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Vibration Attenuation in Helicopters using an Active Trailing-edge Flap Blade

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Key Words: Active Trailing-edge Flap (ATF), piezoelectric actuator, vibration control, active rotor blade

ABSTRACT

Seoul National University Flap (SNUF) blade is a small-scaled rotor blade incorporating a small trailing-edge flap control surface driven by piezoelectric actuators at higher harmonics for vibration attenuation. Initially, the blade was designed using two-dimensional cross-section analysis and a geometrically exact one-dimensional beam analysis, and material configuration was finalized. Flap deflection angle of ±4° was established as the criterion for better vibration reduction performance based on an earlier simulation. Flap linkage mechanism design is carried out and static bench tests are conducted to verify the flap actuation mechanism performance. Different versions of test beds are developed and tested with the flap and chosen APA 200M piezoelectric actuators. Through significant improvements, a maximum deflection of ± 3.7° was achieved. High frequency experiments are conducted to evaluate the performance and transfer function of the test bed is determined experimentally. As the static tests are almost completed, rotor power required for testing the blade in whirl tower (centrifugal environment) is calculated and further preparations are under way.

Nomenclature

c_d	=	drag coefficient of the airfoil
$c_{l\alpha}$	=	lift curve slope of airfoil
ν_β	=	rotating flap frequency
P_H	=	hover power
P_i	=	induced power
P_o	=	profile power
ρ	=	local air density
σ	=	rotor solidity

1. Introduction

In helicopters, among various sources of vibration like engine, transmission system, aerodynamic sources on the fuselage, tail rotor and so on; the prime source of vibration is the main rotor. High levels of vibration are observed during forward and transition flights[1]. For a better crew comfort, increased equipment life, low maintenance and operating costs, it becomes necessary to have a vibration reduction device.

Various passive devices[2] are used to achieve the vibration reduction. Simple mass/spring dynamic vibration absorption and isolation devices are used in helicopters like Westland Lynx, Westland Seaking, Sikorsky Blackhawk and Bell 206L Long Ranger helicopters. Large weight penalties and ineffectiveness over a wide range of flight conditions are some of the significant demerits of the passive techniques.

Apart from passive methods, active control of vibration is also widely considered and implemented in rotorcrafts. Active Twist Rotor (ATR) and Active Trailing-edge Flap (ATF) are the famous approaches in the recent years. In ATR blade[3], [4] and [5], piezoelectric materials are embedded in rotor blades or by integrating piezoceramic fibers in a resin matrix to create a Active Fiber Composite (AFC) material, which on actuation results in a linear twist along the blade thereby, altering hub loads and reduces vibration. The AFC requires much higher input voltage (approximately 1,000 volts) however; it doesn't increase the profile drag like the Active Trailing-edge Flap (ATF) concept. Vibratory aerodynamic loads on the rotor can be counteracted using unsteady forces generated by actuating

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the rotor blades at higher harmonics of the rotor rotation frequency. The ATF method incorporates a small trailing edge flap which is used to alter the aerodynamics of the blade for achieving the desired vibration and/or noise reduction. It is generally installed at the outboard portion of the blade. Since it uses relatively smaller electrical hardware to drive the flap, the electrical voltage input required is small.

An experimental Eurocopter BK 117 helicopter[(6), (7)] with piezoelectric driven trailing-edge flaps was the first to demonstrate vibration reduction in flight tests. The flight test started in 2005. The Boeing full-scale Smart Material Actuated Rotor Technology (SMART) rotor[(8), (9)] based on MD-900 rotor is another famous full-scale rotor example. Active Blade Concept (ABC) project by DLR, Germany and ONERA, France[(10)] and Smart Hybrid Active Rotor Control System (SHARCS)[(11), (12)] are some of the model scale rotors with piezostack type actuators driven trailing-edge flaps.

Seoul National University Flap (SNUF) blade is an active rotor blade that uses ATF method aimed primarily to alleviate the N/rev hub vibratory loads in the hub vertical direction. In this article, the bench experiments carried out to validate the flap mechanism and preparations required for testing the blade in whirl tower are discussed in detail.

