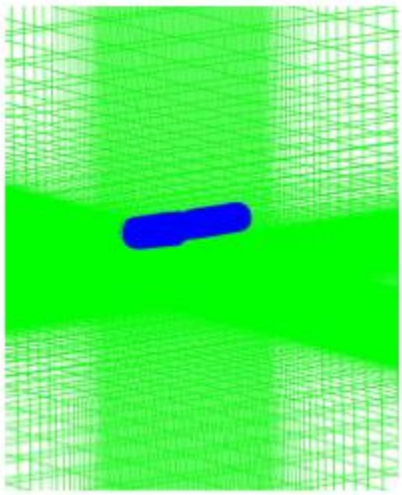
Farassat, et. al.(2007)

11

Objective and Methodology



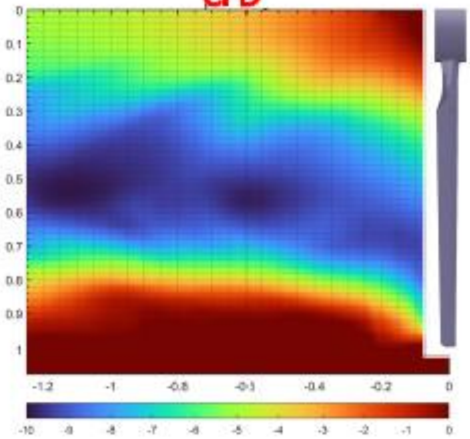
Rotational speed	5400rpm
Diameter	200mm
Pitch angel	14deg
background	195*195*147(X*Y*Z)
Blade grid(each)	121*143*61
M_TURB_IG	0
Output number(Msd)	1024
Fs(Hz)	92,160



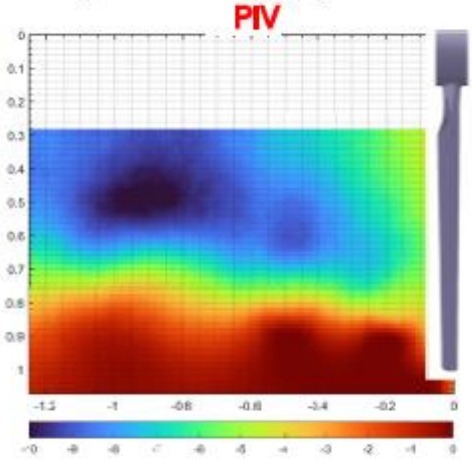
12

Comparison – FLOW field (phase-average)

CFD



PIV

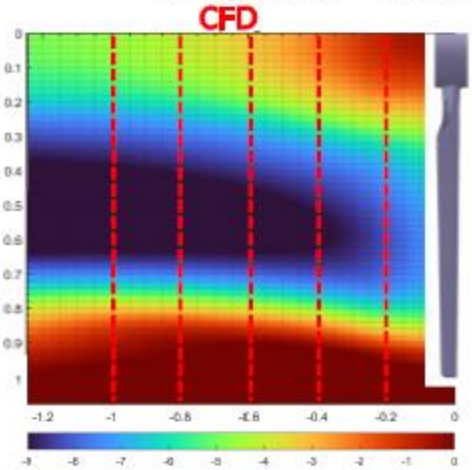


- Our phase-averaged results present the velocity fluctuation in the slipstream of the drone propeller, which can inform future design improvements.

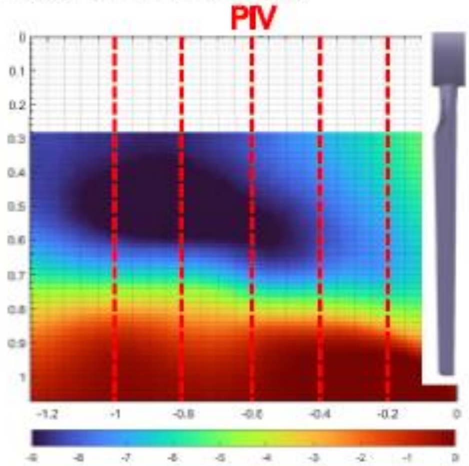
13

Comparison – FLOW field (time-average)

CFD



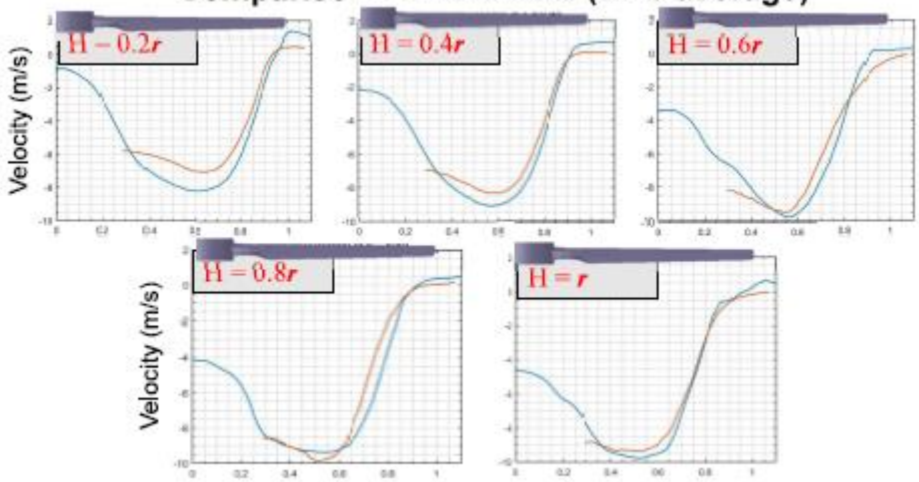
PIV



- Time-averaged result shows reasonable agreement in the slipstream between PIV and CFD methods, providing confidence in the accuracy of our methods and results.

14

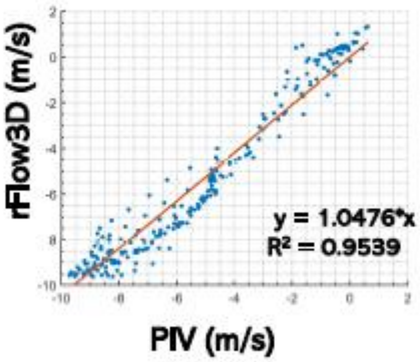
Comparison – FLOW field (time-average)

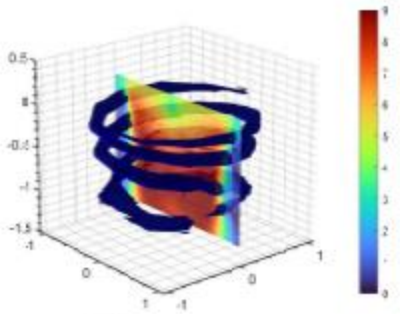


- Comparison of velocity distribution at different planes parallel to the rotational plane between CFD and PIV shows good agreement, with slight discrepancies at H = 0.2r and 0.4r.

15

Comparison – FLOW field (time-average)





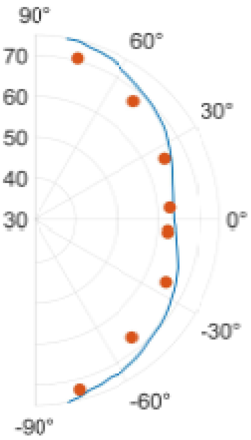
PIV measurement

- The high R-squared value obtained between the time-averaged results of PIV and CFD methods indicates a good agreement between the two methods in terms of the velocity values.

16

Comparison – acoustic

Overall SPL SIM. vs. EXP.



simulation   experiment

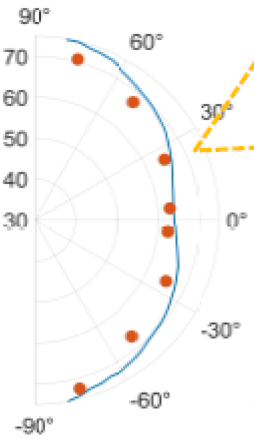
< 3.2dB

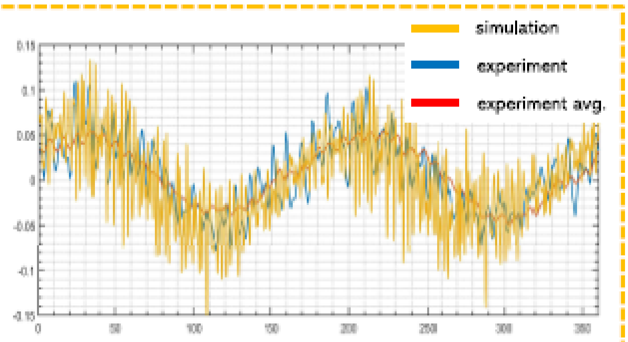
- Our comparison of predicted and experimental OASPL results shows good agreement, with a difference of less than 3.2 dB

17

Comparison – acoustic

Overall SPL SIM. vs. EXP.





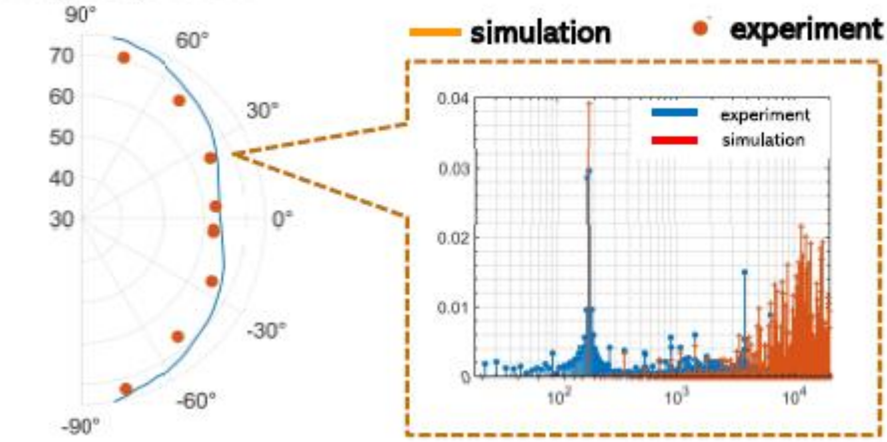
64.8dB (exp.) vs 66.2 dB (sim.)

- A similar trend between the predicted and experimental results in the time domain, especially at blade passing frequency (BPF), although the simulation result has more high-frequency noise.

18

Comparison – acoustic

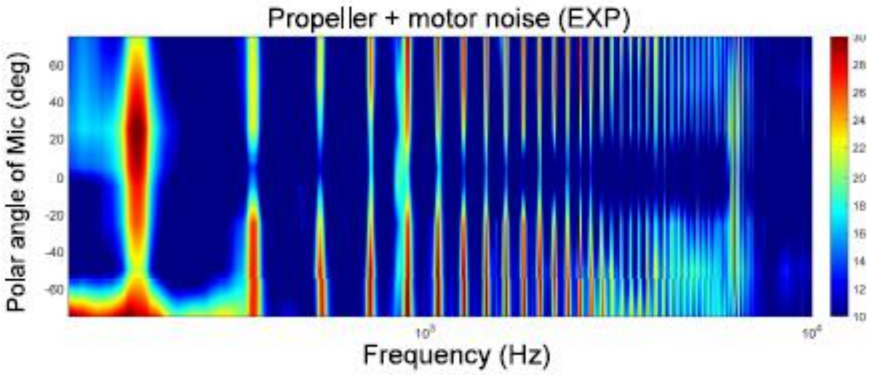
Overall SPL SIM. vs. EXP.



- Our frequency analysis confirms that the CFD model predicts more high-frequency noise than the experimental result.

19

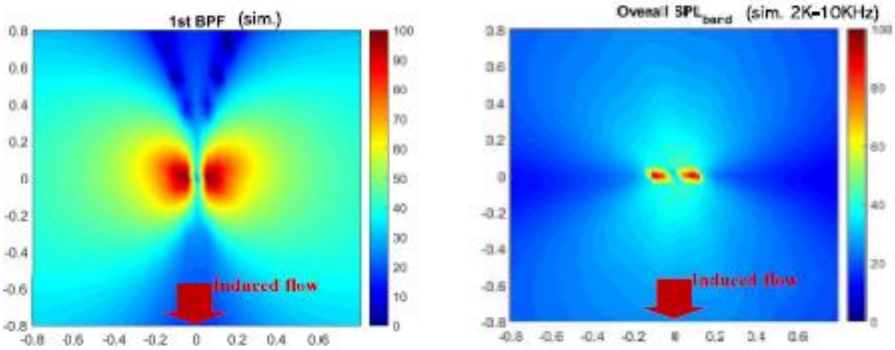
Comparison – acoustic



- The noise SPL at the BPF of the propeller reveals that the noise level is higher at lower polar angles, while the high-frequency noise is higher at higher polar angles.

20

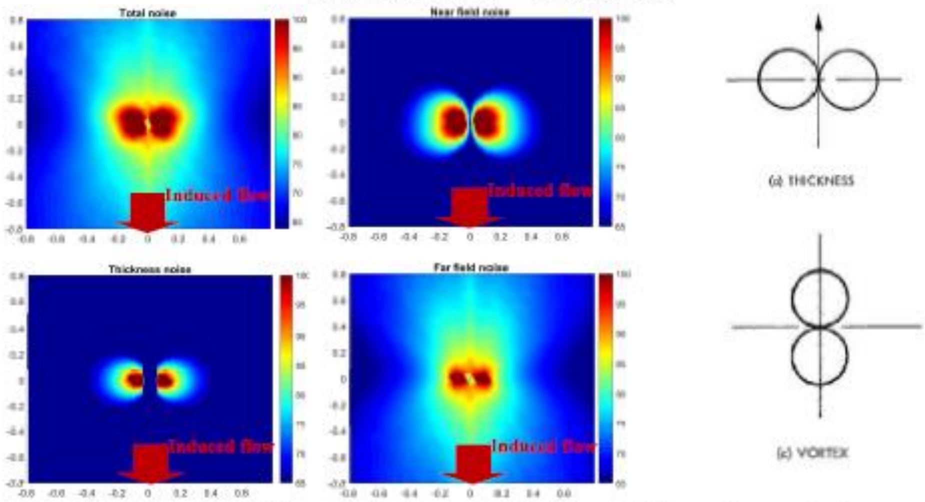
Comparison – acoustic



- The CFD simulations predict the similar noise emission pattern with the experimental result.

