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Experimental and numerical investigation of the power-on effect for a propeller-driven UAV

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ABSTRACT

The power-on effect contributes to the performance and the stability of a propeller-driven aircraft. In the present study, the power-on effect for a propeller-driven unmanned aerial vehicle with a pusher propeller has been investigated through the wind tunnel test and the computational fluid dynamics simulation. The positive power-on effect is to increase the maximum lift and delay the stall of the aircraft. However, the most common power-on effect is to produce the slipstream drag and the nose-up pitching moment of the aircraft. The slipstream interaction with the wing and the fuselage increases the fuselage pressure drag leading to an overall increase in aircraft drag. Moreover, the slipstream interaction increases the downwash angle and dynamic pressure in the vicinity of the horizontal tail leads to an overall increase in aircraft nose-up pitching moment. Therefore, the power-on effects tend to reduce the performance and longitudinal stability of the propeller-driven aircraft. The power-on effect is pronounced at slower speeds and higher thrust levels. It is expected that the analysis results presented and discussed in this paper will contribute to the development of the propeller-driven aircraft with the pusher propeller.

1. Introduction

The power-on effect created by the propeller contributes to the performance and the stability of a propeller-driven aircraft. The forces created by the propeller and the effects of the propeller slipstream on the wing and tail surface contribute to the equilibrium condition directly and indirectly. Especially the propeller creates considerable indirect effects as a result of the interaction between the propeller slipstream and the wing. The indirect effects are no less important than the direct effect. Actually the indirect effects are more important in many cases. Some of the more important of these indirect effects are increase in downwash angle of the wing, increase in dynamic pressure at the tail, and change in pitching moment of the wing due to the propeller slipstream [24]. These effects are all related and interact with each other to produce various moments on the aircraft. The propeller affects the wing characteristics by changing lift, drag, and pitching moment. For the pusher propeller the effect was more intense on the rear of the wing but can also extend to the front by changing the upwash angle. The propeller effects are very dependent on the relative position of the propeller and the wing [3]. The increase in velocity of the air at the horizontal stabilizer increases its effectiveness and the increase in velocity of the air at the wing changes its pitching moment, requiring more elevator deflection when the horizontal stabilizer is positioned above the propeller disk. The most common overall effect of these three phenomena is to produce a nose-up pitching moment of the aircraft and therefore tends to reduce the longitudinal stability of the aircraft.

However, the indirect effects are extremely complex in nature and therefore the indirect effects are difficult to account for with accuracy. Therefore the wind tunnel tests of powered model are usually performed to evaluate the aerodynamic characteristics of the aircraft [7,8,11,15,19,20,22,26].

The research efforts that analyze a rotating object such as a propeller or helicopter rotor have been continued for a long time. Since the momentum theory or disk actuator theory was developed to analyze the propeller performance, Blade Element Momentum theory (BEM) has been used to calculate steady-state flow properties behind rotating propellers [2,9,14,17,25]. BEM uses momentum theory to calculate the local induced velocity and incorporates this information into the blade element model. In the second place, singularity methods such as lifting-line and lifting surface method have been used to model the propeller blade and the airframe [4,18]. The lifting surface panel method uses the free-wake model based on the time-marching method to calculate the flow-field of a propeller vortex wake and propeller performance parameters [13,16].

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Nomenclature

c	mean aerodynamic chord of the wing
C_D	aircraft drag coefficient $C_D = D/qS$
C_L	aircraft lift coefficient $C_L = L/qS$
C_m	aircraft pitching moment coefficient about center of gravity of aircraft $C_m = m/qSc$
C_P	propeller power coefficient $C_P = P/\rho n^3 D^5$
C_T	propeller thrust coefficient $C_T = T/\rho n^2 D^4$
C_X	force coefficient in the streamwise direction $C_X = F_X/qS$
C_Y	aircraft side force coefficient $C_Y = F_Y/qS$, propeller lateral force coefficient $C_Y = F_Y/\rho n^2 D^4$
C_Z	propeller lift force coefficient $C_Z = F_Z/\rho n^2 D^4$
D	aircraft drag, propeller diameter
F_X	force in the streamwise direction
F_Y	aircraft side force, propeller lateral force
F_Z	propeller lift force
J	advance ratio $J = U_\infty/nD$
L	aircraft lift
M	freestream Mach number
m	aircraft pitching moment about center of gravity of aircraft
n	propeller rotational speed
P	propeller shaft power
q	dynamic pressure $q = (1/2)\rho U_\infty^2$
S	wing reference area
T	propeller thrust
U_∞	freestream velocity
α	angle of attack
η	propeller efficiency $\eta = J(C_T/C_P)$
ρ	fluid density
Ψ	azimuthal angle

Henceforward advances for Computational Fluid Dynamics (CFD) have been made over the years. In theory, Direct Numerical Simulation (DNS) can solve a fully turbulent unsteady rotational flow without approximation, albeit at low Reynolds numbers. Such calculations are not yet achievable for complex turbulent unsteady rotational flows because the method is computational exhaustive. Although Large Eddy Simulation (LES) is less computational extensive, it still require significant computational effort.

