DEVELOPMENT OF IMPROVED ROTOR BLADE TIP SHAPE USING MULTIDISCIPLINARY DESIGN ANALYSIS AND OPTIMIZATION

Joonbae Lee, joonbae.lee@koreaaero.com, Korea Aerospace Industries, LTD., Republic of Korea
Sang Nam Kang, snkang2@koreaaero.com, Korea Aerospace Industries, LTD., Republic of Korea
Sang Gi Lee, sglee@koreaaero.com, Korea Aerospace Industries, LTD., Republic of Korea
Dong Kyun Im, im1304@naver.com, Youngsan University, Republic of Korea
Hee Jung Kang, hkang@kari.re.kr, Korea Aerospace Research Institute, Republic of Korea
Duck-Joo Lee, djlee@kaist.ac.kr, Korea Advanced Institute of Science and Technology, Republic of Korea

Abstract

Tip shape optimization of rotor blade is performed to improve hover performance and to reduce required power and forward flight noise by using multidisciplinary design analysis and optimization framework with ModelCenter. The blade tip above radius of 93.5% is optimized from the Light Civil Helicopter being developed in Korea. The single sweep tip is slightly good at hover performance and forward flight noise. The single sweep tip is superior to approach noise and dynamic load of pitch link in particular. It is inferred that the single sweep tip is the optimal solution. The optimal design is analyzed in noise condition using CSD/CFD coupling method to validate results from MDAO process. The single sweep tip shape has lower noise level than baseline.

1. INTRODUCTION

Helicopters operate under extreme vibration environments intrinsically which are dominated by complicated interactions of aerodynamic and structural impacts. The vibrations of the helicopter may degrade the performance and noise and shorten the structural life. In addition, the combined effects of unsteady aerodynamic behaviour and flexible rotor blade result in aeromechanic instability, which may significantly influence the stability of the aircraft structure. Therefore, there is an ample need for the multidisciplinary design including aerodynamics, structures, dynamics and acoustics, which can be implemented in optimized design and development of helicopters.
Since the early 1990s, ONERA has performed several design studies in the framework of single optimization programs such as the ORPHEE and B2005 for aerodynamics[1-3] and for dynamics[4] and ERATO for acoustics[5]. These efforts contributed to the new Airbus Helicopter's Blue Edge blade, based on a double swept blade planform[6]. In the same way, since 1975, the different phases of the British Experimental Rotor Programme (BERP[7,8]) led to the design of an optimized rotor blade with increased hover and forward flight performance and reduce vibration. These technologies were demonstrated on AgustaWestland helicopters. Since 1980, several studies on optimization for rotor blade planforms have been performed at NASA, dealing with multi-objective optimization procedures, relative to the aerodynamics, structures and dynamics.

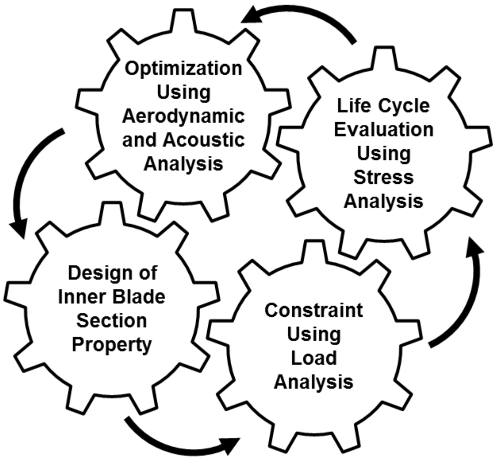

Figure 1. Process on Development of Blades

Most previous studies show that an optimum solution found from an aerodynamic design can present some unrealistic shape when additional structural constraints are not taken into account in the optimization procedure. Recently, ONERA has been studied rotor aerodynamic optimization including structural data update[9]. This optimization study was performed on acoustics and aerodynamics.
Korea Aerospace Industries, LTD. (KAI) is going to develop Light Civil Helicopter based on EC155B1 and to develop LCH with improved rotor blades[10]. Figure 1 shows the process on development of rotor blade. This iterative method needs too many resources and time requirement. Therefore, we choose the Multidisciplinary Design

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Analysis and Optimization (MDAO) which updated automatically input/output variables of each module to reduce resources and time. In this study, tip shape optimization of rotor blade is performed to improve hover performance and to reduce required power and forward flight noise compared to LCH.

