FLUTTER SOLUTION METHODS UNDER UNCERTAINTIES OF THE JOBY EVTOL AIRCRAFT

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ABSTRACT

This paper presents a comparison of the continuation method and structured singular value (mu) analysis for assessing the impact of uncertainties on aircraft flutter. The two methods are applied for a real industrial test case, the Joby S4 eVTOL aircraft, and specifically focusing on whirl flutter. The continuation method allows an efficient solution of the flutter problem and tracking of modal frequencies and damping vs. speed. The speed can be replaced by any other continuation parameter, namely an uncertain parameter. The mu analysis framework is a widely used robust stability tool used in the control systems field, but it can be extended to deal with flutter problems too.

First, the whirl flutter equations are presented, formulated in frequency domain with DLM-based unsteady aerodynamics of lifting surfaces. The Joby S4 eVTOL features six distributed propellers and flutter mechanisms are dominated by the propeller effects, namely gyroscopic and aerodynamics. The classical whirl flutter formulation developed by NASA in the 1960s is adopted and propellers are introduced in the modal equations via aerodynamic derivatives of forces and moments due to changes in axial and edgewise inflow ratios. Forces and moments at the propeller hub are given, for instance, by

$$F_z = \rho\pi\Omega^2 R^4 C_{F_z}(\mu_z, \mu_x)$$

$$M_z = \rho\pi\Omega^2 R^5 C_{M_z}(\mu_z, \mu_x)$$

Similar expressions apply to in-plane hub forces and moments F_X, F_Y, M_X, M_Y. These are linearized about the trim point, such as

$$\Delta F_z = \left(\rho\pi\Omega^2 R^4 \frac{\partial C_{F_z}}{\partial \mu_z}\right)\Delta\mu_z + \left(\rho\pi\Omega^2 R^4 \frac{\partial C_{F_z}}{\partial \mu_x}\right)\Delta\mu_x$$

Inflow ratio perturbations are tied to aircraft motion and to structural modes rotations and velocities of the hub nodes and to tilt angle command $\Delta\vartheta$, by

$$\Delta\mu_z = \frac{v_{axial}}{\Omega R} = \frac{V_\infty}{\Omega R}{\Phi_x}^T \frac{\dot{q}_h}{V_\infty} + \frac{-V_\infty}{\Omega^2 R}\Delta\Omega$$

$$\Delta\mu_x = \frac{v_{edge}}{\Omega R} = \frac{V_\infty}{\Omega R}{\Phi_{\theta_y}}^T q_h + \frac{V_\infty}{\Omega R}{\Phi_{\theta_z}}^T \frac{\dot{q}_h}{V_\infty} + \frac{V_\infty}{\Omega R}\Delta\vartheta + \frac{-V_\infty}{\Omega^2 R}\Delta\Omega$$

This linearization gives equivalent aerodynamic stiffness and damping matrices, in addition to the gyroscopic damping matrix.

The whirl flutter speed is driven by the values of such propeller derivatives, which are often difficult to estimate or measure experimentally and carry uncertainties. The continuation method solution to the flutter equations allows to follow any parameter of the system and to determine the damping of the structural modes and/or the direct solution of the flutter speed. In the present application, the parameters are propeller aerodynamic derivatives. Bounds on these values that still the certification requirements of freedom from flutter up to 1.2VD can be calculated by applying the continuation method. In parallel, the mu analysis method is also applied to show that the same results can be obtained. In the mu analysis framework, the equations are reformulated with the uncertain parameter being in a closed-loop feedback with the plant (i.e. aeroelastic aircraft) and the singular values corresponding to the neutral stability of the system are computed. This gives the critical value of the uncertain parameter, i.e. the propeller aerodynamic derivative. Some notional results are shown below, Figure 1 showing the frequencies and damping of structural modes, at fixed speed, for a range of value of one propeller aerodynamic derivatives obtained with the continuation method, and Figure 2 showing the critical value of such parameter vs speed, results obtained applying the mu analysis.

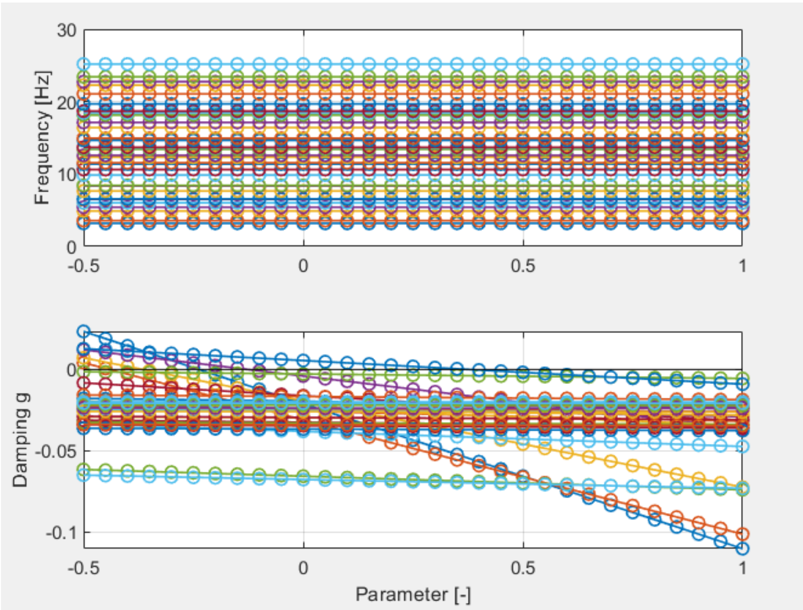

Figure 1: Continuation solution, frequency and damping vs parameter at fixed speed

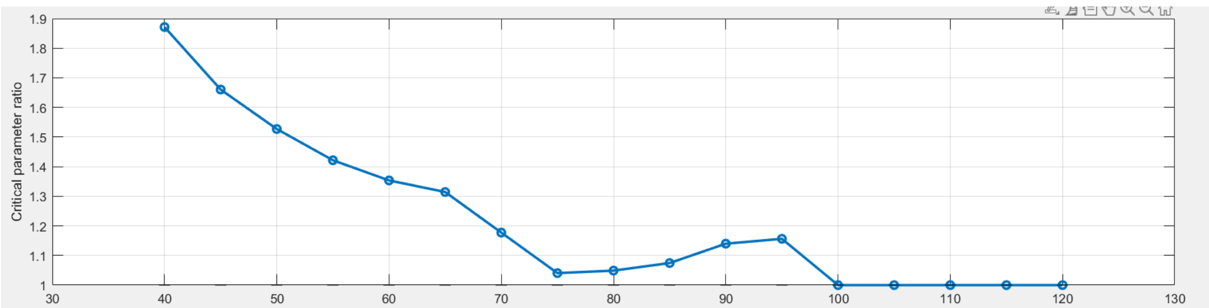

Figure 2: critical parameter for neutral stability sweeping speed, mu analysis framework