CONCEPTUAL DESIGN FOR A SUAV PROPULSION SYSTEM SIZING

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Abstract

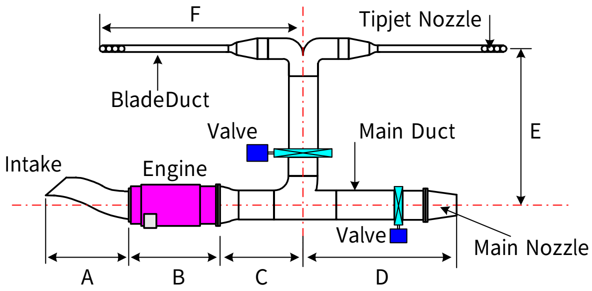
The concept of a tipjet rotor drive system is to use tipjet as power source to drive a rotor with its reaction force. As the aircraft is required to take-off and land vertically and cruise with high speed, it employed one rotor for hovering and cruising modes with rotor and fixed wing mechanisms respectively. In hovering mode, the exhaust gas which came from a turbojet engine passed through an internal duct system controlled by mode selection valves and went to two rotor blades. In cruising mode, the gas was controlled not to go to the rotor but to go to the main nozzle at the back of the aircraft. Inside a rotating duct, compressible flow is affected by two additional forces; centrifugal force and coriolis force and they govern the performance of the tipjet rotor system in hovering mode. The loss coefficients for the internal duct system model were chosen by empirical relations and 3-D CFD results. The conceptual design for the tipjet drive propulsion system was mainly dependant on the design code which consists of two parts, engine model and internal duct system model. In this paper, key design parameters were revealed by analyzing the characteristics of the engine and the tipjet rotor system regarding the various configurations of the internal duct system. The direction for the next design step was shown by the results of the parametric study and the sensitivity analysis.

1 General Introduction

Korea Aerospace Research Institute (KARI) launched the Smart UAV (SUAV) program as one of the '21st century frontier research and development program' sponsored by Ministry of Science & Technology in 2002. The objectives of this program are to develop a reliable Smart UAV system capable of high speed cruise, vertical takeoff/landing applying smart technology and to satisfy market ability and effectiveness for the civil UAV market in the near future. As the first step of the program, feasibility study on UAV was performed and tipjet rotor CRW (canard rotor wing), cartercopter and tilt rotor craft were the favorite candidates. In this paper, the issues were addressed associated with sizing and optimizing the configurations of a tipjet rotor propulsion system in hovering mode.

The concept study of a tipjet rotor system was started since 1950s. Cohan and Hirsh [1] showed the possibility of hovering flight with a tipjet rotor system which was powered by exhaust gas from a turbojet engine through tipjet nozzles. Bachmann [2] calculated the available power of a tipjet rotor system considering duct pressure loss between engine and rotor hub, gas conditions at blade duct and tipjet nozzle and centrifugal force along the rotating blade ducts. Crossley and Rutherford [3] suggested a new methodology to design a tipjet drive CRW aircraft and showed design point vehicle parameters using this method. Tai [4] sized and optimized a stopped rotor/wing configuration which incorporates a tipjet drive system and circulation control devices. He also formulated a methodology as a foundation for a new sizing code capable of developing the tipjet drive stopped rotor/wing concept.

The concept of the SUAV is to rotate the rotor with tipjet power in hovering mode for vertical takeoff/landing and to stop the rotor as a



	Length(mm)
A	1070
B	730
C	895
D	900
E	1080
F	2408

Fig. 1 Scheme of the SUAV propulsion system

fixed wing in cruising mode for high speed flight. The power source of a tipjet drive system is the exhaust gas of a turbojet (or turbofan) engine. In hovering mode, the engine exhaust gas passes through an internal duct system, controlled by mode selection valves and goes to two rotor blades. In cruising mode, the gas is controlled not to go to the rotor but to go to the main nozzle at the back of the aircraft to give a jet propulsive power.