21

Comparison – acoustic

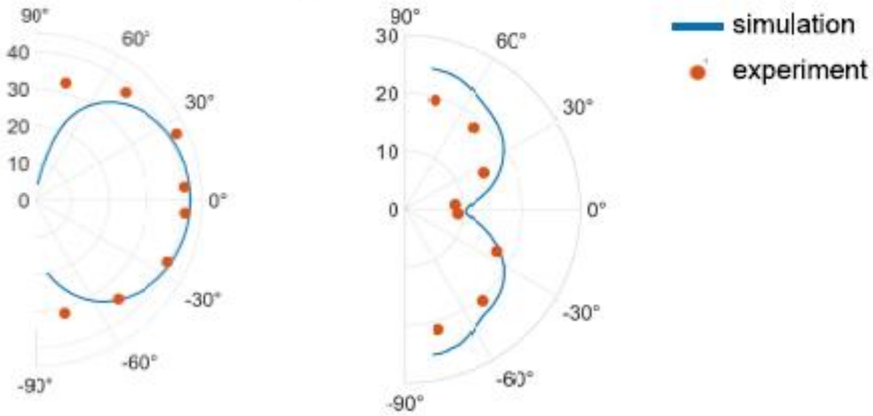


- The rFlow3D/rNoise simulations predict the similar noise emission pattern with the theoretical result.

Made, et. al.(1970)

22

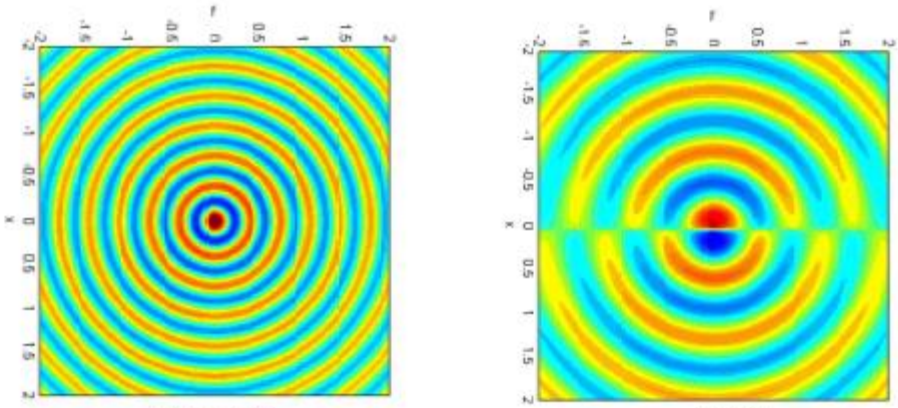
Comparison – acoustic



1st BPF SPL

$OASPL_{band}$ (2K-10K)

Comparison – acoustic

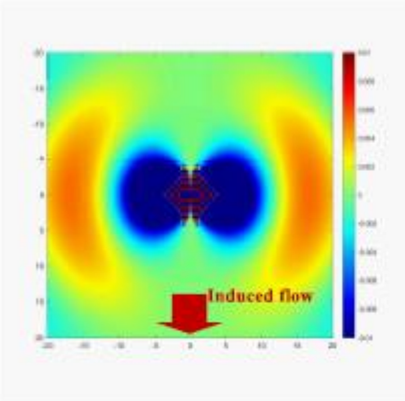


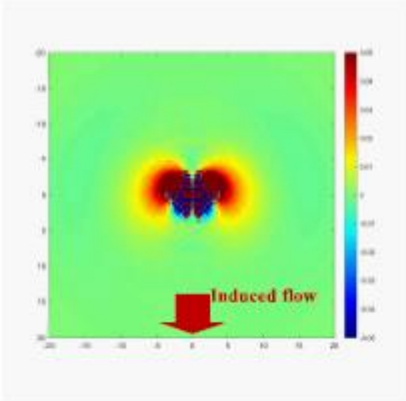
Monopole Dipole

- Acoustic Radiator Models: Monopole model and Dipole model.

https://en.wikibooks.org/wiki/Aeroacoustics/Acoustic_Sources

Comparison – acoustic



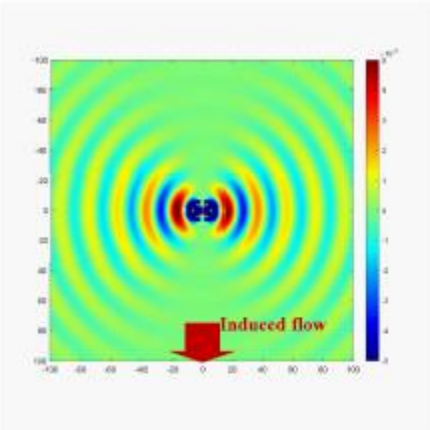


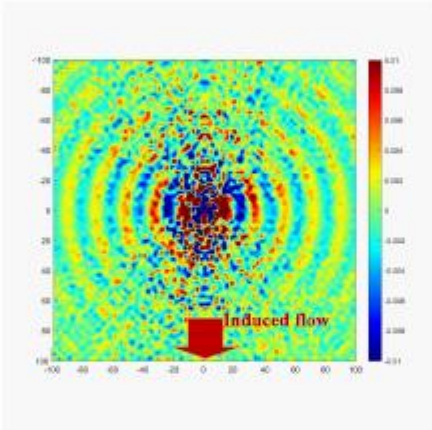
Thickness noise-Monopole Loading noise (near)-Dipole

- The rFlow3D/rNoise simulations predict the sound source emission pattern in time scale.

25

Comparison – acoustic





Thickness noise-Monopole Total noise (PTF + PNL+PFL)

- The rFlow3D/rNoise simulations result explain that the tonal noise is enhanced at lower polar angle, broadband noise is enhanced at higher polar angle.

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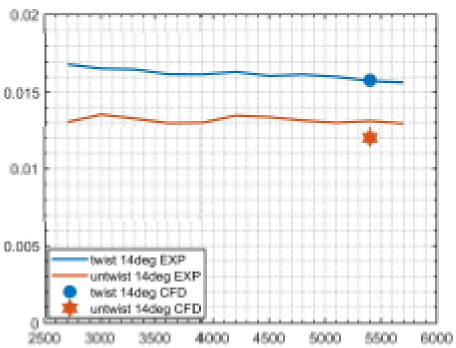
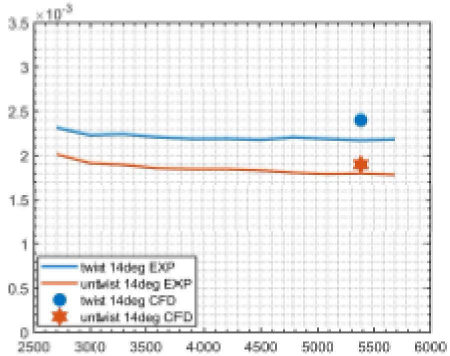
Comparison – Aerodynamic performance





< 6.5% **< 8.0%**

- The evaluation of aerodynamic forces using rFlow3D shows an error rate of less than 8%

Conclusion

- The results indicate that rFlow3D produces flow field velocity data that is consistent with PIV measurement, as verified by goodness-of-fit analysis.
- However, it should be noted that *rFlow3D/rNoise* may introduce an overestimation of noise levels in positions where the polar angle is greater than 60 degrees due to the influence of higher frequency components. Nonetheless, the patterns of noise emission observed align with theoretical predictions and experimental evidence.
- Furthermore, the evaluation of aerodynamic forces using rFlow3D shows an error rate of less than 8%, which is acceptable. These findings suggest that rFlow3D is a reliable tool for analyzing aerodynamic performance.

ロータの影響を受けるプロペラの振動計測

防衛大学校
有田俊作，糸賀紀晶

研究背景

ロータ下にプロペラを有する形態が提案されている

https://www.aero.jaxa.jp/spsite/helicopter/002.html

K-RACERの図

https://www.khi.co.jp/pressrelease/detail/20201006_1.html

RACERの図

https://www.airbus.com/en/innovation/disruptive-concepts/disruptive-design/racer

Conceptual model by Jaunt air mobility

https://evtol.news/jaunt-air-mobility/

研究背景

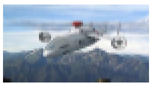
特に**ホバリング時**，ロータ，主翼，プロペラが干渉し，性能が変化する

・プロペラ性能への影響
・主翼ダウンロードへの影響
引き続き研究中

・プロペラ振動への影響
今回発表

研究背景

・プロペラ振動への影響
今回発表



https://www.airbus.com/en/innovation/disruptive-concepts/disruptive-design/racer

JAXAコンセプトモデル，RACERについて，ロータ下のプロペラ性能をCFD解析により調べ，振動に言及している研究例がある（木村2020, Frey2022, Ohrle2019, Stokkermans2018 等）

・プロペラBPF（Blade Passing Frequency）の振動が励起される

・ロータBPFの振動は励起される場合とされない場合がある

Fig 12 of
Frey et al., Aerodynamic Interactions on Airbus Helicopters Compound Helicopter RACER in Hover, J. AHS, Vol. 67, 012007-1-17, 2022

プロペラ面の推力分布が不均一になるので，プロペラBPFが励起されることは自明

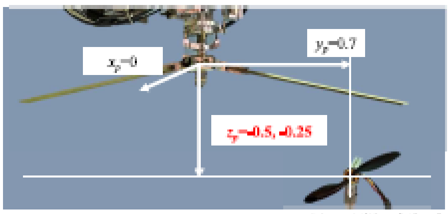
研究目的

ロータの影響を受けるプロペラに生じる振動を実験的に確認する。
様々な条件における結果を整理し，振動の観点から有利あるいは不利な作動条件を明らかにする。

その前段階として・・・

本研究会で，振動測定の現状を報告し，手法や条件についてご意見をいただきたい．

実験装置



※ロータ半径で無次元化

今回の実験パラメータ
・プロペラピッチ
・ロータ・プロペラ鉛直距離
・プロペラ回転数

模型ロータ諸元	
翼型	NACA0015
ロータ半径	469mm
翼弦長	60mm
ブレード枚数	2枚
ねじり下げ	なし
ヒンジオフセット	17mm
ルートカットアウト	113mm
プロペラ諸元	
プロペラ直径	6inch（152mm）
ブレード枚数	2枚
幾何ピッチ	3inch, 5inch

実験装置

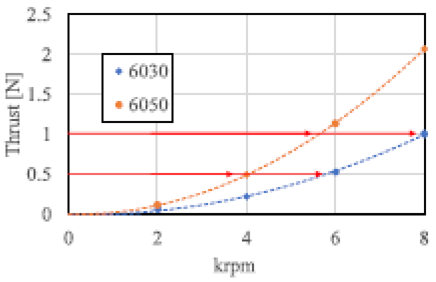
参考：JAXAコンパウンドヘリ模型（木村2020）と実験条件との比較

	X_p		y_p		z_p		プロペラ直径	
	JAXA模型	本実験	JAXA模型	本実験	JAXA模型	本実験	JAXA模型	本実験
実寸 [mm]	−63	0	527	328	−180	−235 −117	250	152
ロータ半径比	−0,08	0	0,69	0,70	0,24	0,50 0,25	0.327	0.325

Fig. 10 of
木村等, コンパウンドヘリコプタのメインロータとサイドプロペラの空力干渉, 第58回飛行機シンポジウム, オンライン, JSASS-2020-5153, 2020

サイドプロペラはその全体が後流の影響下にある

実験装置



プロペラ単体での回転数と推力の関係

$$C_T = \frac{T}{\rho n^2 D^4}$$

ただし　n：rev/sec,
D：プロペラ直径　（木村2020）

おおむね $C_T = 0{,}08$（幾何ピッチ3inch）
$C_T = 0{,}17$（幾何ピッチ5inch）

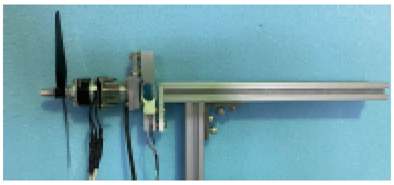
Fig. 6 of
木村等, コンパウンドヘリコプタのメインロータとサイドプロペラの空力干渉, 第58回飛行機シンポジウム, オンライン, JSASS-2020-5153, 2020

$\theta = 10, 17$ deg に相当

プロペラ実験におけるプロペラ回転数は，単体での推力が0,5Nおよび1,0Nとなる回転数とした
幾何ピッチ3inch：5800rpm，8000rpm
幾何ピッチ5inch：4000rpm，5600rpm

※今回の実験条件（$y_p = 0.7$，ロータ作動条件：$C_Q = 6.91 \times 10^{-4}$）で，アンチトルクに必要なプロペラ推力は1.05N

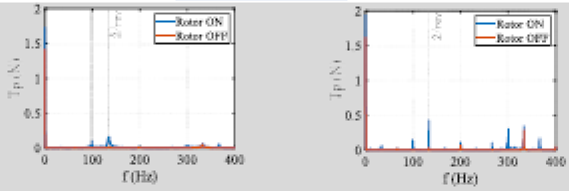
実験装置



6分力計：Leptrino PFS020YA500U6 （サンプリング周波数1200Hz）
SPロードセル：Sensorcon Micro Load Cell SC133（暫定1000Hz）

荷重計が2種類？

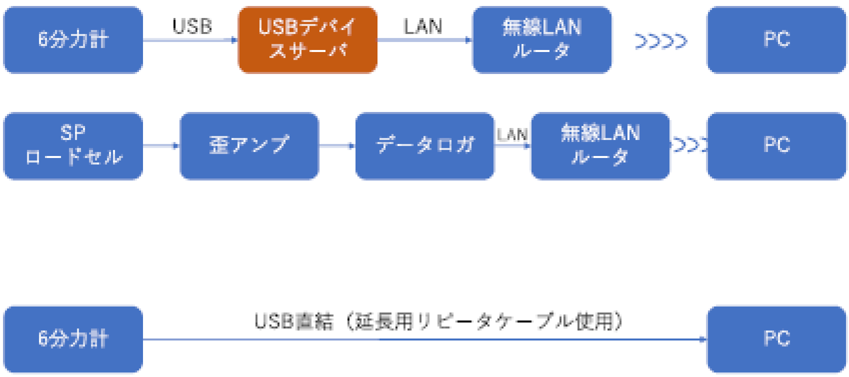
試し取り条件
4000rpm
8045プロペラ
xp=0
yp=0.7
zp=0.5



