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DEVELOPMENT OF LOW NOISE DUCTED-FAN TAIL ROTOR FOR HELICOPTER ANTITORQUE SYSTEM

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Abstract

Ducted fans have advantages in noise as well as operational safety aspects compared with the conventional tail rotor(CTR) and used as an anti-torque system for various classes of helicopters. The final goal of this research is to develop a ducted fan anti-torque system which can be replace CTR of existing helicopters to achieve safety enhancement and low noise level. In this paper, first, a conceptual design process and results are described with optimal unequal angular spacing. Secondly, experimental results of noise test are discussed with computational prediction results.

INTRODUCTION

Rotorcrafts using single main rotor requires an anti-torque system to compensate the torque produced by the main rotor and to acquire yawing moment for directional control. Types of practical helicopter anti-torque systems are categorized as conventional tail rotor(hereinafter CTR), ducted fan and NOTAR as shown in Fig. 1.

(a) CTR-Lynx *(b) NOTAR-MDx* *(c) FENESTRON-EC155*

Fig. 1. Various Types of Helicopter Anti-Torque System

CTR is the most common anti-torque system, but has a disadvantage in operational safety point of view. Actually, the accident rate of CTR is 10 times higher than that of

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ducted fans[1]. Ducted fan type, which is called as ducted tail rotor, fan-in-fin, FENESTRON, FANTAIL by various developers, has good safety and low noise characteristics[1-8]. A project for developing a tail fan system is under going in order to replace the conventional tail rotor of the specific existing helicopter for safety enhancement and noise reduction in Korea Aerospace Research Institute[9]. This paper describes the conceptual design process with the results of the tail fan system design and discuss the experimental results of noise test with computational prediction results.

DESIGN REQUIREMENTS

In order to prepare the design requirement, the relevant regulations on airworthiness qualification, competitive system capability and required performance should be considered. In addition, the weight and geometry constraints should also be the design requirement in this study because the developed system is to be applied to the specific existing helicopter(hereinafter target helicopter). Most of the requirements specified in the relevant regulations such as FAR Pt.29, MIL-F-83300 and ADS-33E are related to the handling quality. Part of the requirements are: the initial yaw acceleration is at least 1 rad/s2 and the air vehicle has a station keeping capability within 35kts wind in any direction. In the present study, the target yaw acceleration is set 1.1 rad/s2 considering the 10% margin as shown in Fig. 2. The input rpm for the tail gear box, moment arm, ground clearance etc. are set by considering the constraints imposed by the geometry and the specification of target helicopter.

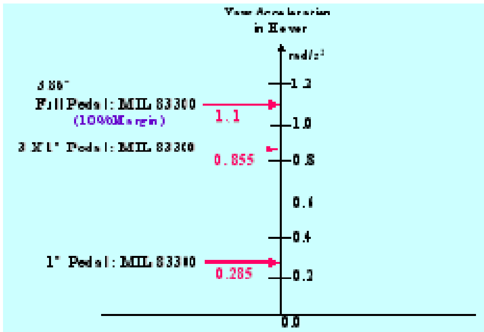


Fig. 2. Relation between Pedal Displacement and Yaw Acceleration of the Target Helicopter

SPECIFICATION OF TARGET HELICOPTER AND INITIAL SIZING

Fig. 3 shows the major parameters for the tail fan configuration design. The initial sizing process is summarized in Figs. 4 and 5. Here P, Q represent the power and torque, respectively. Also, B, I and Ψ are number of blades, mass moment of inertia and yaw angle, respectively. The specification of the target helicopter is summarized in Table 1.

