Multidisciplinary Analysis Framework for Rotorcraft Research and Development

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(Received 20 January 2024; revised 20 February 2024; accepted 21 February)

Abstract: A multidisciplinary analysis toolchain specifically for rotorcraft has been developed at JAXA. HeliDesign provides the sizing of a conventional or a compound helicopter to meet the specified mission requirement based on preliminary semi-empirical relations. rFlight delivers the trim analysis and performance of a rotorcraft together with the linearized flight dynamics models based on analytical formulations of the rotor aerodynamics from blade-element theory. rBET/RMT is a low fidelity tool based on blade-element theory. For high-fidelity aeroelastic analysis of a rotating blade, rFlow3D is constructed based on high-resolution CFD and loosely coupled with computational structural dynamics (CSD) to obtain the elastic deformations of a rotor blade, while the natural frequencies and modes are obtained using rMode. rGrid tools support the automatic grid generations around a rotor blade to be computed in rFlow3D. Acoustic signature from a rotorcraft can be predicted using rNoise based on the FW-H equations using the output from rFlow3D. These tools have been applied for new rotorcraft developments and the high-fidelity toolchain has been validated with reliable test data with satisfactory accuracy.

Key words: rotorcraft; multidisciplinary analysis; high-fidelity simulations; design tools

CLC number: V221 **Document code:** A **Article ID:** 1005-1120(2024)01-0043-10

0 Introduction

A series of rotorcraft related research projects, such as active controls of the rotor blade to reduce the BVI noise from a helicopter[1-2], high-speed compound helicopter conceptual studies[3-5], variable-pitch controlled drone protype development[6-8] and multirotor eVTOL aircraft research[9-10], have been carried out in JAXA in recent years as shown in Fig.1. Analyses have been carried out along with the wind tunnel testing and flight tests with the conceptual models. Several analysis codes specifically for rotorcraft have been developed at JAXA so far. This paper will focus on the analysis framework built in JAXA together with brief descriptions of these codes.

For development of a rotorcraft, at each design phase, tools with different levels of fidelity are required. At the conceptual design phase, the estimation of size and weight of the rotorcraft alongside with power requirement and the powerplant selection to satisfy the given missions are requested. Generally, estimations based on empirical or statistical relations are carried out, where low fidelity empirically corrected analytical formulations are often utilized. At the preliminary design phase, to confirm the feasibility of the aircraft configurations, performance and stability and control analyses based on trim analysis and the linearized flight dynamics models are often performed. At the detailed design phase, refinement of the performance and structural analysis based on high fidelity of aerodynamics are required. To support follow-on tests toward a type certification, vibrational loads together with acoustic signature predictions are desired.

In JAXA, a series of analysis codes have been

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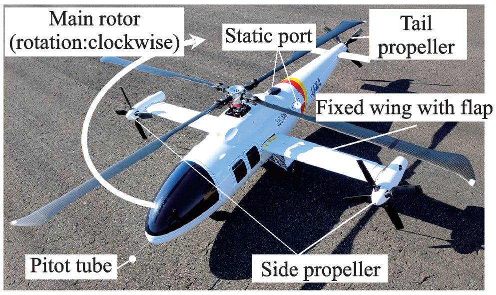
How to cite this article: TANABE Yasutada, SUGAWARA Hideaki, KIWURA Keita. Multidisciplinary analysis frame-work for rotorcraft research and development[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2024, 41(1):43-52.
http://dx.doi.org/10.16356/j.1005-1120.2024.01.003



(a) HARIOS-1/7 scale high-speed compound helicopter conceptual model

(b) Prototypes of variable-pitch controlled drones

(c) UGUISS-Lift + Cruise eVTOL aircraft concept

Fig.1 Rotorcraft R&Ds in JAXA

developed to meet the requirements at each design stage. As shown in Fig.2, HeliDesign code[3] is used for the sizing estimation of a rotorcraft at the initial conceptual design phase. rFlight[11] is developed to carry out the trim analysis of a rotorcraft with arbitrary number of rotors/propellers and fixed wings to study the flight feasibility associates with specific control mixings for different flight modes at the preliminary design phase. The aerodynamics of the rotor/propeller is based on blade element theory (BET) and integrated analytical formula are used for speedy iterations during the trim process. Linearized flight dynamics models around the trim state are provided through small perturbations of the flight conditions and control settings. Based on these models, flight stability and control laws can be investigated. For detailed aerodynamic and structural study of a rotor blade, low- and high-fidelity tools are developed. Especially the low-fidelity, BET based tools rBET/RMT[12] are efficient to deliver evaluations of a rotor blade during optimal design process. The code rMode[13] provides natural frequencies and mode shapes of a rotor blade which are inputs to rBET or rFlow3D[14] for fluid/structure coupling analysis of the rotor blade. The overlapping moving grid CFD solver rFlow3D/JANUS[15] can be combined with an unstructured-grid solver (FsSTAR[16] or TAS-code[17]) to handle the complex geometry of a rotorcraft fuselage. Finally, based on the obtained pressure distributions on the blades and fuselage by rFlow3D, rNoise[18] predicts the acoustic signatures using the Farassat formulation 1[19]. Brief descriptions of these analysis tools are given below.