2. NUMERICAL METHOD

2.1. Reference Rotor Definition

Rotor blade of LCH based on EC155B1 helicopter is chosen by baseline model. The reference rotor is five-bladed and full scale, with an aspect ratio of 16.3. The blade planform is presented in Fig. 2.
The blade planform is rectangular with parabolic shape of leading edge at the tip. The blade is equipped with the three airfoils OA212, OA209, OA207. Linear interpolation is performed in the area between these airfoils.

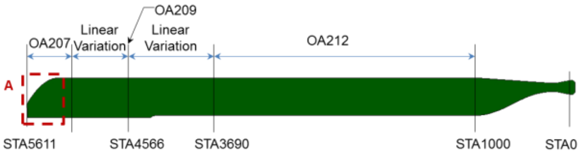


Figure 2. Main Rotor Blade Planform

2.1.1. Optimization Procedure

The multi objective of this study is to improve hover performance and to reduce noise and required power. It is optimized above 93.5% radius of tip region for easy manufacturing.
Table 1 shows the objective functions to find optimal solutions. Each objective functions are consist of a few flight conditions and are applied as single function imposed weighting factors. In the objective function of noise, the weighting factor is the largest in approach generated by Blade Vortex Interactions (BVI). In the objective function of hover performance, three collective pitch angles are analysed to consider the performance curves. Among them, it is focused in 7 degree of collective pitch angle which is close to that of Maximum Take-Off Gross Weight (MTOGW) of baseline helicopter. It is simplified to three flight conditions by analysing mission profiles in the objective function of required power. The constraints are presented in Table 2. The dynamic loads of pitch link and damper have 10% margins those of baseline. The noise conditions are added to the constraints so that they do not exceed the noise of baseline.

The design variables are shown in Table 3. The optimization is performed in two design spaces, single sweep and double sweep. Chord ratio of double sweep tip is a ratio of chord length from r/R=93.5% to r/R=96%. Taper ratio is a ratio is a ratio of chord length from r/R=96% to tip. Sweep angle is swept back/forward angle from r/R=93.5%. Anhedral starts from r/R=94.5% to tip.

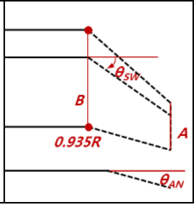
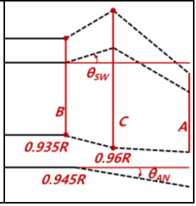
Table 1. Objective Function

	Objective Function		
	Check Item		Weighting Factor
Noise	Approach	$\frac{OASPL}{OASPL_0}$	0.60
	Overflight		0.20
	Takeoff		0.20
Figure of Merit	$\theta_0 = 5^\circ$	$\frac{FM}{FM_0}$	0.10
	$\theta_0 = 7^\circ$		0.80
	$\theta_0 = 9^\circ$		0.10
Required Power	Hover	$\frac{P}{P_0}$	0.15
	Vy		0.55
	0.9Vh		0.30

Table 2. Constraints

	Constraints		
	Check Item		Range
Autorotation Index	Blade First Moment of Inertia	$\frac{MoI}{MoI_0}$	≥ 0.95
Frequency	Isolated Rotor Frequency	$\lvert f_m - f_{m0} \rvert$	≤ 0.3
Limit Load	Pitch Link & Damper Load	$\frac{Load_{dyn}}{Load_{0,dyn}}$	≤ 1.1
Noise	Approach	$\frac{OASPL}{OASPL_0}$	≤ 1.0
	Overflight		
	Takeoff		