6分力計　　SPロードセル

6分力計のデータを利用するとピーク周波数が1Hz程度ずれており，鋭いピークが立たない

失敗の原因



SPロードセル（1000Hz，5000Hz）の結果と比較

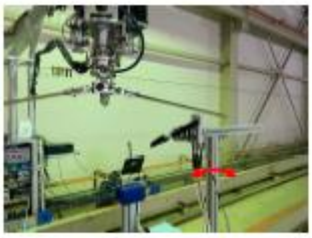
6分力計も振動解析に利用可能と判断

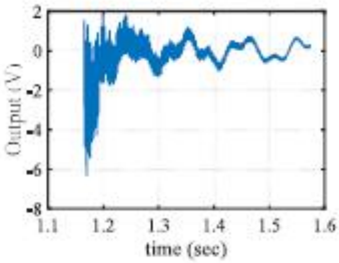
実験装置

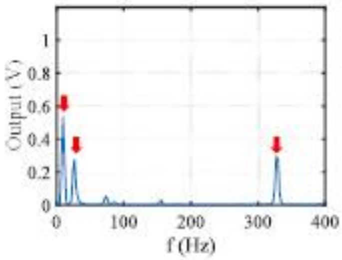
実験装置の固有振動数確認（タッピング）
サンプリング周波数5000Hz，データ長2048，矩形窓

取付治具の振動：約10Hz，**約27Hz**（z_pに応じて変化）

SPロードセルの振動：約330Hz







実験結果

（振動以外の性能変化）

$z_p = 0.25$

ピッチ	回転数	推力[N]（ロータ有）	推力[N]（ロータ無）	推力比	パワー[W]（ロータ有）	パワー[W]（ロータ無）	パワー比
3inch	5800	0.57	0.47	1.21	2.39	2.98	0.80
	8000	1.05	0.97	1.08	7.11	7.92	0.90
5inch	4000	0.57	0.50	1.14	3.19	2.89	1.10
	5600	1.05	0.97	1.08	8.45	7.90	1.07

z_pが大きい方が，推力変化が大きい

3inchプロペラはロータの影響で推力が増加するにもかかわらず，パワーは減少する．z_pが小さい場合に顕著

$z_p = 0.5$

ピッチ	回転数	推力[N]（ロータ有）	推力[N]（ロータ無）	推力比	パワー[W]（ロータ有）	パワー[W]（ロータ無）	パワー比
3inch	5800	0.60	0.47	1.26	2.88	2.96	0.97
	8000	1.09	0.98	1.11	7.70	7.99	0.96
5inch	4000	0.59	0.48	1.23	3.44	2.88	1.19
	5600	1.10	0.97	1.13	9.21	7.88	1.17

実験結果 サンプリング周波数1200Hz，データ長2048×10，矩形窓

$z_p = 0{,}25$

幾何ピッチ
3inch

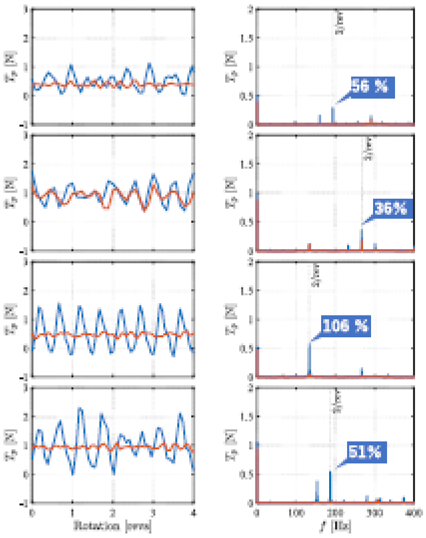
5800rpm

8000rpm

幾何ピッチ
5inch

4000rpm

5600rpm



振幅は推力よりもピッチ角
に依存する

ロータBPF(34Hz)はほとん
ど観測できない

木村2020の結果
（θ_{sp} = 10degの時，4%程度）
に比べて振幅が大きい
※本実験のプロペラのC_Tは，
θ_{sp} = 10,17degに相当

実験結果 サンプリング周波数1200Hz，データ長2048×10，矩形窓

$z_p = 0{,}5$

幾何ピッチ
3inch

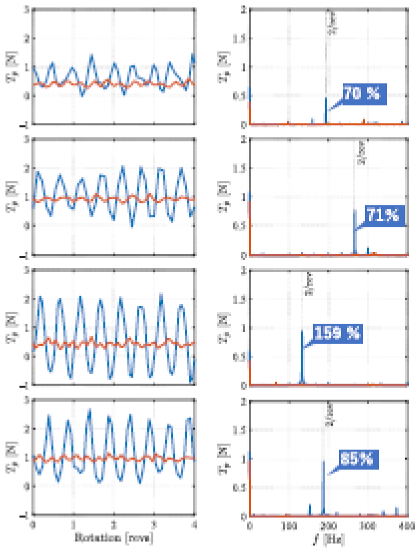
5800rpm

8000rpm

幾何ピッチ
5inch

4000rpm

5600rpm



振幅は推力よりもピッチ角
に依存する
ただし幾何ピッチ3inchの場合は推力
に応じて振幅も大きくなっている

ロータBPF(34Hz)はほとん
ど観測できない

木村2020の結果
（θ_{sp} = 10degの時，4%程度）
に比べて振幅が大きい
※本実験のプロペラのC_Tは，
θ_{sp} = 10,17degに相当

z_p = 0,5の方が0,25の場合より
も振幅が大きい
(吹きおろしの大きさが関係？)

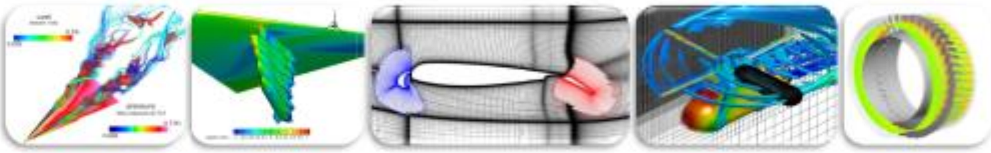
結論

- ロータの影響によるプロペラの振動はプロペラBPFが最も顕著
- 実験ではロータBPFの振動は観測できなかった
- CFD解析の結果よりも大きな振幅を観測
- 振幅は推力よりもピッチ角に依存（推力変化とは相関あり）
- ロータ・プロペラ鉛直距離が大きい方が振幅が大きい

★結果の背景にある現象について考察中

移動物体対応流体解析ソルバ FaSTAR-Moveの回転翼解析事例 および最新機能紹介

保江 かな子, 南部 太介
宇宙航空研究開発機構 (JAXA) 航空技術部門
航空機ライフサイクルイノベーションハブ



2022年度将来回転翼機研究会／回転翼解析技術交流会, 2023/3/24

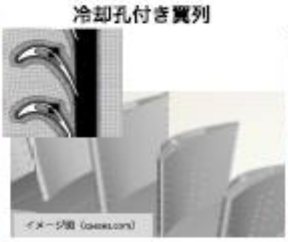
航空機設計開発におけるCFD活用

- CFD (Computational Fluid Dynamics) の発展に伴い, 航空機設計開発段階においてCFDが多用されるようになっている
- 近年では, より**複雑な形状の解析**や**物体の運動を伴う解析**等への適用に対する需要が高まっている
  ✓ファン, タービン, 圧縮機等の航空エンジンのターボ機械要素
  ✓ヘリコプタやeVTOL等の回転翼機

航空機におけるCFDの活用

Spalart et al., The Aeronautical Journal, vol 120, No. 1223, pp. 209−232, 2016

冷却孔付き翼列



eVTOL

2

本研究の目的・手段

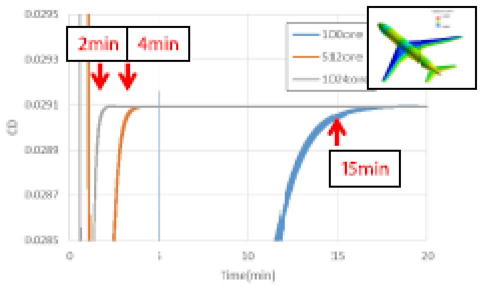
目的

- 運動や回転, 変形を伴う複雑形状の物体周りの流体解析を可能とする, 非常に高速な流体解析ソルバを構築する

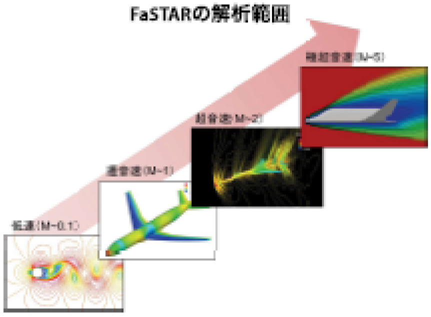
手段

- JAXAで開発してきた世界最高速レベルのCFDソルバ『FaSTAR※』に, 移動重合格子機能, 変形格子機能, スライディング格子機能等を追加することで, 複雑形状かつ動きを伴う解析を可能とする

FaSTARの高速性



FaSTARの解析範囲



※FaSTAR: FaST Aerodynamic Routineの略。 1000コアのJAXA Supercomputer System generation 2 (JSS2)で、航空機空力解析を2分で実行可能

3

FaSTAR-Moveの研究開発

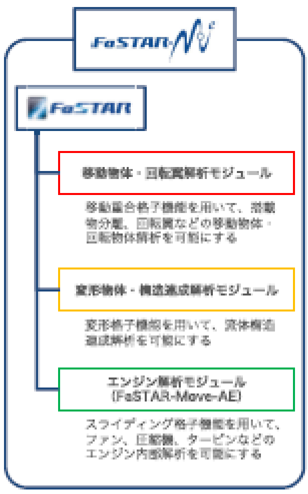
解析対象

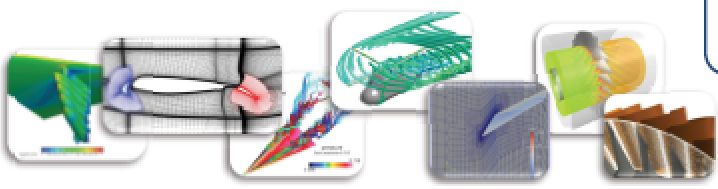
- 高揚力装置周りの解析や, 運動連成解析
- ヘリやeVTOL等の回転翼機周りの流体解析
- フラッタ等, 構造振動を伴う流体解析（流体構造連成）
- ファン, 圧縮機, タービン等エンジン内部解析

FaSTAR-Moveの特徴

- 複雑形状周りの解析が可能
- 物体の移動・変形・回転等の動きを模擬可能
- 世界最先端レベルの精度
- 世界最高レベルの高速性

FaSTAR-Moveの構成



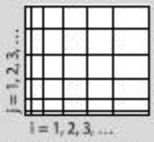


4

複雑な形状を解析する方法

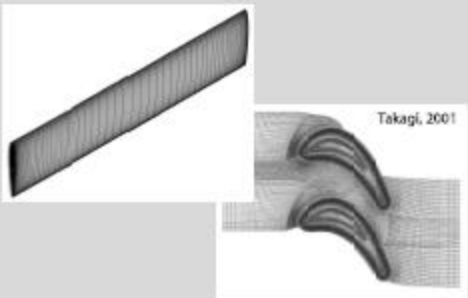
構造格子
【UPACS/rFlow3D】

特徴
- 六面体の計算セルで構成
- 計算セルが規則的に並んでいる格子



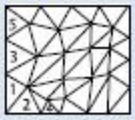
メリット
- 計算セルが規則的に並んでいるため，コード実装が容易

デメリット
- 複雑な形状に対しては，計算格子の生成の難易度高



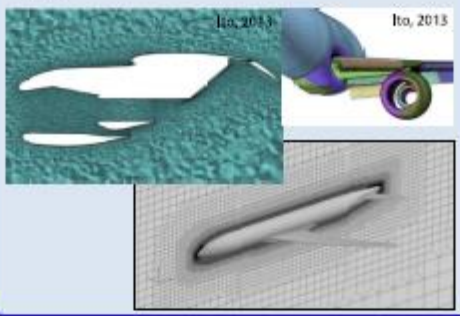
非構造格子
【FaSTAR/FaSTAR-Move/TAS】

特徴
- 多面体（六面体，四面体，プリズム，ピラミッドなど）の計算セルで構成
- 計算セルが不規則に並んでいる格子



メリット
- 複雑な形状でも，容易に計算格子を生成可能

デメリット
- 計算セルが不規則に並んでいるため，コード実装の難易度高

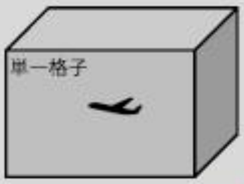


5

物体の運動を伴う解析の方法

単一格子
【FaSTAR】

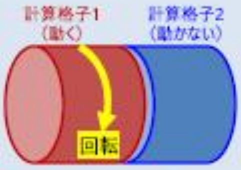
固定翼機解析の方法
- 物体の周りを覆う単一の計算格子を用いて流体計算を実施

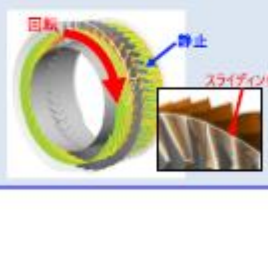


スライディング格子
【FaSTAR-Move エンジン】

固定翼機解析との主な違い
- 計算格子を特定の界面に沿ってスライドさせることで物体移動を伴う解析を実施

課題
- 内部流解析で重要となる流量を100%保持したまま解析（保存則の保証）するには，複雑な処理が必要

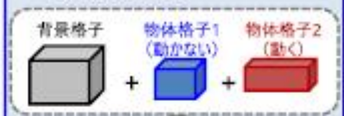


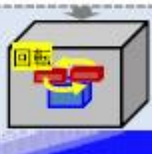


移動重合格子
【FaSTAR-Move 回転翼】

固定翼機解析との主な違い
- 移動する物体，固定物体，その周りを取り囲む領域に対して別々の計算格子を用意し，重ねて解析

課題
- 複数格子間の情報授受のために必要な処理（ホールカット処理）が非常に高負荷





6

FaSTAR-Moveの研究開発

解析対象

- 高揚力装置周りの解析や,運動連成解析
- ヘリやeVTOL等の回転翼機周りの流体解析
- フラッタ等,構造振動を伴う流体解析（流体構造連成）
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- 世界最高レベルの高速性

