Impact of axial separation distance on tip vortex evolution between coaxial counter-rotating propellers

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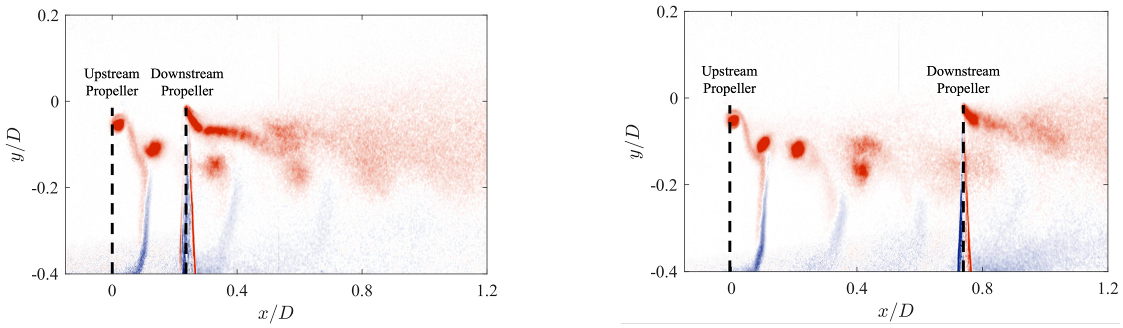
As the drone delivery market continues to grow, the need for drones with higher payload capacities has led to the increased adoption of compact drone architectures, such as co-axial and overlapping propeller systems. Despite the notable benefits these multi-rotor systems offer, they also pose significant challenges. One of the main concerns affecting the adoption of drones is the noise generated by overlapping rotor systems. To design efficient and quiet multi-rotor systems, it is crucial to gain a deeper understanding of the aerodynamic noise sources resulting from rotor interactions. In this study, we experimentally investigate the effect of axial separation distance on the aerodynamic interaction between coaxial counter-rotating propellers under hover conditions. The experiments were conducted in a semi-anechoic room at the University of Southampton. Axial separation distance was varied using a modular rig equipped with two two-bladed, 16-inch diameter propellers. We employed force measurements and phase-locked high-resolution, low-speed Particle Image Velocimetry (PIV). Phase-locking was performed for both upstream and downstream rotors at five blade phase angles ($\psi = 30°, 60°, 110°, 140°$, and $180°$). Four different axial separation distances ($0.1D$, $0.25D$, $0.5D$, and $0.75D$, where D is the diameter of the propellers) were examined. For all cases, the system was set to produce 16 N of thrust and zero torque. Two sample phase-averaged vorticity fields are presented in Figure 1 for 0.25D and 0.75D separation distances at an upstream blade angle of $180°$. It is apparent from this figure that the tip vortices shed from the upstream rotor impinge on the downstream rotor, significantly influencing wake behavior. In this work, we primarily focus on the characteristics of the upstream rotor wake, as the incoming flow to the downstream propeller is a major contributor to rotor-rotor interaction noise. The phase-averaged vorticity field for $0.25D$ in Figure 1(a) shows that the tip vortices shed from the upstream rotor are coherent ahead of the downstream propeller. Conversely, when the separation distance is larger (Figure 1(b)), the wake of the upstream propeller resembles that of an isolated rotor, consisting of strong vortices in the early wake ages and turbulence further downstream. Using the Γ_1 criteria, we identified the tip vortex positions, while the Γ_2 criteria provided information on the strength of the tip vortices. Additionally, we extracted the velocity profile and core radius of these tip vortices. The final presentation will include a detailed analysis of tip vortex characteristics and vortex meandering with varying separation distances. Finally, we will compare rotor wakes with the Kocurek-Tangler wake model to quantify the effect of the added pressure gradient due to the second rotor. This research contributes valuable insights for the development of quieter and more efficient multi-rotor drone propulsion systems, ultimately enhancing their acceptance and integration into various applications.



(a) $x/D = 0.25$ (b) $x/D = 0.75$

Figure 1: Phase-averaged vorticity fields for axial seperation distances of 0.25D and 0.75D when the upstream rotor phase angle is $180°$. The dashed lines on the figures represent the position of the rotors when they are at $90°$.

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