Table 3. Design Variables

Design Variables	Single Sweep	Double Sweep
Chord Ratio (C/B)	-	1.0 ~ 1.5
Taper Ratio (A/B)	0˚ ~ 30˚	-40˚ ~ 0˚
Sweep Angle (θ_{SW})	0.34 ~ 0.70	
Anhedral (θ_{AN})	0˚ ~ 15˚	
Concept		

2.1.2. Multidisciplinary Design Analysis and Optimization Framework

The optimization procedure is integrated into commercial tool ModelCenter[11], using genetic algorithm as shown in Fig. 3. The objective functions are the minimization of the noise level and required power and the maximization of Figure of Merit (FM). The goal is evaluated with the CAMRAD II[12] comprehensive analysis, developed by Wayne Johnson. The noise analysis is calculated by in-house code[13].

The blade planform is changed by design variables. To analyse elastic blades, the structural properties are updated by using Mach scaling method.

Initial 100 sample points produced by Latin-Hypercube sampling are analysed to build surrogate model. Response surface model is constructed by polynomial and Kriging model. Response surface model is improved by adding other 100 sample points of design space including pareto fronts.

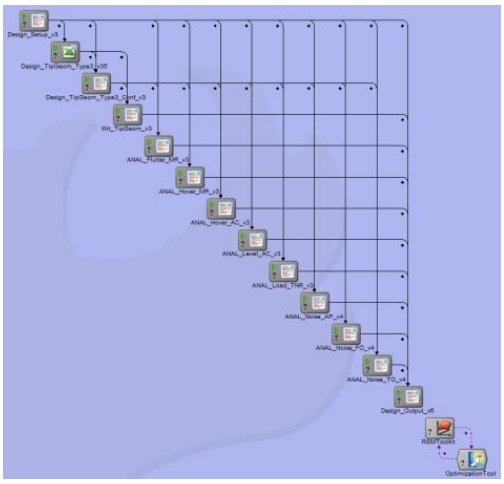


Figure 3. MDAO Framework

2.1.3. CFD/CSD Coupled Analysis

The blade tip shape from optimal solution is analysed in two flight conditions for noise (approach, overflight) by CSD/CFD coupling method, which is more accurate than pure comprehensive analysis for the evaluation of three-dimensional effects of the flow field. The KFLOW[14], developed by KU, is used to CFD analysis. In this study, the flow field is calculated by Euler solver to reduce time resources.

The loosely coupled analysis of CAMRAD II (CSD) and KFLOW (CFD) is performed by using the delta airloads technique[15] as shown in Fig. 4.

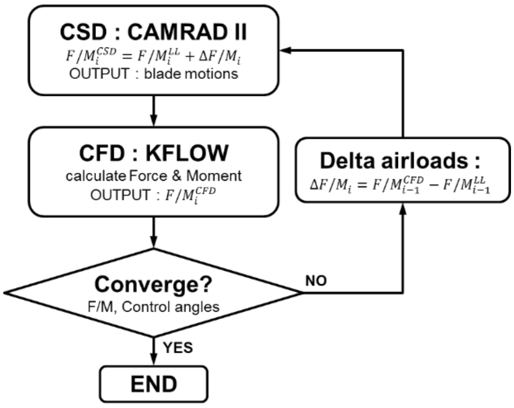


Figure 4. Loose Coupling Procedure

3. RESULTS

3.1. Optimization Results

Table 4 shows the overall optimization results. These values are relative results of the baseline. The lower taper ratio and higher anhedral, the tip shapes are close to optimal solution. The optimized tip configurations are presented in Fig. 5. The dynamic load of pitch link of double sweep tip configuration is increased by 6% compared with that of baseline. The single sweep tip configuration is an advantage in life cycle of blade components. It is inferred that the single sweep tip is optimal solution from overall results.