FaSTAR-Moveの構成

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最先端レベルの計算精度実現に向けて (2/2)

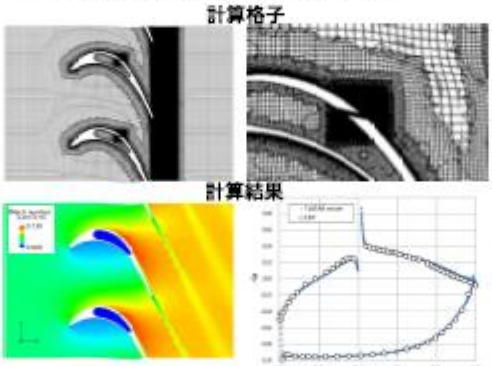
- さまざまな解析を実施し,精度の良い妥当な解を得られることを確認
- 実績のあるコードや,実験データ等との比較検証を実施中

冷却孔付き直線翼列解析

- ✓ 翼面に冷却孔を持つ直線翼列(T106A）の解析
- ✓ 微細な形状を含み,低速部と高速部が共存する流れ場でも安定的に解析可能であることを確認
- ✓ 翼面のCp分布は実験と良好な一致

計算格子

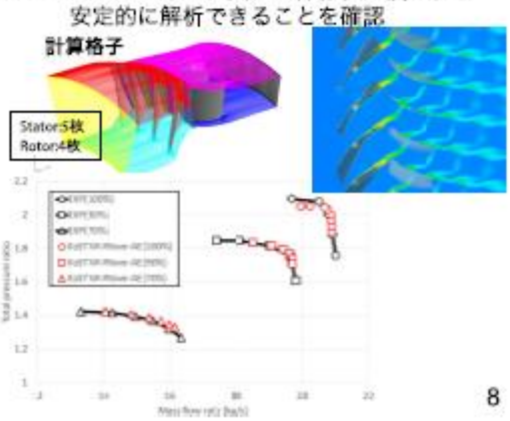
計算結果



圧縮機動静翼列解析

- ✓ 動静翼列（stage37）の解析
- ✓ 周期境界角度40deg格子を用いて解析
- ✓ スライディング面での保存性を損なわず安定的に解析できることを確認

計算格子



8

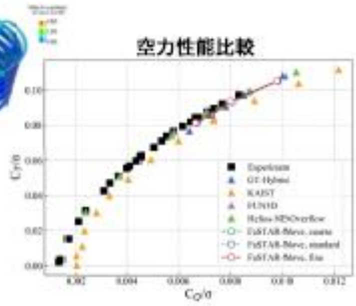
世界最高レベルの高速性 (2/2)

- 海外ソルバや商用ソルバとの比較検証を実施
- 計算時間に関する公開されている情報を見る限りでは，世界最高速の計算速度を実現

S-76ロータによる妥当性検証および高速化効果確認

✓ Rotor Hover Prediction Workshop (AIAA) にて検証問題として取り上げられたロータ空力性能比較において，実験値との良い一致を示すと共に，海外ソルバと同等の計算精度で解が得られることを確認

✓ 高速化手法（前頁で紹介した方法以外の高速化も組み合わせている）を実装することにより，非構造ベースの移動重合格子ソルバとして世界を牽引しているFUN3D（NASA）より約3倍高速



10周分の計算時間比較（1億セル規模，2048並列）

9

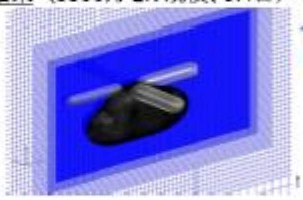
解析例：トリム解析②

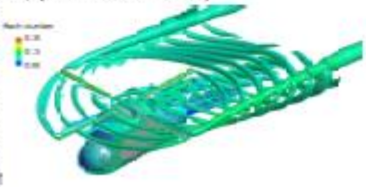
胴体／ロータ干渉（JMRTS）トリム解析

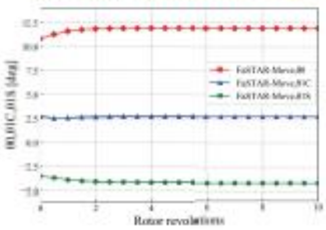
- 推力およびモーメントが平衡となるようなトリム解析を実施
- JAXA実施の風洞試験データと結果を比較し，空力弾性の影響が大きいUH-60Aに比べて，実験値と良い一致が得られることをを確認

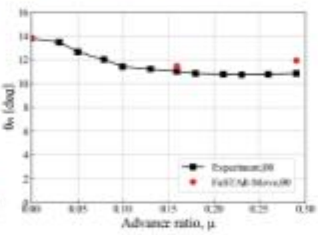
※rFlow3D：構造格子ベース回転翼解析ソルバ（JAXAインハウスコード）

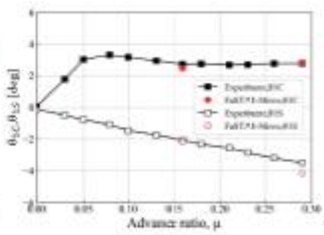
前進飛行時の解析結果（3500万セル規模、9.4日／10周@JSS2-2048コア）











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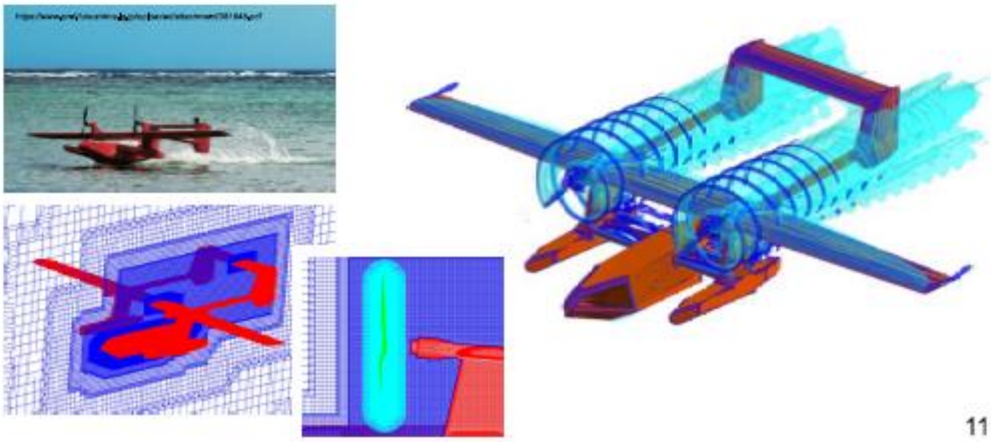
解析例：全機解析例①

Special Thanks:
株式会社スペースエンターテインメントラボラトリー殿

小型無人機全機解析

- プロペラを有する小型無人機（水上飛行艇）の全機解析を実施
- プロペラ後流が空力特性に与える影響を検討するとともに，飛行試験との比較や分析も実施

解析格子および結果例



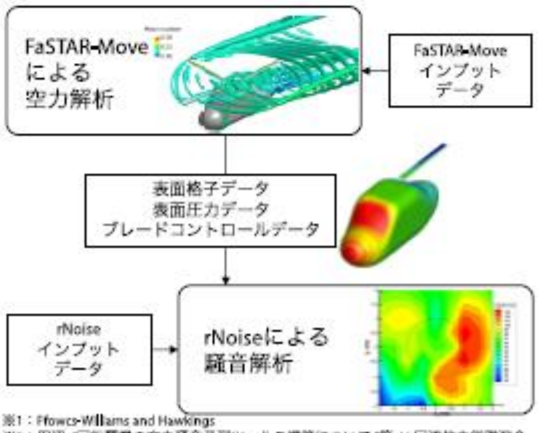
11

最新機能紹介

rNoiseとの連成による騒音解析機能

- FaSTAR-MoveとFW-H※1法ベースの騒音解析ツールrNoise※2との連成機能を追加
- ソルバ実行時に，PARAMDAT.rNoiseという入力ファイルを計算ディレクトリに置いておくことでrNoise用のインプットファイルを出力

解析の流れと出力ファイル



※1：Ffowcs-Williams and Hawkings
※2：田辺, "回転翼機の空力騒音予測ツールの構築について,"第 44 回流体力学講演会 / 航空宇宙数値シミュレーション技術シンポジウム 2012講演論文集, 2012

```
作業ディレクトリ
├ GRID
├ GEOM
├ RESULT
├ UNSTEADY
│ └ rNoise
│    ├ gridnumber_correspondence.dat
│    ├ mrcontrol_IG**.dat
│    ├ surfgrid.dat
│    └ surfcpa_******step.dat
├ fastar.MPI
├ PARAMDAT
├ PARAMDAT.MOVE
└ PARAMDAT.rNoise
```

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まとめ

- 高速な非構造格子流体解析ソルバFaSTARに移動物体の解析に必要となる機能を追加したFaSTAR-Moveの概要と最新の研究成果を紹介した
- 回転翼解析等に必要な各種機能の実装や妥当性検証解析を実施しており高精度な結果を高速に得られること確認している
- 今年度は, FW-H法ベースの騒音解析ツールrNoiseとの連成機能を実装し, 複雑形状に対する空力・騒音連成解析を可能とした
- 今後, さらなる機能拡張を進めていき, 非常に複雑な形状であっても高速に解析可能な移動物体対応流体解析ソルバを完成させる予定である

15

謝辞

FaSTAR-Moveの研究開発を進めるにあたり, 以下の方々に多大なるご協力を頂いております.

回転翼解析モジュール

- JAXA 環境適合ハブ　高速ヘリT　田辺 安忠氏・菅原 瑛明氏

また, 本研究では, JSS3（一部はJSS2）を用いて解析を実行しております.

この場をお借りして, 心より御礼申し上げます.

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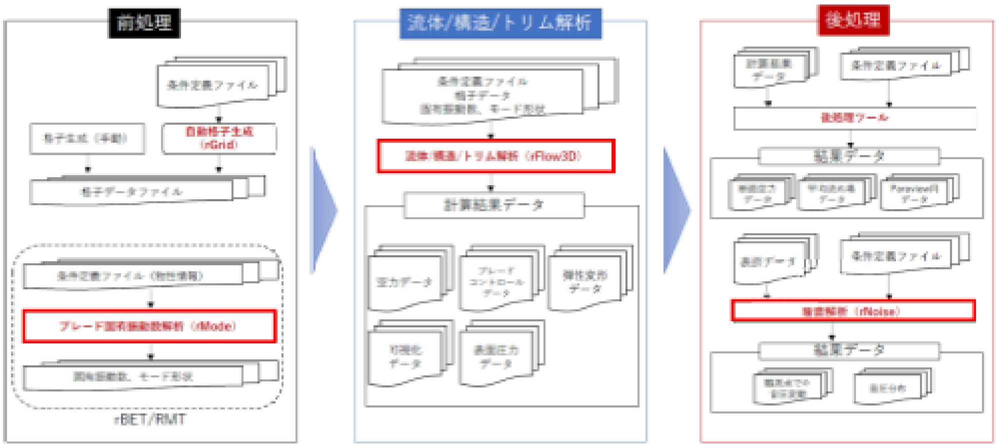
rGrid
~rFlow3D用自動格子生成ツール~

国立研究開発法人　宇宙航空研究開発機構
航空技術部門　航空環境適合イノベーションハブ
回転翼機高速化技術チーム
木村　桂大

2023.3.23

rFlow3Dの機能一覧

ブレードの物性値（質量、剛性分布など）から弾性変形のモードを予測する：rMode
弾性変形の考慮や飛行条件の模擬（トリム）機能を備えたCFDソルバー：rFlow3D
CFDで得られた圧力分布等から音の伝播を予測する騒音解析ツール：rNoise



2023.3.23 2

前処理・後処理のサポート

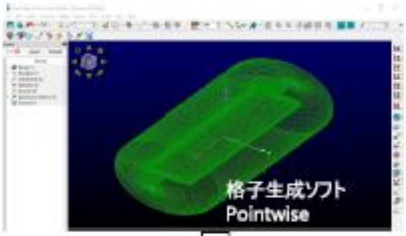
rFlow3Dは流体解析・構造解析・音響解析と多くの機能を持ち、幅広い解析が可能

