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Numerical investigations of ducted fan aerodynamic performance with tip-jet

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ABSTRACT

Tip-jet technology has the potential value for application in vertical take-off and landing or short take-off and landing concept aircraft. The main objective of this work is to present a rapid prototyping method to model the power of the tip-jet during the concept design phase, and to investigate the aerodynamic performance of a ducted fan with tip-jet in hover through numerical experiments. The calculated data of the rapid method was compared to the numerical results, while the comparative analysis of the performances of an open fan, a ducted fan and a ducted fan with tip-jet were carried out. The results indicate that the fan lift of the ducted fan with tip-jet was augmented by the jets which formed the Coanda effect on the suction surface of the blade to increase the circulation of the blade. The figure of merit of the ducted fan with tip-jet was reduced and slightly affected by the nozzle area. The flow field represents the same flow features when the nozzle works in subsonic to supersonic operational conditions.

1. Introduction

The tip-jet rotor is driven by the reaction torque produced by the jets ejected out of the nozzle at the blade tip. The unique characteristic of the tip-jet rotor mean it could be a potential propulsion unit in the field of take-off or short take-off and landing for aerial vehicles. The tip-jet technology was first applied in helicopters, due to the advantage of the simple structure and light gross weight by removing the mechanical transmission and anti-torque systems. The WNF-342 [1] was the first tip-jet helicopter to take off and land, flown in 1943. During the 1950s, some effort was made try to develop and demonstrate the tip-jet driven rotor. Led by the Hughes Tool Company, this work culminated in the successful demonstration of the XV-9A research aircraft. The XV-9A rotor system, which is driven by the exhaust gases of the turbojet engine, proved the viability of the “hot cycle” pressure jet helicopter concepts. A commercial tip-jet aircraft Fairey Rotodyne was flown in 1957. But the noise and high fuel consumption levels at the time and the control problem of the rigid rotor limited the application of tip-jets in helicopters. As research into new concept aircraft [2,3] rose, the tip-jet was utilized to support these new concept aircraft in gaining the ability of vertical take-off and landing. For example, the Boeing X-50A with the Canard rotor wing concept aircraft applies the tip-jet rotor to provide flight power during the vertical take-off and landing period, and the exhaust nozzle provides high speed cruising ability [4,5].

In this study, a kind of ducted fan with tip-jet is proposed, which combines the merits of the ducted fan [6] with the tip-jet. As the fan works in the duct, the control problem of balancing the roll moment on the rigid blade of a helicopter could be eliminated, while the noise problem caused by the jets may be improved upon. Moreover, this concept maintains the advantage of the simple structure and light gross weight for the energy transfer. So this kind of propulsion unit may be useful in the field of new concept vehicles.

Over the recent decades, Phillips [7] investigated vehicle efficiency using modern tip-jet technologies. The research results show that the overall efficiency of tip-jet drives can be improved to surpass 1950s era technology by coupling a modern high bypass gas generator to a cold cycle tip-jet drive, resulting in the overall vehicle efficiency as measured by hover time improved over the shaft drive at the examined gross weight over 36,400 pounds.

A conceptual design for an unmanned aerial vehicle (UAV) configured with a tip-jet-driven, two-bladed, stoppable rotor and circulation control airfoils was presented by Schwartz et al. [8] in 1991. For the vertical launch and recovery, this UAV's wing becomes a tip-jet-driven helicopter rotor, with the turbofan cold bypass air diverted into the wing to supply the tip-jets. Schwartz et al. [9] also investigated the aerodynamic properties of an in-

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Nomenclature

A	area	m^2
a	loss coefficient	
C_T	lift coefficient	
C_p	pressure coefficient	
C_Q	power coefficient	
c	chord	m
c_p	specific heat at constant pressure	J/(kg K)
h	nozzle height	m
l	nozzle length	m
l_P	pipe width	m
l_{Pt}	nozzle tip distance	m
L	lift	N
M_a	available torque	N m
M_c	Coriolis force torque	N m
M_p	nozzle differential pressure torque	N m
M_j	total jet torque	N m
Ma	Mach number	
mt	momentum	
p	pressure	Pa
p_f	ambient pressure	Pa
p^*	total pressure	Pa
q_m	mass flow rate	kg/s
r	rotor radius	m
r_{P1}	pipe inner corner	degree
r_{P2}	pipe external corner	degree
R	gas constant	J/(kg K)
R_1	blade radius	m
R_{D1}	duct inner radius	m
R_{D2}	duct external radius	m
h_P	pipe height	m
H_D	duct height	m
H_{D1}	duct inlet height	m
T	temperature	K
T^*	total temperature	K
w_c	work of centrifugal force	J
v	velocity	m/s
ρ	density	kg/m^3
λ	velocity coefficient	
w	rotor angular speed	rad/s
k	adiabatic exponent of gas	
σ	rotor solidity	

