반작용 구동로터 시스템의 사이징 방법론에 대한 고찰

Review of Reaction Drive Rotor System Sizing Methodology

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Abstract

Reaction drive rotor system is capable of providing hover and low speed capabilities to different aircraft concepts such as stopped rotor wing, canard rotor wing, compound gyroplane etc. Existing sizing and analysis tools for shaft drive rotor system cannot be applied directly to this system. The available methodologies to size this system were reviewed. Power available calculation procedure and factors affects it were addressed prior to sizing process. Various design issues of this system due to interrelationship of internal gas flow dynamics and rotor external aerodynamics was discussed. Finally, a modification that is required in existing sizing methodologies was identified and combined approach in sizing process to consider the interrelationship among engine, rotor and blade duct was introduced.

Nomenclature

A	cross sectional area
b	number of blade
C_d	discharge coefficient
c_p	specific heat at constant pressure
c_v	specific heat at constant volume
C_{v_e}	nozzle velocity coefficient
D	duct hydraulic diameter
F	thrust
f	friction factor
g	acceleration due to gravity
HP	horsepower
J	Joule's constant
K	specific heat ratio
M	Mach number
P	pressure
Q	rotor torque
R	gas constant
r	blade element radius(radial position)
T	temperature
V	velocity
V_T	rotor tip speed
$\dot{m}$	mass flow rate
Ω	rotor rpm

Subscripts

j	jet
amb	ambient
s	stagnation condition
a	available
req	required

1. Introduction

Reaction drive rotor system is a kind of propulsion system to helicopters. It works based on the principle of Hero’ s turbine [1]. Rotor is driven by reaction forces of jet nozzle at tip of the blades. Therefore no anti-torque and complex gear transmission are needed. This inherent characteristics attracted designers in the past to build many reaction driven helicopters. In recent times, this system finds its application in various high speed rotorcraft concepts such as canard rotor wing[2], stopped rotor wing[3] and compound gyrodyne[4]. To integrate this system into such aircraft concepts, it should be properly analyzed and sized. However existing analyzing and sizing methodologies for shaft driven rotor system is not applicable to this system as there is an interrelationship exists between engine and rotor. Therefore, the main objective of this paper to review available methodologies of reaction drive rotor system as a prerequisite to develop a tool for analyzing and sizing this system. Also to list out the procedure to calculate power available and also to address the conflicting nature in design of such system.

2. Reaction Drive Rotor System Sizing

The main aim of rotor system sizing is to make sure that engine and rotor combination allow the aircraft to hover with an appropriate power margin for climb. This could be checked by matching process. Unlike shaft driven rotor system, design justifications have to be make in this system due to direct relationship between engine and rotor which will be evident in further sections. The main difference between shaft and reaction drive rotor system can be seen in power available determination which is based on not only turbine Inlet temperature, power turbine speed ratio but also flow properties at each sections of engine.

2.1 Step 1: Calculation of power available.

As shown in figure 1, information about flow properties are required at extraction point, at duct that connecting engine and rotor, at duct inside the blade and at tip jet nozzle to calculate power available. At extraction point, flow properties can be calculated once engine cycle is chosen. Based on methods to generate propulsive gas this cycle had been classified and shown in table 1.

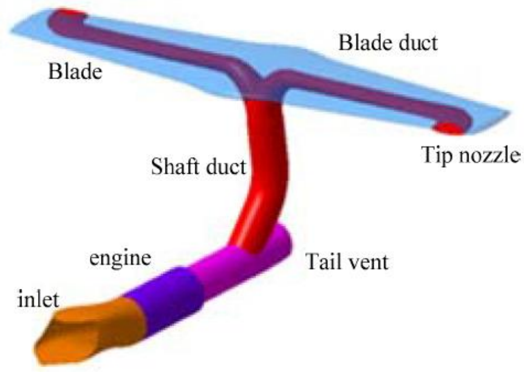

Fig 1. Schematic of reaction drive rotor system[8]

Table 1. Classification of engine cycles

Types of Cycles	Temperature(^oF)
Hot cycle	1300
Warm Cycle	900
Cold Cycle	300

Finally, flow properties such as pressure, temperature, mass flow at extraction point can be determined based on engine cycle analysis. Flow properties at hub is affected by pressure losses due to skin friction, area(convergent/divergent) and compressor inefficiency[5]. Engine' s location has an influence in duct arrangements and dimensions. Normally pressure losses are between 2 and 4 percent of engine exit total pressure[6]. Unlike conditions at hub, flow inside the blade duct is affected by disk loading and tip speed. Therefore effect of rotation must be considered. To capture this effect along with skin friction, changes in area and heat transfer effects equation 1 can be used which is based on one-dimensional, compressible, viscous flow relations[7].

$$\frac{dM}{dr}=\frac{M(1+KM^2)(1+\frac{K-1}{2}M^2)}{2T_s(1-M^2)}\frac{dT_s}{dr}+\frac{2KfM^3(1+\frac{K-1}{2}M^2)}{D(1-M^2)}-\frac{M(1+\frac{K-1}{2}M^2)^2\Omega^2 r}{g(c_p-c_v)JT_s(1-M^2)}-\frac{M(1+\frac{K-1}{2}M^2)}{(1-M^2)}\frac{\frac{dA}{A}}{dr} \quad (1)$$

Area of duct inside the blade can be taken as a percent of blade section area, as a constant diameter. However, a work had been done to predict blade duct area with respect to geometry of rotor blade[8].