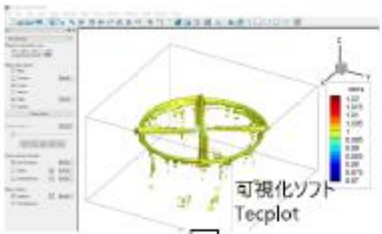
ただし・・・

CFD解析には、別途**格子生成・可視化ソフト**が必要（Pointwise, tecplotなど。高価！）

(1) 専用格子生成ツール（**rGrid**）の開発

(2) フリーの可視化ソフトへの対応　　　　により導入障壁を低く・使いやすく



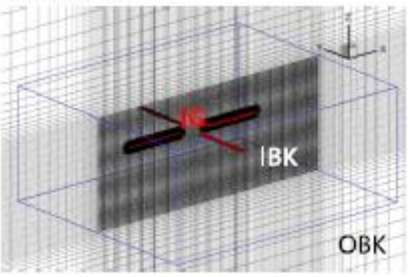


専用自動格子生成ツール rGrid

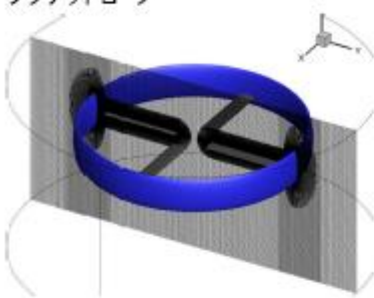
フリー可視化ソフト paraview

rGridによる格子作成例

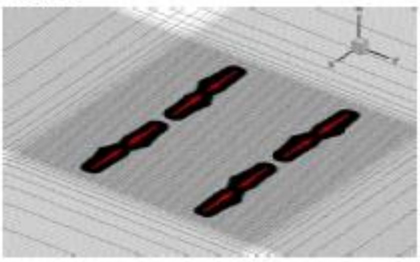
✓ ヘリコプター



✓ ダクテッドロータ



✓ ドローン



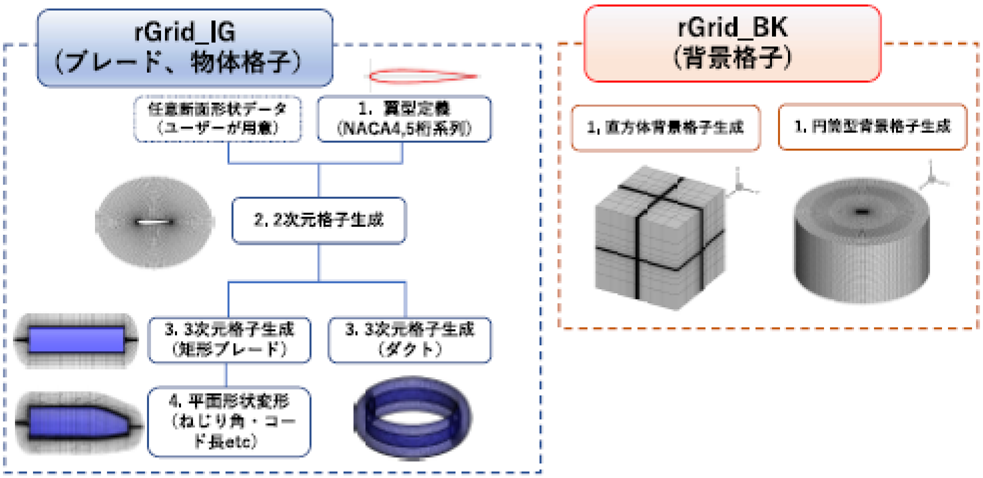
✓ rFlow3Dでは重合格子系のセットを扱う

✓ rGridでは
- 外側背景格子（OBK）
- 内側背景格子（IBK）
- ブレード格子/ダクト格子（IG）

が作成可能

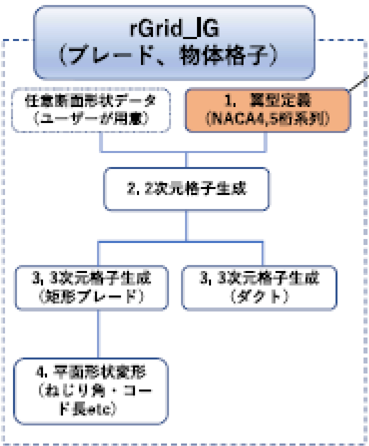
✓ 胴体格子は現状作成不可

rGrid機能一覧

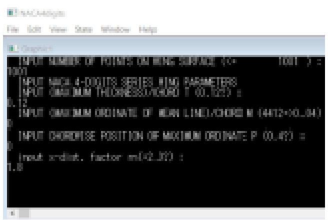


✓ 物体周りの格子を作成するIGファミリーと背景格子を作るBKファミリー

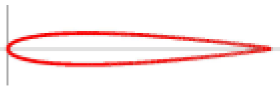
rGrid_IG ：翼型定義



NACA4digits.exe, NACA5digits.exe



操作画面

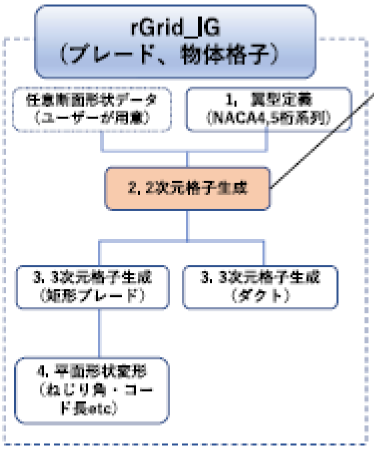


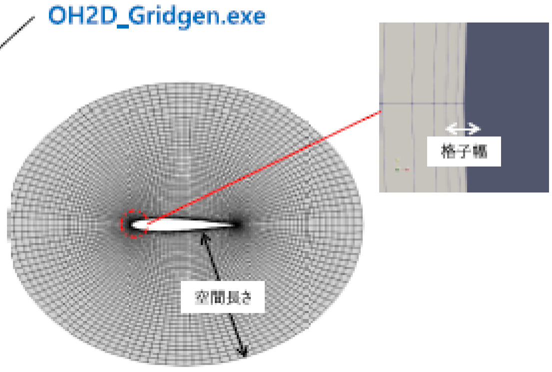
出力例
（NACA0012）

✓ NACA0012、NACA23012などの4桁、5桁の番号の情報から翼型の点群データを出力するモジュール

✓ NACA系列以外の翼型形状についても点群データを準備すれば以降の格子生成ツールの利用が可能

rGrid_IG：2次元格子生成

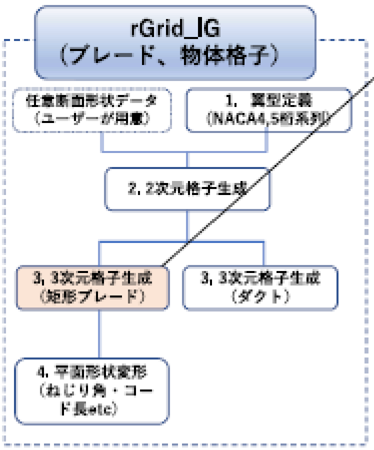


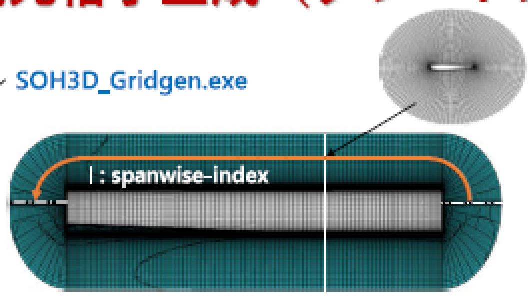


2次元格子外観

- ✓ 用意した翼型形状・断面形状データから2次元格子を作成
- ✓ 物体周りの空間長さや格子幅について設定可能（これらのパラメータの設定についてもカリキュレーターの用意あり）

rGrid_IG：3次元格子生成（ブレード）



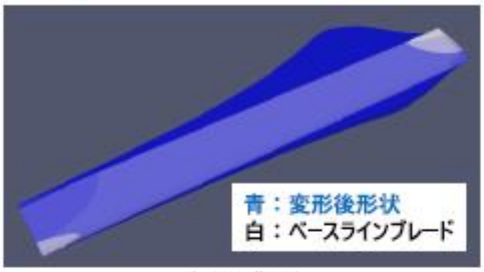


3次元格子（ブレード）外観

- ✓ 2次元格子をスパン方向に並べていくことで3次元格子を作成
- ✓ 翼端・翼根は特異点（線）に集まるように成長
- ✓ 格子点数や翼端・翼根周りの格子解像度を調整可能

rGrid_IG：平面形状変形

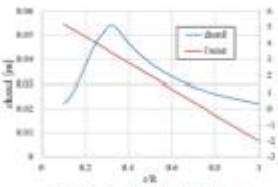
Blade_Modification.exe



変形ツール使用例

- ✓ 4種類の変形モード
  1. ねじり角（スプライン・線形）
  2. コード長（スプライン・線形）
  3. 前進角・後退角
  4. 上反角・下反角

- ✓ ブレード格子の合成機能（ex. 根本はNACA0012で翼端はNACA23012なども作れる）



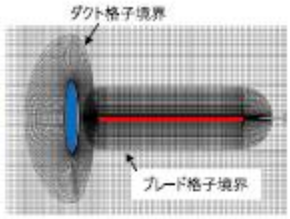
使用例のコード長・ねじり角分布

2023.3.23 9

rGrid_IG：平面形状変形

SOH3D_Gridgen_ducted.exe

ダクト格子外観



重合領域の調節

- ✓ 3次元格子作成の派生形。2次元格子を円周方向にスイープすることで任意断面形状をもつダクト格子を作成

- ✓ 重合領域の調整可（CFD解析手法からくる要求）

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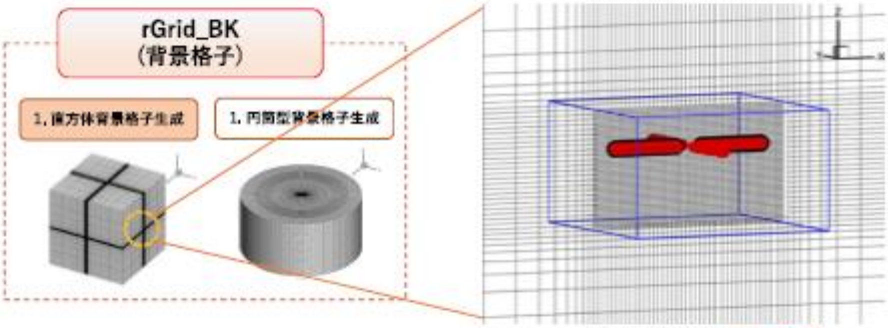
rGrid_BK：直方体背景格子

BK_cubic_Gridgen.exe

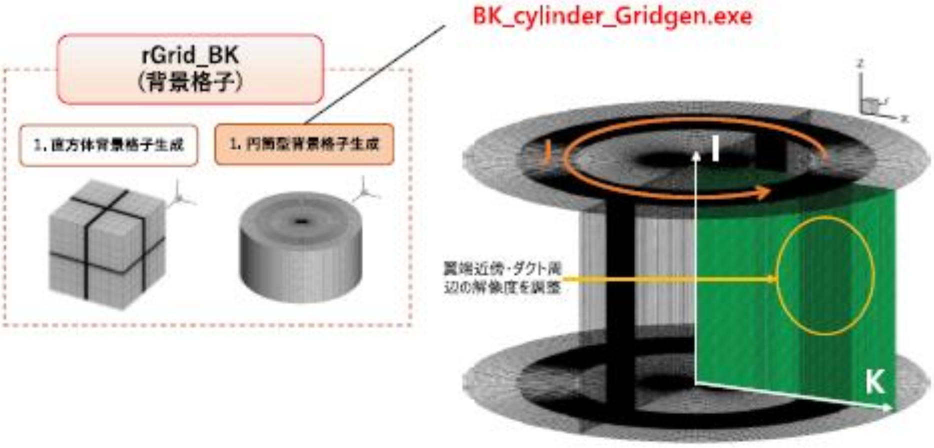


格子セット例（OBK + IBK + ブレード）

- ✓ 解析上の要求から、広範囲の領域を持ち、なおかつ局所的に解像度の高い領域を持つ背景格子が必要
- ✓ ブレード存在領域周辺に格子を寄せる幅寄せ機能付
- ✓ xyz方向それぞれの長さと点数、幅寄せ具合をパラメータとして自動生成

rGrid_BK：円筒型背景格子

BK_cylinder_Gridgen.exe



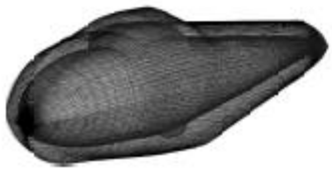
- ✓ ホバリング解析など円周方向に周期性のある条件に適する
- ✓ 半径方向の幅寄せ機能により、例えばダクト周辺の解像度だけを高めるなどの調整が可能

まとめ

- ✓ rFlow3D用自動格子生成ツール “**rGrid**” を開発、機能拡張中
- ✓ rFlow3Dを利用する場合はもれなく付属
- ✓ ダクテッドロータを含む幅広い条件の回転翼解析が自動生成で可能
- ✓ トライ＆エラーを繰り返す（≒格子を作り直す）CFD解析において、多くの手間を削減可能（再現性・利便性UP）

今後の課題

- ✓ 胴体格子の自動生成（トポロジー上はブレード格子と同様に作成可能）



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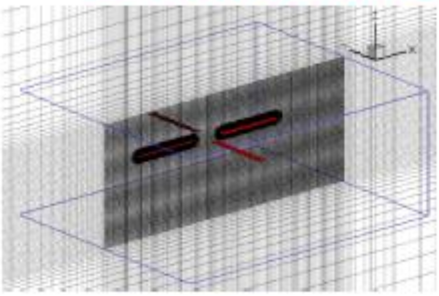
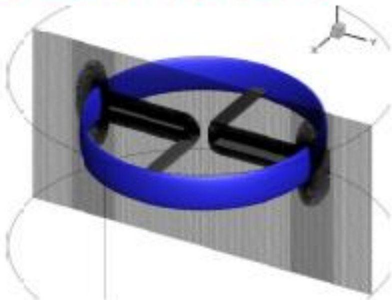
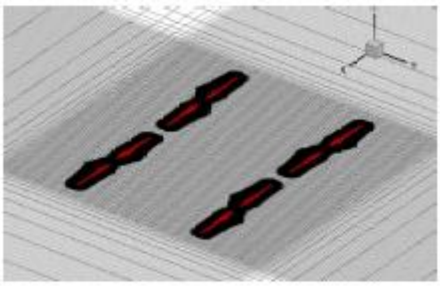






2022年度将来回転翼機研究会／回転翼解析技術交流会
2023年3月24日

回転翼統合解析ツールの最新機能紹介（rBET/RMT, rFlow3D, rNoise）

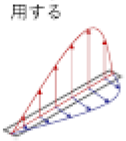
国立研究開発法人宇宙航空研究開発機構
菅原　瑛明

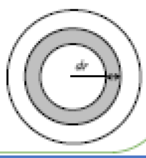
2023.3.24　2022年度将来回転翼機研究会／回転翼解析技術交流会

JAXAで開発している回転翼解析ツール

rBET/RMT

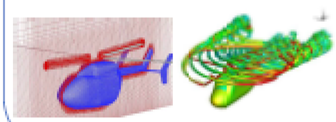
- 翼素理論による簡易解析ツール
- **rBET**
  - ➢ 線形誘導速度モデルを用いたヘリコプタロータの空力性能予測
  - ➢ 空力弾性解析
- **RMT**
  - ➢ 翼素運動量理論で誘導速度を求める軸流ロータの空力性能予測
- **rMode**
  - ➢ ブレードの固有振動モード解析ツール
  - ➢ rBET, rFlow3Dで空力弾性解析で利用する