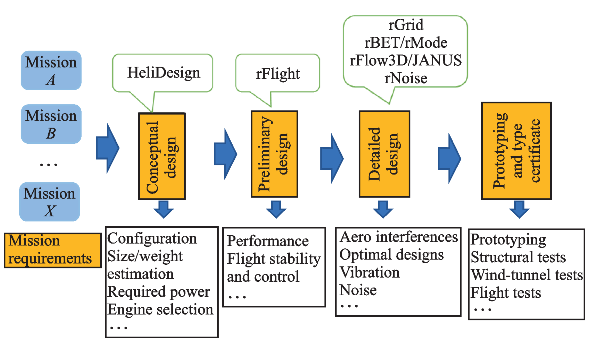


Fig.2 Analysis framework for rotorcraft developed at JAXA

1 Rotorcraft Analysis Framework

As shown in Fig.2, to develop a rotorcraft based on the mission requirements, the design can be roughly divided into four stages, i.e. the conceptual design phase, preliminary design phase, detailed design phase, and prototyping and type certification phase. The tools developed in JAXA weigh more on the research especially on the aerodynamic interactions between components and the fluid/structure coupling effect on the airloads and acoustics so far.

1.1 HeliDesign

To meet the required missions, during the conceptual design phase, after selection of the aircraft configuration, the gross weight of the aircraft can be estimated based on statistical trend study of the same type of aircraft. The sizes of the rotors and wings to match the gross weight can be determined based on empirical relations. The design process for a conventional helicopter is shown in Fig.3. The empty/gross weight ratio of current helicopters can

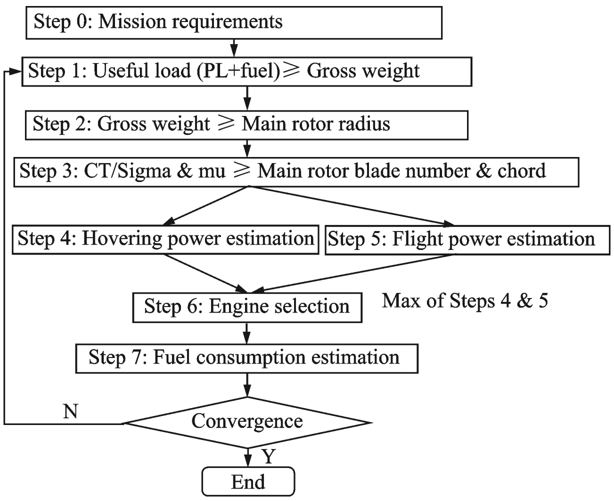


Fig.3 Conceptual design process of a conventional helicopter

be about 0.55 to 0.65. There are plenty of design samples of the conventional helicopter so the obtained designs can be believed to fall into the same design trend and similar performance with other helicopters can be expected.

However, the number of design samples of compound helicopter is small. As shown in Fig.4, based on the conventional helicopter, the addition of the wing and the propeller to the gross weight is required. The required power is estimated separately for the wing and rotor based on the design parameter of the lift-share. Using the fuel consumption rate per horsepower, the required fuel weight satisfying the mission profile can be calculated and the gross weight is updated. A converged gross weight together with the rotor and propeller sizing can be obtained after several tens of iterations.

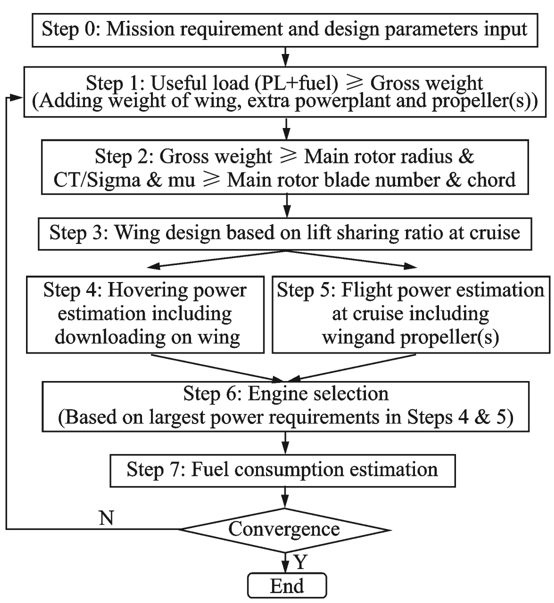


Fig.4 Conceptual design process of a compound helicopter[3]