Table 1. Required Specification of Target Helicopter[9]

Parameter	Target Helicopter	Parameter	Target Helicopter
W_{TOGW}	5,125(kg)	$P_{avail.}$	1,568(hp)
$V_{tip\ M/R}$	218.5(m/s)	$R_{M/R}$	6.4(m)
Tail Arm	7.66 (m)	I_{zz}	2,070,412(kg/m^2)

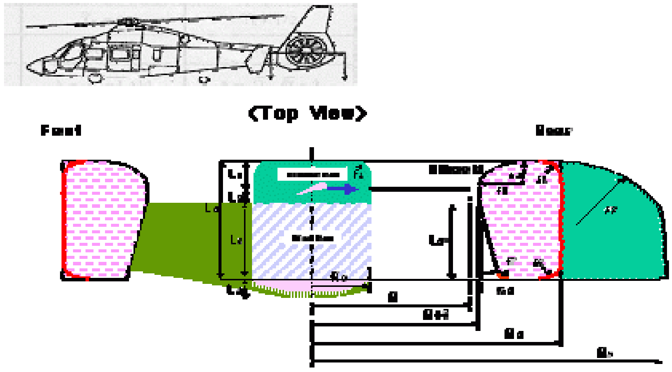
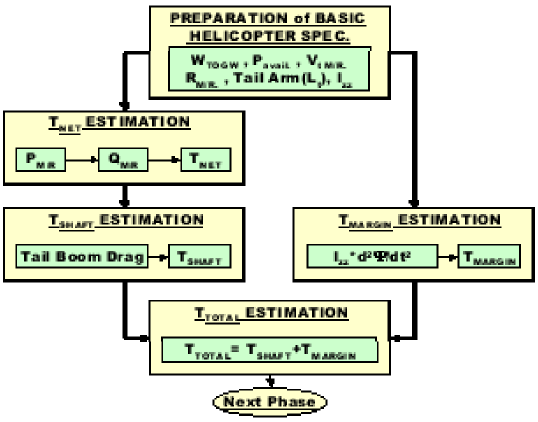


Fig. 3. Major Parameters for Ducted Fan Configuration Design



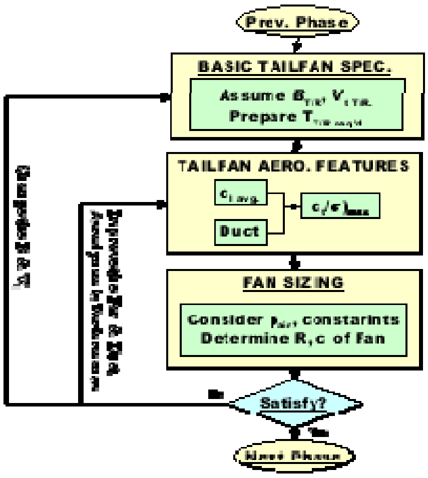


Fig. 4. Process of Evaluating a Maximum Required Thrust

Fig. 5. Initial Sizing Process

Deficiency of the thrust level, manufacturing availability especially of the tail gear box, required space for rotating balance are the main reasons for configuration changes. The tip speed is slightly changed because the final gear ratio is fixed. Space for the rotating balance is considered because it is necessary for measuring the axial force and the torque. Three dimensional solid modeling of the final configuration is presented in Fig. 6.

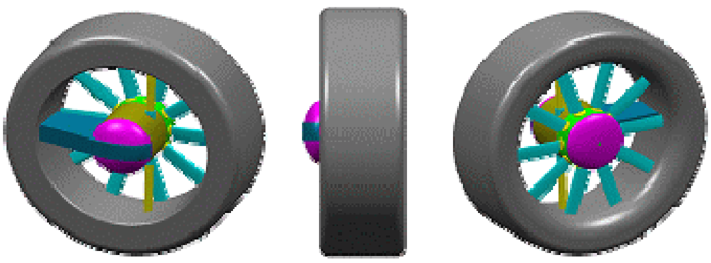


Fig. 6. 3D Solid Modeling of Final Tail Fan Configuration

OPTIMAL UNEQUAL ANGULAR SPACING

To reduce the noise of designed ducted fan tail rotor, unequal angular spacing concept is applied. The theoretical method followed here is based upon a simple mathematical analysis of phase-shifted periodic functions proposed by Serge Lewy[10]. The Fourier series of the sound pressure $p_0(t)$, of period 1/N, is