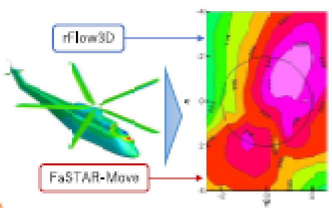
rFlow3D

- 移動重合格子法を用いた回転翼用CFDツール
- ロータのトリム解析
  - ➢ Single rotor
  - ➢ Coaxial rotor
- CFD/CSD解析
  - ➢ ブレードの空力弾性解析
  - ➢ rModeが必要
- 物体格子20個、背景格子7個配置可能
- 非構造格子
  - ➢ FaSTAR
- 部分重合格子(Chimera grid)
- 自動格子生成ツール, rGrid



rNoise

- FW-H法に基づいたFarassat Formulation 1による騒音解析
- CFDで求めた表面圧力分布を用いて、観測点に伝わる音圧を計算する
- rFlow3DとFaSTAR-Moveに対応
- 観測点における音圧変動、音圧分布を出力



2023.3.24　2022年度将来回転翼機研究会／回転翼解析技術交流会　1

JAXA

解析ツールパッケージ

rBET/RMT

- rBET
- RMT

→ 標準配布　マニュアル

- rMode ―― 希望者への限定配布　マニュアル

rFlow3D

rGrid　rFlow3D　Post処理関係

マニュアル

チュートリアル

※空力弾性解析にはrBET/RMTのライセンスが必要

rNoise

rNoise　マニュアル

※マニュアル整備中

※FaSTAR-Moveとは別ライセンス

- ☐ CFD解析で要求される、
  形状作成（CAD）－格子生成－（解析）－可視化
  のすべてが含まれているわけではないことに注意
- ☐ 格子生成はブレードの自動格子生成の整備を進めている
- ☐ 可視化はParaviewで読み込み可能なファイルコンバーターを整備
  - ➢ Paraviewの操作方法はサポートできない

2023.3.24　2022年度将来回転翼機研究会／回転翼解析技術交流会　2

JAXA

最新機能紹介

- ☐ rBET/RMT Ver. 1
  - 更新なし
- ☐ rFlow3D Ver. 8
  - Ver. 7からバージョンアップ
  - 自動格子生成ツール「rGrid」の機能拡張
    - ➢ ダクテッドロータ解析用のダクト格子と背景円筒格子の自動生成機能
  - Chimera gridを用いた部分重合格子法の実装
    - ➢ 構造／構造物体格子間、および、構造／非構造物体格子間のChimera格子機能
  - トリム解析機能改善と拡張
    - ➢ T-H-Mxトリム解析の安定性改善
  - CFD/CSD解析手法の機能拡張
    - ➢ delta-airload法を用いたCFD/CSD連成解析手法の導入
  - 背景直交格子の読み込み可能フォーマットの追加
    - ➢ ファイル名に「.lb8.」と入れることでバイナリファイルと認識（例：BK_grid.lb8.x）
- ☐ rNoise Ver. 2
  - 複数ロータ、複数物体に対応
  - 観測点の設定に平面と球面が可能
  - rFlow3DとFaSTAR-Moveに対応

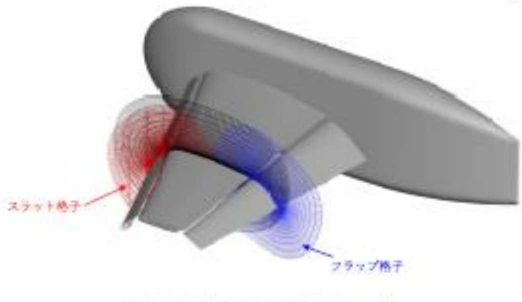
2023.3.24　2022年度将来回転翼機研究会／回転翼解析技術交流会　3

Chimera gridを用いた部分重合格子法の実装

- 部分重合格子はHiLiftPW-1で検証を実施
  - https://hiliftpw.larc.nasa.gov/index-workshop1.html
  - Rumsey, C. L. et al., "Summary of the First AIAA CFD High-Lift Prediction Workshop," Journal of Aircraft, Vol. 48, No.6, Nov.-Dec. 2022.
  - 台形の単純な翼、スラット（30°）、フラップ（25度）あり
  - 多くのCFDソルバーの結果が公開されている

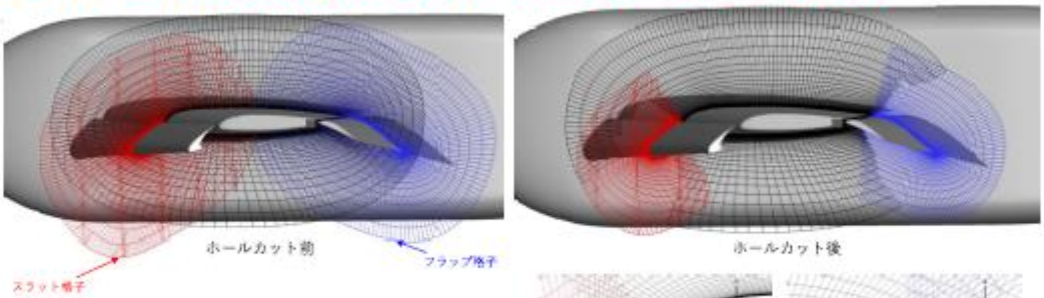
- 計算条件
  - Mach=0.2
  - α=0, 6, 13, 21, 28, 32

- 計算手法
  - 圧縮性N-S方程式
  - 全速度型mSLAUスキーム（数値流束）
  - FCMT法（空間高次精度化, 空間4次精度）
  - 2次精度中心差分（粘性流束）
  - Dual-time stepping/LU-SGS（時間積分法）
  - SA-R（乱流モデル）



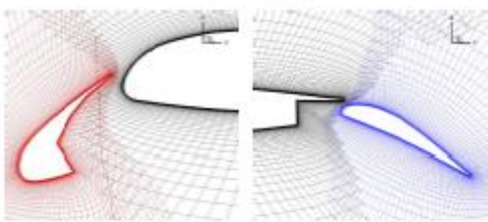
計算モデル（実際は左右対称で解いている）

Chimera gridを用いた部分重合格子の様子

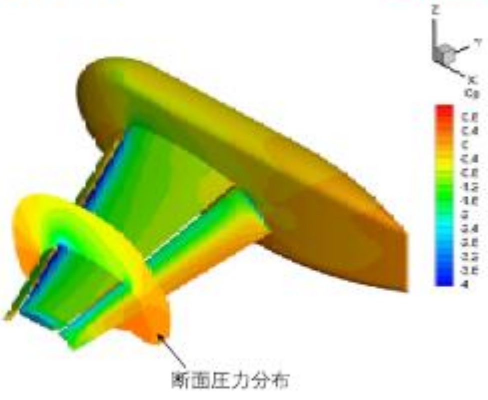


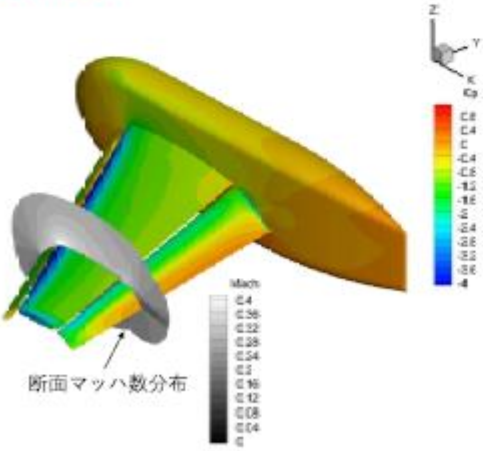
- 壁距離を参照して、各格子の優先順位を決めている
- 物体内部の格子は非計算点としている
- 物体格子間で物理量のやり取りをして計算をしている

- **注意：格子を適切に作成する必要がある**
  - **計算ができているが、補間がうまくできていない場合がある**



表面圧力分布等

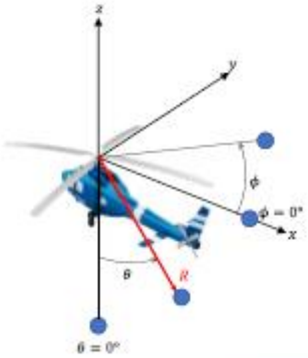




□ 不連続な領域は見られず、重合格子としてうまく解けていることを確認

rNoise新機能

□ rNoise Ver. 2
- 複数ロータ、複数物体に対応
- 観測点の設定に平面と球面が可能
- rFlow3DとFaSTAR-Moveに対応




```
&Mic_Carpet
        i_def_plane = 1                  ! 0:carpet, 1:sphere
! --- Carpet input
        ! *** NImic, NJmic, NKmic :: number of Mic
        ! *** Xmic, Ymic, Zmic   :: Mic locations
        NImic=9, Xmic= ・・・・
        NJmic=9, Ymic= ・・・・
        NKmic=1, Zmic= ・・・
! --- Sphere input
        R_sphere     = 4.0,
        theta_sphere  = 120.0,
        dthera_sphere = 10.0,
        phi_sphere    = 360.0,
        dphi_sphere   = 30.0,
&End
```

まとめ

- 回転翼解析ツールの最新機能を紹介
  - rBETは昨年度と同じ
  - rFlow3DはVer.8にバージョンアップ
  - rNoiseは今年度からrFlow3Dから独立。FaSTAR-Moveにも対応。

日本ヘリコプタ協会規約

施行　平成 元年12月15日
改正　平成 10年 7月 6日
改正　平成 12年 6月22日
改正　平成 15年 7月 3日
改正　平成 18年 4月28日
改正　平成 21年 8月 4日
改正　平成 22年 4月24日
改正　平成 26年 5月13日
改正　平成 28年7月 8日
改正　平成 29年7月 4日

第1章　総　則

(名 称)

第1条　本組織は『日本ヘリコプタ協会（Japan Helicopter Society)』(以下「本協会」という）と呼称する。

(目 的)

第2条　本協会は、広くヘリコプタ及び垂直離着陸飛行の発展に寄与するため、ヘリコプタ並びに垂直離着陸飛行に関する基礎研究、試験、開発、製造、維持、運航並びに広報等、全ての分野にわたる活動の活性化、情報収集の効率化、会員相互の親睦・共生、国際交流の実をあげることを目的とする。

(管理機構)

第3条　本協会の管理運営機構は理事会及び幹事会とする。
理事会はAHSI（American Helicopter Society International）の基本目的、本規約、並びに本協会全体の運営方針に関わる事項を統括する。各担当常任理事は、担当範囲の年間事業計画を策定し執行する。各担当幹事は、担当常任理事の事業執行を補佐する。
本協会の事務局は、会長が指名する機関内におく。

第2章　会　員

(会員の資格)

第4条　本協会は、日本在住のAHSIの正会員、学生会員、法人会員、教育法人会員、並びに本協会の賛助会員他をもって構成する。

(会員の分類)

第5条　本協会の個人会員は、正会員、学生会員、賛助会員、及び名誉会員、法人会員は一般法人会員、教育法人会員、及び賛助法人会員からなる。

① 正会員は、AHSI会員の資格を有するものおよび本協会に入会申込書を提出し理事会で承認をえたもの。
② 学生会員は、AHSI会員の資格を有するものおよび本協会に入会申込書を提出し理事会で学生会員として認められたもの。
③ 一般及び教育法人会員は、AHSI会員の資格を有するものおよび本協会に入会申込書を提出し理事会で夫々一般及び教育法人会員として認められた法人。
④ 賛助会員並びに賛助法人会員は、本協会の目的に賛同し本協会の活動を賛助する個人並びに法人。
⑤ 名誉会員は、所定の審査の結果、本協会の目的達成及び推進に特に顕著な功績があって、名誉会員として遇するに相応しいと認められたもの。

（加入及び脱会）

第6条　前条の各号に該当し、入会を希望するものは所定の申込書を、会長に提出し、理事会の承認を得なければならない、また、脱会を希望するものは所定の脱会届を、会長に提出しなければならない。なお、総会招集時の出欠確認時に会員資格の継続意思確認を行い、継続意思の表明が2回連続で無い場合は脱会とする。

（除名）

第7条　本協会は、会員が本協会の目的に反するような行為があったと認められる場合、理事会で審議のうえこれを除名することができる。

（会員の権利）

第8条　会員は、会のすべての事項に参画する権利及び均等の取扱いをうける権利を持つ。

（会員の義務）

第9条　会員は、次の義務を負う。

① 当規約、別に定める倫理規程及び総会、理事会で定められた事項に従うこと。

第3章　役　員

（役員）

第10条 本協会には、次の役員をおく。

会長	(PRESIDENT)	1名
副会長	(VICE PRESIDENT)	2名
常任理事	(MANAGEING DIRECTOR)	若干名
理事	(DIRECTOR)	若干名
監査役	(AUDITOR)	若干名
幹事長	(PROGRAM CHAIRMAN)	1名
幹事	(MANAGER)	若干名
メンバーシップ担当	(MEMBERSHIP /CHAIRMAN)	1名
リエゾン担当	(LIAISON MANAGER)	若干名

尚、名誉顧問（ADVISER EMERITUS)、顧問（ADVISER）をおくことができる。

（選任）

第11条 常任理事及び理事、監査役は、前期役員が候補者を推薦し、会員の選挙又は総会の承認を得てこれを決定する。

会長、副会長は、常任理事および理事の互選による。

幹事長、メンバーシップ担当並びにリエゾン担当の委嘱は会長が行う。

幹事は理事会が推薦し会長が任命する。

名誉顧問および顧問は、会長、副会長経験者から構成される。名誉顧問または顧問は、理事会での承認をもってこれを承認する。また、会長、副会長経験者でない場合、特別に会長の推薦があった場合にはこれを認める。