For the newly developed eVTOL aircraft, statistical design trend, especially the empty/gross weight ratio about 0.8 is gradually being established. However, with the quick advancement of the battery capacity and other electrical components, refinement of the aircraft construction can be expected to realize lighter and more practical eVTOLs which can compete with the conventional helicopters in terms of flight speed and range while the acoustic signature can be extremely low at the same level of an automobile.

1.2 rFlight

After the rotorcraft sizing is determined by HeliDesign, as a task during the preliminary design phase, especially for current eVTOL designs utilizing multiple rotors, the flight feasibility must be studied. Depending on the aircraft configuration, especially for the Lift+Cruise type and Vectored Thrust type aircraft, the control of the aircraft during take-off and landing, and cruising flight can be very different. Transition between these two modes may add more complexity in the control laws. The allowable tilt angles of the propellers with regard to the flight speed range, i.e. the transition corridor, must be understood better beforehand of the flight tests. A tool for trim analysis, together with stability and control derivative estimation, rFlight[11], which can handle arbitrary number of rotors/propellers and wings is developed. Each rotor/propeller is assumed to have four potential controls: Collective pitch, lateral and longitudinal cyclic pitches, and the rotor rotating speed. Each wing is assumed to have a trailing edge flap for control. The mixing matrix of the controls is changed with regard to the aircraft configuration and flight mode. The wake interaction between the aerodynamic components can also be simulated.

rFlight has been applied to various types of aircraft so far. The conventional helicopter and fixed-wing airplane are among the simplest configurations. Tandem rotor helicopters, winged compound helicopters, the multicopter, Lift+Cruise and Vectored Thrust type eVTOL aircraft are also test calculated and some are verified with the existing test data.

Samples of rFlight trim analysis results for a vectored thrust type aircraft with six tilt propellers and two wings (treated as four wings in rFlight) are shown in Fig.5. The graphs are organized with the hover mode at the left, transition mode with propeller tilt angle of 45° in the middle and the cruising mode on the right. The first line shows the net forces and moments acting on the aircraft after trim analysis. The trim criteria in this analysis are to reach accelerations of less than 0.01 m/s^2 or 0.01 rad/s^2, where the net forces and moments should be very small. If the trim is not converged and large residue of forces and moments remains, it means that the flight of the aircraft is not feasible at this flight speed in the defined flight mode. It can be seen that for this aircraft, in hover mode, after flight speed of 30 Mi/h, trim state cannot be achieved. With a propeller tilt angle of 45°, the trim cannot be achieved at flight speed less than 50 Mi/h. The cruising flight can be established at flight speed greater than 60 Mi/h (practically 70 considering the attitude) with flap deflections on the main fixed wing. The required flap