The propulsion system of the SUAV consists of an engine, an internal duct system and circulation devices. SUAV decided to use a turbojet engine and an internal duct system which connected the engine, the rotor system and the cruising nozzle with complex configurations. The configurations of the connecting parts between the rotor hub and the blade ducts and of the blade ducts were key parameters for the performance of the tipjet drive rotor system. Minimizing the pressure loss of the internal duct system would make the propulsion efficiency higher. As the internal duct system was connected to the engine, the performance analysis for the engine and the internal duct were coupled. Empirical data and correlations of duct pressure loss were used compared with 3D-CFD results to model the internal duct system considering compressible fluid characteristics. Based on this code, configurations of the tipjet propulsion system were studied to show the next step for the propulsion system design.

2 Propulsion system design

2.1 Concept of the propulsion system

It is important for the tipjet drive CRW aircraft which has one rotor/wing to control the propulsive power generated by one engine for two different flight modes. Fig. 1 shows the scheme of the SUAV propulsion system. Air came to the engine through a S-shape duct and transmitted to the rotor hub or the main nozzle through the T-shape connecting part. The circulation devices decide the flight modes; hovering and cruising modes. In hovering mode, the hot exhaust gas leaving the T-shape connecting part moves up to the rotor hub and is divided into two rotors. In each rotor, the exhaust gas is distributed into 3 or 4 smaller ducts which fits in the thinner blades and ejects through the tipjet nozzles.

The characteristics of the engine exhaust gas classify the cycle of the tipjet propulsion system as shown in Table 1[4].

Table 1 Cycle classification of tipjet propulsion system regarding gas characteristic

Cycle	Characteristics	Temp.
Hot cycle	Exhaust gas from turbojet engine	> 1,000K
Warm cycle	Exhaust gas from turbofan engine	~ 700K
Cold cycle	Bleed air from turbojet/turbofan engine	~ 400K

For example, a cycle that uses a mixture of cold air (turbofan bypassed air) mixed with the engine exhaust is termed “warm” cycle. The selection of the most suitable cycle for the tipjet drive system can be viewed as an exercise in compromise where the thermodynamic advantages of a more efficient cycle are weighted against the aerodynamic reduction in efficiency and the structural problems caused by the higher temperature. And another problem is the availability of proper engines for the wanted cycle. SUAV decided to use ‘Hot cycle’ and 800lb-class turbojet engine was used to make an engine model.

2.2 Engine modeling

The target turbojet engine has 3-stages axial compressors and 1-stage axial turbine with a single spool. The detail performance spec. is shown in Table 2.

Table 2 Performance spec. of target engine (@SLS)

Net thrust	809	lbf
SFC	1.24	lbm/lbf/hr
Airflow	6.24	kg/s
Pressure Ratio (PR)	3.77	
Turbine Inlet Temp (TIT)	1204	K
Turbine Exit Temp (TET)	1062	K

Engine component models for compressor, combustor and turbine compose the engine model and it estimates the engine performance with its components data.

2.3 Internal duct modeling

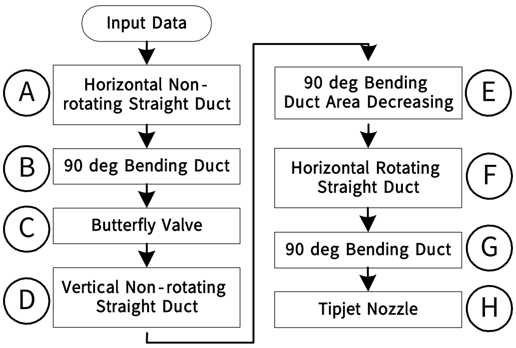


Fig. 3 Internal duct flow chart

As the engine exhaust gas transmitted along the internal duct system, it should consider the hot compressible gas behavior. In this paper, heat transfer effect was ignored to use 1-D Fanno line analysis. And fluid compressibility, duct pressure loss, rotating effects and valve disturbances were considered. There are two contraction parts in the system, one is between the rotor hub and rotor duct which is reduced by half area and the other one is at the end of the rotor duct where the blade ducts start. As the internal duct area has reduced down to 1/6 or 1/8 of that of the main duct, obviously duct loss would be an important design parameter. Only one blade duct was modeled and linearly multiplied by 6 or 8 regarding the number of total blade ducts.