$$F_0(f_1) = N\int_0^{1/N} p_0(t)\exp(-2\pi il\ Nt) \quad (1)$$

with the frequency $f_l = lN$ (l :integer). Each blade is marked by the subscript j ($0 \le j \le B-1$). If there is no interaction between blades,

$$p(t) = \sum_{j=0}^{B-1} p_j(t) \quad (2)$$

The above signal $p_0(t)$ is associated with the blade $j = 0$, located at the angle $\theta_0 = 0$ in the rotor frame, and $p_j(t) = p_0(t-\tau)$ with the time lag $\tau_j = \theta_j/(2\pi N) = j/(BN)$.
The Fourier series of $p(t)$ is

$$F(lN) = F_0(lN)\sum_{j=0}^{B-1}\exp(\frac{-2\pi ilj}{B}) \quad (3)$$

Here, $F(lN) = 0$ except if the denominator is zero, i.e., if $l = nB$ (n being an integer). Each term of sum is then equal to 1 and $F(nBN) = BF_0(nBN)$.
For a unequally spaced blades, $p(t)$ is same with equation (2), but it can only be written that $\tau_j = \theta_j/(2\pi N)$, because the angles θ_j can take any value here. Thus

$$F(lN) = F_0(lN)(1+\sum_{j=1}^{B-1}\exp(-il\theta_j)) \quad (4)$$

Since the angles are referred to the blade $j = 0\,(\theta_0 = 0)$. All rotation harmonics may exist and the Fourier series no longer has the period BN.
In the previous unequal spacing researches, R. C. Mellin[11] proposed the general blade spacing function as below, for the analytic optimization of unequal spacing blades.

$$S_n = \frac{360}{B + j\beta\cos\left[\frac{2\pi j}{B}(n-\frac{1}{2})\right]} \quad (5)$$

where S is the angle (in degree) between adjacent blades; n=1,2,3,…B, and represents the various particular blade spaces around the circumference of a rotor; j is any integer which is ≥ 1; and β is a parameter representing the degree of non-uniformity in the blade spacing, and is ≥ 0. When j=1, the arrangement produces an unbalanced rotor and when j is any larger integer, the rotor is naturally balanced. By using equation (5), optimal β is proposed as below;

$$\beta_{opt} = 0.8964 + 8.047\times10^{-2}(\frac{B}{j}) - 4.730\times10^{-3}(\frac{B}{j})^2 + 9.533\times10^{-5}(\frac{B}{j})^3 \quad for\ \frac{B}{j} \le 20 \quad (7)$$

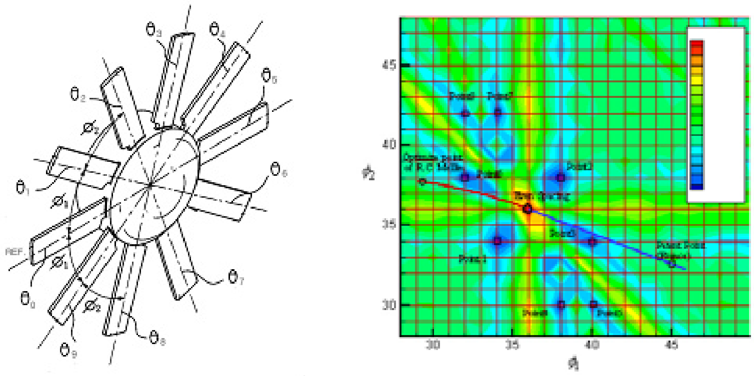


Fig. 7. Unequal Spacing Configuration and Predicted PNL map

In Korea Aerospace Research Institute(KARI), accounting the geometric symmetry for rotational stability, 10 blades rotor system can be modeled with 2 parameter angles ϕ_1, ϕ_2 as shown in Fig. 7(a) instead of using the general spacing function(equation 5). Fig. 7(b) shows the perceived noise level(PNL) prediction results by using the upper phase-shifted periodic functions approach with variation of angles ϕ_1, ϕ_2. From this predicted PNL result, 8 optimal angle points, those are different from a previous research and patent point, are found as show in Fig. 7(b).