2. Blade Design and Tests

2.1 Design configuration

SNUF blade is a small-scale articulated type rotor blade based on the design of the existing SHARCS[(11), (12)] and NASA/ARMY/MIT Active Twist Rotor (ATR) blades[(4)]. The ATR blade showed satisfactory performance in vibration reduction during a test at the NASA Langley wind tunnel test[(5)] in a heavy gas environment. Therefore, its structural properties were selected as the target properties in the design of the present SNUF blade. But, the SNUF blade is planned to be tested in normal atmospheric conditions and hence, its rotating speed should be higher. The normal rotation speed of the ATR blade is 688 RPM, and that of the SNUF blade is 1,528 RPM. To match the tip Mach number value of 0.6 of the ATR blade, the rotation speed of the SNUF blade was chosen as 1,528 RPM. The design configuration of the SNUF blade is described in Table 1.

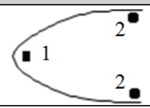
Table 1 SNUF design configuration

Rotor type	Articulated
Rotor radius, R (cm)	128
Rotation speed (rpm)	1,528
Blade chord, c (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
Flap displacement	±4°

2.2 Cross-section and spanwise design

For SNUF blade, a single spar configuration is chosen similar to that of ATR blade. Due to the non-availability of materials used in the ATR blade, the cross-section is designed with the available materials. The complicated front spar configuration of ATR blade is also replaced. The final design is shown in Figure 1. The new design provides improved axial and flapwise bending stiffness[(13)]. A linear built-in twist distribution is chosen for the SNUF blade. Ballast weights (Table 2) are added in the nose region of the cross-section to maintain the C.G. at 25% of the chord. The twist angle desired is -10°. But, due to the presence of flap axis, no twist is applied in the flap actuation region. The resulting built-in twist angle distribution is -8°[(13)].

Table 2 Ballast weight distribution

Ballast Weights	Ballast No	Weight/Unit span (kg/m)
	1	0.1959
	2	0.0667

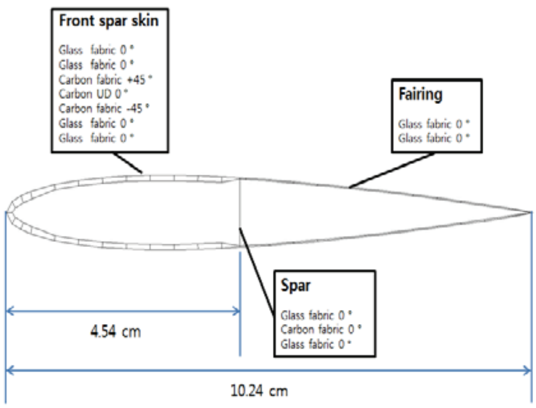


Figure 1 SNUF cross-section design

2.3 Mechanism design and tests

The mechanism design depends mainly on the kind of actuator selected. The block force should be sufficient enough to overcome the moments due to aerodynamic, inertial and centrifugal forces against the flap deflection. Also, the actuator needs to be smaller in size for a small-scale blade. Based on these criteria, the piezostack type APA 200M(14) actuator was selected. The width of the actuator was decreased from 7 mm to 5 mm for the requirements of SNUF blade by the manufacturer.

A schematic of the linkage mechanism to convert the linear motion into rotary motion is shown in Figure 2. An appropriate length (L_2) of the moment arm needs to be chosen to deflect the flap up to the desired angle against the externally acting flap hinge moment. The block force of single APA 200M actuator is 73 N. However, its free/maximum stroke is 0.23 mm, according to the product specification. By equating the force available (actuator block force) and the force required (force due to the aerodynamic hinge moment), it was found that the block force of a single actuator may not be sufficient to deflect the flap under the rotating condition. Therefore, it was concluded that multiple actuators would be required to achieve the required flap deflection.

The relationship between L_2 and the number of actuators was found to be non-linear. The appropriate value of L2 and number of actuators are determined by examining such nonlinear relationship between the flap deflection and the moment arm length. This prediction is performed via a manual iterative process. Two actuators mechanically in parallel yielded a maximum flap deflection angle of $\pm 2.7^o$ with a length of the hinge moment arm (L_2) of about 1.2 mm. However, this is insufficient compared to the target value of $\pm 4^o$ and therefore, three actuators were considered to be used in parallel. It resulted in a maximum flap deflection of $\pm 3.4^o$ for a moment arm length of about 0.9 mm.

