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Flutter behavior of a flexible airfoil: Multiparameter experimental study

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ABSTRACT

The flutter behavior of a flexible airfoil is experimentally studied, with the goal to increase the flutter stability boundary due to the airfoil flexibility effect. The flexible airfoil concept is realized as an elastically supported symmetrical airfoil with a laminated composite plate attached to its trailing edge. A series of multiparameter wind tunnel flutter tests were conducted to investigate the flutter behavior of a flexible airfoil at various aeroelastic system configurations. The airfoil flexibility effect on the flutter behavior is studied in terms of two main dynamic properties of a flexible plate, the flexural stiffness and the areal density, which are introduced through two non-dimensional laminate design parameters. It is shown that the flutter behavior of a flexible airfoil is characterized by two types of flutter, namely the classical airfoil flutter and the plate flutter. The increase in the critical flutter speed due to airfoil flexibility effect is significant for aeroelastic system configurations with high plunge to pitch natural frequency ratios in the region of the aeroelastic system bimodal behavior, where the two types of flutter occur simultaneously. Furthermore, the experimental evidence of the bimodal behavior of the observed aeroelastic system is presented.

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1. Introduction

There is a continuing desire to improve aerodynamic performance and reduce structural weight of aircraft designs to achieve expanded flight envelope and long flight endurance. To achieve these ambitious goals, the development trends in aircraft design go in the direction of slender, lighter and even adaptive wing structures made of advanced composite materials [2,31]. However, such slender wing structures are consequently very flexible and usually imply aeroelastic stability problems. Therefore, in recent years a considerable effort has been taken to study aeroelastic behavior and flutter instabilities of flexible wing structures [7,18,25], with the application to aeroelastic optimization problems using aeroelastic composite tailoring [1,9,20]. Recently, flexible lifting surface constructions are also widely used in the field of bio-inspired flapping flight research [21], but with the main focus on improvements of the maximum trust and propulsion efficiency [10]. The authors believe that besides the trust and propulsion efficiency, also aeroelastic stability problems of such constructions should be considered. Now, let us first revise some basic problems of aeroelasticity, with a main focus on the experimental contributions.

The classical airfoil flutter is a fundamental flow-induced instability mechanism described as self-excited plunging and pitching oscillations of an airfoil subjected to flow. One of the first fundamental studies considering the classical airfoil flutter was published by Theodorsen [27] and Theodorsen and Garrick [28], who obtained a closed-form solution of the flutter instability in the frequency domain with the experimental validation. An extensive review of the work on this topic was given by Dowell et al. [5]. Through the years numerous experimental studies, considering the flutter behavior of airfoil sections, were published. To mention only a few examples, wind tunnel flutter tests considering typical-section models were presented by McIntosh Jr. et al. [13], Razak et al. [17] and Song et al. [23]. Furthermore, Hemon et al. [11] presented the experimental evidence of transient growth of energy at subcritical behavior of a typical-section model just below the flutter speed. Additionally, some theoretical investigations of aeroelastic stability problems considering flexible airfoils can be found in the literature [12,14,15].

The flutter of cantilevered plates subjected to axial flow represents another fundamental example of flow-induced instability and results from the interaction of the destabilizing pressure impact across the plate due to its lateral deflection and the stabilizing bending stiffness of the plate, similar to flag flutter [24], where this type of instability can be observed in everyday life as a flag waving in the wind. A systematic study of cantilevered plates in axial flow

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regarding flow-induced instabilities can be found in a monograph by Dowell [4], and more recently by Païdoussis [16]. Considering experimental studies, Taneda [24] conducted one of the earliest flutter experiments for a vertically hanging flag. Measurements of the flutter speed for sheet and web paper considering various materials, sizes and tensions were done by Watanabe et al. [30]. Experimental investigation of flutter and limit cycle oscillations of cantilevered two-dimensional elastic plates in axial flow was conducted by Tang et al. [26], where also the hysteresis phenomenon of the flow velocity at flutter onset was experimentally addressed. Recently, experiments for cantilevered flexible plates subjected to axial flow were done by Zhao et al. [32]. The effect of spanwise clearance on flutter of a cantilevered plate in a channel flow was experimentally studied by Doare et al. [3]. Besides, experiments on a heavy self-supporting flag undergoing oscillations in water flow were performed by Shelley et al. [19].

In the present work, focusing on chordwise flexibility only, an elastically supported flexible airfoil, implemented as symmetrical airfoil-shaped segment with a flexible plate attached to its trailing edge, is experimentally studied. The goal is to increase the flutter stability boundary due to the airfoil flexibility effect, where besides the classical two-degree of freedom (2-DOF) airfoil flutter, also the plate flutter is taken into consideration. The airfoil flexibility effect on the flutter behavior is studied according to the two main dynamic properties of the flexible plate, the flexural stiffness and the areal density of the plate, which are introduced through two non-dimensional laminate design parameters. For the experimental study, a chordwise flexible test wing model was designed and mounted on the 2-DOF support system [8] representing the aeroelastic system. The support system enables plunge and pitch motion of the flexible airfoil, as also the variation of plunge and pitch stiffness of the aeroelastic system in the wind tunnel test section. The variations of the flexural stiffness and the areal density of flexible plates were achieved by using laminated composite plates made of different fiber materials and number of laminate plies.

