Conceptual Design of a Ducted Fan for Helicopter Anti-Torque System

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Abstract

Ducted fans have advantages in noise as well as operational safety aspects compared to conventional tail rotors and are used as an anti-torque system for various classes of helicopters. The final goal of this study is to develop a ducted fan anti-torque system which can replace conventional tail rotors of existing helicopters to achieve safety enhancement and low noise level. In this paper, a conceptual design process and the results are described. Initially, the design requirement and the design parameter characteristics are analysed, and then initial sizing and configuration design are performed. There are several configuration changes due to specific technical reasons in each case. Finally, the required power and the pitch link load are predicted as an initial estimation. The conceptual design technique for the ducted fan in this study can be easily applied to the design of other ducted fans such as the lift fan for unmanned aerial vehicle.

Key Word : Tail Fan, Conceptual Design, Anti-Torque System, Helicopter

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. 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 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]. The ducted fan type anti-torque system, referred as tail fan in this paper, generally requires 40% more power compared to that of CTR. Eurocopter applied this concept to SA341, EC120, AS365 series, EC155[1-4]. Other examples are Ka-60/64(Kamov)[5], RAH-66(Boeing-Sikorsky)[6], MH2000 (Mitsubishi), OH-1(Kawasaki)[7]. The maximum take-off weight of these helicopters ranges from 1,678kg to 6,486kg. NOTAR, which was applied to MD-x series(2,835kg), can be applied only to small class helicopter due to the high level of required power.

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 and the results of the tail fan system design. At first, the design requirement and the design parameter characteristics are analysed. Then initial sizing and configuration design are

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

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

performed. Several configuration changes are made due to the specific technical reasons in each case. Finally, the required power and the pitch link load are predicted as an initial estimation for the next development phase.

General Characteristics of Conceptual Design Parameters

There are several conceptual design parameters to consider in designing the tail fan, such as fan rotation direction, blade diameter, fan tip speed, solidity, number of fan blades and so on. The general characteristics of those parameters are listed in Table 1.

Table 1. General Characteristics of Conceptual Design Parameters[10, 11]

Design Parameters	Characteristics
Fan Rotation Direction	Top blade afterward(TBA) direction makes the inflow dynamic pressure distribution uniform, so that aerodynamic and acoustic attributes are better.
Blade Diameter	If large, low required power and high control power. If small, low weight and low hub drag. Diameter of the existing tail fan ranges 0.7m to 1.37m
Fan Tip Speed	In forward flight, blade is unloading. Fin makes most of the anti-torque force. Advancing side problem is not critical. Around the main rotor tip speed is usually employed.
Solidity	$c_t/\sigma)_{max}$ and maximum thrust required determine a solidity. Range 0.5 to 0.56. 0.63 for RAH-66
Number of Blades	Aspect ratio is a main parameter. Even number is better for uneven blade spacing because of dynamics. Blades number ranges 8 to 12

From the momentum theory, the following relations can be derived under the assumption of an isentropic process[3]. From the continuity equation,

$$\dot{m} = \rho A(V+v_i) = \rho k A(V+v_e) \tag{1}$$

and the momentum equations,

$$T_{total} = T_{duct} + T_{fan} = \dot{m}(V+v_e-V) = \rho k A(V+v_e)v_e \tag{2}$$

By applying the Bernoulli equations at regions 0~1 and 2~3 in Fig.2 respectively and then subtracting the two equations,

$$T_{fan} = A(p_2 - p_1) = \rho A\left(V+\frac{v_e}{2}\right)v_e \neq T_{total} \tag{3}$$

From Eqs.(2) and (3),

$$\frac{T_{fan}}{T_{total}} = \frac{1}{2k}\frac{2V+v_e}{V+v_e} = \frac{1}{2k}\frac{(1+k)V+v_i}{V+v_i} \tag{4}$$

where ρ is the medium density, V is the sideward flight speed. Other variables in the above equations are defined in Fig. 2. If k=1, which depends on the diffuser angle, the fan thrust(T_{fan}) is 50% of the total thrust and is equal to the duct thrust(T_{duct}). It is important to design the duct inlet and the diffuser free from flow separation to avoid reduction in the duct thrust.

