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Experimental investigation of the impact of a propeller on a streamwise impinging vortex

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ABSTRACT

By employing a wing-tip vortex impinging onto a propeller, the impact of the propeller on this vortex is studied with the help of Particle Image Velocimetry measurements. The effects of the propeller on the vortex are compared in the flow fields in the vicinity of the blades, i.e. one plane upstream and one plane downstream of the propeller. The meandering of the vortex downstream of the propeller increases by approximately one order of magnitude with respect to that upstream of the propeller. The circulation of the downstream vortex is at the same level as the upstream vortex, and this means the downstream vortex still has the potential to influence the airframe further downstream. As the vortex impinges at different radial positions of the propeller, the stretching effect depends on the local thrust of the propeller, which is different from the case with a vortex impinging on a steady wing. The Proper Orthogonal Decomposition analysis shows that the first and second modes of the flow upstream of the propeller are induced by the blade passing, whilst the third and the fourth modes are induced by the vortex meandering.

1. Introduction

During the operation of propellers, the inflow of the propeller may be complex and even involve concentrated vorticity. When propeller aircraft are operated near the ground, there are probabilities of a ground vortex being ingested into the propeller [1]. A vortex could also be shed from the upstream lifting surface of the airframe, such as the canard [2] and the wing [3] of an aircraft with pusher propellers. Furthermore, for counter-rotating open rotors, a vortex shed from the front rotor impinging onto the aft rotor has been reported in [2,4]. In this paper, a vortex aligned with the propeller axis (streamwise vortex as defined in [5]) is chosen to study the impact of the propeller on the vortex, because this is the dominant component for a ground vortex, a canard-tip vortex and a wing-tip vortex when they impinge onto propellers [1–3].

Research of interactions between a streamwise-vortex and a blade has been extensively conducted on simplified models, e.g. a vortex impinging onto a steady wing. The effect of the vertical distance between the wing and the impinging vortex has been investigated in [6–8]. It is found that the interaction has little influence on the vortex when the distance between the wing and the vortex is beyond 0.3 chord length of the wing [7]. As the distance decreases, the interaction substantially weakens the vortex core and increases its size downstream of the wing [7,8]. Although parameters of the impinging vortex change as a result of the distance variation, the wing-tip vortex experiences minor changes [8].

The effect of the impinging position in the spanwise direction of the wing has been studied in [9–11]. When the impingement is in the outboard position and close to the wing-tip vortex, the two vortices form a vortex dipole [9]. As the impinging position moves inward to be aligned with the wing-tip vortex, the size of the wing-tip vortex increases with respect to the outboard-positioned case [9]. At the same time, the strengths of the two vortices both decrease [9], and it should be noted this is for the case that the impinging vortex and the wing-tip vortex have opposite signs. When the two vortices have the same sign, the impinging vortex is paired and even merged with the wing tip vortex and they together feature a higher circulation than the incident vortex [10,11]. As the impinging vortex moves to a further inboard position, the impinging vortex is disrupted into two sections and they show a spanwise

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Nomenclature

English symbols

c	Chord length of the vortex generator
D	Diameter of the propeller
M	Mach number
$\vec{i}$	Unit vector in the X direction
J	Advance ratio of the propeller
n	Rotating speed of the propeller [revolutions/second]
R	Radius of the propeller
Re	Reynolds number
$r_{V,cor}$	Radius of the vortex core
r_{imp}	Radial position of the impinging vortex
r_V	Radius distance from the vortex centre
T	Thrust of the propeller
T_c	Thrust coefficient of the propeller
U_t	Velocity in the tangential direction of the vortex
U_X	Velocity in the axial direction of the propeller
U_∞	Free stream velocity
X, Y, Z	Coordinates in the reference frame of the fixed propeller

Greek symbols

Ψ	Phase angle of the blade
ω	Vorticity
Γ	Circulation

Abbreviations

AOA	Angle of attack of the vortex generator
CFD	Computational Fluid Dynamics
PIV	Particle Image Velocimetry

drift [9]. The vorticity in the impinging vortex is also entrained in the spanwise direction [9].

