AN ONERA/JAXA CO-OPERATIVE RESEARCH ON THE ASSESSMENT OF AERODYNAMIC METHODS FOR THE OPTIMIZATION OF HELICOPTER ROTOR BLADES, PHASE II

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Abstract

Efficient Global Optimization methods combined with high fidelity CFD analysis have been developed at ONERA and JAXA, respectively. Considering the technical requirements aroused from design of next generation high speed rotorcraft, it is beneficial to both parties to carry out a cooperative research on the optimization of helicopter rotor blades to share experience for best practice in this field. This co-operative research consists of two phases. As Phase 1, the aerodynamic optimization of rotor twist at a given thrust in hovering was discussed. As a result, the Kriging model based methods of both parties gave similar results. In this paper, multi-point optimization for hovering and forward flight is analysed as Phase 2. The obtained multi-point optimization results show reasonable twist distribution, which is intermediate between single objective optimization results of hovering and forward flight. In all of cases, a BO-105 40% scaled rotor is used as a baseline.

1. INTRODUCTION

ONERA has been performing optimized designs of rotary blades since 1970s and many of resulting accomplishment have been applied to real industrial designs. As a state of the art, high fidelity CFD analysis is utilized combined with the adoption of updated optimization algorithms. [1, 2] On the other hand, JAXA has been using advanced Multi-Objective Genetic Algorithms for optimizing the rotor noise and performance based on advanced numerical flow simulations. [3-5] Considering the technical requirements aroused from design of next generation high speed rotorcraft and the complex feature of the flowfield around rotary wings, it is beneficial to both parties to carry out a co-operative research on “Assessment of Aerodynamic Methods for the Optimization of Helicopter Rotor Blades” to share experience and recommendations for best practice in this field through working on common test cases using original software developed in each party.

Common test cases are defined based on a step-by-step strategy. In all of these cases, a BO-105 40% scaled rotor is used as a baseline. Each partner will perform an aerodynamic optimization on each test-case using its own tool and methodology. The results obtained on ONERA side and JAXA side will be then used for comparisons in order to promote discussions on the optimization strategies applied.

This cooperative research consists of two phases. A number of tasks were agreed with Phase 1 devoted to the aerodynamic optimization of rotor twist at a given rotary wing tip velocity for optimal figure of merit at a given thrust in hovering. Multi-point optimization for hovering and forward flight is analysed as Phase 2 in this paper. Number of design variables and parameterization used to describe the twist, and also the optimizing methodology adopted are at the discretion of each party.

2. OPTIMIZATION METHODOLOGIES

Each party has been developing the optimization methodologies independently though, the fundamental optimization procedures are identical as follows. For the modification of blade geometry, optimization technique is combined with CFD solver. In the present research, CFD technique to get aerodynamic solution and optimization technique to obtain optimized blade geometry are weakly coupled. Grid for CFD analysis is modified using blade geometry design variables which are suggested by the optimization method. The results of CFD analysis is used to evaluate the objective functions for optimization process. In this section, each party’s optimization procedure is elaborated.

2.1. ONERA

The optimization framework in ONERA is shown in Fig. 1. ONERA employs two optimization strategies.

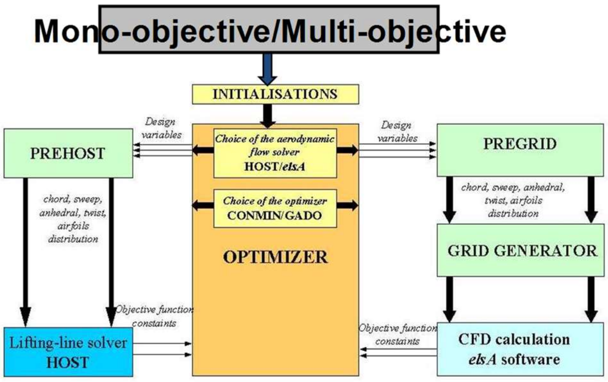

Fig. 1. ONERA existing CFD based rotor optimization framework.

The first one is based on a gradient descent algorithm (conmin_mfd, from the DAKOTA open-source library). The gradients of the parameters with respect to the objective function are obtained by finite differences. The second method consists in using an Efficient Global Optimization (EGO) strategy. This approach starts by constructing a surrogate model of the objective function by Kriging fitting on a sample of CFD results obtained by Latin Hypercube Sampling (LHS) of the design space. Next, the EGO method refines iteratively the accuracy of the surrogate model by adding, at each new iteration, two extra points to the CFD sampling. The first point corresponds to the minimum of the surrogate model. The second point corresponds to the maximum expected improvement (EI) of the surrogate model. The maximum expected improvement is sought by a Non Sorting Genetic Algorithm (NSGA_2).