The stability boundary was obtained by monitoring plunge and pitch response of the system to an initial disturbance. The measurement process was automated with the implementation of LabVIEW® and Matlab® numerical code in the measurement algorithm. The obtained stability boundaries are presented in terms of the critical flutter speed related to the non-dimensional laminate design parameters at different aeroelastic system configurations, represented as plunge to pitch natural frequency ratios.

Special focus of the present work is observation of bimodal flutter behavior of the flexible airfoil. Due to the aeroelastic coupling mechanism, the stability boundary of such aeroelastic system is usually determined as a critical flutter speed with single-frequency response, either as airfoil flutter or as plate flutter response, which can be characterized as unimodal flutter behavior. However, at some special configurations of the aeroelastic system, superposition of unimodal responses is possible, i.e. airfoil flutter and plate flutter occur simultaneously, which is characterized as bimodal flutter behavior. Although numerous research works address the stability analysis of aeroelastic systems considering either a two-dimensional typical wing section or cantilevered plate subjected to axial flow, the authors did not find a similar case study where the classical airfoil flutter and the plate flutter occur simultaneously, representing a bimodal behavior.

2. Flexible airfoil concept and the non-dimensional design parameters

The flexible airfoil concept used in this study is based on an elastically supported symmetrical airfoil segment with a flexible plate attached to its trailing edge, as mentioned in the previous section. The basic objectives of this concept are to consider the effects of the flexural stiffness and the areal density of laminated composite plates on the flutter behavior, depending on configuration of the aeroelastic system, and to investigate the possibilities of increasing the flutter stability boundary. For this purpose, two non-dimensional design parameters adapted to the nature of laminated composite plates and a non-dimensional parameter that describes general dynamic properties of the aeroelastic system are introduced in the present section.

According to theoretical background, when dealing with flexural stiffness of plates [29], we assume a third power relation between the flexural stiffness of a laminated composite plate and the number of plies of the laminate, given as

$$D_{n,i} = D_i^* n^3, \qquad (1)$$

where $D_{n,i}$ is the flexural stiffness of a laminated composite plate made of n-ply laminate of i-th fiber type and n is the actual number of laminate plies. The coefficient D_i^*, representing the effective flexural stiffness of a single-ply laminate of i-th fiber type, is obtained from the approximation of the corresponding experimental data by the function given in Eq. (1), for each fiber type separately. Now, to unify the expression of the flexural stiffness of laminated composite plates, regardless of the fiber type, we express the flexural stiffness as a function of equivalent number of plies n_{eq} as

$$D_{n,i} = D^* n_{eq}^3, \qquad (2)$$

where D^* is the effective flexural stiffness of a single-ply laminate of the chosen reference fiber type. Using Eqs. (1) and (2), the equivalent number of plies is obtained as

$$n_{eq} = \sqrt[3]{\frac{D_i^*}{D^*}}\, n, \qquad (3)$$

which characterizes the flexural stiffness of the laminated composite plates in general. It should be noted that a higher value of the equivalent number of plies n_{eq} than the actual number of plies n means higher flexural stiffness of a given fiber material in comparison to the chosen reference fiber type.

Next, dealing with the areal density of the laminated composite plates, we assume a proportional relation to the actual number of plies as

$$\rho_{A_{n,i}} = \rho_{A_i}^* n, \qquad (4)$$

where $\rho_{A_{n,i}}$ is the areal density of a laminated composite plate made of n-ply laminate of i-th fiber type and $\rho_{A_i}^*$ is the effective areal density of a single-ply laminate of i-th fiber type. The corresponding experimental data was approximated by the function given in Eq. (4) to obtain the value of the coefficient $\rho_{A_i}^*$, for each fiber type separately. Now, besides the non-dimensional design parameter n_{eq} which is a measure for the flexural stiffness, we introduce the equivalent areal density ratio μ_{eq} which is a relative measure for the areal density of a laminated composite plate, as

$$\mu_{eq} = \frac{\rho_{A_{n,i}}}{\rho^* n_{eq}}, \qquad (5)$$

where ρ^* is the effective areal density of a single-ply laminate of the chosen reference fiber type. The equivalent areal density ratio represents the ratio of the areal density of a given n-ply laminate and the areal density of n_{eq}-ply reference laminate, where both laminates are of the same flexural stiffness. Using Eqs. (3) and (4), we obtain the equivalent areal density ratio, given in Eq. (5), as

$$\mu_{eq} = \frac{\rho_{A_i}^*}{\rho^*} \sqrt[3]{\frac{D^*}{D_i^*}}. \qquad (6)$$

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