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Flow characteristics of the wandering blade tip vortex

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Abstract: The blade tip vortex moves around its mean position, and thus various vortex identification methods are applied to identify its center location. The averaged flow field around the blade tip vortex is obtained by aligning instantaneous flow fields with the identified vortex center. The instantaneous flow fields are obtained by performing a large eddy simulation of an isolated multirotor propeller at hovering condition. Mislocating vortex centers results in incorrect mean vortex parameters and evolutionary characteristics. Especially, turbulence statistics inside the vortex core exhibit very different distributions depending on the methods used. Among the methods applied, the Γ method is the most effective way to identify the vortex center.

Keywords: Tip Vortex, Wandering Motion, Turbulence Statistics, Large Eddy Simulation.

1 Introduction

The blade tip vortex is one of the major features of a rotary wing wake, and its close proximity to the blade results in various aerodynamic and aeroacoustic phenomena. It is therefore crucial to understand the underlying flow physics to predict the strength and position of the blade tip vortex. The flowfield of a rotary wing is often predicted using mathematical wake models, i.e. free wake models [1, 2], due to relatively lower computational cost compared to Navier-Stokes based calculations. The models usually incorporate semi-empirical representations of tip vortex characteristics and accurate modelling of the vortex core is shown to be important in estimating rotorcraft performance and acoustics [3, 4].

However, the tip vortices exhibit wandering motions about their mean position, which leads to large errors in obtaining the mean statistics. Previous studies investigated the flow characteristics by overlapping instantaneous flow fields with respect to their vortex centers to remove the effect of wandering motion [5, 6]. Several vortex identification methods were utilized for identifying the center location, but they did not produce same results even in a qualitative sense. In the present study, we perform a large eddy simulation of tip vortices trailing from an isolated two-bladed multirotor propeller, and apply different center identification methods to the flow fields to find their center locations, which allows us to examine the flow characteristics of wandering blade tip vortices.

2 Numerical details

The governing equations are the spatially filtered continuity and Navier-Stokes equations in the frame rotating with the rotor. The sub-grid scale stress tensor is modeled with a dynamic global

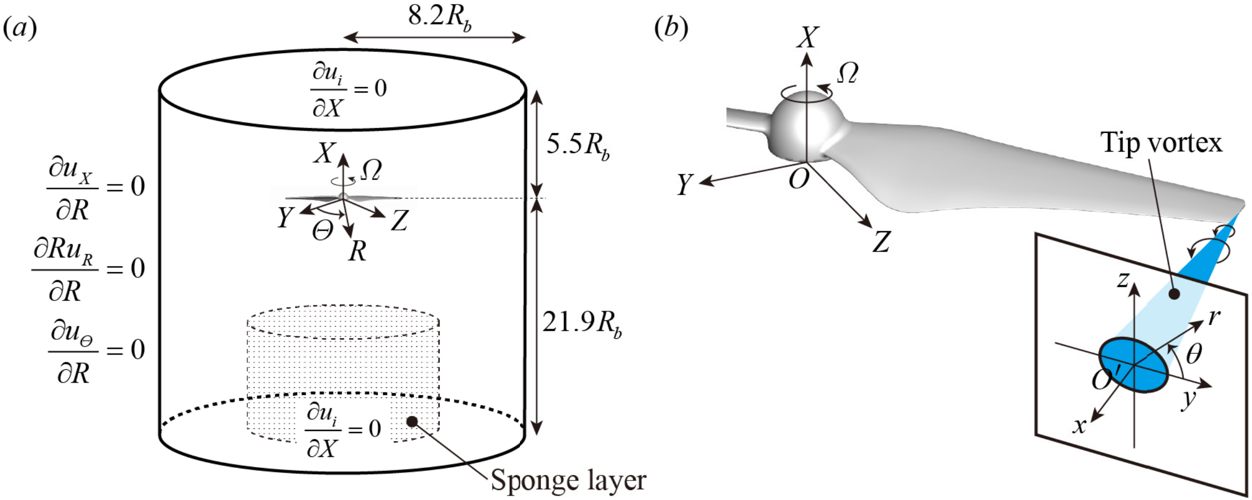

Figure 1: Schematics of the computational details: (a) computational domain and boundary conditions; (b) a rotor-fixed coordinate system, O_{XYZ} and a coordinate system attached to the center of a tip vortex, O'_{xyz}.