Initially, three and two actuators in parallel configuration test beds were developed and tested. Deflection of $\pm 2.5^o$

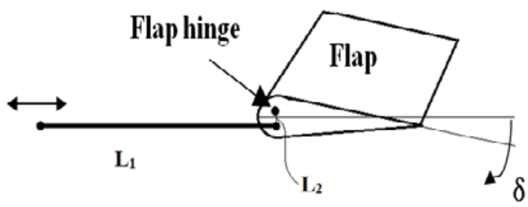


Figure 2 Schematic of the linkage mechanism

with two actuators in parallel configuration for a sinusoidal voltage input of 145 V at 1 Hz was achieved. More details on the two and three actuators configuration results can be found in [13].

To improve the design further for increased deflection performance, four actuators are decided to be incorporated. Two sets of actuators will be used mechanically in parallel and each set of actuators will have two actuators connected in series. The analytical non-linear prediction indicated a flap deflection of $\pm 3.9^o$ and hinge moment arm of 1.7 mm (Figure 3). The current version of test bed (Figure 4) incorporated the following two major changes:

i) New flap design and flap horn due to the increase in moment arm length L_2.

ii) An updated housing that combines the separate fairing block and old housing design into one.

During initial tests, the four actuator configuration performed worse than the two actuators in parallel configuration. It was found out that during the process of curing the composite flap along with the hinge pins and

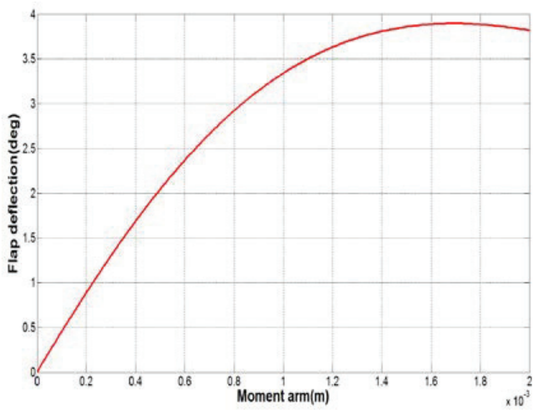


Figure 3 Flap deflection vs. Moment arm (L2) relation when four actuators are used

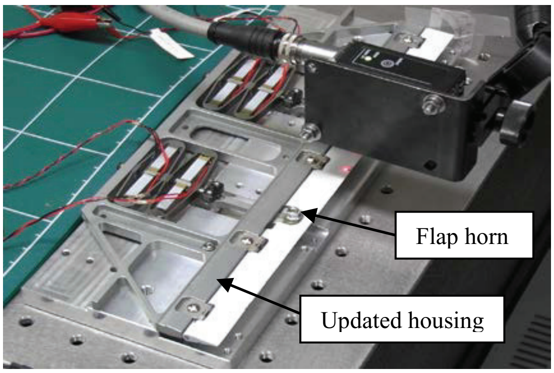


Figure 4 Updated housing and flap with flap horn

brackets, resin entered the space between hinge pins and hinge brackets thereby, preventing any rotation of hinge pins and increasing the friction. After removing the resin, flap actuation tests were conducted and a maximum flap deflection of ± 3.7° (Figure 5) was achieved at 142 V and 1 Hz. Different versions of test bed results are summarized in Table 3.

2.4 High frequency tests and transfer function

Apart from the tests at 1 Hz, the actuator needs to provide sufficient stroke and block force at high frequencies of the order of 128 Hz (~ 5/rev for SNUF) for vibration reduction performance. Tests were conducted in increments of 5 Hz up to 25 Hz and the results can be observed in

Table 3 Results of different test beds

Version	Configuration	Flap deflection
1	Single actuator	± 2°
2	Two actuators in parallel	± 1.5°
3	Three actuators in parallel	± 2.5°
4	Four actuators in parallel and series	± 3.7°