2.2. JAXA

In JAXA, a Kriging model based GA optimization as shown in Fig. 2 is adopted. Once the GA optimization is over, the validity of the search region is exammined using Kriging model. The sample points are interpolated with the Gaussian random function as the correlation function to estimate the trend of the stochastic processes. EI of objective function is directly used as fitness values in the optimization. GA maximizes Eis of objective functions to find the non-dominated solutions about EIs and several points are selected from the non-dominated solutions to update the Kriging model. The details of GA and Kriging model are described in [6, 7].

3. CFD

The details of CFD solvers are described here.

3.1. ONERA

The CFD *elsA* code, [8] developed at ONERA,

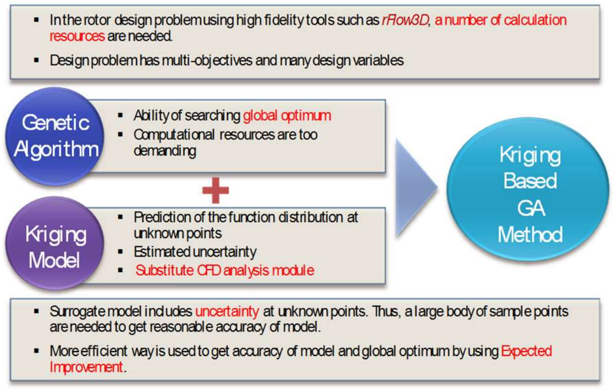

Fig. 2. Kriging based GA optimization method combined with rotor CFD code used in JAXA.

solves the three dimensional URANS (Unsteady Reynolds-Averaged Navier-Stokes) equations for both background Cartesian grids and blade curvilinear grids. The spatial discretization of the equations is performed with Jameson's cell-centered second order scheme, using 2nd and 4th order coefficients of artificial viscosity. Turbulence is taken into account by the Kok k-ω model, with Shear-Stress Transport (SST) corrections and Zheng limiter. The flow is supposed to be fully turbulent (no transition model is applied).

3.2. JAXA

CFD solver for rotorcraft (rFlow3D) has been systematically developed at JAXA. [9] The rFlow3D is a highly versatile CFD code that can numerically simulate flows around helicopter in a wide range of flow conditions, considering trimming and blade elastic deformation. The governing equations of rFlow3D for blade grids are the three dimensional compressible URANS equations. Turbulence is taken into account by the Spalart-Allmaras model without ft2 term (SA-noft2). Finite volume method and moving overlapped grid method are used in this numerical solution. mSLAU (modified Simple Low-dissipation AUSM) which is modified for applying all-speed SLAU scheme to moving overlapped grid method is used for numerical velocity, and fourth spatial precision FCMT (Fourth-order Compact MUSCL TVD) scheme is used for reconstruction of physical values. For time integration, fourth-order Runge-Kutta method is used in background orthogonal grid, and dual-time stepping method is used in blade grids to construct unsteady implicit method. LU-SGS/DP-LUR is used for simulated time integration. Tri-Linear interpolation method is used for exchange of values among grids.

Main differences of the optimization methods and the CFD solvers between ONERA and JAXA are summarized in Table 1, where FD stands for a gradient algorithm based on finite difference.

4. OPTIMIZATION CONDITIONS

HOTIS (Hover Tip vortex Structure test, [10]) and HART II (2nd HHC Aeroacoustic Rotor Test, [11]) data is employed to compare the optimization results of each party. The experimental setup of HOTIS is shown in Fig. 3. A fuselage was added to the rotor in HART II, but an isolated rotor is assumed in this study as a first step. Tables 2, 3, and 4 summarize the blade specifications and test conditions, respectively. The parametrization of the twist distribution is agreed between two parties to use a common method based on cubic splines, limiting the

Table 1: Main differences between ONERA and JAXA.