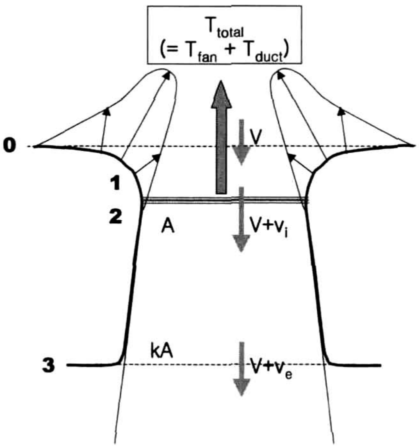

Fig. 2. Schematics of Ducted Fan for Momentum Theory

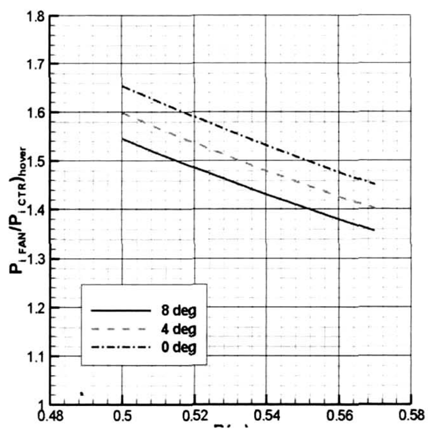

Fig. 3. R and P_i Relations with respect to Different Diffuser Angles

The induced power of the ducted fan can be derived as follows:

$$P_{i_{fan}} = T_{fan}(V+v_i) = T_{total}(V+v_e/2) \tag{5}$$

$$\frac{P_{i_{fan}}}{P_{i_{CTR}}} = \frac{T_{total}\left[\frac{3}{4}V+\frac{1}{2}\sqrt{V/2^2+T_{total}/(\rho k A_{fan})}\right]}{T\left[\frac{1}{2}V+\sqrt{V/2^2+T/(2\rho A_{CTR})}\right]} \tag{6}$$

If the thrust required and the figure of merit of the ducted fan are same to those of CTR, the induced power ratio in hover depends on only k, A_{CTR} and A_{fan} as shown in Eq.(6). Fig. 3 shows that the power of ducted fan is 50% higher than that of CTR.

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[12], MIL-F-83300[13] and ADS-33E[14] are related to the handling quality. Part of the requirements are: the initial yaw acceleration is at least 1 rad/s^2 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/s^2 considering the 10% margin as shown in Fig. 4.

The total weight of target helicopter anti-torque system is 173kg. In this case a special material

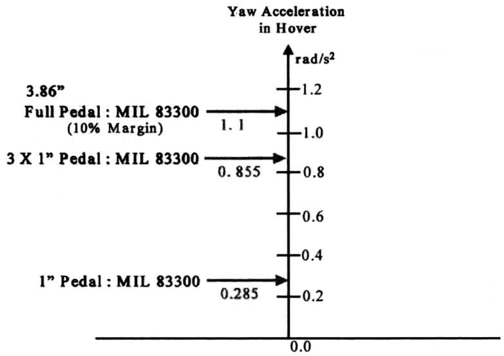

Fig. 4. Relation between Pedal Displacement and Yaw Acceleration of the Target Helicopter

for tail gear box is necessary to meet this weight limit. However, since the special material is not available for developing a prototype, the weight limit is not considered in this project. 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.

Specification of Target Helicopter and Initial Sizing

Initial Sizing Process

Fig. 5 shows the major parameters for the tail fan configuration design. The initial sizing process is summarized in Figs. 6 and 7. 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 2.