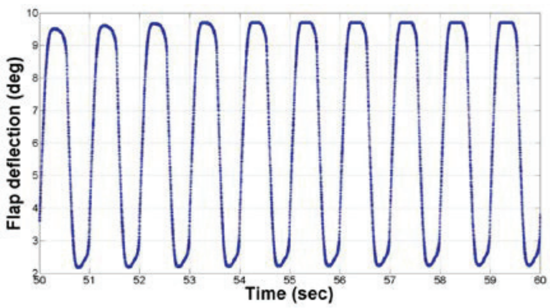


Figure 5 Flap deflection for 4 actuators (142 $V_{pk\text{-}pk}$, 1Hz)

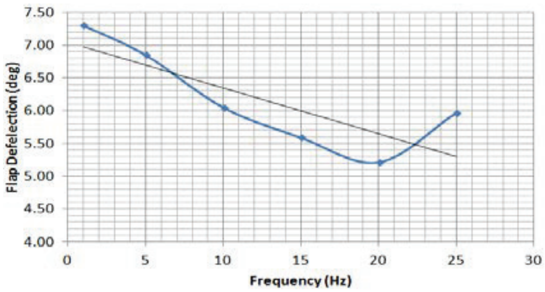


Figure 6 Deflection vs frequency (4 actuators at 140V)

Figure 6. Variations can be observed in the flap deflection amplitude with frequency and moreover, a sudden decrease in flap deflection amplitude with time was observed at constant high frequencies for the same amplitude of input voltage. The reason for this abnormal behavior is under investigation.

To identify the transfer function[15] of flap mechanism, a swept sine signal was given as input (Figure 7). It was a constant amplitude sine wave signal of 140 V linearly increasing in frequency from 1 Hz to 25 Hz in a given time, followed by the actuators dwelling at 25 Hz for some time and returning to 1 Hz. From the captured flap deflection vector and input voltage vector (after amplification), transfer function was estimated using *tfestimate*[16] command in MATLAB. Transfer function of the flap mechanism is observed to be about 0.05 °/V. (Figure 8)

Table 4 Parameters used for power estimation

Gross weight (lb)	450
Solidity, σ	0.102
Blade built-in twist (°)	-8
Tip speed (ft/sec)	669.3
Lift curve slope, $c_{l\alpha}$	6.3
Drag coefficient, c_d	0.01
Rotating flap frequency, ν_β	1.03
Local air density, ρ (lb/ft^3)	0.00238

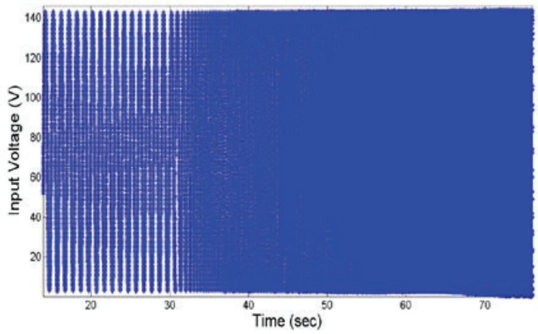


Figure 7 Sine sweep input signal

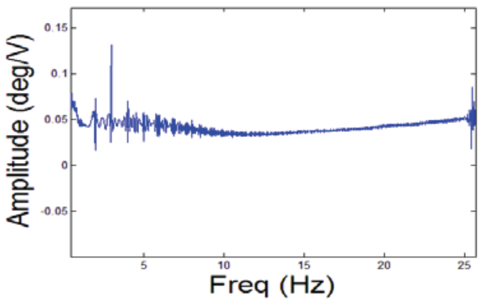


Figure 8 Transfer function of the flap mechanism

3. Whirl Test Preparations

3.1 Power estimation

In order to conduct a whirl test of the rotor in an existing or new facility, the rotor torque and power estimation becomes the prime step. In the case of hover[17], the power required is composed into two important categories namely, profile power (P_o) required to rotate or translate the rotor and the induced power (P_i) needed to generate the rotor thrust.

$$P_H = P_o + P_i \tag{1}$$

The profile power is a function of the weight and the induced power is related to the rotor drag. In our small-scale rotor design, which is not based on any helicopter, the gross weight is assumed as 450 lb corresponding to normal C_T/σ values of 0.075. The parameters used in the analysis are tabulated in Table 4 and the total hover power is found to be 48 H.P. using the procedure indicated in [17]. While deciding the drive system power, the losses also need to be accounted apart from the predicted power.