COMPUTATIONAL AND EXPERIMENTAL RESULTS

Computational Results

Within predicted optimal 8 points of previous section, 4 points are chosen by manufacturing limitations and used to detailed noise predictions before fixing a final configuration. In this study, a time-marching free vortex wake method is applied to predicting the high resolution airloads and rotor wake instability[12]. Three dimensional velocity potential equation is employed as a governing equation which represents incompressible, inviscid and irrotational flow. Rotor blade is modeled by a vortex lattice, and wake is composed of free vortex elements trailed and shedding. Explicit time integration with parabolic blending technique for vortex element is applied. And the generalized Farrasat formulation 1-A[13] based on the FW-H equation is applied for noise prediction. The present methods are validated with the experimental data in case of the various axial fans[14,15].

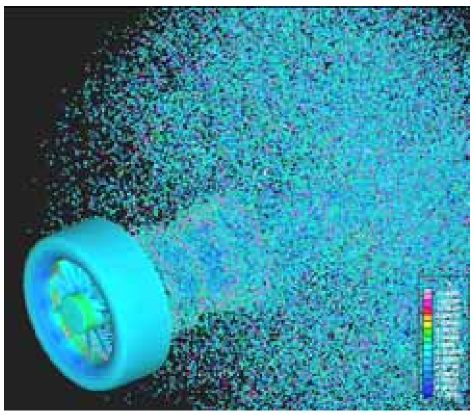
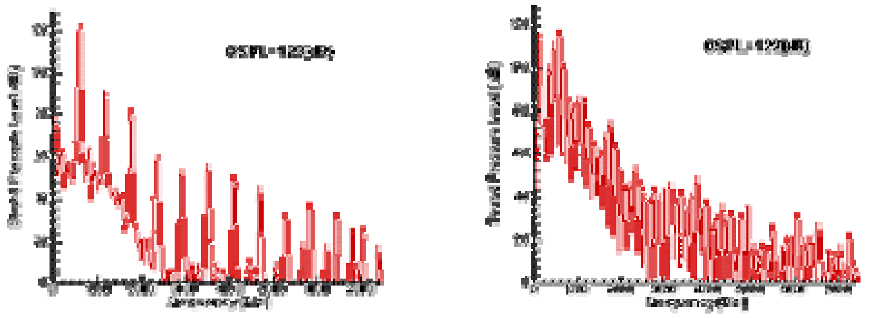


Fig. 8. Unsteady Airloads Prediction of Ducted Fan

Fig. 8 shows the ducted fan and wakes, those are shaded from the rotor and duct. The effect of unequal blade spacing in reducing tonal annoyance is shown in Fig. 9. A predicted spectrum for an equally spaced rotor is shown in Fig. 9(a), with the blade passing frequency(BPF) and harmonics of BPF. With unequal spacing of the blade (Fig. 9(b)) sound energy from the major order is spread to adjacent harmonics and, even though the overall sound pressure level(OSPL) is maintained almost same, the calculated tone corrected perceived noise level(PNLT) is reduced 5 dB by the table 2.



(a) Equally Spaced Blade Case *(b) Unequal Spaced Blade Case*

Fig. 9. Predicted Noise Spectrums

Table 2. Predicted OSPL and PNLT

	OSPL (dB)	PLNT (dB)
Equally Spacing Blades	123	132
Opt 1 of Unequal Spacing Blade	122	128
Opt 2 of Unequal Spacing Blade	122	127
Opt 3 of Unequal Spacing Blade	122	128
Opt 4 of Unequal Spacing Blade	123	129

Experimental Results

Fig. 10. Real Scale Ducted Fan Anti-Torque System

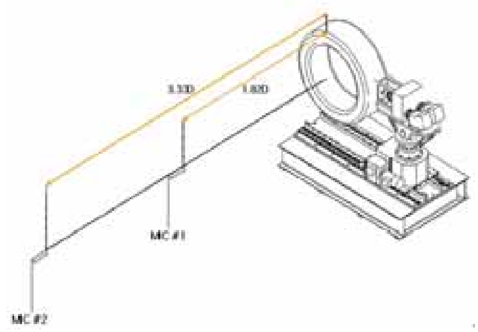


Fig. 11. Microphone Location of Noise Measurement

Based on the predicted PNLT results of table 2, the configuration of unequal spaced blade is fixed and manufactured with equally spaced one. Fig. 10 shows the manufactured real scale ducted fan anti-torque system. For the noise measurement, the following B&K instruments are used and microphones are located at r/R=1.82D and 3.33D as shown in Fig. 11.