model [7]. No-slip boundary condition at the propeller surface is achieved using an immersed boundary method [8]. Figure 1 shows the computational domain, boundary conditions and coordinate systems used in this study. The computation is performed in a cylindrical coordinate system. The Neumann boundary conditions are applied at all sides to allow flow to entrain and exhaust through the boundaries. A sponge layer is applied at the outlet for computational stability. A second-order semi-implicit fractional-step method with the domain decomposition method [9] is used, and the second-order central difference method is used for spatial discretization.

We simulate a two-bladed, fixed-pitch and hingeless rotor that is used in a small-scale multirotor. The radius of the blade is $R_b = 119.78$ mm and the rotational speed is $\Omega = 555$ rad/s (or 5300 revolutions per minute) which is a typical value of this rotor during the hovering condition. The corresponding Reynolds number based on the tip speed V_{tip} and chord length at 75% span c is about 73,000.

The center of a tip vortex is identified at a given wake age and the surrounding flowfield is shifted to the mean location. This procedure is repeated every time step to obtain the mean field. That is, for a generic flow variable φ, the mean value Φ is obtained by

$$\Phi(\boldsymbol{x}) = \frac{1}{T}\int_{t_0}^{t_0+T} \varphi(\boldsymbol{x} + \boldsymbol{x}_c(t), t)\mathrm{d}t, \tag{1}$$

where $\boldsymbol{x}_c(t)$ is the position of the instantaneous vortex center at time t. The vortex centers are identified using the axial vorticity, helicity, axial velocity, pressure, λ_2 criterion [10], and Γ method [11], respectively.

3 Results

The vortex parameters such as the peak swirl velocity and core radius significantly vary depending on the vortex identification methods (figure 2). The difference in the core radius is as large as 10% even in an early wake age. Identifying vortex centers with the Γ method and minimum static