3.2 Design improvements

As the flap bench tests are almost completed, the blade design and the instrumentation are to be finalized for the whirl tests. Regarding the blade design, a new improvement, inclusion of thrust bearing, is found to provide improved flap deflection[18]. Considering the larger magnitude of centrifugal loads, the maximum constraint forces acting on the flap support needs to be lower than the load rating of the thrust bearing. Thrust bearing F2-6 has a static load rating of 30 kgf and a dynamic load rating of 16 kgf[19]. Since the force gets distributed along the 5 flap hinge brackets (Figure 4), a NASTRAN analysis was conducted to estimate the force distribution.

In the NASTRAN model, only the flap was modeled using the QUAD4 elements. Carbon UD and glass fabric material properties were applied. The total mass was around 10 g and a 0D mass element of 6 g was added at the flap c.g. to increase the flap mass to 16g. The 0D mass element was connected to the QUAD4 elements using RBE2 elements. Nodes in the holes which house the hinge pin were constrained along 3 translational and 2 rotational directions, allowing it to rotate in one direction. RFORCE data card is used to apply the centrifugal force about the rotor center.

A linear static analysis was conducted subjecting the flap to centrifugal forces. The maximum constraint force is observed at the middle of the 5 hinge bracket locations and is of the order of 36.6 N (~ 4kgf) (Figure 9). Hence, it is concluded that thrust bearing F2-6 would be suitable for SNUF blade. Because of the manufacturing complexities, just one thrust bearing is decided to be added at the middle hinge pin (Figures 10a and b), where the maximum constraint forces are observed.

For the complete validation and load studies, the blade has to be carefully instrumented with pressure sensors and strain gages at appropriate locations. But, during the initial whirl tests, it is decided to check only the flap deflection amplitude in the rotating environment. A laser sensor is being currently used during the static tests for flap deflection measurement. For the rotary position sensing, the most commonly used sensors are Hall Effect sensors. Honeywell SS495A1[10] is considered based on its smaller size. The magnet is attached to the rotating flap while the sensor on the housing in the inboard side (Figure 10c).

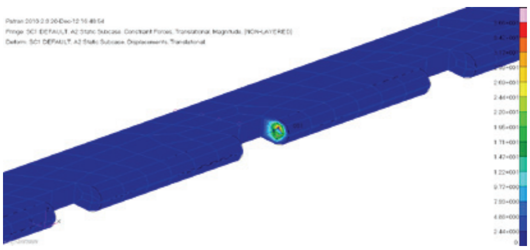


Figure 9 Maximum constraint force in the middle

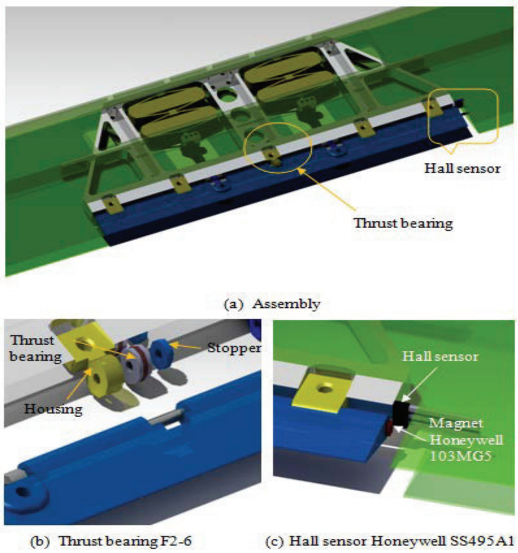


Figure 10 Thrust bearing and hall sensor locations

4. Conclusion

In this paper, actuation tests conducted for Seoul National University Flap (SNUF) blade were discussed. Test beds including the actual flap were fabricated with different actuator configurations. It was understood that there should be minimum components between the actuators and flap to minimize the loss of actuation force and a high precision manufacturing for a better flap performance. Flap deflection of $\pm 3.7^{o}$ was achieved with the four actuator configuration. High frequency tests were conducted up to 25 Hz and sudden degradation of flap deflection was observed. In order to conduct a whirl tower test as a next step, power requirement for rotor testing was estimated and design improvements carried out are also presented.

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