Subscripts

1	internal radius
2	outer radius
h	rotor hub
j	jets

tegrated pneumatic lift/reaction-drive rotor system in hover. This rotor concept combines circulation control aerodynamics and cold-cycle reaction dive technologies into a single system with a common air supply. The test results revealed a significant impact on the induced power efficiency due to the non-lifting tip nozzle region of the blade and the presence of the tip nozzle jet had no discernible impact on the external aerodynamics of the lift system.

Holloway and Richardson [10] studied the effect of vortex core distortion on vortex decay of trailing vortices with wing spanwise tip jets, and found that the spanwise tip jets added swirls and streamwise jets to the vortex core that rapidly diminished with downstream distance. Elmahmodi [11] investigated the performance of a tip-jet rotor powered by a rocket motor. The results showing that the rocket jet rotor configuration is capable of a considerably higher payload for flights of very short duration, but that it was only possible for short flights. Kenneth S. Brentner et al. [12] explored a new approach to predict the noise of the tip-jet rotor. They found that increasing the exit area and reducing the weight of the aircraft have a strong effect on the noise.

Because the published researches were mainly related to helicopter rotor, understanding of the effect of the jets on the performance and flow field of a ducted fan system require further study. The basic flow principle of the tip-jet reaction was presented in reference [13]. However, this study presents an alternate method that is convenient for use in conceptual design cases, because the related functions do connect the bleeding air parameters to the aerodynamic parameters of the jets under a set of specific geometric conditions.

The first objective of this study is to propose a rapid prototyping method that can estimate the power supplied by the jets in a tip-jet fan system and can rapidly size a prototype tip-jet fan during the concept design phase. The second objective is to investigate the effects of the jets out of the nozzle on the performance of a ducted fan. The numerical computations showed that the jets have a certain effect on the internal flow of the ducted fan, resulting in the lift augment of the fan and the lift drop of the duct. This is due to the changes of the blade circulation and the average pressure on the duct lip. For the rest of this paper, the concept of the ducted fan with tip-jet system will first be introduced followed by detailed descriptions of the configuration of the open fan, ducted fan and ducted fan with tip-jet used in the investigation. A rapid prototyping method is then proposed to estimate the available torque and power produced by the jets under different bleeding air parameters at a specific rotational speed, based on the known geometrical conditions. The computational methods are then presented for data comparison, and to model the effect of the jets in the internal flow of the ducted fan. In the results and discussion section, comparison of the aerodynamic performances of the open fan, ducted fan and ducted fan with tip-jet in hover will be presented first, followed by the mechanism analysis of the interior flow field of the fans, based on the high fidelity computational simulations.

2. Ducted fan with tip-jet system

The features of the ducted fan with tip-jet were mentioned before as the fan's rotor is totally driven by the tip jets, which can provide a flexible approach for transferring the power of the core engine with high rotational speed to the fan with lower rotational speed, to therefore augment the engine's thrust and to turn the thrust direction at the cost of a lighter weight and simpler facilities. The diagram of the ducted fan with tip-jet system concept is depicted in Fig. 1.

The bleeding air with high energy for propelling the rotor can be bled from a core engine or a compressor. Then, the bleeding air can pass through the pipeline, duct and blade internal pipe, to then eventually reach the blade tip, where it can be ejected out of the nozzle. The flow path of the air is shown as red arrows in Fig. 1. Out of the nozzle, the jets flow phenomenon of expansion, dissipation and entrainment are developed inside the ducted fan, which have an inevitable influence on the performance of the ducted fan. So to clearly illustrate such influence, the performances of an open fan, a ducted fan and a ducted fan with tip jets were obtained. Then, the comparison and analysis of the performances and flow characteristics between these fans could reveal the properties of the jets inside the duct, which will be discussed in Section 6.