	ONERA	JAXA
Optimization Method	Gradient-Based, FD Gradient-Free, GA on Kriging + EI	Kriging Model Based Genetic Algorithm Search for Maximum Expected Improvement
CFD Solver	*elsA*, RANS	rFlow3D, RANS

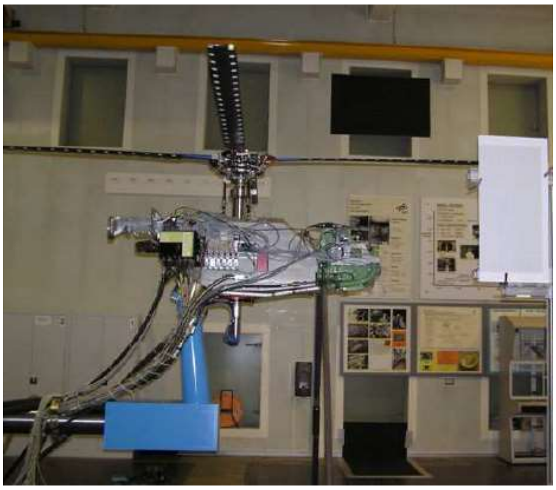

Fig. 3. HOTIS (HOver TIp vortex Structure test) setup. [10]

Table 2: Rotor properties. [10]

Number of blades	4
Airfoil section	NACA23012
Rotor radius, m	2.0
Chord length ,m	0.121
Twist ,deg	-8.0
Root cutout ,m	0.4

Table 3: Test condition of hovering. [10]

Tip Mach Number M_{tip}	0.641
Trim Condition C_T/σ	0.1
Shaft Angle, deg	0.0

Table 4: Test condition of forward flight. [11]

Advance ratio μ	0.303
Tip Mach Number M_{tip}	0.641
Trim Condition C_T/σ	0.0639
Shaft Angle, deg	-7.2

Fig. 4. Common ONERA/JAXA parametrization of the twist through cubic splines, with two degrees of freedom at r/R=0.875 and r/R=1.0.

Table 5: Common ONERA/JAXA parametrization of the twist through cubic splines, with two degrees of freedom at r/R=0.875 and r/R=1.0.

Control Points	Constraints
r/R=0.75	fixed
r/R=0.875	$\Delta\theta_1$=-10~+10°
r/R=1.0	$\Delta\theta_2$=-10~+10°

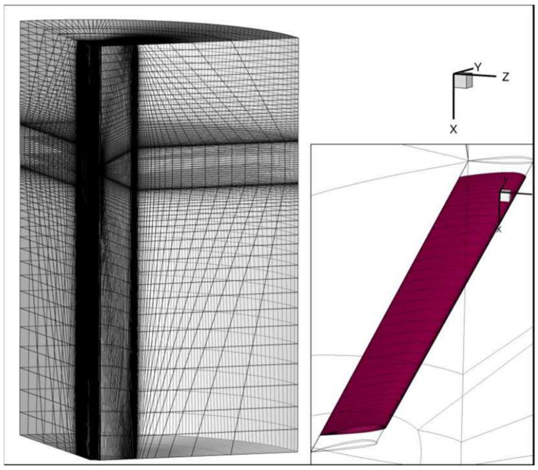

Fig. 5. ONERA CFD grid around blade.

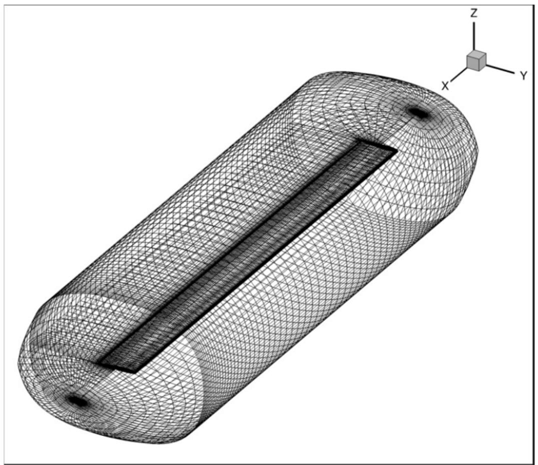

Fig. 6. JAXA CFD grid around blade.

design freedom to only two by defining the twist angles at r/R=0.875 and at the blade tip. The values are bounded within 10 degrees changing from the baseline blade with a linear twist of 8 degrees as shown in Table 5. CFD grids of each party are shown in Figs. 5 and 6, respectively. Objective functions of hovering and forward flight are figure of merit (FM) and thrust coefficient and torque coefficient ratio (C_T/C_Q).

5. OPTIMIZATION RESULTS

The optimal twist distribution in hovering as results of the applied optimization methods are shown in Fig. 7 and in Table 6. The Kriging model based methods of both parties gave similar results while the FD method suggested a more limited twist down at the blade tip. Figure 8 shows the objective function distribution of JAXA Kriging model.

On the other hand, the optimal twist in forward flight is shown in Fig. 9 and Table 7. The twist distribution is shallower than hovering. The objective function distribution is also shown in Fig. 10.