The developed internal duct model has a flow chart as shown in Fig. 2. The internal duct model receives input data from the engine model and calculates through nine steps. As duct loss leads lower performance, it is important to minimize the loss. In Fig.3, four kinds of complicated duct configurations are shown and their basic modeling concepts were carefully studied. In Fig.3 (a) part, the T-shape divider should have a proper radius of curvature and consider the recirculation region which is caused by the cavity space. Because the second valve which blocks the flow to the main nozzle is located at the end of the aircraft, there is a cavity space between the upward duct of the T-shape divider and the second valve. This effect is also considered in the duct model at block Ⓑ with empirical data and 3-D CFD. Part (b) modeled duct section from the rotor hub to the two rotors. There are two assumptions; no centrifugal /coriolis effects and the same mass in each rotor. Two rotational effects, centrifugal and coriolis forces, will be presented but the radius of them are small enough to ignore them. And it is obvious that two rotors does not have

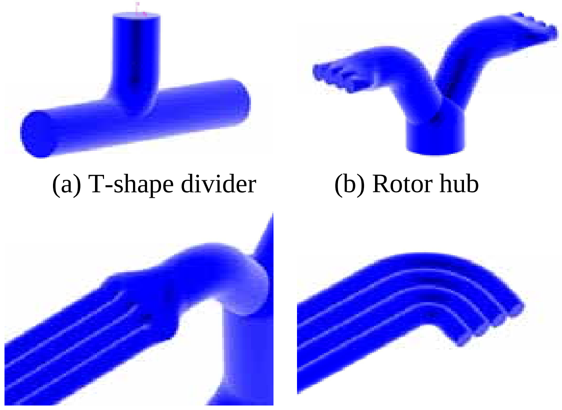


Fig. 2 Configurations of curved ducts

the same flow rate but it is beyond the scope of this paper. Part (c) distributes the divided flow from the rotor duct to 3 or 4 blade ducts. Considering the thickness of the rotor blades, the blade ducts have limited outer diameter. Part (d) is the last bending part in the blade ducts just before the tipjet nozzles. Each of them has different radius of curvature and they have different rotational effects which are ignored in this research. The tipjet nozzle is a simple convergent configuration with small area change.

Mathematically the internal duct system has three kinds of important models. 1) Horizontal non-rotating straight duct model like block Ⓐ in Fig. 2. Compressible flow behavior is modeled with Eq. (1) and Colebrook equation in Eq. (2) is used as the loss coefficient

$$\frac{4fdx}{D}=\frac{2}{\gamma M^2}(1-M^2)\left[1+\frac{1}{2}(\gamma-1)M^2\right]^{-1}\frac{dM}{M} \qquad (1)$$

$$\frac{1}{\sqrt{f}}=-2.0log\left[\frac{\varepsilon/D}{3.7}+\frac{2.51}{R\sqrt{f}}\right] \qquad (2)$$

2) 90° bending duct model like block Ⓑ,Ⓔ,Ⓖ in Fig.2 and (a), (b), (d) in Fig. 3. The same mathematical model was applied for the three cases with different input data regarding the configurations. Loss coefficients and pressure losses for the bending ducts were carefully studied by comparing empirical data and 3-D CFD analysis result [5]. To evaluate the comparison data, pressure loss evaluation tests for the internal duct system will be performed in the near future. Part modeling for (b), (c) in Fig.3 were simplified like block Ⓔ in Fig.2 and one loss coefficient was used. In Table 3, the loss coefficients for the three bending parts are shown which were decided by the internal duct analysis [5]. Loss coefficient sensitivity analysis result shows that the performance of the propulsion system is highly sensitive to loss coefficient k3 which is for the tipjet nozzle bending part as shown in Fig. 4.

