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헬리콥터의 진동하중 저감을 위한 지능형 능동 뒷전 플랩 로터 제어 시스템 개발

Development of an Intelligent Active Trailing-edge Flap Rotor to Reduce Vibratory Loads in Helicopter

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Key Words: Active Trailing-edge Flap blade, piezoelectric Actuator, composite material

ABSTRACT

Helicopter uses a rotor system to generate lift, thrust and forces, and its aerodynamic environment is generally complex. Unsteady aerodynamic environment arises such as blade vortex interaction. This unsteady aerodynamic environment induces vibratory aerodynamic loads and high aeroacoustic noise. Those are at N times the rotor blade revolutions (N/rev). But conventional rotor control system composed of pitch links and swash plate is not capable of adjusting such vibratory loads because its control is restricted to 1/rev. Many active control methodologies have been examined to alleviate the problem. The blade using active control device manipulates the blade pitch angle at arbitrary frequencies. In this paper, Active Trailing-edge Flap blade, which is one of the active control methods, is designed to modify the unsteady aerodynamic loads. Active Trailing-edge Flap blade uses a trailing edge flap manipulated by an actuator to change camber of the airfoil. Piezoelectric actuators are installed inside the blade to manipulate the trailing edge flap

일반적으로 헬리콥터는 양력, 추력 그리고 힘을 발생시키기 위해 로터 시스템을 사용하기 때문에 공력환경이 매우 복잡하다. 블레이드 와류 간섭과 같은 비정상 공력 환경이 발생한다. 이러한 비정상 공력 환경은 진동하중과 높은 공력소음을 유발한다. 진동하중과 공력소음은 로터 블레이드 회전수에 N 배의 해당하는 주파수(N/rev)를 갖는다. 하지만 스와시 판과 피치링크로 이루어진 전통적인 로터 조종계통은 블레이드가 1 회 회전하는 동안 한번의 조종 변위를 발생시킬 수 있기 때문에 그러한 진동하중을 조절하기에는 한계가 있다. 이러한 문제를 해결하기 위해 많은 능동 제어 기법들이 개발되었다. 능동 제어기법은 임의의 주파수로 블레이드의 피치 각을 조종할 수 있다. 본 논문에서는 비정상 공력 하중을 변화시키기 위해 능동 제어 기법 중 한 가지인 능동 뒷전 플랩 블레이드의 설계를 수행하였다. 능동 뒷전 플랩 블레이드는 에어포일의 캠버를 변화시키기 위해 작동기에 의해 구동되는 뒷전 플랩을 장착한다. 뒷전 플랩을 작동시키기 위해 블레이드 내부에 위치 압전 작동기를 사용하였다.

1. INTRODUCTION

Helicopter has a wide area of mission capability such as the vertical flight and hover. Therefore it may accomplish many special tasks. But due to a rotor system to generate thrust, lift and control forces, helicopters are operated in a quite complex aerodynamic environment compared to that of the fixed wing aircraft. Unsteady aerodynamic environments induce high vibratory load and critical aeroacoustic noise. Those have N times the rotor blade revolution (N/rev). Conventional rotor control system composed of swash plate and pitch links is incapable of adjusting such vibratory loads because its control is

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restricted to 1/rev. Therefore there have been both passive and active methods studied to reduce such vibratory load and noise. Passive control methods use simple additional components on the rotor, for example, bifilar vibration absorber and rotor head absorber. But these methods lead to increase in the gross weight of the aircraft. Besides, these methods show lack of adaptability with respect to changes dynamic characteristics caused by cargo, fuel, and, passenger changes(1). Therefore several active control methods have been recently investigated to reduce the vibratory loads. Active control methods manipulate blade pitch with a higher harmonic displacement by using intelligent materials. Particularly, researches using piezoelectric materials have been widely conducted. There have been several active control methods studied, such as Active Twist Rotor (ATR) blade(2) and Active Trailing-edge Flap (ATF) blade. There has also been a hybrid type using several methods simultaneously(3). ATF method uses the trailing edge flap to change camber of the blade. Since ATF method uses small control device, trailing edge flap, compare with other methods, relatively lower electric voltage input is required to generate a desired flap deflection. According to the separate analysis by DYMORE(4), ATF method has shown better performance(5). Thus ATF method is selected in this paper. The present active blade in this paper is called as Seoul National University Flap (SNUF) blade. This paper presents a detailed design of SNUF active blade. Its primary purpose is to reduce the vibratory loads. And the secondary purpose is to replace a conventional rotor control system. In this paper, the former purpose will be focused.