Table 4. Overall Optimization Results

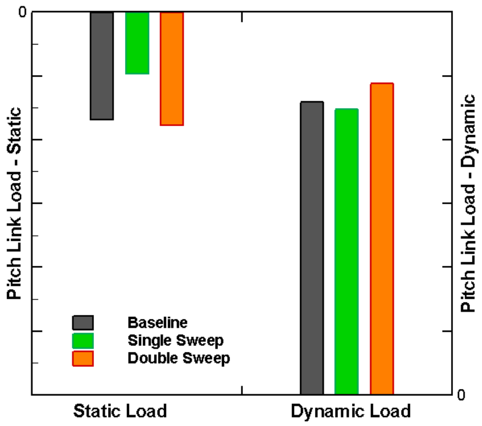
Design Variable		Single Sweep	Double Sweep
Chord Ratio		-	1.005
Taper Ratio		0.36	0.35
Sweep Angle		10.04	-38.32
Anhedral		14.30	14.03
OPT.		Single Sweep	Double Sweep
Noise	Approach	**3.28dB▼**	2.63dB▼
	Overflight	0.88dB▼	**1.51dB▼**
	Takeoff	0.56dB▼	0.39dB▼
FM	$\theta_0 = 5^\circ$	11.03%▲	11.56%▲
	$\theta_0 = 7^\circ$	**7.78%▲**	6.84%▲
	$\theta_0 = 9^\circ$	5.89%▲	5.89%▲
Power	Hover	**0.44%▼**	0.83%▲
	Vy	**0.16%▼**	0.00%—
	0.9Vh	0.35%▲	2.73%▲
Constraints		Single Sweep	Double Sweep
Pitch Link Load (dynamic)		**2.48%▼**	6.19%▲
Damper Load (dynamic)		**2.68%▼**	1.86%▼

	Blade Planform
Baseline	
Single Sweep	
Double Sweep	

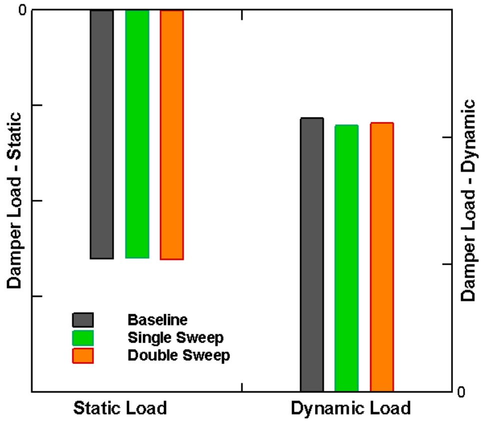
Figure 5. Optimized Tip Configurations

3.1.1. Loads Results (TURN)

Figure 6 shows loads analysis results of turn maneuver. The effect of the change in tip shape on the damper load appears to be negligible. It can be judged that the single sweep tip configuration is superior in terms of the loads, because the single sweep tip shape has the lowest dynamic load of pitch link.



(a) Pitch Link Load

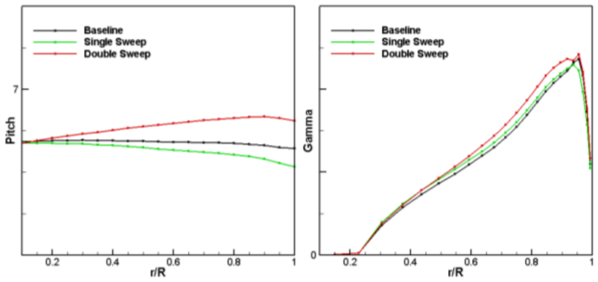


(b) Damper Load

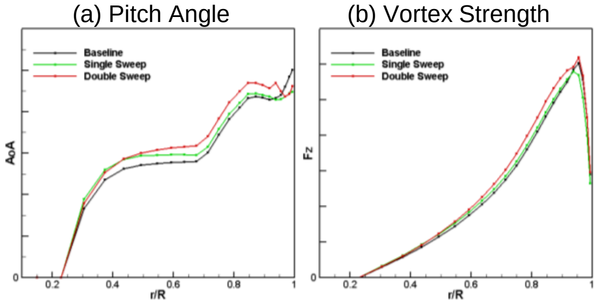
Figure 6. Loads Results (TURN)

3.1.2. Performance Results (Hover θ_0=7°)

Figure 7 shows hover performance results of isolated rotor model. The fluctuation is presented in tip by notch of double sweep tip. Pitch angle is increased by nose-up pitching moment of forward swept angle in double sweep tip and is decreased by nose-down pitching moment of backward swept angle in single sweep tip. The tip geometry affects the entire blade and causes a change in the bound vortex strength. The effective angle of attack (AoA) is changed by the vortex strength, and thus the lift can be changed.