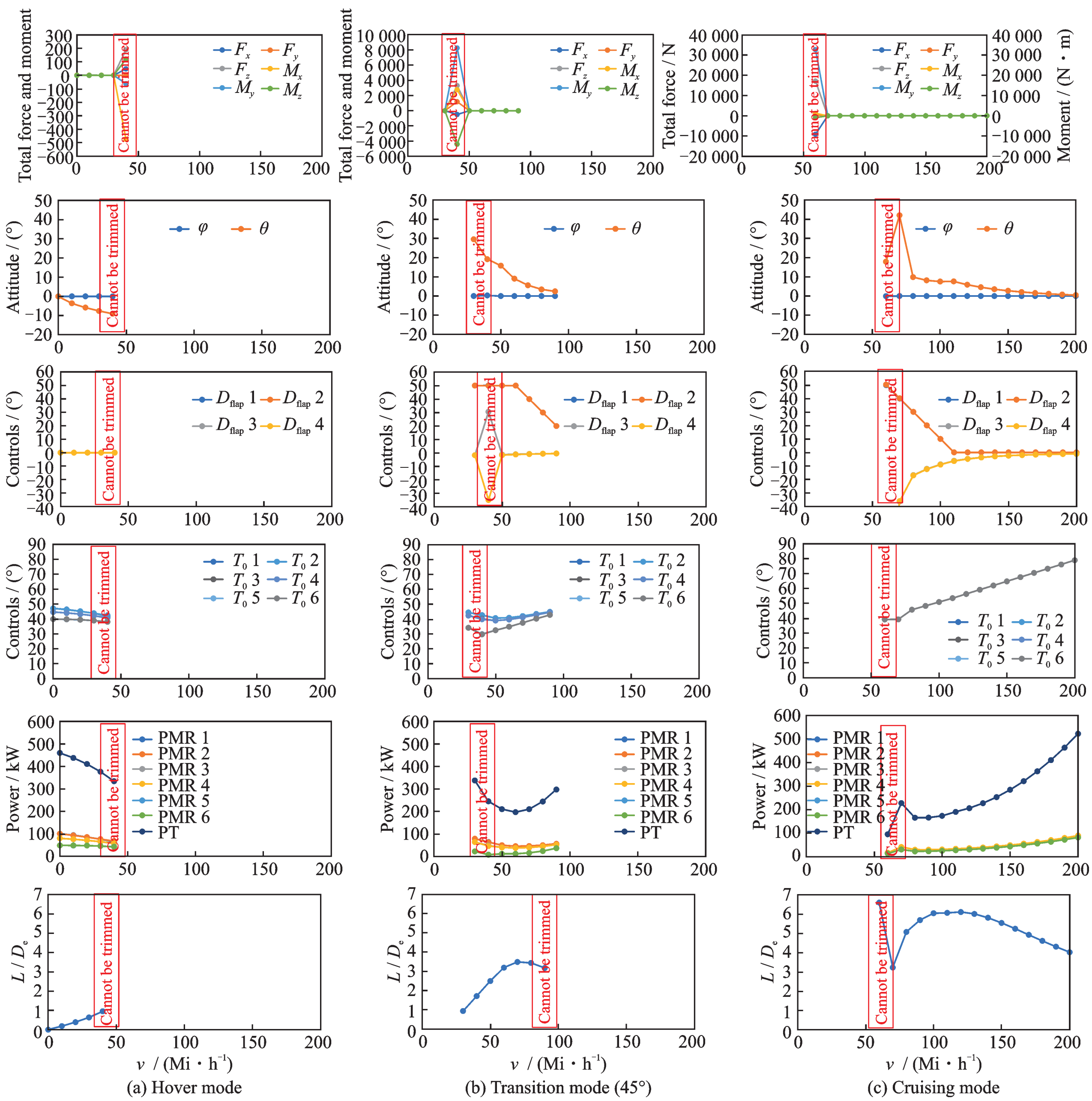


Fig.5 Sample trim analysis of a Vectored Thrust type eVTOL aircraft

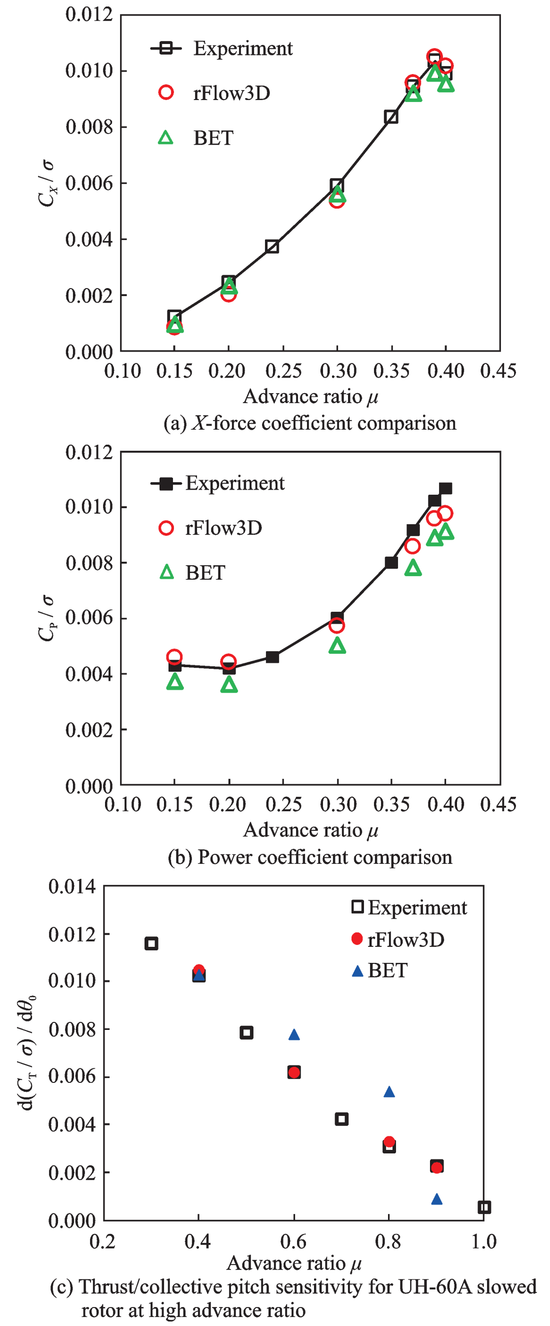
angles on each wing trailing edge ($D_{flap}1$—$D_{flap}4$) are shown in the 3rd line of Fig.5. The pitch angles of the rotors ($T_0 1$—$T_0 6$) are shown in the 4th line of Fig.5. The required powers of each rotor together with the total power are shown in the 5th line of Fig. 5. The maximum effective lift to drag ratio L/D_e is more than 6, but at the target cruising speed of 200 Mi/h, it decreases to about 4. It must be mentioned that the aircraft parameters are not based on the trusted manufacturer's data, but roughly estimated, some guessed by authors. The results are shown here only to demonstrate the analysis ability of rFlight. By adjusting the aerodynamic coefficients in the rFlight input list through comparison with CFD or test results, the reliability of the results can be improved significantly.