2. DESIGN REQUIREMENT

SNUF blade is small-scaled rotor blade based on the design of SHARCS(3) and ATR blade (NASA/ARMY/M.I.T). ATR blade has shown a satisfactory performance during the test in NASA Langley wind tunnel test. Therefore its structural properties and materials are selected and used in the present SNUF blade. However, those need to be modified to be suitable to the present testing condition. ATR blade was tested in heavy gas condition. Since SNUF blade will be rotated under normal atmospheric condition, its rotating speed need to be higher than that of ATR blade is. The following similarities are considered to obtain the deign requirement of SNUF blade.

1. Aeroelastic similarity
2. Mach Number similarity
3. Lock Number similarity

Design requirements of SNUF blade are established and evaluated with analysis by using UMARC(6), which is one of the comprehensive helicopter analyses. Design requirements of SNUF blade are described in Table1. SNUF blade has a uniform cross section and linear built-in twist distribution. And SNUF blade is an articulated rotor.

Table 1. Design requirement of SNUF blade

Property	Value
Articulated rotor	
Rotor radius (cm)	128
Rotation speed (rpm)	1,528
Blade chord (cm)	10.24
Hinge offset (cm)	5.12
Root cutout (% span)	20
Airfoil type	NACA0012
Tip Mach number	0.60
Lock number	5.0
Mass per unit length (kg/m)	0.55
Pretwist (deg)	-10
GJ (N.m^2)	68
EI_{flap} (N.m^2)	57
EI_{lag} (N.m^2)	1900
EA (N)	4.6×10^{6}
I_{yy} (kg.m)	2.7×10^{-5}
I_{zz} (kg.m)	2.25×10^{-4}
I_{polar}(kg.m)	2.52×10^{-4}
Flap displacement	±4°

3. BLADE DESIGN

3.1. Blade design

Cross sectional design of SNUF blade is conducted based on the previous ATR blade. Therefore its cross section is designed to be fabricated with a similar spar and the same composite materials used in ATR blade. Generally, 1-D beam analysis and 2-D cross section analysis has been used in helicopter rotor blade analysis instead of the direct 3-D structural analysis, because it usually has a slender span shape and uniform cross section. Cross section design is conducted with analysis by using 2-cell thin walled analysis(2). The resulting cross section design is described in Figure 1.

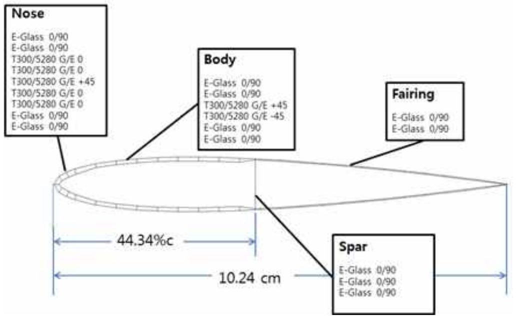


Figure 1. Preliminary cross section configuration

Result of the present cross sectional analysis is described in Table 2. There are few differences between the present result and target properties. Since there are several components located inside the blade, concentrated load will be induced by centrifugal force on the flap actuation region. Leading edge and nose are further reinforced to withstand the centrifugal force. Because the responses for the torsional and the flapping bending mode are required to be satisfactory, design effort needs to be conducted to minimize the differences. Ballast weight will be added to this cross sectional design to meet the target weight.

Table 2. Comparison of the cross sectional properties

	Target Properties	Present result	Difference (%)
EA(N)	4.600×10^{6}	4.421×10^{6}	7.0
GJ(N.m^2)	6.600×10^{1}	6.792×10^{1}	0.5
EI$_{flap}$(N.m^2)	5.700×10^{1}	5.828×10^{1}	2.5
EI$_{lag}$(N.m^2)	1.900×10^{3}	2.736×10^{3}	29.0
Mass(kg/m)	5.500×10^{-1}	5.502×10^{-1}	0.0
I_{yy}(kg.m)	2.700×10^{-5}	1.638×10^{-5}	39.3
I_{zz}(kg.m)	2.250×10^{-4}	1.596×10^{-4}	29.0

SNUF blade has a constant chord and linear built-in twist distribution along the blade span. The target built-in twist angle of the blade is -10°. Since it is found to be difficult to fabricate a blade with the twist in the flap actuation region, built-in twist is not applied in this region. But since the distribution slope is required to enable a constant lift distribution, the resulting built-in twist angle at the tip is -8° (Figure 2). The actuators and other relevant components are located inside the blade. Therefore a specially designed housing and hatch are used in this region as shown in Figure 3.