Reynolds Averaged Navier–Stokes (RANS), and its unsteady counterpart uRANS, have developed into widely applicable methods that can be applied to a broad variety of flows in a standardized fashion. One of the most common RANS-based CFD approach frequently used to model the presence of propeller blade inside the flow-field is Multiple Reference Frame (MRF) implemented for the commercial CFD code [10,12]. MRF is a model to simulate rotating flows with axisymmetric boundary condition in a simplified environment. At the same time, Virtual Blade Model (VBM) based on the coupling of the blade element theory with CFD has been adapted in order to simulate propeller blades [21]. VBM does not require explicitly the propeller geometry so that there is no need to generate individual meshes over each of the propeller blades reducing significantly the number of cells in the domain and consequently reducing computing time. However, MRF and VBM are unable to simulate physical phenomena such as the swirl flow and complex wake accurately compared to the Sliding Mesh Model (SMM) although these methods are less computational exhaustive. Because these methods are models that are applied to steady-state cases, thus neglecting unsteady interactions arises from the relative motion of stationary and rotating components in a rotating machine. Therefore, when unsteady interaction between the stationary and moving parts is important, SMM can be a great alternative to compute the unsteady flow-field, but also the most computational demanding [6,23].

In the present study, CFD simulations have been performed for the power-on effect using the MRF and SMM approach and have been validated using the wind tunnel test.

2. Analysis model

The analysis model is a propeller-driven Unmanned Aerial Vehicle (UAV) with a pusher propeller as shown in Fig. 1. The body is composed of distinct and separate wing structure, though the wings are smoothly blended into the body.

The propeller model used in the simulation is a 2-blades fixed-pitch propeller which is mostly used in the UAV. The propeller diameter and the pitch are 28 inch and 22 inch, respectively. The propeller performance curve provided by the propeller manufacturer is shown in Fig. 2. The principle dimensions and data are shown in Table 1.

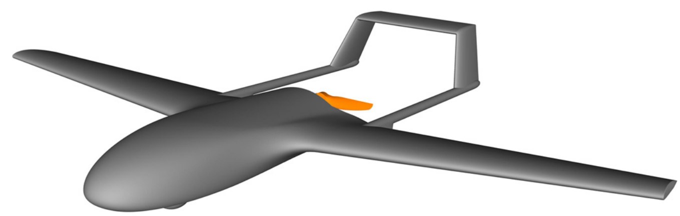

Fig. 1. Unmanned aerial vehicle with a pusher propeller.

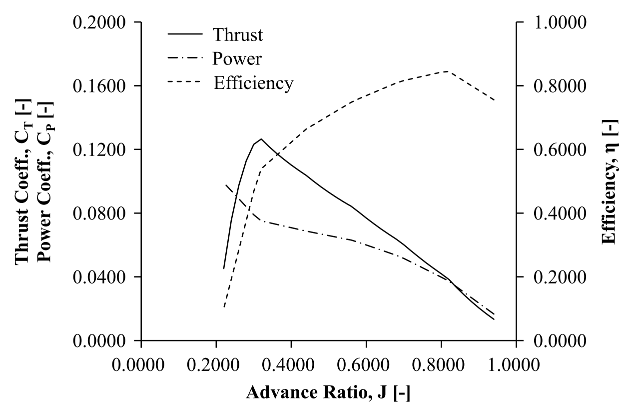

Fig. 2. Propeller performance curve.

3. Methodologies

3.1. Wind tunnel test

The experiments had been performed by UAV Engines Ltd. in the Airbus Filton low-speed wind tunnel facility. Fig. 3 shows a full scale model of the aircraft was used in the wind tunnel test. However, the model had a wing span clipped at 2700 mm and included no tail booms, a simplified under carriage and payload dome were also installed onto the airframe.

The specification of the wind tunnel facility is shown in Table 2. All data recorded from the Engine Control Unit (ECU) and on board logging system were sent to the centralized wind tunnel data acquisition system by means of User Datagram Protocol (UDP)