In multi-point optimization of hovering and forward flight, the optimization method suggests a twist distribution whose performance is high in both FM and C_T/C_Q (see Fig. 11). Figure 12 and Table 8 show the twist distribution of the highest performance. From this figure, it is seen that this twist distribution is in between Fig. 7 and Fig. 9. Each objective function distribution is shown in Figs. 13 and 14. Both figures are assumed to approach to Fig. 8 and Fig. 10, respectively, by increasing the number of sampling points.

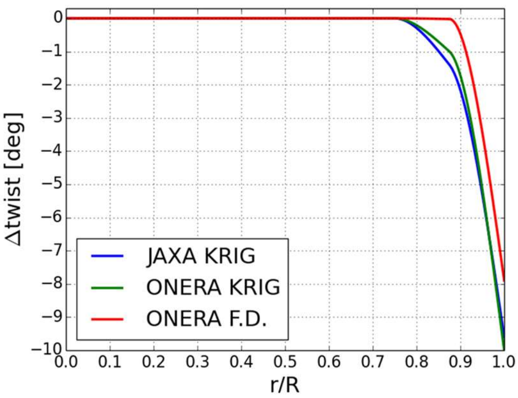

Fig. 7. Results of optimal twist distribution at blade tip portion in hovering. [5]

Table 6: Optimization results of hovering. [5]

	$\Delta\theta_1$	$\Delta\theta_2$
ONERA F. D.	-0.023	-7.896
ONERA Kriging	-1.0	-10.0
JAXA Kriging	-1.40	-9.60

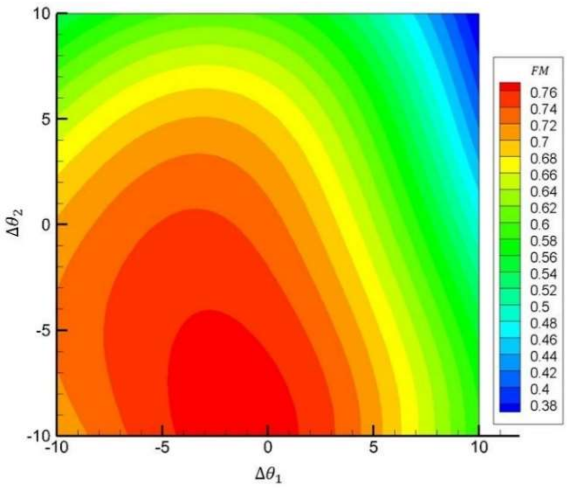

Fig. 8. Objective function distribution contour of JAXA Kriging model in hovering. [5]

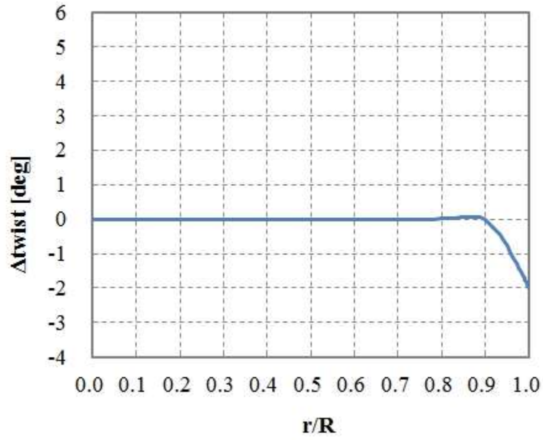

Fig. 9. Result of optimal twist distribution at blade tip portion in forward flight.

Table 7: Optimization result of forward flight.

	$\Delta\theta_1$	$\Delta\theta_2$
JAXA Kriging	0.08	-2.00

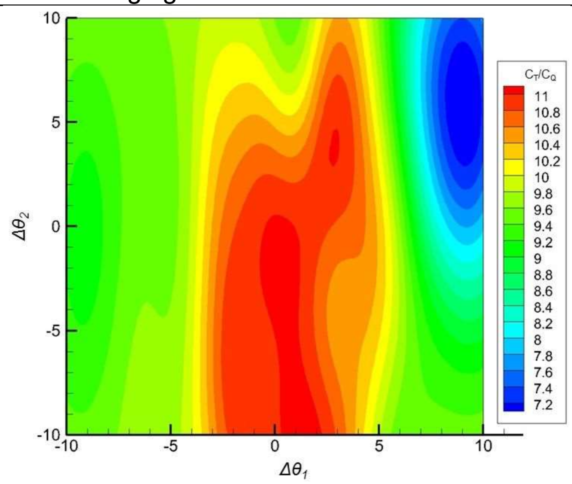

Fig. 10. Objective function distribution contour of JAXA Kriging model in forward flight.

