Soaring to New Heights: Investigating the Aeroelastic Stability of Composite Aircraft Wings

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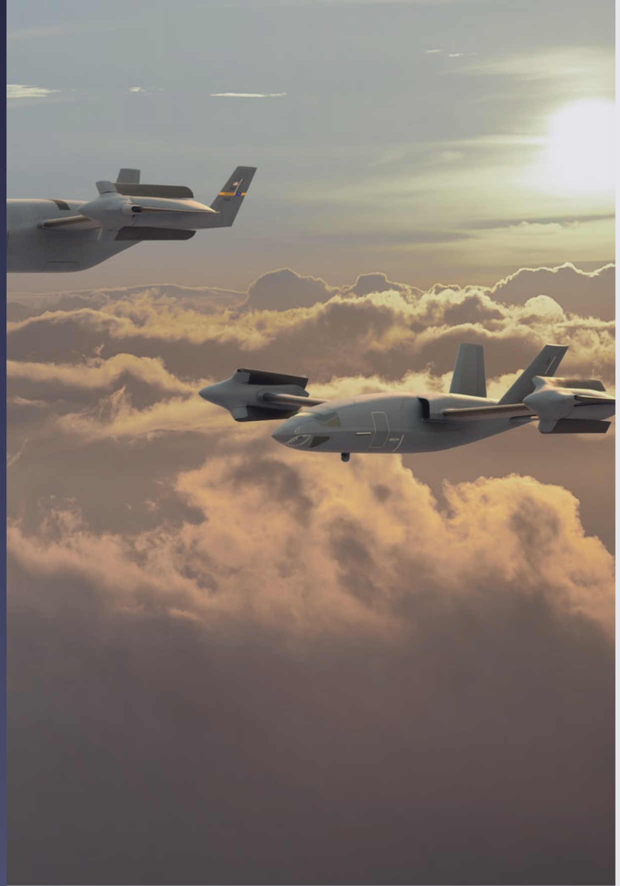