なお、任期中に役員に欠員が生じた場合の後任者の選任は、その都度、理事会の合議によって決定し、常任理事の場合には総会で承認する。

（任期）

第12条 役員の任期は、2ヵ年とする。なお、副会長に関しては2名のうち1名を1年毎に交互に選出される。

但し、前条、後任役員の任期は前任者の残りの期間とする。

（職務）

第13条 役員は下記の職務を遂行する。

① 会長は、本協会を代表して、会務を統括し、会の運営に対する一切の責任を負う。
会長は総会、理事会の議長となる。

② 副会長は、会長を補佐し、会長事故あるときは、その職務を代行する。なお、2名のうちどちらかの副会長がメンバーシップ担当を受け持つ。また、副会長は次期会長の候補となる。
常任理事、理事は、理事会を構成し、本協会の運営に関わる基本的事項を決定する。

③ 常任理事には、次の担当を設ける。

- 総務担当
- 企画担当
- 編集担当
- 広報担当
- 国際担当
- 行事担当
- JHST（Japan Helicopter Safety Team）担当

④ 各担当常任理事は付表1に定める担当ごとの職務を担当幹事と共に遂行し、本協会の運営につき、会長並びに理事会を補佐する。

⑤ メンバーシップ担当（副会長）は、会員の増加に関する基本施策を立案遂行すると共に、会員名簿を維持管理する。

⑥ リエゾン担当は、国内における外部関係機関との情報交換、協力関係の強化に努める。

⑦ 幹事長は、総務担当常任理事を補佐し、本協会の運営に関して、担当常任理事の決定した基本事項を具体化し遂行する。また、幹事会を主催し、各担当常任理事との調整を行う。

⑧ 幹事は、幹事長より指示された業務を行う。

⑨ 監査役は本協会の会計が適正に行なわれていることを監査する。

⑩ 名誉顧問および顧問は、会の運営に関して意見を具申する。また、顧問は担当常任理事の相談役として常任理事をかねることができる。

（理事会）

第14条 理事会は、必要に応じて、会長がこれを招集する。顧問、名誉顧問は、理事会に出席できるが、議決に参加はできない。理事会の議決は、全常任理事・理事の過半数を持って成立する。

（幹事会）

第15条 幹事会は、必要に応じ、幹事長がこれを招集する。リエゾン担当は、幹事会に出席できるが、議決には参加できない。幹事会の議決は、全幹事の過半数を持って成立する。

（内規）

第16条 本協会の運営に内規を必要とする場合は理事会の決議によりこれを定める。

第4章　総会及び行事

（総会）

第17条 総会は、本協会の最高決議機関であり、会員全員をもって構成し、原則として新年度に入って3ヶ月以内に会長が招集し、次の事項を協議するものである。ただし、理事会が必要を認めたとき、また会員の総数3分の１以上のものが、議題を明示して請求したときは、会長は臨時に総会を招集しなければならない。

① 役員の選出並びに解任

② 規約の改廃

③ 予算及び決算

④ その他役員が発案し、理事会で必要と認めた事項

⑤ 会員からの提案事項

総会は、会員の過半数の出席又は委任状がなければ成立しない。

総会の決議は出席した会員の多数決による。議長は、賛否同数の場合のみ決議に加わることが

④ その他役員が発案し、理事会で必要と認めた事項
⑤ 会員からの提案事項
総会は、会員の過半数の出席又は委任状がなければ成立しない。
総会の決議は、議決権を持つ出席者（議長への委任を含む）の多数決による。議長は、賛否同数の場合のみ決議に加わることができる。賛助法人会員については、一口当たり一議決権を持つ。

(行事)
第18条　本協会は、理事会の承認を得て、研究会・講演会を開催するほか、本協会の目的に沿った各種の行事を行うことができる。　法人会員となっている法人からの最大参加者数や、会員外の行事参加可否については、必要に応じて行事主催者の判断で設定することができる。

第5章　会　計

(会の経費)
第19条　本協会の経費は、賛助会費、臨時会費及び寄付金他をもってあてる。

(会費)
第20条　会費の徴収は、次により行う。
① 賛助会費は、年額1口10,000円以上の賛助会費を納入する。原則として新年度に入って3ヶ月以内にこれを徴収する。
② 臨時会費は、理事会の決議により、必要に応じ適宜徴収する。

(会計年度)
第21条　本協会の会計年度は毎年4月1日から翌年3月31日までの1ヵ年とする。

(会計)
第22条　本協会の会計は、総務担当常任理事／幹事が担当して行う。
会計は監査役の監査を経た上で、定期総会に会計報告を行い、承認を得るものとする。

第6章　附　則

(効力)
第23条　当規約の効力は、平成元年12月15日から効力を発するものとする。

以上

付表１　担当常任理事における職務（なお、各項目については適宜見直す）

担　　当	職　　務
メンバーシップ担当	• 会員名簿の維持管理をする • 会員誘致活動（VFS Japan Chapter 会員への案内等）
総務担当	• 総会、理事会、定例研究会、特別講演会及び臨時委員会等の開催の事前通知ないし、これらの会議についての議事録を作成し保存する • 本協会の会計記録を保存し、資産の安全保管の責任を負う • 本規約が、明示又は暗示に規定するその他の職務、或は会長又理事会から付託された業務を遂行する • 表彰を取り扱う • その他
企画担当	• 年間の行事を立案する • 協会のホームページの作成を助言する • 各種イベントを企画（臨時組織、特別広報企画等）する • 各種情報発信を企画する（アーカイブス、臨時委員会、広報活動等） • 人物紹介の記事等を取りまとめる • その他
編集担当	• HP の作成に協力する • 年 1 回会報を作成する • 発信情報（アーカイブス）を作成する • 年間の発表論文を“e-Library”化する • その他
広報担当	• HP を作成し運営する • 対外的な関係を構築する • 広告を募集する • 寄付を募る • その他
国際担当	• VFS 対応 • Heli Japan 国際会議および ARF 対応 • 海外対応 • その他
JHST 担当	• JHST 事務局 • その他
JVFET 担当	• JVFET 事務局 • 国内における教育機関との関係を構築 • その他

日本ヘリコプタ協会倫理規定

施行　平成２８年７月８日

（前 文）

日本ヘリコプタ協会会員（以下、会員という）は、広くヘリコプタ及び垂直離着陸飛行の発展に寄与するため、全ての分野にわたる活動の活発化、情報収集の効率化、会員相互の親睦・共生、国際交流の実をあげることを目的とする。この目的を実現するために、会員自らの良心と良識に従う自立ある行動が、ヘリコプタ産業の発展と安心・安全な社会の構築ひいては人類の福祉にとって不可欠であることを自覚し、社会からの信頼と尊敬を得るために、以下に定める綱領を遵守することを誓う。

（綱 領）

1. 法令等の遵守
   会員は、職務の遂行に際して、社会規範、法令及び関係規則を遵守する。
2. 会員間の接触
   協会における活動が、私的独占の禁止及び公正取引の確保に関する法律及び諸外国の競争法（以下、併せて「独占禁止法」という）に抵触することがないよう、協会における会議、並びに懇親会等名目を問わず会員各位が接触する機会において、独占禁止法上問題となるおそれのある議論及び意見交換等を行わないものとする。

（改 正）

この規程の改正は、総会の決議を経て行う。

附則

この規程は、平成 28 年 7 月 8 日から施行する。

２０２２/２０２３年度　賛助会員名簿

法人賛助会員

No.	名称	口数	代表者･所属（役職）	連絡先
1	（株）アイ・ティー・シー・アエロリーシング	1	中山 智夫 取締役会長	〒104-0033　東京都中央区新川2-1-5　THE WALL 5階 電話：03-3555-3621　FAX：03-3555-3627
2	朝日航洋（株）	1	青木 久幸 常務取締役 航空事業本部長	〒136-0082　東京都江東区新木場4丁目7番41号　東京ヘリポート内 電話：03-3522-0647　FAX：03-3522-1853
3	エアバス・ヘリコプターズ・ジャパン（株）	5	大西 博伸 営業企画部	〒107-6119　東京都港区六本木6-10-1　六本木ヒルズ森タワー19F　私書箱78号 電話：03-5414-3408　FAX：03-5414-3328
4	川崎重工業（株）	5	田村 勝巳 航空宇宙システムカンパニー 航空宇宙ディビジョン ヘリコプタプロジェクト統括部長	〒504-8710　岐阜県各務原市川崎町1 電話：058-382-2258　FAX：058-382-8413
5	（株）島津製作所	1	那須 竜太郎 航空機器事業部 技術部 部長	〒604-8511　京都市中央区西ノ京桑原町1 電話：075-823-1102　FAX：075-823-1472
6	（株）ジャムコ	1	伊田 幸男 航空機整備事業部 航空機整備事業部長	〒989-2471　宮城県岩沼市下野郷字新拓70　(仙台空港内) 電話：0223-22-2126　FAX：0223-22-6009
7	新東亜交易（株）	1	荻原 厚史 航空・艦船部長	〒100-8383　東京都千代田区丸の内1-6-1　丸の内センタービル8階 電話：03-3286-0355　FAX：03-3213-2405
8	（株）ダイセル	1	平松 泰 セイフティSBU インダストリBU長	〒530-0011　大阪府大阪市北区大深町3-1　グランフロント大阪タワーB 電話：06-7639-7231　FAX：06-7639-7238
9	（株）タクト・ワン	1	富塚 昌孝 代表取締役	〒162-0066　東京都新宿区市谷台町14-5　MSビル市谷台501 電話：03-3356-0649　FAX：03-3356-8769
10	テクノブレーン（株）	1	加藤 利孝 代表取締役社長	〒504-0814　岐阜県各務原蘇原興亜町1-17-1 電話：058-371-3443　FAX：058-371-2738
11	ナビコムアビエーション（株）	1	玉中 宏明 代表取締役社長	〒102-0072　東京都千代田区飯田橋3-4-4　第5田中ビル9F 電話：03-3265-6747　FAX：03-3265-6748
12	日本エアロスペース（株）	1	藏前 浩 代表取締役社長	〒107-0062　東京都港区南青山1-1-1　新青山ビル西館20階 電話：03-5785-5970（代表）　FAX：03-5785-5964
13	（株）ＳＵＢＡＲＵ	5	東稔 俊史 航空宇宙カンパニー　技術開発センター 回転翼機設計部　部長	〒320-8564　栃木県宇都宮市陽南1丁目1-11 電話：028-684-7537　FAX：028-684-7530
14	古河電池（株）	1	酒井 宏明 産業機器営業統括部 産機第三営業部 宇宙航空グループ長	〒141-0021　東京都品川区上大崎4-5-37　本多電機ビル3F 電話：03-3492-2972　FAX：03-3492-2973
15	ベストテック（株）	1	井口　邦 代表取締役社長	〒460-0015　名古屋市中区大井町3番15号　日重ビル8F 電話：052-321-8755　FAX：052-321-8758
16	三井物産エアロスペース（株）	1	河津　直行 ヘリコプター第二部 部長	〒100-0005　東京都千代田区丸の内1-8-2　鉄鋼ビルディング22階 電話：03-4586-1962　FAX：03-4586-1974
17	三菱重工業（株）	5	萩原　賢一 防衛・宇宙セグメント 航空機・飛昇体事業部 ヘリコプタ技術部 部長	〒480-0293　愛知県西春日井郡豊山町大字豊場1 電話：0568-28-6681　FAX：0568-28-6683
18	三菱プレシジョン（株）	1	平賀 好文 鎌倉事業所 シミュレーションシステム 統括部 副統括部長	〒247-8505　神奈川県鎌倉市上町屋345 電話：0467-42-5752　FAX：
19	ヤマハ発動機（株）	1	平城　大典 ヤマハ発動機（株） UMS事業推進部 開発部 機体設計グループ	〒437-0066　静岡県浜松市北区新都田1-9-3 電話：053-484-1873　FAX：053-482-7441
20	タレスジャパン（株）	1	シリル・ルネ・ジル・デュポン 代表取締役社長	〒107-0052　東京都港区赤坂2-17-7　赤坂溜池タワー8階 電話：03-6234-8100　FAX：03-6234-8101
21	レオナルド日本支社	1	ダニエレ　アルゼッタ アジア・パシフィックリム統括部長	〒100-0013　東京都千代田区霞が関3-2-1　霞が関コモンゲート西館24階 電話：03-5860-9828　FAX：03-5850-9826

２０２２年度　役員名簿

JHS 役職	氏 名	所 属 先
会　長	青山　剛史	国立研究開発法人宇宙航空研究開発機構　航空技術部門 航空機ライフサイクルイノベーションハブ長
副会長	佐藤　彰	静岡理工科大学　理工学部　機械工学科　教授
副会長	櫻田　武士	川崎重工業（株）航空宇宙システムカンパニー 航空宇宙ディビジョン　ヘリコプタプロジェクト総括部
常任理事（総務担当） （兼）幹事長	田辺　安忠	国立研究開発法人宇宙航空研究開発機構 航空技術部門 航空環境適合イノベーションハブマネージャ
常任理事（企画担当）	阿部　達也	（株）ＳＵＢＡＲＵ 航空宇宙カンパニー 技術開発センター 回転翼機設計部　回転翼機設計課　課長
常任理事（編集担当）	富塚　昌孝	タクトワン（株）代表取締役
常任理事（広報担当）	荻原　賢一	三菱重工業（株）防衛・宇宙セグメント 航空機・飛昇体事業部 ヘリコプタ技術部 部長
常任理事（国際担当）	小曳　昇	国立研究開発法人宇宙航空研究開発機構　航空技術部門 航空環境適合イノベーションハブ　主任研究開発員
常任理事（JHST 担当）	鷲田　修	朝日航洋（株）航空事業本部 資材部部長
理事	砂田　茂	名古屋大学大学院工学研究科　航空宇宙工学専攻 航空宇宙機運動システム工学研究グループ　教授
理事	伊藤　健	陸上自衛隊　東部方面航空隊　副隊長
理事	竹内　繁吉	エアバス・ヘリコプターズ・ジャパン（株） 業務本部 技術部 主席
理事	鹿野　誠	朝日航洋（株）航空事業本部 整備統括部 品質保証室　室長
理事	平城　大典	ヤマハ発動機（株）UMS 事業推進部 開発部 設計グループ
理事	石井　寛一	国立研究開発法人宇宙航空研究開発機構 航空技術部門 設備技術研究ユニット　主任研究開発員
監査役	太田　智基	（株）ＳＵＢＡＲＵ 航空宇宙カンパニー 技術開発センター 回転翼機設計部　主査
幹事（総務担当）	保江　かな子	国立研究開発法人宇宙航空研究開発機構　航空技術部門 航空機ライフサイクルイノベーションハブ　主任研究開発員
幹事（企画担当）	塚本　紘理	（株）ＳＵＢＡＲＵ 航空宇宙カンパニー 技術開発センター 回転翼機設計部　回転翼機設計課
幹事（広報担当）	澤田　実宏	三菱重工業（株）防衛・宇宙セグメント 航空機・飛昇体事業部 ヘリコプタ技術部 構造システム課 主任
幹事（編集担当）	松下　博彦	（株）エアロパートナーズ 業務部 顧問
幹事（国際担当）	杉浦　正彦	国立研究開発法人宇宙航空研究開発機構 航空技術部門 航空環境適合イノベーションハブ　主任研究開発員
幹事（JHST 担当）	藤井　羅馬	エアバス・ヘリコプターズ・ジャパン（株） 業務本部 技術部