Table 2. 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)

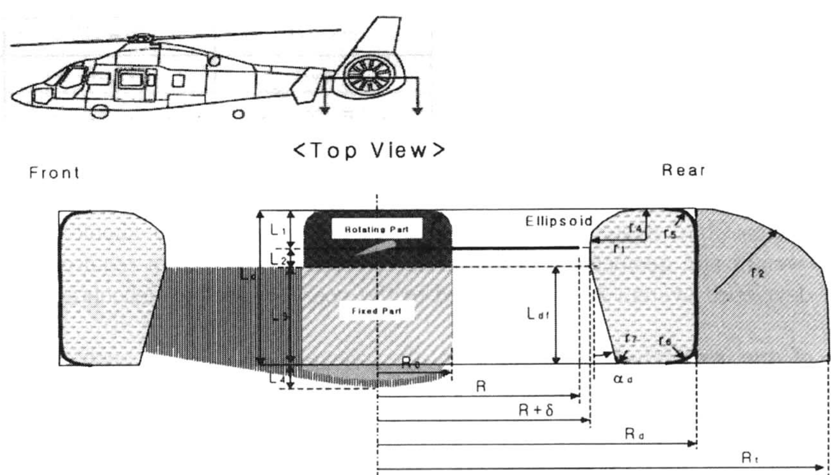

Fig. 5. Major Parameters for Ducted Fan Configuration Design

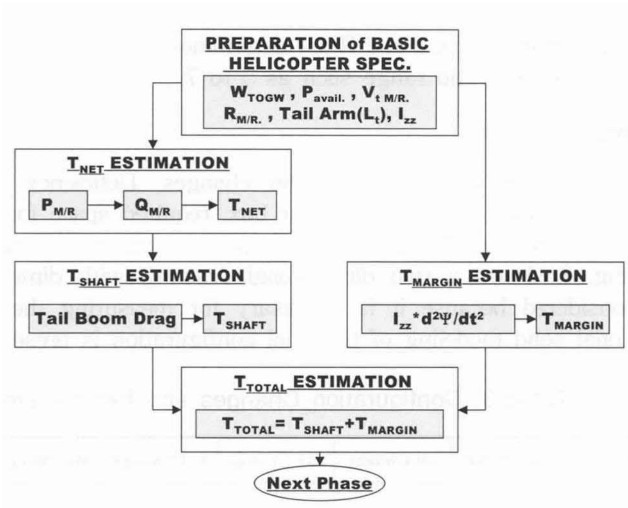

Fig. 6. Process of Evaluating a Maximum Required Thrust

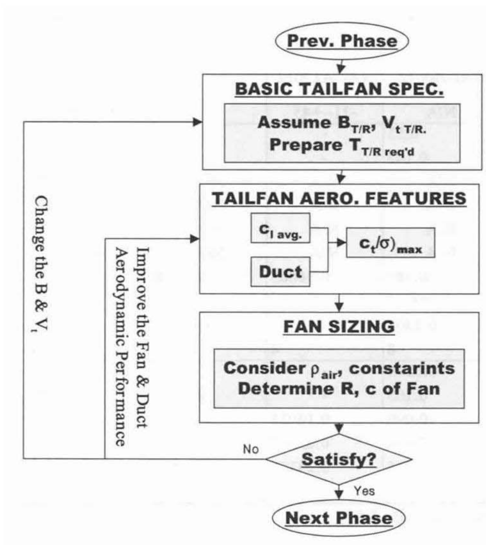

Fig. 7. Initial Sizing Process

It is assumed that the fin blockage and tail boom drag effects are 3% of T_{net} to calculate the T_{shaft}[3, 11]. The resultant maximum required total thrust obtained was 7,174N.