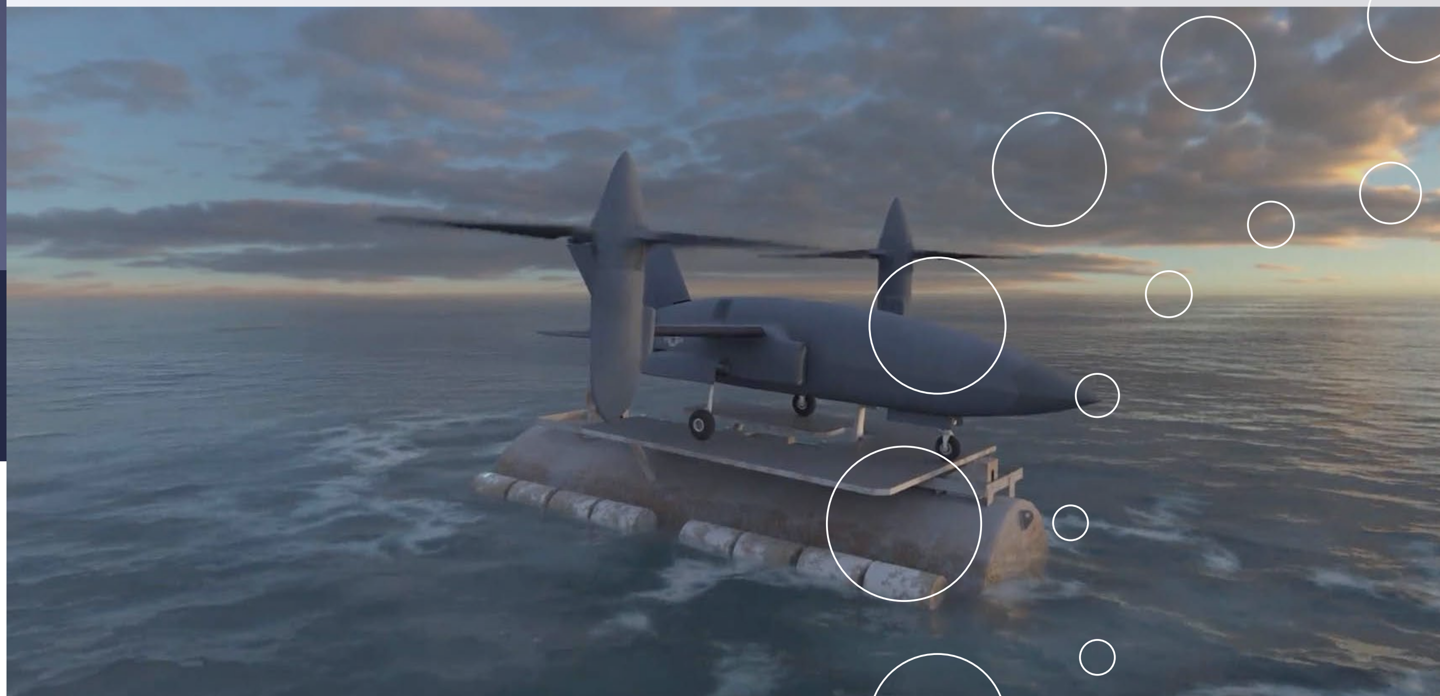

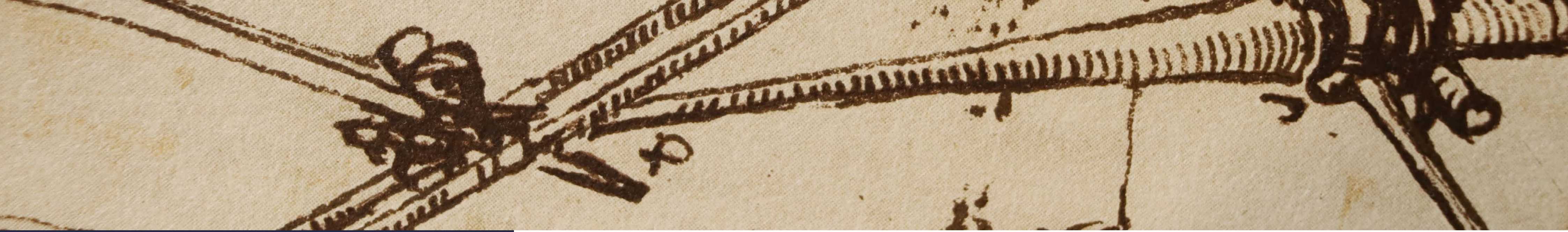

Soaring to New Heights: Investigating the Aeroelastic Stability of Composite Aircraft Wings

Combining the best aspects of helicopters and fixed-wing aircraft into a single vehicle has been a long-held ambition in the aerospace industry. From Leonardo da Vinci's early drawings of an 'aerial screw' to the V-22 Osprey tiltrotor aircraft used by the U.S. military today, engineers have grappled with the challenge of creating aircraft capable of both vertical take-off and landing (VTOL) and high-speed forward flight. While helicopters offer unparalleled VTOL performance, their top speeds are limited to around 300 km/h. Fixed-wing aircraft offer greater speed but require long runways for take-off and landing. Reconciling these conflicting design requirements is a major challenge.

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Folding Tiltrotors as a Solution to High-Speed Vertical Take-Off and Landing (HSVTOL)

Professor Edward Smith and his team at Penn State University have spent years at the forefront of research, making this dream a reality. One promising approach is the idea of a folding tiltrotor aircraft. This type of aircraft takes off vertically using tilting rotors – rotors that can tilt from a vertical (helicopter-like) orientation to a horizontal (propeller-like) orientation – and then transition to high-speed forward flight.

Crucially, the rotors stop and fold away along the nacelle at this stage, greatly reducing drag. This configuration benefits from a forward-swept wing to accommodate rotor-wing clearance during the folding process. Unfortunately, forward-swept wings are notoriously unstable at high speeds. As the wings bend upwards, they twist in a way that increases the lift force, causing the wings to bend and twist even more. This feedback loop, called aeroelastic divergence, can quickly lead to structural failure. The wing configuration also features a large mass – the folded rotor and its engine – at the wingtip. The substantial aerodynamic drag force of the wing tip-mounted mass also contributes to aeroelastic behaviours.