Table 3 Loss coefficients for three bending models

Part	(a)	(b) + (c)	(d)
Loss coefficient	k1	k2	k3
	0.3	0.6	0.4

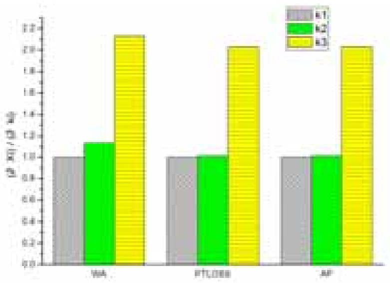


Fig. 4 Loss coefficient sensitivity analysis

3) Horizontal rotating straight duct model like block Ⓕ. Eq. (3) shows the characteristics of compressible gas flow inside a rotating duct. It shows that the mach number of the gas flow is a function of four key parameters, area change, skin friction loss, total temperature loss and centrifugal force change regarding the radius of rotation. As this research assumes that there are no area change in ducts and no heat transfer, these terms are removed.

$$\frac{dM}{dr}=\frac{M\left\{1+\left[\frac{\gamma-1}{2}\right]M^2\right\}}{1-M^2}\left(-\frac{1}{A}\frac{dA}{dr}+\frac{\gamma M^2}{2}\left(\frac{4f}{D}\right)+\frac{(1+\gamma M^2)}{2T}\frac{dT}{dr}-\frac{\left\{1+\left[\frac{(\gamma-1)}{2}\right]M^2\right\}}{RT}\Omega^2 r\right) \qquad (3)$$

2.4 System performance prediction

Power requirement for the SUAV is defined in Eq. (4) and is shown in Table 4.

$$P_{req}=C_p\pi R^2\rho V_{tip}^3 \qquad (4)$$

Table 4 System required power

Conditions	Required power
ISA, SLS	370 shp
Alt=300m, Hotday (43.3℃)	401 shp

Available power of the propulsion system shall satisfy the requirements and it is defined in Eq. (5).

$$Available\ power = Tipjet\ power - Coriolis\ power \quad (5)$$

Tipjet power is generated by the simple convergent tipjet nozzles and is defined in Eq. (6). In Eq (6), 'N' designates 'nozzle', 'a' is ambient and 'e' is the nozzle exit plane.

$$F_N = (C_D \dot{m})V_{jet} + (P_e - P_a)A_N \quad (6)$$

There are two reasons why the tipjet nozzle employs simple convergent configuration; to reduce jet noise and guarantee better off-design performance. With the same concept, the exhaust jet speed is limited in subsonic range.

As the flow transmitted through rotating ducts, coriolis force $\dot{m}(\Omega R)^2$ acts on the opposite direction of rotation works as a negative term.

3 Results

3.1 Engine operational characteristics

As the internal duct system was directly connected to the engine, the configuration and the rotational speed of the system changed the operational characteristics of the engine. The change of the engine operating lines is shown in Fig. 5 where the case 0 is the uninstalled operating line and the case 1 is the operating line with initial configuration duct system which will be explained later. Compressor surge margin has been reduced by 15.7%, 27.7%, 51.9% compared with uninstalled conditions at 83%, 93% and 100% compressor rpm. This result shows that the compressor surge margin reduction shall be carefully studied when the SUAV employs this type of turbojet engine.

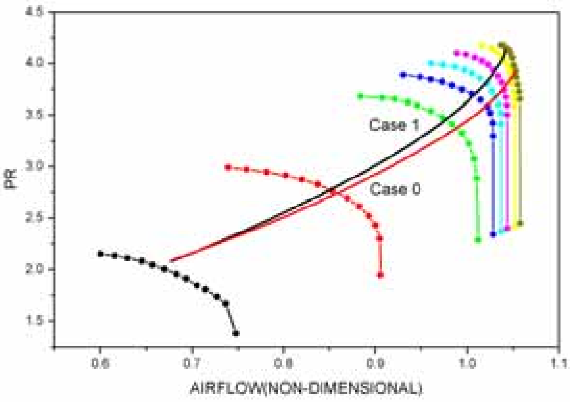


Fig. 5 Change of engine operating lines

3.2 Propulsion system sizing

As a first step for the conceptual design and sizing, sensitivity analysis and parametric study were performed. Through these results, we could find key design parameters and determine a design direction. The sensitivity analysis regarding blade duct, tipjet nozzle, main duct areas and RPM was performed and the result is shown in Fig. 6. In this figure, parameters P, T, WA, PTLOSS, AP and SFC represent pressure, temperature, gas flow rate at the tipjet nozzle, pressure loss between the engine and the tipjet nozzle, available power and specific fuel consumption respectively. This analysis result shows that the power and the efficiency of the SUAV propulsion system are mainly governed by the tipjet nozzle.