1.3 rBET/RMT

In the detailed design phase, optimal design of the rotor/propeller blades is often required. Quick check of the elastic deformation of the rotor blade is also required. In rBET, based on the integrated airloads of airfoil elements, nonlinear distribution of blade chord length and pre-twist can be treated. BET is a common content in textbooks (e.g., Ref. [20]) about the aerodynamics of rotary wings. The aerodynamic characteristics of the airfoil can be interpolated from a C81 table format. rBET is a low-fidelity comprehensive analysis tool for rotor analysis. rBET has been validated with CFD and experiments for a slowed UH-60A rotor[12,21-24]. Some comparisons are shown in Fig.6. The normal force coefficients C_N divided by the rotor solidity σ are compared in Figs.6(a) and (b), and the sensitivity of the normal force coefficient to the rotor collective pitch angle ϑ_0 is compared in Fig.6(c). Good agreement of rotor performance is achieved.

rBET can also be coupled with elastic deformation analysis based on the natural frequencies and mode shapes obtained by rMode. Though lack of accuracy compared to the high-fidelity CFD-CSD based analysis, the 1st order elastic deformation amplitude provide quick estimation of vibratory loads on the blade.

Code RMT is specifically for the analysis of rotors in axial flow based on Ring-Momentum-Theory.



(a) *X*-force coefficient comparison
(b) Power coefficient comparison
(c) Thrust/collective pitch sensitivity for UH-60A slowed rotor at high advance ratio

Fig.6 Validation of rBET with CFD and experiments[12]

1.4 rMode

As a part of the high-fidelity multidisciplinary analysis toolchain as shown in Fig.7, rMode provides the natural frequencies and mode shapes to be used in rFlow3D (also rBET) for Fluid/Structure coupling analysis. Treating the rator blade as a rotating beam, rMode can calculate the natural frequencies and mode shapes based on Myklestad method. sample results for HART-Ⅱ[25] rotor blade are shown in Figs.8 and 9.

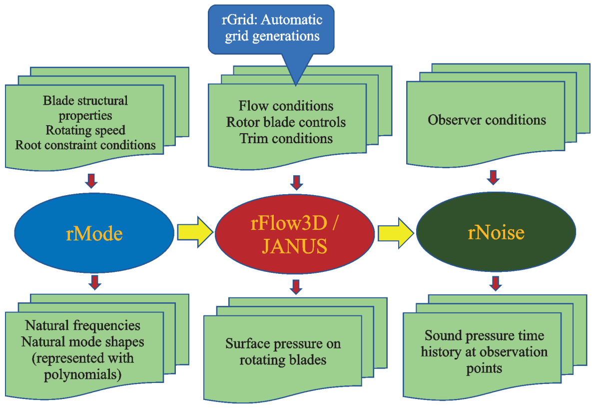


Fig.7 High fidelity CFD/CSD/Trim/Noise analysis toolchain

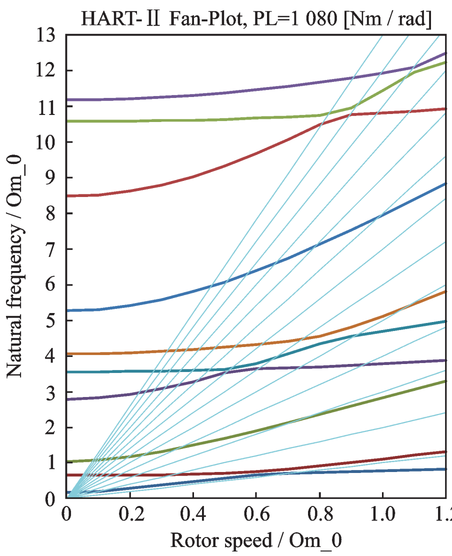


Fig.8 Change of natural frequency with rotating speed for HART-II rotor blade

1.5 rGrid

rGrid provides a toolset for grid generation to be used in rFlow3D as shown in Fig.10. Standard structured blade grid adopted in rFlow3D is SOH (Singular line at I index ends, O-type in J index and H-type in K index) type, where a singular line is formed at each blade end, which provides high flexibility of blade planforms.