Assuring a Stable System in All Flight Modes

While the folding tiltrotor concept has been around since the 1960s, making it a practical reality has proven to be a formidable engineering task. Engineers in the industry have made significant progress in developing and testing reliable fold/unfold mechanisms for the rotors in flight. Although a promising concept, the stop-fold tiltrotor has historically faced a key challenge – the added mass and aerodynamic forces from the rotors must avoid aeroelastic divergence of the forward-swept wing at high speeds.

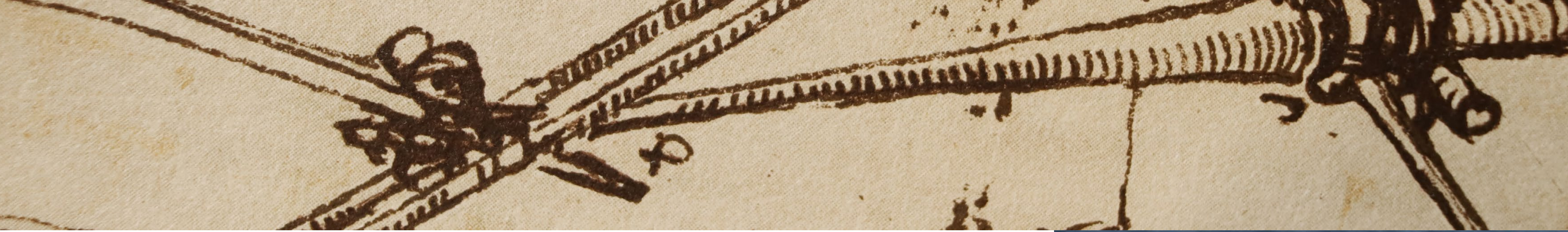
Professor Smith has dedicated many years to studying the composite tailoring of tiltrotor wings to determine the divergence characteristics of forward-swept wings with folded rotors and see if composite material offers a design solution. His work aims to advance the fundamental knowledge and modelling capabilities required to successfully develop stop-fold tiltrotor aircraft.

A Multi-Stage Approach

First, Smith and his team (Master's Degree student Jason Slaby) developed a physics-based structural model of a composite wing using established composite beam theory. Next, they created an aerodynamic model to represent the forces generated by a folded rotor pylon at the wingtip. They next integrated these structural and aerodynamic models into a finite element analysis framework, allowing them to numerically predict the onset of wing aeroelastic divergence in various configurations. Finally, they used this modelling capability to evaluate the impact of key design variables like wing sweep, composite ply angles, pylon placement, and size on the divergence behaviour.

Pylons as a Pivotal Influence

With a structural model in hand, Professor Smith and his team turned to capturing the aerodynamic loads that act on the wing, particularly those generated at the wing tip by the folded rotor pylon. As the wing flies through the air, its angle of attack generates lift forces. Wing bending under load can create an additional twist due to the sweep angle, changing the lift distribution. Furthermore, the pylon itself generates significant lift, drag, and twisting moments.



To model the pylon aerodynamics, Professor Smith made some simplifying assumptions about its shape. He represented the pylon/nacelle as a cone at the front, transitioning to a streamlined "boat-tail" shape at the rear. The dimensions were scaled based on the size of the folded rotor blades. Using analytical methods from the U.S. Air Force's DATCOM reference, Dr Smith calculated the lift generated by the pylon shape. Drawing from aerodynamic conventions, he estimated the pylon centre of pressure at the midpoint between its leading edge and point of maximum thickness. The drag generated by the pylon was also considered. As the wing bent under load, it created a vertical offset between the pylon and the rest of the wing, causing the pylon drag force to impose a twisting moment. Professor Smith assumed a drag coefficient for the pylon similar to that of streamlined aircraft fuselages.