Initial Sizing

At first, $B_{T/R}$ and $V_{tip\ T/R}$ are required for the determination of the initial sizing values. $B_{T/R}$ is set to 10 by considering the improved design of uneven blade spacing system in near future, and the tip speed is used same as that of CTR, 209.4m/s. c_t/σ is closely related to the airfoil c_l characteristics. The baseline airfoil is NACA0012, however it is changed to NACA23012 to increase the thrust. Conservatively, maximum c_l is assumed to be 1.0, and then c_t/σ is 1/3. Considering the duct thrust(k=1) additionally, c_t/σ is set to 2/3, however 1/2 is used for the final calculation because Euler calculation[15] shows 2/3 is too high to achieve.

$$\frac{c_t}{\sigma} = \frac{T}{0.5\,\rho_{air} BcR\ V_t^2} \tag{7}$$

After cR is obtained from Eq.(7), c and R are determined as 0.1m and 1.57m, respectively by considering the preferable aspect ratio range such as 5 to 7.

Configuration Changes

Table 3 shows the history of configuration changes. 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. Fig. 8 shows a two dimensional drawing with dimension. 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. 9.

Table 3. Configuration Changes and Final Value

Parameters		Initial Size	1st Change	2nd Change	3rd Change	4th Change	Final Value
Fan Blade	B	10	-	-	-	-	-
	R(m)	0.55	-	-	0.57	-	-
	c(m)	0.078	-	0.094	0.1	-	-
	Vt(m/s)	209.7	-	209.4	-	-	209.8
	RPM	3641	-	3636	3508	-	3514.42
	Twist(deg)	-8	-	-	-	-	-
	Airfoil	NACA0012	NACA23012	-	-	-	-
	Pitch Range	N/A	-21~+45	-	-20~+45	-21~+45	-
Duct	Ld(m)	0.55	-	-	-	-	-
	r1(m)	0.143	-	0.11	0.15	-	-
	r4(m)	N/A	N/A	N/A	0.115	-	-
	r5(m)	N/A	N/A	N/A	0.07	-	-
	r6(m)	N/A	N/A	N/A	0.07	-	-
	r7(m)	N/A	N/A	N/A	N/A	0.02	-
	Ldf(m)	0.385	0.38005	0.3498	-	0.35	-
	d(m)	0.0055	-	-	0.0057	-	-
	Rd(m)	0.8305	-	-	0.85	-	-
	ad(deg)	8	4	-	-	-	-
Hub	r3(m)	0.0275	-	-	-	-	-
	R0(m)	0.165	-	0.1925	0.2125	-	-
	L1(m)	0.099	0.14025	-	-	0.14	-
	L2(m)	0.044	0.05995	-	-	0.06	-
	L3(m)	0.3025	0.24255	0.3498	-	0.35	-
	L4(m)	-0.0825	-	0.06	0.06	0.128	0.17

Note : - means the value used same as the left

<Top View>

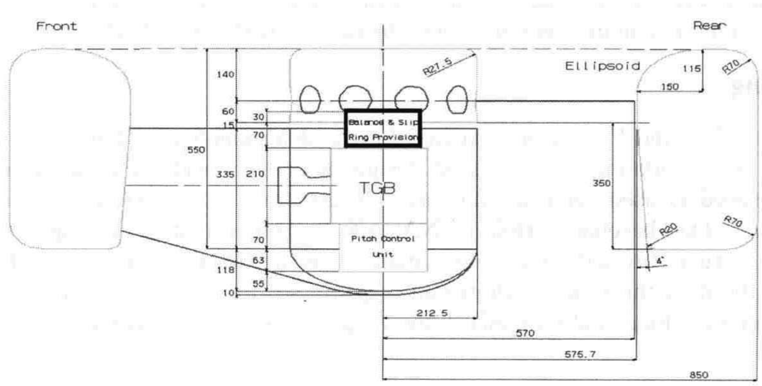

Fig. 8. Final Configuration of Tail Fan

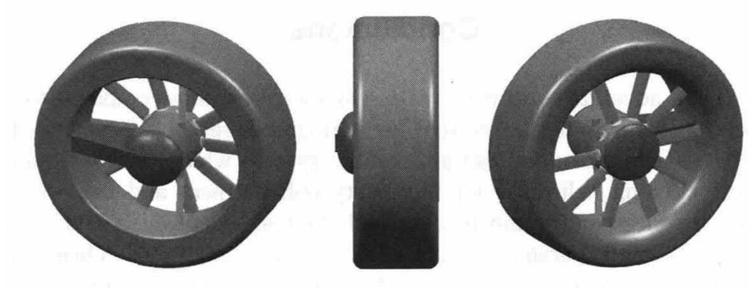

Fig. 9. 3D Solid Modeling of Final Tail Fan Configuration

Initial Estimations for Required Power and Pitch Link Load

As the next development phase, the required power and the pitch link load are estimated. In the following sections, the method for the initial estimation is briefly described.

