Input Data Determination for Flutter Resistance of Small Aircraft

Jan Šplíchal[1)], Jan Navrátil[1)], Jaroslav Juračka[1)]
[1)] Brno University of Technology, Institute of Aerospace Engineering

Abstract:

In recent years, especially in Europe, the category of small aircraft with a maximum take-off weight up to 600 kg has significantly developed. Previously, ultralight aircraft up to 450 kg did not require aeroelastic (AE) evaluation, except for unconventional designs or those with cruise speeds above 200 km/h. However, such assessments are now mandated for UL2, CS-VLA, and CS-LSA type certificates.

Advancements in computer technology and numerical methods had led to the development of various modal aeroelastic analysis methods, such as the k-method and p-k method [1], currently full used. These methods, implemented in computational tools like MSC.Nastran, generate aeroelastic analyses in the form of "v-g" diagrams.

Despite the reliability of classical methods in calculating critical flutter rates, the main challenge lies in determining accurate stiffness (elastic) characteristics, particularly for composite aircraft where material property scatter is significant. Researchers have tackled this by introducing uncertainties (aerodynamic, mass, and stiffness) into flutter equations [2]–[4].

This paper presents the Institute of Aerospace Engineering (IAE) at Brno University of Technology findings and experiences with AE analyses of small sport aircraft, focusing on the impact of input stiffness determination on critical flutter speeds.

Ground vibration test (GVT): To evaluate of mass-elastic model of aircraft resistance to aeroelastic effects, it's essential to identify the dynamic behaviour of its structure, including natural frequencies, vibration modes, and damping ratio. This is typically achieved through ground vibration testing in critical configurations, focusing on mass and control system configurations. Dedicated vibration tests are conducted to identify the natural rotational frequencies of control and trim surfaces, with measurements taken for free and fixed control stick and pedals. The data obtained is used to validate the finite-element (FE) model of the aircraft.

Elastic FE model: The basic input for aeroelastic analyses is an elastic model of the whole aircraft, for these models 1D BEAM elements are most often used to replace the whole structure. The elastic behaviour of elements in the FE model is defined by cross-sectional area A, two perpendicular second moments of area I1 and I2, torsional constant J, and material properties. Determining these characteristics based on structural geometry and material properties involves significant uncertainty.

The mass model for small aircraft aeroelastic analyses is derived from the aircraft's mass analysis, geometric model, and realistic weights of individual parts. These data are incorporated into the FEM mass model, often using 0D CONM2 elements, to specify both mass and moments of inertia. Determining moments of inertia of individual elements can be challenging, often requiring the division of structural units into multiple CONM2 elements to approximate these moments.

Tuning of the FE model: Initial FEM models for aeroelastic resistance are often inaccurate and require tuning to match ground vibration test results. This is achieved using modal analysis and SOL 200 [5] in MSC.Nastran, which allows for parametric optimizations. The objective for optimization is to minimize the deviation of FEM frequency modes from ground vibration test frequencies:

$$\min f = \sum_{i=1}^{n} X_i \left(\frac{F_i^{GVT} - F_i^{FEM}}{F_i^{GVT}} \right)^2 \quad (1)$$

where X_i *is the weight for frequency* f_i *(typically 1, with higher values for low frequencies),* F_i^{GVT} *is the i-th natural frequency from GVT and* F_i^{FEM} *is the i-th natural frequency from the FE model*.

Aeroelastic FE model: The aeroelastic analysis using MSC.Patran/MSC.Nastran relies on the finite element method supplemented with aerodynamic elements. The primary inputs include the structural stiffness represented by the elastic model, mass and moments of inertia represented by lumped masses, and aerodynamic excitation linked to the elastic model to provide structural excitation.

Determination of the critical flutter speed - p-k method: The p-k method, which is widely used to calculate the critical flutter speed, is an iterative process. For each airspeed and natural mode of the structure, a matrix equation is solved. The solution is a complex eigenvalue of the matrix equation, which provides the damping value g, where zero damping indicates the aeroelastic stability limit of the mode and the corresponding airspeed is the critical flutter speed.

Results: Aeroelastic analysis results are the v-g and v-f diagrams which are velocity-damping and velocity-frequency diagrams, respectively. Flutter is indicated when the damping value g reaches zero (g = 0), while g < 0 indicates damped oscillations. Analyses performed at the Institute of Aerospace Engineering (IAE) have shown that flutter predominantly occurs due to unbalanced tail control surfaces. This issue often arises from a combination of the aft fuselage oscillations and the rudder or elevator rotation. By balancing the control surfaces, the flutter speed can be increased, thereby mitigating these aeroelastic instabilities.

References:

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