During the study of ground vortices, suction tubes are utilized to generate the ground vortex and model the effect of the propulsor on the ground vortex. The flow fields involving the ground vortex are measured at the planes near the ground and upstream of the suction tube [12,13]. In the plane near the ground, the meandering magnitude and the standard deviation of the size of the vortex increase as the velocity ratio (the ratio between the intake velocity which is kept constant and the free stream velocity) decreases [12]. As the vortex approaches the suction tube, the vortex meandering versus the velocity ratio follows the same trend as that found in the plane near the ground, but its amplitude decreases [13]. The Proper Orthogonal Decomposition (*POD*) analysis indicates that the first mode represents a displacement of the ground vortex in the direction of the crosswind, and the second mode represents a displacement of the ground vortex in the direction perpendicular to the crosswind [13].

Although extensive descriptions have been presented on vortex features under the impact of a steady wing [7,9,10], the steady wing does not allow replicating the effect of the dynamic cutting process by the rotating blade or the strong axial-velocity acceleration near the propeller. In addition, although a suction tube is applied to substitute the effect of a propulsor [13], there is no blade in the flow. Therefore, the current investigation is conducted so as to analyse the impact of a realistic propeller (rather than simplified models) upon an impinging vortex. The objective of this investigation is twofold. First, the vortex responses are analysed with the objective of revealing the physics, e.g. the size, the meandering amplitude, the spectral modes, and the strength of the vortex. Second, the results aim at producing a database for the validation of numerical simulations, by which a three-dimensional flow topology can be built and flow details in the regions where *PIV* measurements are not accessible can be investigated.

2. Definitions and experimental methods

2.1. Definitions

Before the introduction of the experimental methods, definitions related to propellers are given. The operating condition of the propeller is characterized by the advance ratio J, which is dependent on the free stream velocity, U_∞, the rotating speed, n, and the propeller diameter, D. The equation for the advance ratio is defined as

$$J = \frac{U_\infty}{nD}. \tag{1}$$

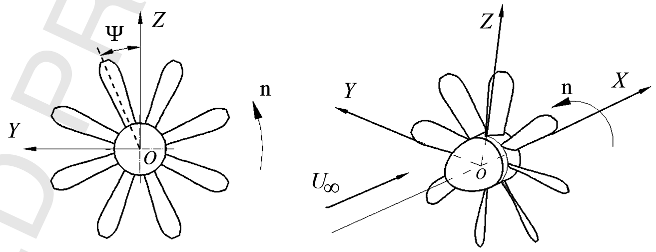

Fig. 1. Left: definition of the phase angle of the blade; right: coordinate system of the propeller.

The thrust of the propeller is normalized by twice the dynamic pressure of the free stream and the square of the propeller diameter,

$$T_C = \frac{T}{\rho U_\infty^2 D^2}. \tag{2}$$

As the vortex is intermittently cut by the blade, it is necessary to define the phase angle of the blade as shown in the left-hand side of Fig. 1. The phase angle Ψ is defined by the angle between the OZ axis and the dashed line, which is the virtual line for the blade to change the pitch angle. The coordinate system, with its origin located at the propeller axis and aligned with the leading edge of the blade root, is shown on the right-hand side of Fig. 1.

2.2. Experimental methods

2.2.1. Experimental setup

The experimental tests are carried out in a low-speed, closed-loop open-jet wind tunnel at Delft University of Technology. The tunnel has an octagonal test section, and the maximum height and width are 2.85 m × 2.85 m (18 $R \times 18$ R, where $R = 0.152$ m is the propeller radius). The cross-section area of the tunnel is nearly 100 times that of the propeller disk.

The schematic of the experimental setup for studying the interaction between the vortex and the propeller is shown in Fig. 2. The spinner (part 1), rotating shaft balance (part 2), hub (part 3) and blades (part 4) are the rotating parts. The rotating shaft balance is utilized to measure the loadings solely on the propeller, excluding the forces on the nacelle and the strut. High pressure air (part 9) is fed from the tube inside the strut (part 8) to run the air motor (part 5). A horizontal plate (part 7) is positioned at the bottom of the free jet test section, to avoid interaction with the shear layer of the wind tunnel. The inflow velocity chosen in the experiments is 18.6 m/s which is below the maximum speed (35 m/s) of the

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