Background Oriented Schlieren for Tip Vortex Visualization in Compressed Air

Colby Medina[1] & Mark A. Miller[2]
1 Graduate Research Fellow, Dept. of Aerospace Engineering, Penn State University, University Park, Pennsylvania, UNITED STATES
2 Assistant Professor, Dept. of Aerospace Engineering, Penn State University, University Park, Pennsylvania, UNITED STATES

Understanding how rotor wakes evolve is crucial to improving aerodynamic modeling and rotorcraft design. Tip vortices at the blade tips define wake boundaries, which can be particularly important in coaxial rotor systems where the ingestion of vortices by a second rotor can influence aerodynamic performance. However, accurately capturing and analyzing these vortices experimentally is challenging, especially at full-scale Reynolds numbers. Testing with full-scale rotors is often impractical due to size and cost constraints, as it typically requires outdoor testing with limited control over environmental factors or using extremely large and costly wind tunnel facilities. On the other hand, scaling down rotor dimensions makes it difficult to achieve relevant non-dimensional flow characteristics, as smaller rotors fail to match full-scale Reynolds numbers. Smaller rotors also tend to produce weaker tip vortices as a result of the lower thrust generated, making them more difficult to detect and analyze.

One approach to address this issue is by testing small models in a heavy gas environment. At Penn State, the Miller Fluids Lab is using the Compressed Air Wind Tunnel (CAWT) to achieve full-scale relevant conditions on small models. The CAWT is a pressurized wind tunnel that has a maximum wind speed of 15 m/s and maximum pressure of 35 atm. The ability to vary both wind speed and fluid density allow for the decoupling of Mach Number and Reynolds Number which is not achievable in conventional wind tunnels. This advantage enables the collection of full-scale non-dimensional data with small-size rotors, as the non-dimensional rotor data scales linearly with pressure. For example, a rotor blade with a diameter of 0.34 meters operating in air pressurized to 34 atm would generate thrust and torque coefficients equivalent to those of a 10.88-meter diameter blade under standard atmospheric conditions.

Background Oriented Schlieren (BOS) is used in this study to visualize the wake contraction of rotors across different pressure conditions. BOS is an optical flow visualization technique that detects density variations in a fluid by analyzing the distortion of a background pattern. As light passes through regions of varying density, such as those caused by tip vortices, it refracts slightly, shifting the perceived position of the background pattern. By capturing and analyzing these shifts with image correlation software, BOS enables the visualization of vortex structures without the introduction of physical seeding particles. BOS is also a particularly simple and non-intrusive technique, making it especially well suited for this initial investigation.

By using BOS, this study assesses how changes in density affect the strength and evolution of tip vortices. Pressurizing the tunnel generates stronger vortices, which are tracked more effectively using this method. In addition, the ensemble analysis process was used to enhance the resolution of the data beyond what is possible with single-frame imaging, improving the clarity of vortex structures. The initial results validate the feasibility of this approach, showing that the method successfully captures coherent vortex structures. Future work will focus on tracking tip vortices as they are ingested by a second rotor in a coaxial configuration, providing insight into the aerodynamic interactions observed in systems like NASA's Dragonfly project.

Email address for correspondence: *cmm9112@psu.edu*