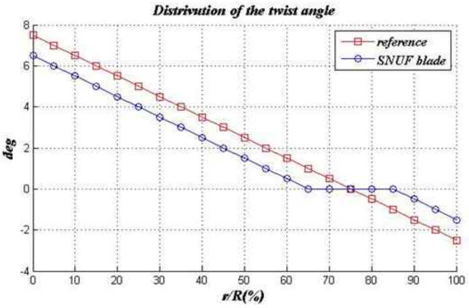


Figure 2. Built-in twist angle distribution of SNUF blade

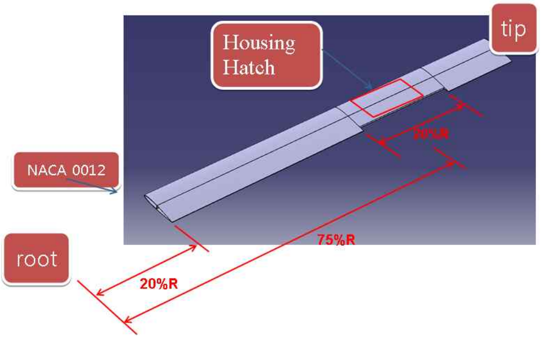


Figure 3. External configuration of SNUF blade

3.4. Flap actuation region design

Aerodynamic analysis is conduct to estimate the hinge moment and Amplified Piezoelectric Actuator(APA, figure 4) made by Cedrat is selected to manipulate the trailing-edge flap(7). According to that analysis, target hinge moment is 0.1268 N·m.

Figure 4. APA 200M actuaotr

It will be important to design the flap actuation region carefully in order to obtain a sufficient deflection of the flap. The lighter the flap actuation region is designed to be, the better it will be for the structural point of view. The best way is to fabricate this region using the composite material. But difficulties of fabrication due to the small space still need to be considered. Therefore aluminum is considered for the housing and faring block. And the push rod will be fabricated by using steel to prevent buckling. One of the most important components is the flap hinge, because the friction force is expected to occur due to deformation of the flap during the rotating situation. A skin hinge may be a good solution in order to minimize the friction force. Since the rotational speed is quite high and the blade size is small, this type of hinge is incapable of withstanding the loads acting on the hinge. Thus a pin hinge is also considered and it will be fabricated with steel. The schematic of the linkage mechanism is described in Figure 5. Appropriate length of the moment arm (L_2) needs to be chosen to deflect the flap with desired angle against the flap hinge moment.

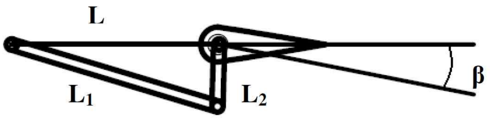
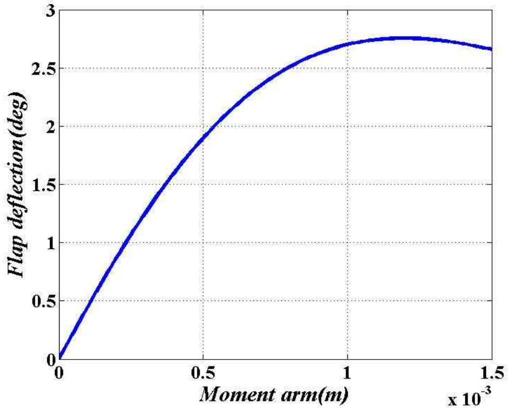
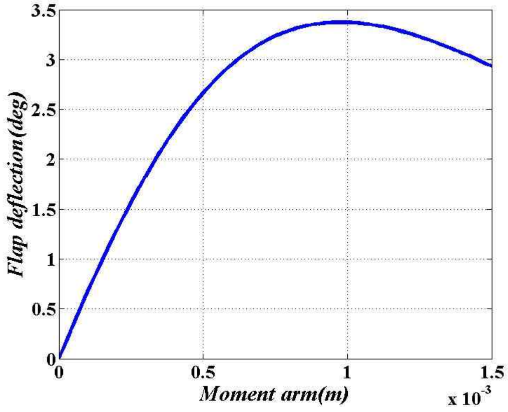