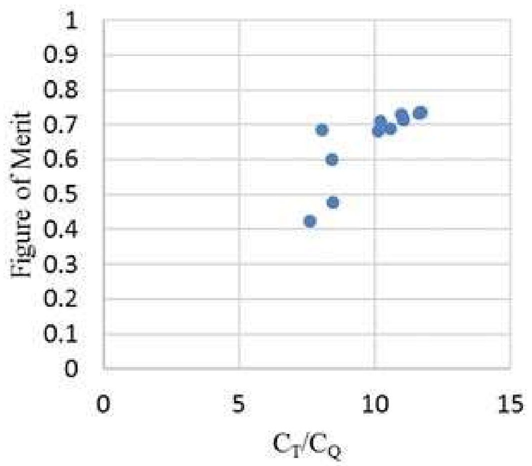

Fig. 11. Sampling data points in multi-point optimization.

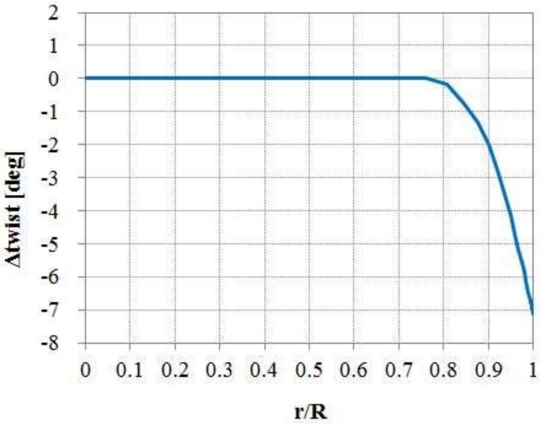

Fig. 12. Result of multi-point optimal twist distribution at blade tip portion.

Table 8: Multi-point optimization result.

	$\Delta\theta_1$	$\Delta\theta_2$
JAXA Kriging	-1.56	-7.38

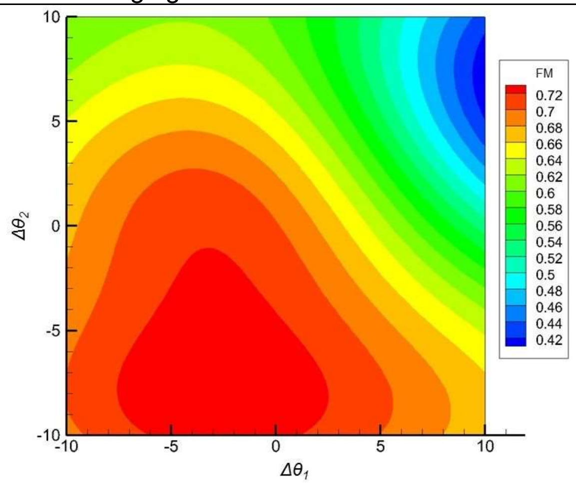

Fig. 13. Objective function distribution contour of JAXA Kriging model in hovering.

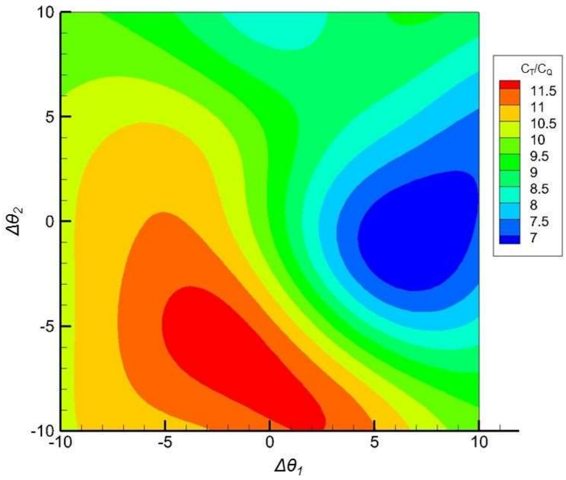

Fig. 14. Objective function distribution contour of JAXA Kriging model in forward flight.

6. CONCLUSIONS

In this study, multi-point optimization was conducted as the reference of ONERA/JAXA co-operative research. As a result, a reasonable twist distribution was obtained. Pareto front will be investigated by increasing the number of sampling data in the near future. And the Pareto front will be validated by comparing JAXA's with ONERA's. In addition to twist, chord length, sweep angle, and dihedral angle will be included in the blade geometry parameter.

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