Required Power

Fig. 10 shows the test datum of OH-1[7] and Bell DTR[8]. Unfortunately, the available test datum is much lower than the required range, because the maximum weights of OH-1(3,500kg) and Bell M222(3,742kg) are smaller than that of the target helicopter. Thus, the quadratic extrapolation is used to obtain the power at $c_t/\sigma)_{fan}$=0.25. 359kW and 462kW are obtained from each curve. For example, the maximum required power of AS365 is 300kW(T_{max}=5,600N) and 704kW(T_{max}=10,522N) in the case of LHX of Boeing-Sikorsky[9]. The other approach is also possible by using Eq.(6) on the assumption of same figure of merit. The maximum required power of the target helicopter CTR is 209kW and the result is 300kW. Bell data is not considered because Bell DTR has only 4 blades and relatively short duct depth which leads to overestimation of power. Finally, 400kW is set as an initially estimated value by considering a margin[16].

Pitch Link Load

The moment summation at the center of rotation should be zero as shown in Fig. 11. The pitch link load deviation(ΔP_b) due to the airload is initially estimated as 6,420N using NACA23012 aerodynamic tables[17].

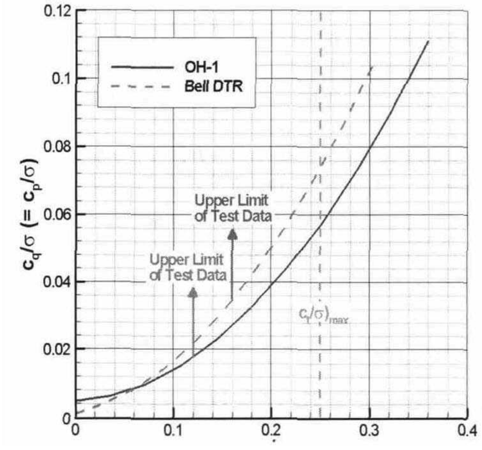

Fig. 10. Thrust and Power Coefficients[1,2]

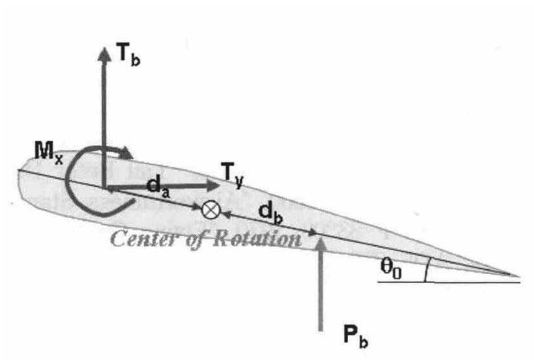

Fig. 11. Schematic Drawing for Pitch Load Calculation

Conclusions

Ducted fans have advantages in both noise and safety aspects compared to conventional tail rotors, and are used as an anti-torque system for various classes of helicopters. The final goal of this study is the development of a tail fan anti-torque system which replaces the conventional tail rotor of the specific existing helicopter for the safety enhancement and the noise level reduction.

In this paper, a conceptual design process and the results are described. At first, the design requirement and the design parameter characteristics are analysed. Then initial sizing and configuration design are performed. Several configuration changes are made due to the specific technical reasons in each case. Finally, the required power and the pitch link load are predicted as initial estimations. The conceptual design technique for the ducted fan in this study can be easily applied for the design of ducted fans such as the lift fan for unmanned aerial vehicles.

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