1.6 rFlow3D/JANUS

rFlow3D is the core CFD tool in the high-fidelity analysis toolchain developed at JAXA for rotorcraft and it has been applied to various types of rotary wings. The key numerical method is the adoption of an all-speed numerical scheme, modified SLAU[26], which specifically fits for the rotary wings where a wide range of flow speed co-exists[27]. To handle the complex geometry of a rotorcraft fuselage, rFlow3D can be combined with an unstructured-grid solver (FsSTAR[16] or TAS-code[17]) and called as rFlow3D/JANUS[15]. FCMT reconstruction[28] delivers the 4th order of spatial accuracy for shock-free flows. Explicit 4-stages Runge-Kutta time integration for Cartesian background grid while implicit time integration is adapted for blade/body grids. High fidelity CFD/CSD/Trim loose coupling analysis can be carried out. Any number of rotors can be treated theoretically (only machine power and memory limitation).

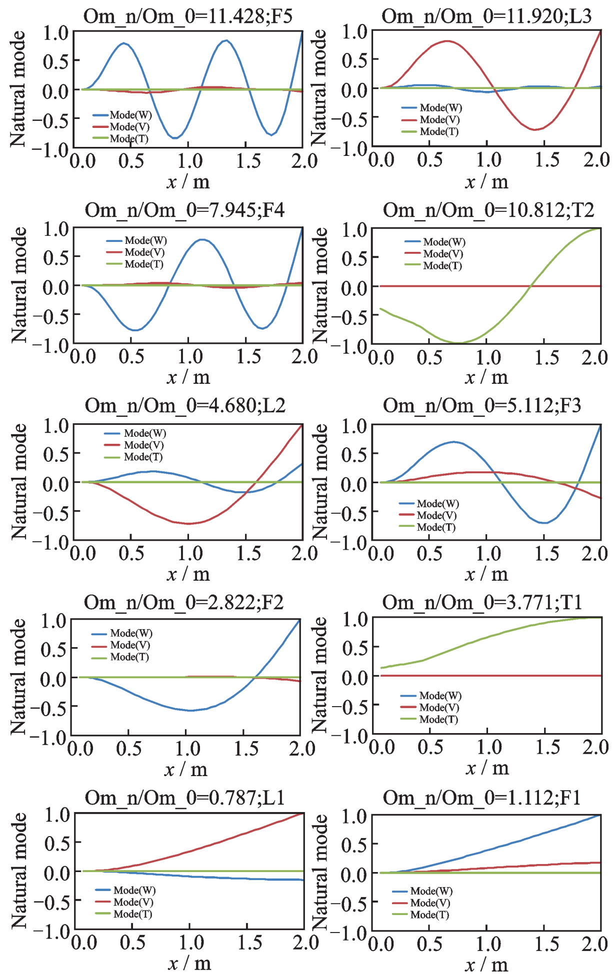


Fig.9 Mode shapes of HART Ⅱ blade at 100% RPM

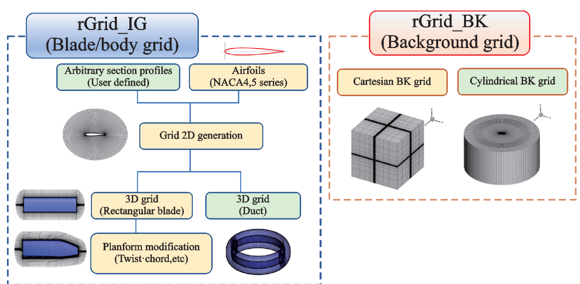
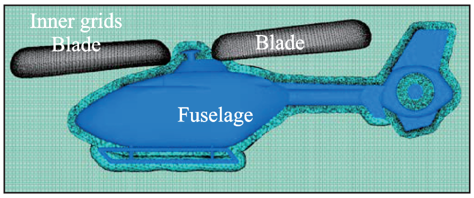
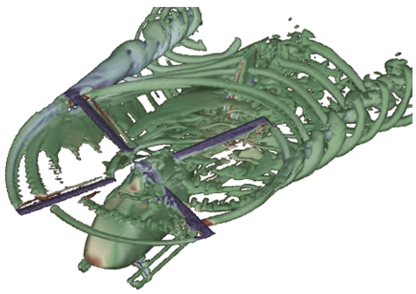


Fig.10 rGrid toolset

An example of the results obtained by rFlow3D/JANUS is shown in Fig.11. A realistic helicopter fuselage with skids and empennage stabilizers is surrounded by a thin layer of unstructured grid. The flow within the unstructured grid is computed by TAS-code and interpolated between the background grids.