- Portable PULSE Type 3506C
- PULSE Ver.8.0 (Software)
- 2-ch Microphone Conditioning Amplifier NEXUS 2690 A OF2
- Pressure-Field Microphone Type 4192 (X2)

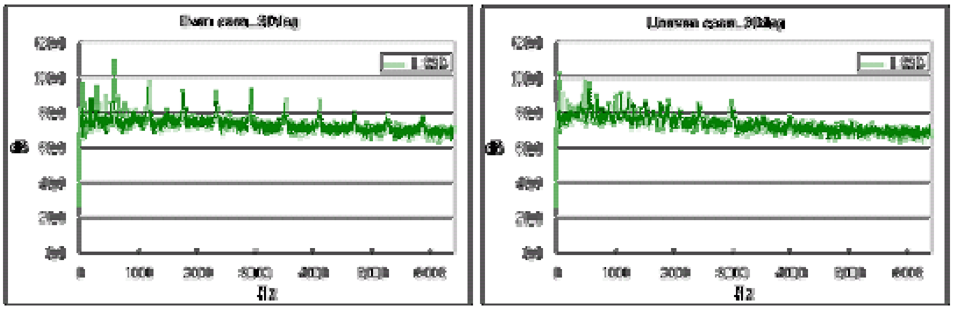
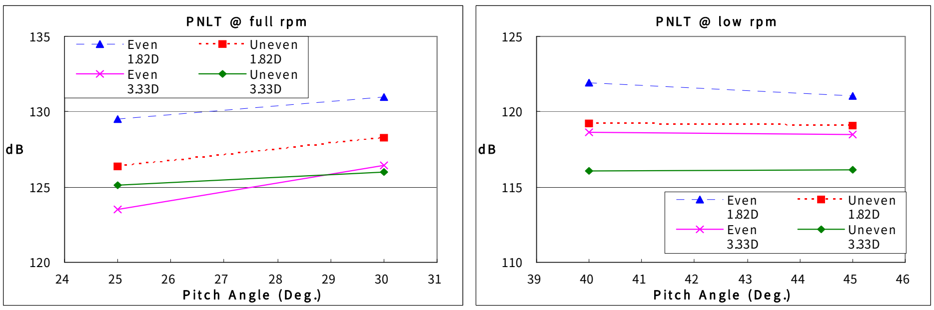


Fig. 12. Measured Noise Spectrums



(a) Full RPM Case *(b) Full Pitch Case*

Fig. 13. PNLT Comparisons of Measurements Noise

Fig. 12 shows the measured noise spectrums of the equally spaced blades and unequal one. Due to the lack of available power in real scale anti-torque system, Fig. 13(a) tests are performed with 10 degree less collective angles than the computation cases and Fig. 13(b) tests are performed with full pitch but with some less RPM conditions. As shown in Fig.9, major peaks of BPF harmonic elements are spread to adjacent harmonics with 10dB peak reduction even though OSPLs are almost same within the difference of 1dB. From the measured noise spectrums, PLNT conversions are performed and shown in Fig. 13. From the Fig. 13, it can be shown that PNLT is reduced almost 3dB by unequal spacing blades.

SUMMARY

Ducted fans have advantages in noise as well as operational safety aspects compared with the conventional tail rotor(CTR) and used as an anti-torque system for various classes of helicopters. The final goal of this research is to develop a ducted fan anti-torque system which can be replace CTR of existing helicopters to achieve safety enhancement and low noise level. In this paper, first, a conceptual design process and results are described with optimal unequal angular spacing. Secondly, experimental results of noise test are discussed with computational prediction results.

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