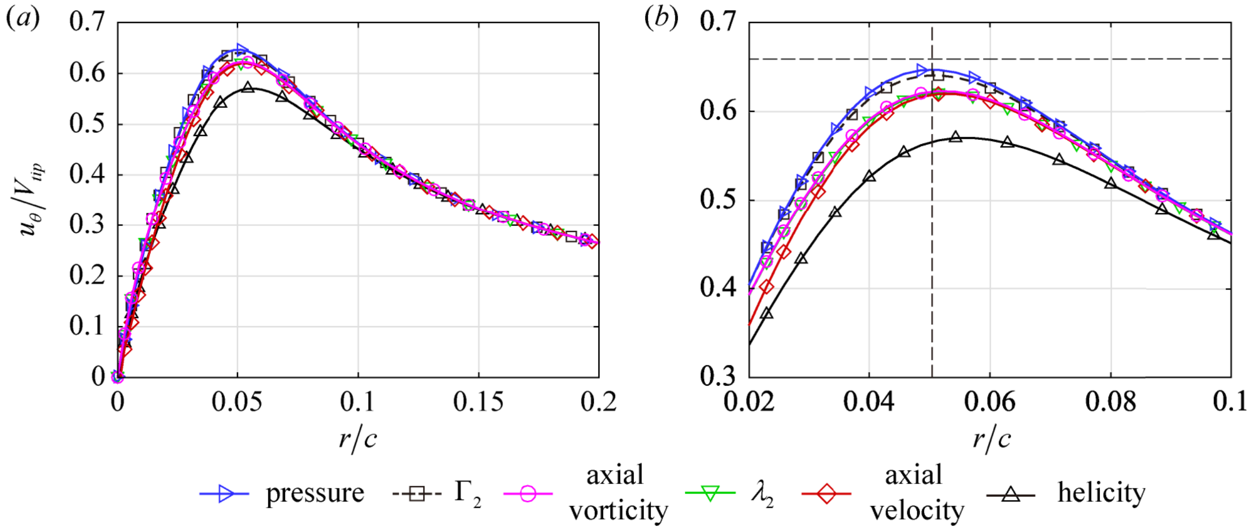

Figure 2: (a) Mean swirl velocity at the wake age of 25° using various vortex identification methods and (b) magnified view near the maximum swirl velocity. Dashed lines represent average of the peak swirl velocity and core radius from instantaneous fields.

pressure result in consistent mean characteristics of the tip vortex.

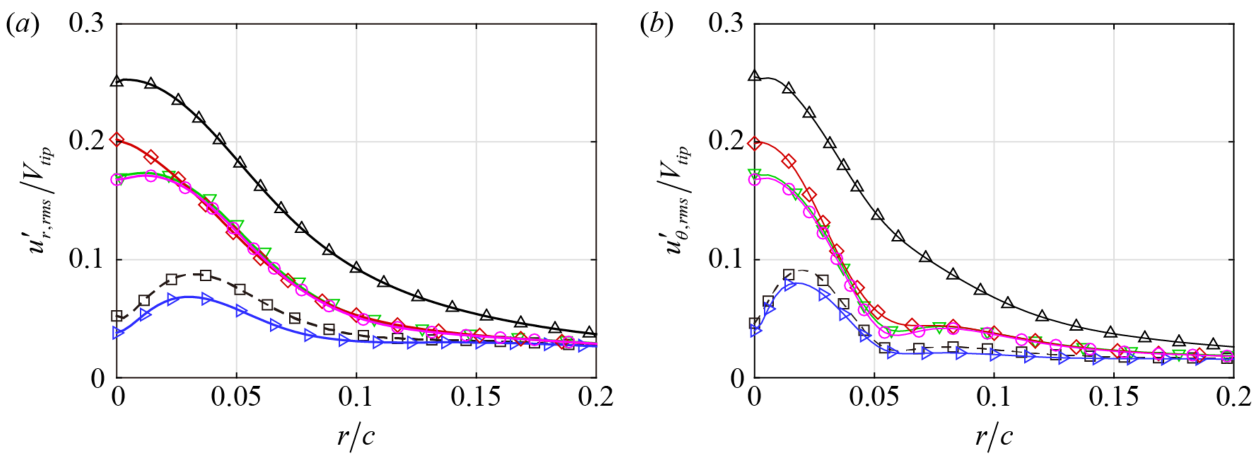

Figure 3: Root-mean-square velocity fluctuations at wake age of 25°: (a) $u'_{r,rms}$; (b) $u'_{\theta,rms}$. Refer to figure 2 for legends.

Figure 3 shows the radial and azimuthal rms velocity fluctuations by different identification methods. Very different distributions of turbulence intensity are found within the core. The criteria based on the helicity, axial velocity, λ_2 and vorticity result in high rms values at the center and produce their monotonic decrease with increasing radial direction. This is due to false identification of vortex centers. On the other hand, the criteria based on the minimum static pressure and Γ show significantly lower rms values than other methods, which indicates that high rms values inside the core by latter methods are likely the result of false identifications of tip vortex.

4 Conclusion

In the present study, we applied various vortex identification methods to find tip vortex center locations, and examined the flow characteristics of wandering blade tip vortices. Mean vortex parameters and velocity fluctuations inside the core showed very different results with the methods considered. We found that both minimum static pressure and Γ methods showed physically reasonable results, and the Γ method is the most effective way as it only utilizes the velocity information of the tip vortex.

Acknowledgements

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