Table 5 Initial duct size (case 1)

Parts	Dia (mm)
Main duct	280
Blade duct	80
Tipjet nozzle	73

Duct sizing started with a set of initial sizes as shown in Table 5 and it was called case number 1. With this configuration, environmental effect of the hotday condition is simulated as shown in Fig. 7. In the standard

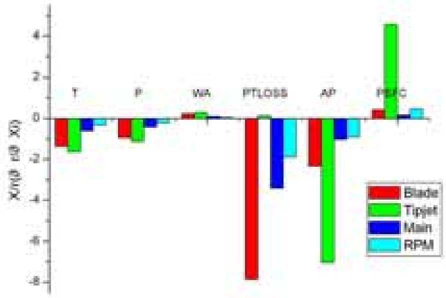


Fig. 6 Sensitivity analysis for the key parameters

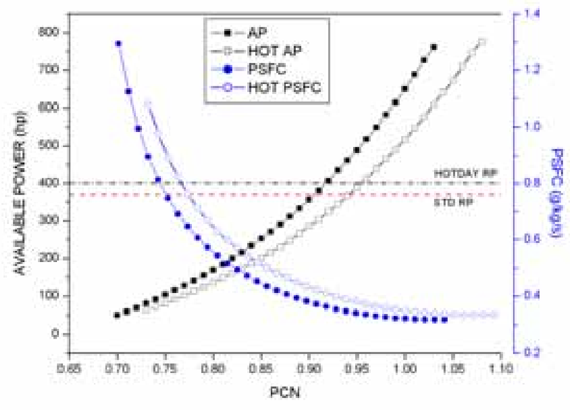


Fig. 7 Performance difference in hotday and standard day

day condition, output power above the range of PCN(percentage rpm) = 91 satisfies the required power in Table 4. Max available power is 760shp and PSFC is 0.319 ~ 0.363. In the hotday condition which has 43.3℃ ambient temperature, the required power is satisfied above the range of PCN = 96, with 776 shp max available power and 0.337 ~ 0.366 PSFC. Near the full loading condition, there is small difference in PSFC but big difference in available power.

Referring to the result of the sensitivity analysis, sizing parametric studies for blade duct configuration, nozzle area and rotor rpm have been performed. Comparing with the initial blade duct area (case 1), case 2 has -15% and case 3 has +15% changed area. Minimum PCN to achieve the required power moves from 91 (case 1) to 88 (case 2) and 93 (case 3). And PSFC has changed from 0.367 (case 1) to 0.396 (case 2) and 0.348 (case 3). By reducing the cross sectional area of the blade ducts, internal flow has been accelerated and transmits higher momentum. But it also accompanies with higher exhaust gas temperature and it changes from 983K (case 1) to 1097K (case 2). Because area reduced blade ducts increase pressure loss inside the ducts and the engine back pressure, engine needs more fuel to overcome the increased back pressure. In case 1 and 3, the upper limits of the engine operating ranges are over PCN = 100 but, in case 2, the upper limit moves down to 97. As the engine back pressure increases, the compressor operating point moves toward surge and PCN = 97 becomes the limit point.

Nozzle area is reduced 20% in case 4 and 20% increased in case 5, comparing with the initial area (case 1). According to the nozzle area change, minimum PCN to satisfy the required power changes from 91 (case 1) to 81 (case 4) and 101 (case 5). And PSFC has changed from 0.367 (case 1) to 0.348 (case 4) and 0.427 (case 5). Similar to the case of blade duct area change, nozzle area reduction causes flow acceleration and skin friction loss increment simultaneously. This leads to higher exhaust gas temperature which is 1086K and 1025K for case 4 and case 5 respectively. Though increasing the nozzle area, the exhaust gas temperature raises in case 5. Because the tipjet nozzle loses the role as a nozzle, as the nozzle area has enlarged and the engine is forced to generate more power. Case 4 shows similar behavior to case 2 which is caused by area reduction and they end up with compressor