(a) Grid geometry for rFlow3D/JANUS



(b) ISO Q-criteria surface and surface pressure contour

Fig.11 Flowfield around a helicopter with realistic fuselage geometry by rFlow3D/JANUS[15]

A sample of applications of rFlow3D to the analysis of a quadrotor drone in ground effect is shown in Fig.12[29]. The rotor wake interaction with the ground and the central fuselage forms a highly complex flowfield and a local flow recirculation on the rotor at certain altitudes is observed which causes rotor performance to decrease and may lead to flight instability.

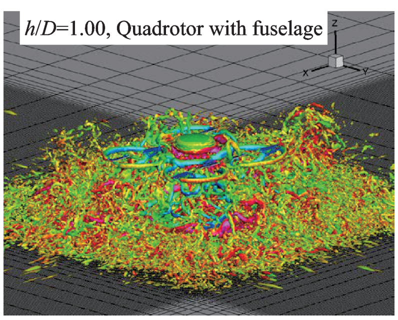


Fig.12 A quadrotor drone in ground effect

Understanding the interaction between the multiple rotors in forward flight is also important to correctly estimate the power requirement of an eVTOL aircraft. As shown in Fig.13, for a three-rotor layout, position shift of the second rotor can significantly reduce the interference effect between the three rotors at high advance ratio flight.

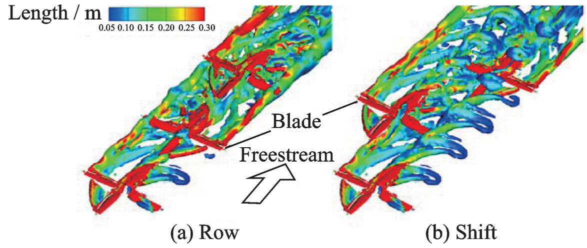


Fig.13 Comparison of flowfeild around three rotors between straight and shifted layout at $\mu = 0.7$[10]

1.7 rNoise

The acoustic signatures from a rotor at a given observation location can be predicted from the periodic surface pressure distributions on the rotor blades using rNoise[18] based on Farassat formulation 1[19]. The elastic motions can also be taken into account, which are also part of the output from rFlow3D. The prediction accuracy of rNoise combined with rFlow3D has been validated in numerous test cases so far, e. g., Refs.[14, 30].

The predicted noise level, especially for the impulsive BVI noise, has a strong correlation with the grid resolution which is directly related to the preservation of the tip vortices from the rotor blades as shown in Figs.14 and 15[14].

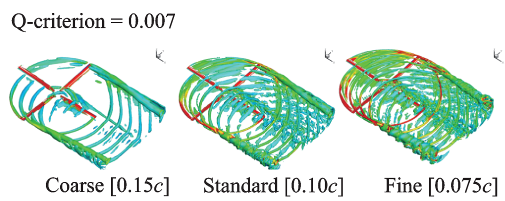


Fig.14 Blade tip vortices capturing dependent on grid resolution[14]

2 Summary and Outlook

The analysis framework for rotorcraft research and development built in JAXA is introduced. HeliDesign is for the sizing of a rotorcraft at the conceptual design phase, while rFlight is developed with the intendance to be used in the preliminary design phase of a rotorcraft with multiple rotors. At the detailed design phase, multidisciplinary analysis is required, where low- and high-fidelity toolchains are prepared. Using the natural frequencies and mode