The thrust at nozzle exit can be defined based on how much mass flow, velocity exists and addition of back pressure effect.

$$F_j = C_d \dot{m}_j V_j + (P_j - P_{amb}) A_j \qquad (2)$$

$$V_j = C_{v_e} \left(2 \frac{K-1}{K} g R T_s \left[1 - \left(\frac{P_{amb}}{P_s}\right)^{\frac{K-1}{K}}\right]\right)^{0.5} \qquad (3)$$

Tipjet power can be estimated in a similar fashion as that of shaft driven helicopter. But it is classified into two terms. Nozzle power and Coriolis power due to rotation. Therefore net power available power is given as below

$$HP_a = \frac{b V_T}{550} [F_j - \dot{m} V_T] \qquad (4)$$

One can easily identify that mass flow rate and tip speed are the two variables that shows interrelation of engine with rotor.

2.2 Step 2: Calculation of power required.

Blade element theory can be used to find out the power required of rotor by considering each radial position and thickness of blade element.

2.3 Step 3: Matching Process. There are two methods are available.

2.3.1 Power Matching Sizing Methodology[9]

Power matching process can be done by either by varying engine output conditions or by varying rotor geometry or by varying both. However changing engine conditions may not be easy as both rubber and fixed engine exercises may either oversize or undersize the engine to meet hover requirements of aircraft. Changing rotor geometry may provide solution but it would conflicts with design issues that must be carefully considered. They are (1) Minimum thickness to chord ratio to maintain lower profile power but it will lower the duct area thereby causing choking condition. (2) Mach number inside the duct must be lower. To do so duct area can be increased which increase blade planform area results in increasing profile drag. (3) Reducing blade planform area will increase blade loading which is directly related to blade mean lift coefficient. From these points it is understood that area of blade can only be reduced until maximum blade loading or internal flow limit are reached.

2.3.2 Mass Flow Matching Sizing Methodology[10]

It was identified that mass flow rate is one of the variables that directly relates engine and rotor. In this method, engine's mass flow at hub condition is matched with required mass flow rate at hovering conditions. In this approach, it was assumed that flow at hub would expands isentropically through out to the tip of blade where nozzle is placed. The required mass flow rate can be determined by equation 5 assuming that torque is obtained from rotor performance calculation. Therefore, required mass flow rate including blade rotation effect and flow properties at tipjet nozzle condition can be calculated as follows

$$\dot{m}_{req} = \frac{\frac{Q}{br} - (P_j - P_{amb}) A_j}{C_d V_j} \qquad (5)$$

3. Conclusion

Upon review of these two methodologies, either mass flow or power matching is required in sizing process of this unique system. It can be clearly seen in above power available calculation procedure that this system requires flow properties of propulsive gas. However in mass flow matching process the effect of blade rotation on flow properties inside the blade duct was not considered. It is understood that blade rotation will affect flow properties inside the duct and so power available at tipjet nozzle. Therefore this phenomenon must be considered and this approach has to be modified to capture the effect of rotation. Also it was already seen that by power matching process the geometry of both rotor blade and blade duct can be predictable. These two methods could be combined together in sizing process to consider the mutual relationship between rotor & engine and also to realize the compromises to be made in prediction of rotor blade and blade duct design due to conflicts of internal flow dynamics and rotor external aerodynamics. Figure 2 depicts the integration of mass flow and power matching into sizing process including the effect of rotation to flow properties inside the blade duct for cold cycle system at hover condition. However this approach must be analysed numerically to make sure that these two methodologies can be combined or not which will be achieved in future.

The expected output of this integrated approach will be blade thickness, rotor rpm, blade tip speed, blade duct cross sectional area, tipjet power and thrust.

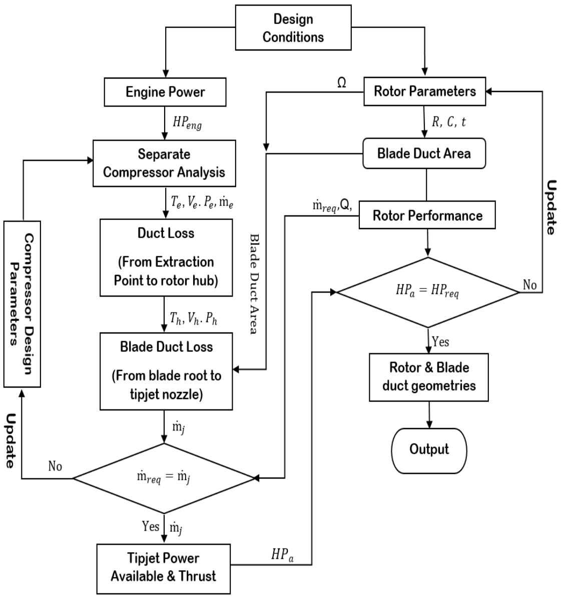

Fig 2. Integrated Sizing Process

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