Figure 5. Schematic of the linkage mechanism

The block force of APA 200M actuator is 73N at zero displacement. But the force of the actuator at the maximum displacement, 0.23 mm, will become 0 N. For this reason, it will be cumbersome to determine t the value of L_2 and the number of the actuators used for the flap linkage mechanism. Appropriate value of L_2 and the number of actuator is sought by examining the relationship curve between flap deflection and moment arm length. As a first attempt, the relation curve of the dual actuators is illustrated in Figure 6(a). According to the curves, maximum flap deflection angle will be ±2.7° when dual actuators are used. And appropriate length of the hinge moment arm will be about 1.2 mm. However ±2.7° will not be sufficient compared to the target value, ±4°. Therefore three actuators are considered to provide the required flap hinge moment. Then the resulting relation curve is illustrated in Figure 6(b). According to figure, the maximum flap deflection will be about ±3.4° when three actuators are used. Then, the length of flap hinge moment will be about 0.9mm. This value will still be insufficient compared with the target value. However when the number of actuators used is more than three, inner space to install the actuators will not be sufficient and additional structural problem will be caused by the increased weight of the flap actuation region. Therefore three actuators are presently selected and used for the flap actuation design.



(a) Dual actuators



(b) Three actuators

Figure 6. Relation curve between flap deflection and moment arm length

Since the components including the actuator and linkage mechanism needs to be located inside the blade, and thus an access capability to these components is required, a hatch will be attached on the flap actuation region. If the hatch is used, structural weakness may be resulted. A housing will be also used to overcome this problem. Flap actuation region design with three actuators is described in Figure 7.

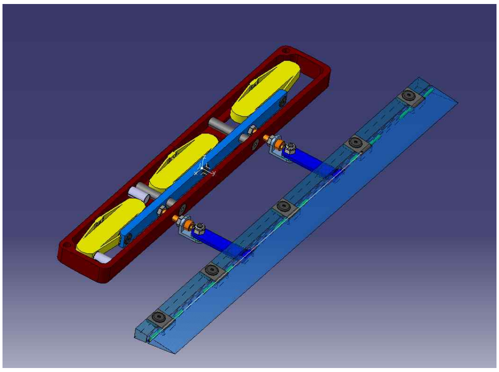


Figure 7. Design of the flap actuation region

3.5. Stress/strain recovery analysis

SNUF blade is rotated under a quite fast speed i.e., 1,528 rpm. And there are relatively heavy components inside the blade comparing to blade skin. Since this region is narrow, concentrated loads may act upon the flap actuation region. Therefore a careful stress/strain recovery analysis will be required to estimate whether the failure may occur or not. 1-D beam analysis is conducted to estimate the loads existing on the reference line of the beam by the geometrically exact beam analysis(8). And the aerodynamic result of ATR blade is used to apply the maximum loads in forward flight. This result is obtained by CAMRAD(9), one of the comprehensive helicopter analysis programs. Stress/strain recovery analysis is conducted using 10 nodes located on the spanwise reference line by using the 2-cell thin walled analysis(2). 10 nodes used for analysis are described in and Figure 8. Stress/strain recovery analysis results are described in Table 3. Failure of the materials is not found according to the present results.

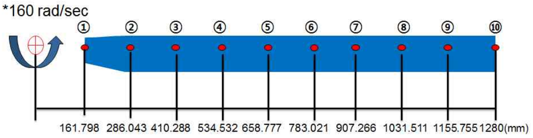


Figure 8. Spanwise node location and test condition of the stress/strain recovery analysis

Table 3. Stress/strain analysis results

direction	stress(MPa)	strain (micro strain)	allowable strain
longitudinal	989.674	13761.551	0.9633
transverse	77.982	4488.742	1.1510
shear	-3.693	-8916.602	0.9386

3.6. Fan plot

Fan plot is created to verify the dynamic characteristic of the SNUF blade during the rotation. Flan plot of the SNUF blade is described in Figure 9. Cross over between N/rev curve and normal mode curve at the nominal speed, 160 rad/sec, is not observed. Therefore SNUF blade is predicted to be stable in a nominal rotational speed.

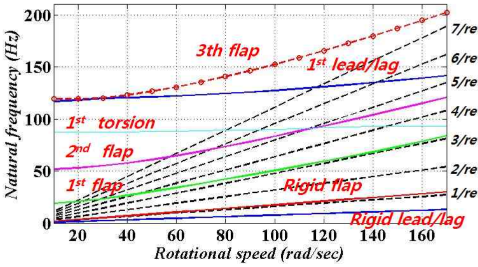


Figure 9. Fan plot of SNUF blade

4. FINAL DESIGN

4.1. Blade design

Cross sectional design of SNUF blade is conducted to satisfy the design requirements established by adapting the materials in ATR blade. But those specific materials are not available in Korea. Different raw material is required to fabricate the present blade. Therefore cross section of the SNUF blade is redesigned by using the material available. In the original design of ATR blade, the front spar has two different regions of the ply lay-up in order to accommodate the piezoelectric fibers. However such complicated design of the front spar is not required in the present blade design. Under the presently simplified design of the front spar, both flapwise bending and axial stiffness are increased. Axial stiffness is required to overcome the increased centrifugal force, and it is finally reinforced by redesign. However, flapwise bending stiffness is also increased unavoidably. Design result is described Figure 10 and Table 4.