JHS 役職	氏　名	所　属　先
幹事	小澤　康弘	防衛省 海上自衛隊 第 51 航空隊 訓練指導隊 課程教育班長
幹事	豊丸　建二	（株）ジャムコ 航空機整備事業部　顧問
幹事	饗庭　昌行	防衛装備庁 航空装備研究所　航空機技術研究部　部長
幹事	奥野　善則	国立研究開発法人宇宙航空研究開発機構 航空技術部門 航空利用拡大イノベーションハブマネージャ
幹事	赤坂　剛史	金沢工業大学 工学部 機械系 航空システム工学科 准教授
リエゾン担当		
全日本航空事業連合会 ヘリコプタ部会	鹿野　誠	朝日航洋（株）航空事業本部 整備統括部 品質保証室　室長
日本航空宇宙学会	小曳　昇	国立研究開発法人宇宙航空研究開発機構　航空技術部門 航空環境適合イノベーションハブ　主任研究開発員
経産省（SJAC）	上村　誠	VFS 日本支部
国交省（IHST）	鷲田　修	朝日航洋（株）航空事業本部 資材部部長
航空振興財団（IFR 研究会）	石井　寛一	国立研究開発法人宇宙航空研究開発機構 航空技術部門 設備技術研究ユニット　主任研究開発員
厚生労働省 （ドクターヘリ）	長尾　牧	朝日航洋（株）　航空事業本部　事業推進部　フェロー
文科省 （航空科学委員会）	齊藤　茂	国立研究開発法人宇宙航空研究開発機構 チーフエンジニア室　客員
防衛省 （防衛技術協会）	井星　正氣	防衛大学校 名誉教授
総務省（消防庁） （防災ヘリ）	鹿野　誠	朝日航洋（株）航空事業本部 整備統括部 品質保証室　室長
日本航空医療学会		
日本操縦士協会		
ヘリポート研究会		
日本女性航空協会		
日本航空協会		

JHS 役職	氏 名	所 属 先
顧　問		
名誉顧問	東　昭	東京大学 名誉教授
顧問（総務担当）	牧野　健	VFS 日本支部
顧問（企画担当）	佐藤　晃	VFS 日本支部
顧問（編集担当）	長島　知有	防衛大学校 名誉教授
顧問	上村　誠	VFS 日本支部
顧問（国際担当） （兼）VFS 本部技術委員	平本　隆	帝京大学 理工学部 教授 航空宇宙工学科 学科長
顧問（国際担当） （兼）VFS 本部理事 （兼）VFS 本部技術委員	齊藤　茂	国立研究開発法人宇宙航空研究開発機構 チーフエンジニア室 客員
顧問	井口　敦雄	MHI エアロスペースシステムズ株式会社 スペシャリスト・エキスパート
顧問	大林　秀彦	VFS 日本支部
顧問	河内　啓二	東京大学 工学系研究科 航空宇宙工学専攻 名誉教授
顧問	小林　孝	VFS 日本支部
顧問（広報担当）	高木　淳二	VFS 日本支部
顧問	古澤　正人	一般社団法人 中部航空宇宙産業技術センター
顧問	三宅　司朗	国立研究開発法人 宇宙航空研究開発機構
顧問	井星　正氣	防衛大学校 名誉教授
顧問	片山　範明	川重岐阜エンジニアリング株式会社　代表取締役社長
顧問	片山　健	中菱エンジニアリング株式会社 航空宇宙事業部　防衛航空機・宇宙技術部

日本ヘリコプタ協会　略年表

年度	会報番号	会　長（所属先当時）	総会/講演会	定例研究会、（　）内は通算回数		特別講演会 等	AHS年次総会 等
				夏　季	冬　季		
1989	–	義若 基（川崎重工）	12.15 航空会館[設立総会]	–	3.16 東大先端研 [第6回ヘリコプタ研究会]	3.13 川崎重工 –Prouty氏	義若 基氏–特別会員
1990	–		–	7.18 三菱重工(1)	2.16 幕張メッセ [第2回国際航空宇宙シンポジウム・ヘリコプタセッション]	10.5 帝国ホテル –Buckley氏(Sikorsky社長/AHS会長)	日本支部 会員増加数及び 会員増加率第1位(42名, 49%)
1991	1		5.29 川崎重工本社	7.19 富士重工(2)	2.7 防衛大学校(3)	10.24-25 東大山上会館 –Schrage教授(ジョージアエ科大)	日本支部 会員増加数及び 会員増加率第1位(15名, 11.9%)
1992	2	牧野 健（富士重工）	6.23 川崎重工本社	9.18 三菱重工(4)	2.5 山上会館(5)	12.4航空宇宙技術研究所 –Carlsorn氏(米陸軍ATCOM)	–
1983	3		6.18 富士重工本社	9.10 川崎重工(6)	2.15 山上会館(7)	7.6 健保会館 –フランスヘリコプタ技術 11.18 防大 –Ham教授(MIT)	日本支部 会員増加数第1位
1994	4	佐藤 晃（三菱重工）	6.3 富士重工本社	7.22 陸自霞ヶ浦(8)	–	11.8 三菱重工横浜 –Gessow教授(メリーランド大) 11.11 総評会館 –機械学会「交通・物流から見た将来ヘリコプタ技術」	–
1995	5		6.19 三菱重工本社	9.29 川崎重工(10)	2.23 防衛庁3研(11)	11.2 三井物産 –Gaffey氏(ベル社副社長)	–
1996	6	長島 知有（防衛大学校）	5.17 三菱重工名航	10.4 富士重工(12)	2.14 川崎重工(13)	1.20 三菱重工本社 –Crawford氏(ジュージアエ科大)	–
1997	7		6.6 住友重機追浜	10.24 三菱電機(14)	1.23 陸自木更津(15)	–	–
1998	8	西川 渉（地域航空総合研究所）	7.6 ソニー	10.2 富士重工(16)	2.19 東京ヘリポート(17)	4.21-23 Heli Japan98 岐阜県長良川国際会議場 12.22 日大 –Wang氏(シコルスキー社)	OH-X設計チーム(技本/KHI) –Howard Hughes Award
1999	9		6.16 パイオニア	10.26 陸自明野(18)	3.23 東京ビッグサイト(19) [TA2000]	4.16 日大 –Rozhdestvensky(ミル社)	東 昭 東京大学名誉教授–特別会員 義若 基氏–名誉会員 S-92開発チーム(MHI)–Robert Pinckney Award
2000	10	上村 誠（川崎重工）	6.22 川崎重工本社	11.28 陸自立川	2.23 八尾空港(21)	1.23 川崎重工社 –Schmitz教授(メリーランド大)	牧野 健氏－特別会員 S-92開発チーム(MHI) –Agusta International Fellowship Award
2001	11	上村 誠（日本航空宇宙工業会）	7.4 航技研	11.29 ヤマハ発動機(22)	2.28 東京ヘリポート(23)	1.28三菱重工本社 –Johnston氏(米陸軍)	大林 秀彦氏–特別会員
2002	12	高木 淳二（富士重工）	6.28 航空会館	–	3.13 宇都宮大学(24)	11.11-13 Heli Japan 2002 栃木県総合文化センター	定岡 庄治氏–会長特別賞 [ヘリ事始め50周年記念]
2003	13	高木 淳二（宇都宮大学）	7.3 富士重工本社	10.31 電子航法研究所(25)	3.19 海上保安学校宇都宮分校(26)	–	佐藤 晃氏–名誉会員
2004	14	小林 孝（三菱重工）	7.1 三菱重工本社	12.17 防衛庁3研(27)	2.25 名古屋国際会議場(28) [ヘリコプタによる防災シンポジウム]	10.7JA2004ヘリコプタ・セミナー パシフィコ横浜	長島 知有 防衛大学校名誉教授–名誉会員 日本支部–会員数増
2005	15	井口 敦雄（三菱重工）	7.19 グランドヒル市ヶ谷	12.16 三菱重工小牧(29)	–	8.31三菱重工本社 –Friedmann教授(ミシガン大)	–
2006	16	河内 啓二（東京大学）	4.28 三菱重工横浜ビル	10.3 JAXA調布航空宇宙センター(30)	3.15 山上会館(31)	11.5-17 Heli Japan 06 名古屋国際会議場 11.13 JAXA 調布航空宇宙センター –Philippe氏(元ONERA) 2.7 東大本郷キャンパス工学部 –Xia氏(南京航空航天大)	丹羽 義之氏–特別会員
2007	17		7.17 東京大学先端科学技術研究センター	11.20 防衛大学校(32)	–	–	–
2008	18	平本 隆（富士重工）	7.1 東京大学 山上会館	–	–	7.23 JAXA 調布航空宇宙センター –Dr.Hongvi Xu(カナダ航空宇宙研究所) 10.3 航空会館 –Dr.James M.Wang(アグスタ・ウェストランド)	–
2009	19		8.4 三菱重工	4.17 恵比寿スバルビル(33)	–	–	IHST検討委員会発足 Heli Japan2010準備委員会発足
2010	20	齊藤 茂（宇宙航空研究開発機構）	4.26 JAXA 調布航空宇宙センター	9.27 東京スポーツ文化会館(34)	–	11.1-3 Heli Japan2010 大宮ソニックシティ	IHST検討委員会
2011	21		6.17 JAXA 調布航空宇宙センター	10.31 三菱重工(35)	–	2.12-15 2012 1st AARF Busan, Korea	AHS事務局長 MR. R. Flater氏引退 Mike Hirschberg氏就任 東 昭 東京大学名誉教授–名誉会員
2012	22	井星 正氣（防衛大学校）	6.15 航空会館	10.18 海上自衛隊横須賀地方総監部(36)	3.8 ヤマハ発動機(37)		–
2013	23		7.12 ヴェルクよこすか	12.5 陸上自衛隊北宇都宮駐屯地航空学校宇都宮校(38)	–	11.26 JAXA 調布航空宇宙センター –Dr. Ki Hoon, Chung(KARI)	–
2014	24	片山 範明（川崎重工）	5.13 日本大学 駿河台キャンパス	–	–	–	–
2015	25		12.1 川崎重工 東京本社	9.14 DAYS赤坂見附(39)[JHST]	–	–	–
2016	26	片山 健（三菱重工）	7.8 川崎重工 東京本社	–	2.7 JAXA調布航空宇宙センター(40)	–	–
2017	27		7.4 JAXA調布航空宇宙センター	11.10 JAXA調布航空宇宙センター(41)	3.23 DAYS赤坂見附(42)	11.7-9 Heli Japan 2017 KKRホテル金沢	–
2018		東稔 俊史（SUBARU）	8.20 三菱重工 本社	–	–	11.22 豊田市ものづくり創造拠点 SENTAN 2018 年度第 1 回将来回転翼機研究会	–
2019			9.11 JAXA調布航空宇宙センター	–	–	12.13 JAXA 調布航空宇宙センター IADFとの共催	–
2020			–	–	–	–	–
2021		青山 剛史（JAXA）	6.14 メール開催	11.18 JAXA調布航空宇宙センター(43)	–	3.16 JAXA 調布航空宇宙センター 将来回転翼機研究会／回転翼解析技術交流会	–
2022			7.6 JAXA調布航空宇宙センター	–	–	2.10 オンライン Japan-Korea Joint Workshop on Rotorcraft 3.24 電力中央研究所 大手町地区 会議室 将来回転翼機研究会／回転翼解析技術交流会	–

日本ヘリコプタ協会　賛助会員申込書

年　　月　　日

区分 （該当するほうに○）	法人　・　個人 新規
団体（会社）名	
氏名* 役職	
連絡先* 住所 TEL FAX E-mail	〒
入会口数	口，　　万円（1 口=1 万円）
備考 （連絡事項等）	

*法人賛助会員は代表者の氏名・連絡先等をご記入下さい．

本申込書を下記，事務局宛に FAX，E-mail，もしくは郵送でご送付下さい．

〒182-8522　東京都調布市深大寺東町7-44-1
国立研究開発法人宇宙航空研究開発機構　航空技術部門
航空機ライフサイクルイノベーションハブ内
日本ヘリコプタ協会　事務局　保江かな子
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日本ヘリコプタ協会　法人会員申込書

年　　月　　日

※のある欄は必須項目です．

基本情報		
会員区分：※	一般法人会員	教育法人会員
団体（会社）名：※		
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日本ヘリコプタ協会　個人会員申込書

年　　月　　日

※のある欄は必須項目です．

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姓名（ふりがな）：※	
生年月日（西暦）：	
所属先情報	
所属先名：※	
部署名：※	
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郵便番号：※	
住所：※	
TEL：※	FAX：
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住所：※	
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