(a) Pitch Angle (b) Vortex Strength



(c) Effective AoA (d) Cl

Figure 7. Performance Results (Hover θ_0=7°)

3.1.3. Summary of Optimized Results

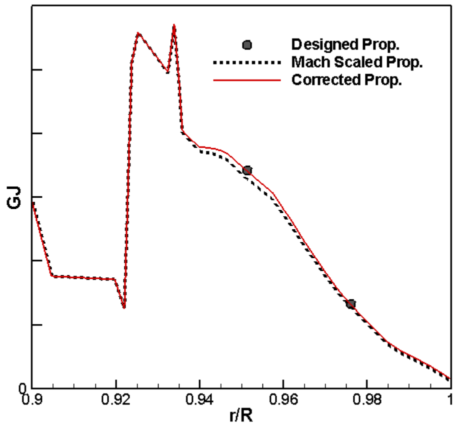
This study optimized two blade tip configurations, single sweep and double sweep, using MDAO framework.

Taper ratio and anhedral are good for hover performance. The noise is reduced by decreased tip Mach by swept angle. Backward sweep restricts elastic twist by moving aft of aerodynamic center in airfoil. The single sweep tip is better than other tip shapes by decreasing pitch link load. Since single sweep tip configuration shows a decrease in dynamic load, there is an advantage in life cycle of blade components. It is found that optimal design results are reasonable to considering the characteristic of design variables. Therefore, the single sweep tip configuration is the optimal design.

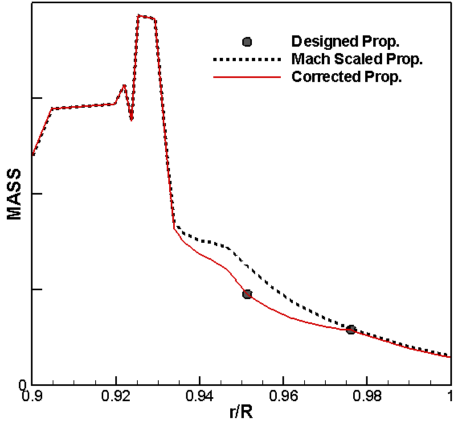
3.2. Section Design

The section properties are calculated from scaling method along the chord length in optimization process. Two sections of optimal solution, single sweep tip, are designed in the preliminary design stages. The more sections will be designed in next detailed design stages.

The section properties from Mach scaling method are corrected by using two section properties since the designed section properties of tip cannot be represented entire elastic blade models. Figure 8 shows corrected section properties.

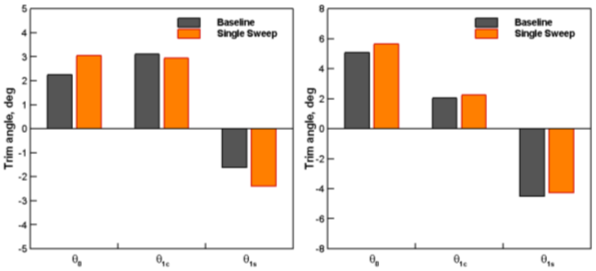


(a) GJ



(b) MASS

Figure 8. Blade Section Properties (Single Sweep)