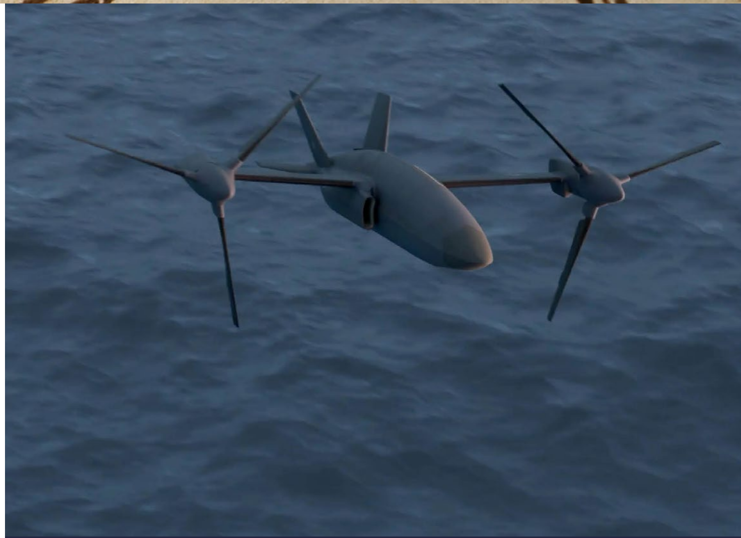
Professor Smith then investigated how the pylon's shape, position, and aerodynamic properties influenced the wing's stability. The results showed that pylon lift and drag forces can either worsen or improve stability, depending on their relative positions and the wing's sweep angle. Interestingly, the team discovered that the pylon's shape had a greater impact on stability than its position. Changing the pylon's shape altered the divergence speed (at which instability occurs) by over 15%, while repositioning it only affected stability by about 4%. The drag force from the pylon proved particularly influential, potentially reducing the divergence speed by 25% to 60%, depending on the wing's sweep angle. This finding highlights the complex interplay of forces at work in aircraft design.

Working with a team of student research assistants and another faculty colleague (Professor Jose Palacios), they designed and fabricated a set of scale-instrumented models to be tested in the wind tunnels at Penn State. These tests will start in August and continue throughout the Fall of 2024. The objective will be to validate the analysis methods and trends predicted by Jason Slaby's thesis research almost 15 years ago!

Engineering the Future of High-speed Vertical Flight

The world of HSVTOL aircraft is constantly evolving. In response to the 2023 Vertical Flight Society Student Design Competition, a new military transport aircraft was proposed by a team of Penn State students and faculty. Dubbed the 'Night Fury', this notional vehicle showcases the progress made in recent years. As well as being able to take off and land vertically, the Night Fury can achieve transonic cruise speeds after take-off, making long-range, high-speed missions possible. Night Fury also features a novel four-rotor design with two tiltrotors for VTOL and two folding rotors for high-speed flight. With a maximum take-off weight of 21,400 kg, it's designed to carry 6–8 tonnes of payload at speeds of up to 650 km/h – more than twice as fast as a conventional helicopter.

By harnessing the power of advanced materials and innovative design techniques, researchers like Professor Smith and his team are helping to shape the future of aviation. His work not only advances our understanding of aircraft structures but also brings us closer to realising novel aircraft concepts that could revolutionise both military and civilian air travel. As this field continues to evolve, we can look forward to seeing how these fundamental research efforts translate into practical applications that take to the skies in the years to come.



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MEET THE RESEARCHER

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Professor Ed Smith has been a member of the Aerospace Engineering faculty at Penn State University since 1992. He was promoted to the rank of Professor in 2004 and Distinguished Professor in 2024. Notably, Professor Smith received a Young Investigator Award from the Army Research Office (1994), followed by the Bagnoud Award from the American Helicopter Society (AHS), for outstanding contributions to vertical flight technology by an AHS member under the age of 30. Several years later, he received the Lawrence Sperry Award from the American Institute of Aeronautics and Astronautics (AIAA). In 2008, he was elected a Technical Fellow of the AHS [now the Vertical Flight Society (VFS)]. Other accolades include the Penn State Engineering Society (PSES) Outstanding Research Award (2002), the PSES Outstanding Advising Award (2007), and the President's Award for Engagement with Students (2013). He was also named an inaugural College of Engineering Deans Fellow (2017–2021).

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