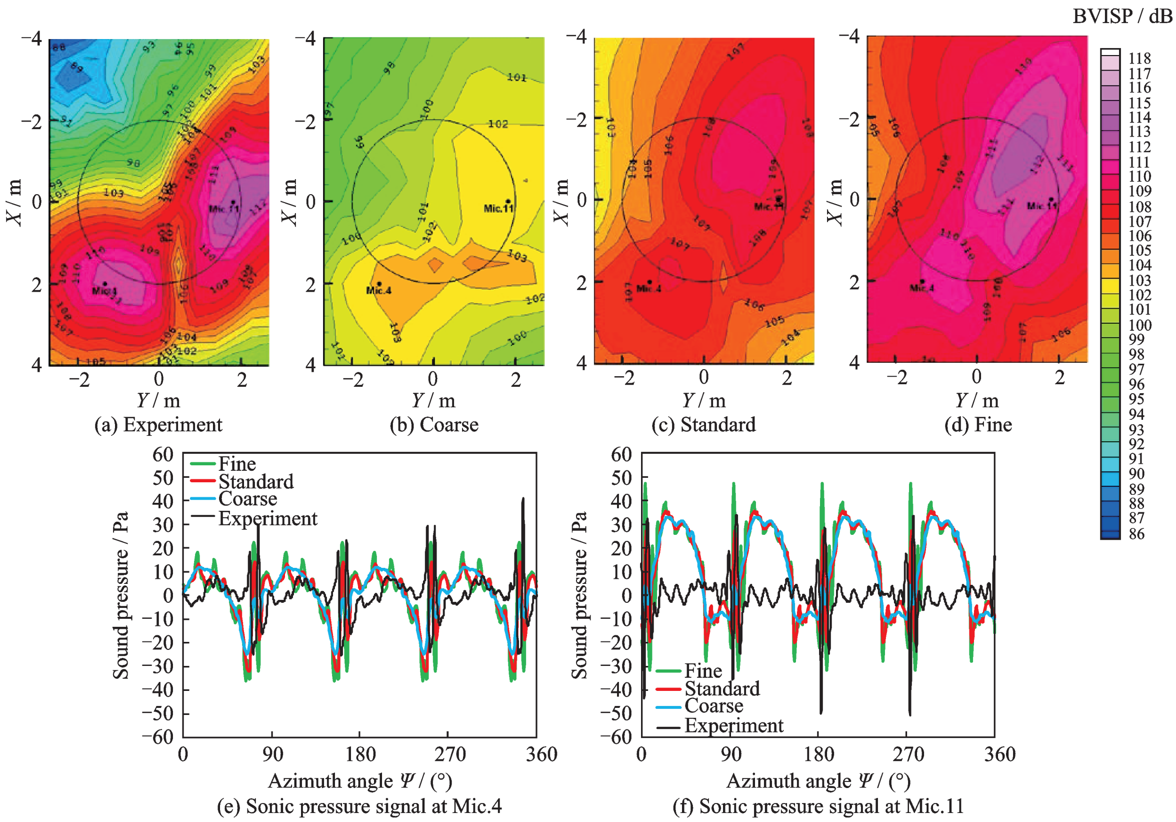


Fig.15 Predicted BVI noise levels dependent on grid resolution[14]

shapes calculated by rMode, the rBET software can provide quick and the 1st order accurate results of the airloads together with the elastic deformations. As a high-fidelity toolchain, rMode/rFlow3D/rNoise can carry out CFD/CSD/Trim loose coupling analysis and the quasi-steady results are used for noise predictions. rGrid toolset provides users with automatic grid generations for rFlow3D.

Most of the analysis tools for rotorcraft developed at JAXA are being licensed to the industries and academic universities and institutes widely in Japan. Continuous refinements and version-ups of these tools are carried out to meet the requirements of users and research and development of new types of rotorcraft, especially the various types of eVTOL aircraft.

So far, the analysis framework built in JAXA focuses on the early stages. From the standpoint of industry, the reduction of the workload especially in the type certification stage is more important. Introduction of MBSE (Model-based system engineering) and CbA (Certification by analysis) looks very attractive. The tools in current analysis framework should be incorporated into the MBSE and CbA process through the cooperation with industry in the near future.

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Competing interests The authors declare no competing interests.

(Production Editor: WANG Jing)

用于旋翼飞机开发研究的多分野解析框架

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摘要:介绍了日本宇宙航空研究开发机构研发的用于旋翼飞机的多分野解析框架。HeliDesign是在各种旋翼飞机初期概念设计时使用的软件;rFlight可以提供在各种飞行条件下的平衡解析和线性化飞行模型;rBET/RMT是基于叶片要素理论的低保真度空力解析软件,和rMode提供的结构模型结合,可以推测旋转翼的弹性变形和各种飞行条件下的空力负载;rFlow3D是基于CFD计算的高保真度数值模拟软件;rGrid系列自动网格构造工具为其提供简单的网格生成;基于rFlow3D的计算结果,rNoise可以预测在任何观测点的噪声。这些软件已经广泛地被应用在各种新型旋翼飞机的开发研究中,其计算精度也已被各种实验结果所应证。

关键词:旋翼飞机;多分野解析;高保真模拟;设计工具