EXPERIMENTAL INVESTIGATION OF A WHIRL FLUTTER USING NOVEL 2 DOF SMALL-SCALE ROTOR-PYLON RIG

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ABSTRACT

Tiltrotor aircraft have attracted extensive research interest due to their superior speed and range compared to conventional and compound helicopters. However, the performance envelope of tiltrotors can be limited by whirl flutter, an aeroelastic instability arising from the coupling among structural, aerodynamic, and gyroscopic effects of a rotor-pylon-wing system. The concept of whirl flutter has been around since the 1930s, with much of the subsequent work devoted to developing numerical models that capture the phenomenon accurately. In recent years, large-scale tiltrotor test rigs such as the Maryland Tiltrotor Rig, ATTILA and the TiltRotor Aeroelastic Stability Testbed have secured substantial funding to generate high-fidelity experimental data and support model validation, serving as cornerstones for modern whirl flutter research. Small-scale rigs form a natural complement to these complex facilities by offering cost-effective testing, enabling tightly controlled parametric studies and robustly exploring nonlinear regions that might manifest in novel rotor configuration. However, dedicated experimental investigations on such rigs have remained scarce.

The study presented here aims to address this gap by developing a novel 2 Degrees of Freedom small-scale rig based on the classical Reed's model, which incorporates a universal joint to represent to pylon pivot point, see Figure 1. Existing small-scale rigs have used a very flexible component to carry the rotor, whose bending modes can couple in a manner analogous to the rotor-flap/wing-torsion coupling that influences whirl flutter. The proposed rig instead uses a pendulum-mounted propeller-motor system, attached to a universal joint via a rigid shaft, allowing two orthogonal tilting motions of the rotor disk, which is consistent with the kinematics captured by the Reed's model. The experimental tests are conducted in the Bristol Vertical Wind Tunnel.

A corresponding numerical model was developed that extends Reed's classical two-degree-of-freedom formulation by including an additional effective gravitational stiffness term arising from the pendulum configuration, which provides a restoring moment as the rotor tilts. The resulting system is cast in state-space form, and eigenvalue analysis is used to compute the complex eigenvalues as functions of rotor speed (Ω) and inflow velocity (V). The subsequent stability boundaries can be determined, and a parametric investigation can be conducted to yield fruitful insights into the rig's characteristics, a taste of which is provided in Figure 1. The paper focuses on validating the modified Reed model using experimental data from modal hammer tests on the pendulum-mounted rig combined with free-response tests to trace the whirl flutter stability boundary. The study examines the effects of propeller types, shaft lengths, and motor types, over a range of rotor speeds and inflow velocities. Frequency-response functions will be used to identify

the modes of the rig and its splitting into forward- and backward-whirl branches. By tracking the evolution of modal damping with rotor speed at each inflow condition, the rig's experimental stability boundary will be determined. The final paper will compare the measured and predicted stability boundaries and quantify the influence of gravitational stiffness on a small-scale pendulum-mounted tiltrotor rig.

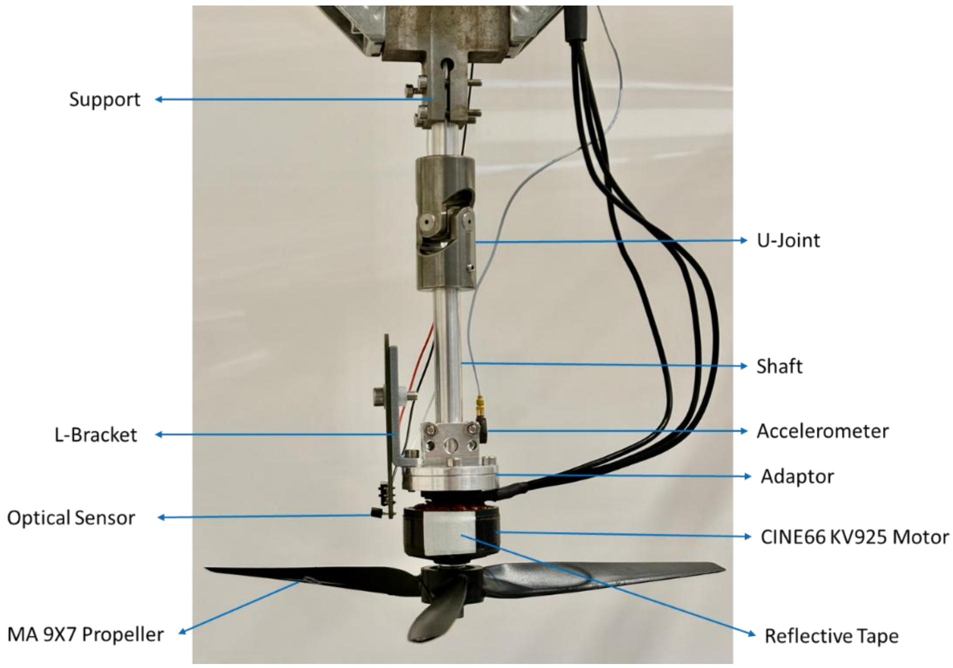

Figure 1 – Description of the 2DoF whirl flutter rig

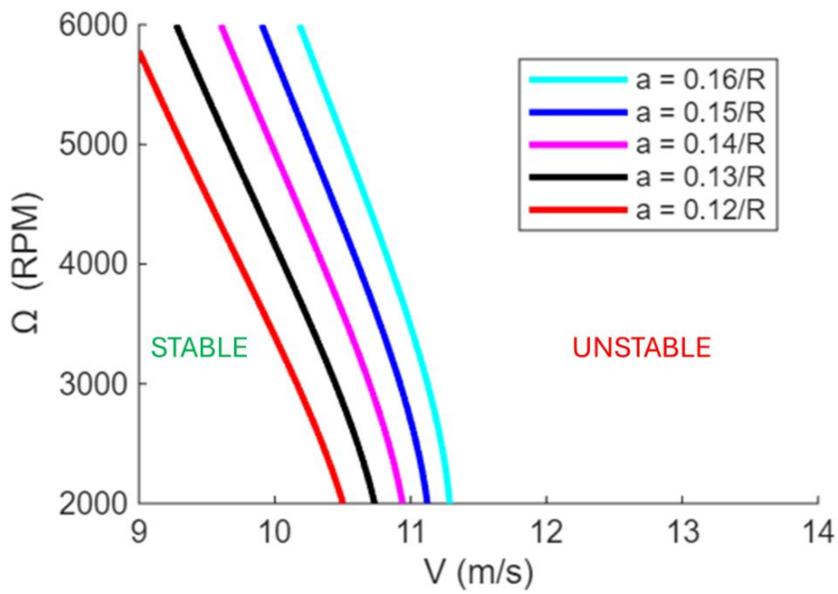

Figure 2 - Effect of varying non-dimensional pivot arm length 'a' on the system's V-Ω stability boundary, R is the rotor radius.