Table 4. Comparison of the cross sectional properties of final design

	Target Properties	Present result	Difference (%)
EA(N)	4.600×10^{6}	4.569×10^{6}	0.7
GJ(N.m^2)	6.600×10^{1}	6.810×10^{1}	3.2
EI$_{flap}$(N.m^2)	5.700×10^{1}	9.892×10^{1}	73.5
EI$_{lag}$(N.m^2)	1.900×10^{3}	2.237×10^{3}	17.7
Mass(kg/m)	5.500×10^{-1}	2.239×10^{-1}	59.3
I$_{yy}$(kg.m)	2.700×10^{-5}	4.491×10^{-6}	83.4
I$_{zz}$(kg.m)	2.250×10^{-4}	1.545×10^{-4}	31.3

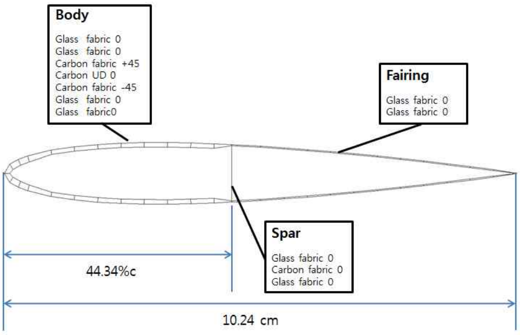


Figure 10. Final configuration of the cross section

5. CONCLUSION

In this paper, the design requirement is established for an active rotor with a trailing edge flap. It is completed by using UMARC. Cross sectional design and structural integrity analysis are performed. 2-cell thin-walled analysis is used for the structural analysis. The configuration of the SNUF blade is designed based on the cross sectional design. Stress/strain recovery analysis is conducted to verify the structural integrity under the centrifugal force. Dynamic characteristics are verified by using fan plot. The aerodynamic analysis is conducted to estimate the hinge moment by using FLUENT. APA200M actuator is selected. The design of the flap actuation region is conducted. Simplification of the cross section design will be progressed with the present front spar lay-up design to overcome the restriction upon the blade inner space.

ACKNOWLEDGMENTS

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REFERENTS

(1) Pearson, J. T., Goodall, R. M., and I. Lyndon, "Active Control of Helicopter Vibration," Computing amd Control Engineering Journal, December, 1994, pp. 277-284

(2) Shin S. -J., “Design, Manufacturing and Testing of an Active Twist Rotor,” Master’s Thesis, Massachusetts Institute of Technology, June 1999

(3) Feszty, D., Nitzsche, F., Khomutov, K. and Lynch, B, K., "Design and Instrumentation of the SHARCS Scaled Rotor with Three Independent Control Systems,"American Helicopter Society 64th Annual Forum, Montreal, Canada, April 29-May 1, 2008

(4) Bauchau, O. A., DYMORE Manual, http://www.ae.gatech.edu/people/obauchau/Dwnld/Dymore Manual.pdf, 2007.

(5) Park, J. S., Kim, T. S., and Shin, S. J., "Design and Aeroelastic Analysis of Advanced Active flap Blades Utilizing Single Crystal Piezoelectric Acuatoros," International Forum on Rotorcraft Mulidisciplinary Technology, Seoul, Korea, October 15-17, 2007.

(6) University of Maryland Advanced Rotor Code (UMARC) Theory Manual, University of Maryland, Department of Aerospace Engineering, College Part, MD, 1991.

(7) 이재환, 김태성, 신상준, "헬리콥터 진동 감소를 위한 지능형 플랩로터의 설계," 한국소음진동공학회 2009년도 춘계학술대회, 2009년 4월 23~24일.

(8) Shang, X., and Hodges, D. H., "Aeroelastic Stability of Composite Rotor Baldes in Hover," In Proceedings of the 36th Structures, Structural Dynamics and Materials Conference, New Orleans, Louisiana, April 10-12, 1995.

(9) Johnson, W., “Technology Drivers in the Development of CAMRAD II,” Proceedings of the 51st Annual Forum of the American Helicopter Society, January 1994.