(a) Approach

(b) Overflight

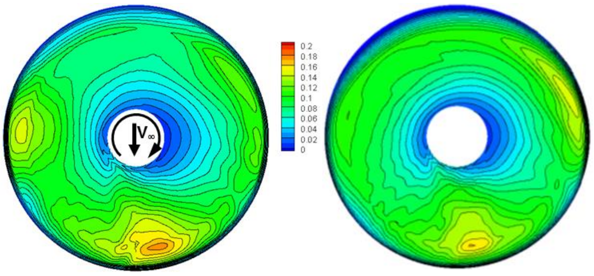
Figure 9. Trim Angles

3.3. CSD/CFD Coupled Analysis Results

The optimal design, single sweep tip, is analysed in noise condition (approach, overflight) using CSD/CFD coupling method to validate results from MDAO process. Take-off condition is excluded due to the negligible wake effect in this study. The corrected section properties are used for CSD analysis. Then, acoustic analysis is performed by using results from CSD/CFD analysis.

Figure 9 shows trim angles of both flight conditions. The collective pitch angles of single swept tip are 30% and 10% higher than those of baseline in each flight conditions because of nose down pitching moment by backward swept.

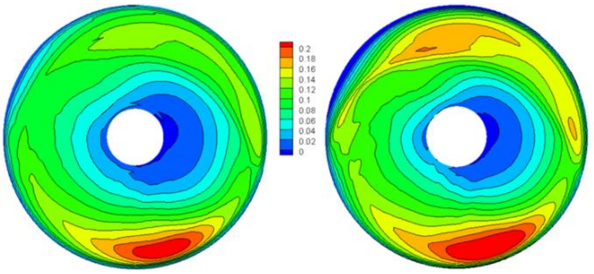
The M^2C_n distributions are presented in Fig. 10 and 11. The single swept tip loses thrust at tip of rotor blade caused by higher anhedral. The fluctuations in approach are captured in azimuth angle 270 degree to 90 degree where the complicated wake behind the rotor has a greater effect on the airflow. These fluctuations must cause blade-vortex interaction noise.



(a) Baseline

(b) Single Sweep

Figure 10. M^2C_n Distribution - Approach



(a) Baseline

(b) Single Sweep

Figure 11. M^2C_n Distribution - Overflight

Figure 12 shows the acoustic analysis results. The noise level of single sweep tip from CSD/CFD analysis is 2.4dB lower than that of baseline in approach condition.

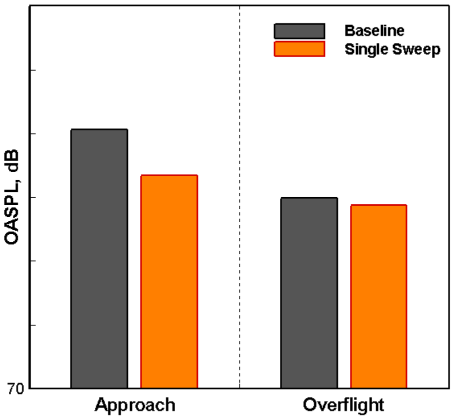


Figure 12. Noise Level

4. CONCLUSIONS

This study optimized blade tip configurations to improve hover performance and to reduce required power and forward flight noise compared with LCH using MDAO.

The single sweep tip is slightly good at hover performance compared with double sweep tip. The double sweep tip has lower noise level than the single sweep tip in overflight. Nevertheless, it is evaluated that the single sweep tip has advantage in forward flight noise considering the averaged noise level and approach noise. The single sweep tip is an advantage in life cycle of blade components, because the tip configuration shows a decrease in dynamic load of pitch link.

It is found that the single sweep tip shape is the optimal solution. The optimal design is analysed in noise condition using CSD/CFD coupling method to validate results from MDAO process.

The optimal solution, single sweep tip, has lower noise level than baseline. Especially, the noise is reduced by 2.4dB in approach.

In the future, detailed elastic beam models will be produced through more blade section designs. Then, safety margins and life cycle of structural components will be predicted by using blade limit loads and spectrum loads. Finally, we have plan to prove improvement in performance and noise reduction of the optimal solution by performing wind tunnel test using small scaled rotor, whirl tower test, and flight test.

5. ACKNOWLEDGEMENT

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Copyright Statement

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