Aircraft Flutter and Aerodynamic Work

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Denis Kholodar

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Denis B. Kholodar*
Transport Canada, Ottawa, Ontario K1A 0N8, Canada

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This paper is about an application of an energy approach to computational aeroelasticity. A frequency-domain calculation of aerodynamic work is presented in a form that has not been previously discussed. In large aeroelastic systems such as aircraft flutter models, the obtained expression allows us to quantify the roles played in flutter by the generalized coordinates, the phases between them, and the generalized aerodynamic forces. This is exemplified in a body-freedom flutter analysis of a flying-wing aircraft: the X-56A. Another interesting feature that is proposed is a diagram of the aerodynamic work as a function of airspeed. Such functions allow an observance of an evolution with the airspeed of the terms that are most reflective of the aeroelastic stability changes: for example, a phase between the two dominant modes. These diagrams can complement typical flutter trends in analysis documentation and aid in flutter suppression. The approach also permits a perspective on flutter as an interaction of aircraft surfaces rather than vibrational modes. Once a sensitivity of an aeroelastic eigenvalue to a surface area is measured with the presented approach, it can be used in the aircraft design to mitigate flutter and other undesirable aeroelastic responses associated with lightly damped eigenvalues. An illustration of this idea is provided. Finally, energy-based computations allow posing energy-efficient active flutter suppression problems. This has been presented before in the literature. Examples of this aspect are made here with aircraft models (for the first time, as far as the author knows).

I. Introduction

TO PREVENT flutter, it is not necessary to completely block an influx of energy into the oscillating system; it is sufficient to satisfy a condition that the influx of energy is less than its dissipation" wrote Grossman in 1937 [1]. In that report, Grossman drew diagrams depicting the extraction and dissipation of energy at flutter for all possible locations of the airfoil center of gravity, the elastic axis, and the aerodynamic center. Fung, in the "Flutter Phenomenon" chapter of his textbook [2] (originally published in 1955) described flutter as follows: "An oscillation will be called aerodynamically unstable if the oscillating body gains energy from the airstream in completing a cycle. If the oscillating body has neither external excitation nor internal friction, then the aerodynamic instability can be identified with flutter." In the period from 1971 to 1988, Nissim in Ref. [3], Nissim and Lottati in Ref. [4], and Nissim and Burken in Ref. [5] treated the flutter suppression of a simplified binary bending–torsion rigid-wing strip, proposed an energy criterion for an optimization method to determine the most important aircraft flutter modes, and developed a method for placement of an active control surface for maximum flutter suppression effectiveness, respectively. Patil, in 2003 [6], considered the energy transfer mechanism of an airfoil for a flapping flight and, in 2003 [7], developed control design strategies based on the transfer. In 2001, Bendiksen [8] reviewed the historical viewpoints on applications of the energy approach to flutter, presented an energy criterion in terms of the total mechanical energy, expanded the analysis to the transonic range by performing fully nonlinear two-degree-of-freedom wing simulations, and demonstrated an active mode control of the wing. The following year, Bendiksen [9] employed these capabilities to discuss the differences between aeroelastic mode zero energy contours in subsonic and transonic airflows.

In aircraft certification, "flutter analyses results are usually presented graphically in the form of frequency versus velocity ($V - f$) and damping versus velocity ($V - g$) curves for each root of the flutter solution" [10,11]. The roots originate at zero airspeed in the frequencies and damping of the natural modes. The modes by means of the Galerkin method reduce the number of degrees of freedom in flutter analyses to be computationally feasible [12]. When structural damping is ignored, a $g = 0$ crossing indicates a flutter onset in a $V - g$ graph.

If "the total mechanical energy of the structural system is the most meaningful gauge of stability in a practical engineering sense" [8], then it is tempting to complement an interpretation of curves in $V - f$ diagrams originating in natural frequencies by an energy-based measure of each natural mode participation in the fluid–structure energy exchange. Functions in $V - w$ graphs (with a zero-crossing representing a neutral energy exchange, i.e., a flutter onset if the equations of motions are satisfied) may lead to new insights about how airspeed affects aircraft aeroelastic stability. This initially motivated a conference presentation [13] in which a boundary (in airfoil theory) between a positive energy exchange and a negative energy exchange with the airflow was revisited with reduced aircraft models to investigate and confirm the theoretical results of a binary bending/torsion flutter. Then, a computation of the aerodynamic work per cycle with an aeroelastic finite element model was created to investigate a body-freedom flutter of the X-56A aircraft in the third NASA-led aeroelastic prediction workshop [14].

Although there is no intent here to provide a through literature review, Refs. [15–21] should also be included as sources of existing knowledge on this exciting subject. The following sections attempt to contribute to it by providing a novel expression for the aerodynamic work as a function of airspeed in linearized frequency-domain aeroelastic analyses, and this expression is then used to develop new analysis tools and insights into aircraft flutter and its suppression.

II. Computation of Aerodynamic Work in Linear Aeroelastic Model

Consider the fundamental flutter equation from the computational aeroelasticity resource and commercial analysis program MSC.Nastran's software manual [22] developed by Rodden et al.:

$$\boldsymbol{M}p^2 + \left(\boldsymbol{B} - q\frac{b}{Vk}\boldsymbol{Q^I}\right)p + (\boldsymbol{K} - q\boldsymbol{Q^R}) = 0 \tag{1}$$

In this equation, p is the eigenvalue; q is the dynamic pressure; b is the reference semichord; $k = b/V$ is the reduced frequency; V is the true airspeed; ω is the frequency; $\boldsymbol{M}$, $\boldsymbol{B}$, and $\boldsymbol{K}$ are the structural mass, viscous damping, and stiffness matrices; and $\boldsymbol{Q}$ is the complex-valued

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*Senior Engineer, Structural Dynamics, National Aircraft Certification, Civil Aviation.