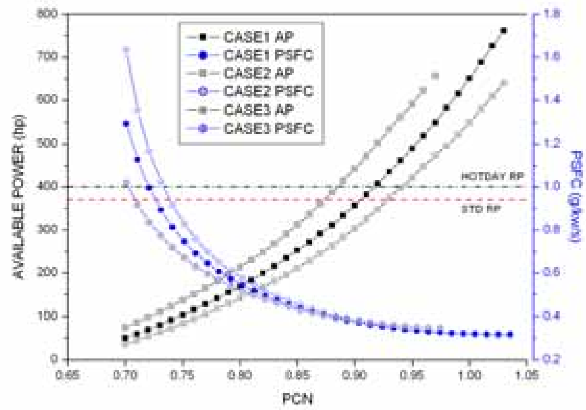


Fig. 8 Blade duct area change

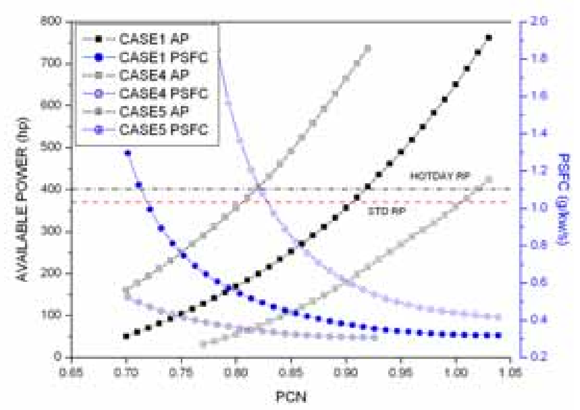


Fig. 9 Nozzle area change

surge. Comparing Fig. 8 with Fig. 9, nozzle area has more influence on available power and PSFC and it coincides with the sensitivity analysis result shown in Fig. 6.

In Fig. 10, rotor rotational rpm changes between 20% (case 6) and -20% (case 7). Minimum PCN for the required power is 94 (case 6) and 91 (case 7) and PSFC changes to 0.341 (case 6) and 0.391 (case 7). As rpm variation shows little influence in the PCN range where the required power is satisfied as shown in Fig. 10, it turns out to be a minor parameter for the system performance design. As rotor rpm is a critical parameter for the rotor system, the propulsion system can provide wide range of rpm choice which does not influence much on the performance.

4 Conclusion

This paper has shown that the sensitivity analysis and parametric study are useful to figure out the next design step in the early conceptual design. Based on the discussions and results shown here, one can get four results.

First, it is important for the tipjet drive propulsion system to verify and to improve the internal duct system with least pressure loss. Sensitivity analysis is performed for the internal duct system and the loss coefficients. And it shows that the blade duct configuration which has high dynamic pressure is one of the most important design parameters.

Second, rotating effects like centrifugal force and coriolis force have important roles in tipjet propulsive power generation. They should be carefully verified and designed, because it is almost impossible to measure them directly.

Third, by reducing the blade duct and the nozzle areas, it is easier to make the required power with lower PCN but it is accompany with higher exhaust gas temperature and worse PSFC.

Fourth, rotor rpm has little influence on the system performance in the PCN range where the required power is satisfied. The propulsion system designers may pay less attention on the rotor rpm.

It is recommended that the internal duct system has smaller areas and simple configurations but it can lead bad effects on the propulsion system like high pressure loss, lower performance and high exhaust temperature,

For this reason, the propulsion system designer is asked to design the internal system with high performance and less size which means less weight.

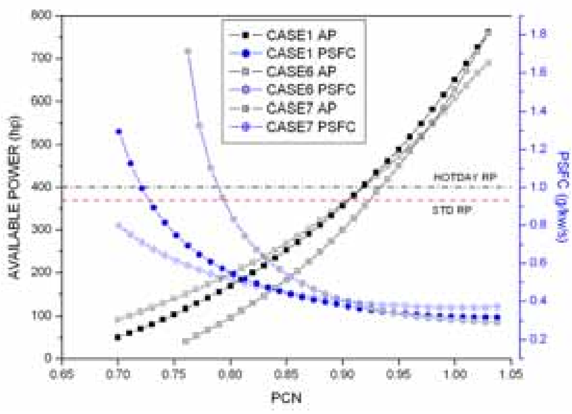


Fig. 10 Rpm change

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