

Theoretical and Experimental Flutter Predictions in High Aspect Ratio Composite Wings

2011-01-2722

Published
10/18/2011

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doi:[10.4271/2011-01-2722](https://doi.org/10.4271/2011-01-2722)

ABSTRACT

Next generation of composite civil aircrafts and unconventional configurations, such as High Altitude Long Endurance HALE-UAV, exhibit aeroelastic instabilities quite different from their rigid counterparts. Consequently, one has to deal with phenomena not usually considered in classical aircraft design. Alternative design criteria are needed in order to maintain the safety levels imposed by the regulations and required for certification. The A2-Net-Team project aims to build a multi-disciplinary network of researchers with complementary expertise to develop analytical methods used for a better understanding and assessment of the factors contributing to the occurrence of critical aeroservoelastic instabilities. Along with modeling and numerical investigations a test article will also provide the opportunity to modify and calibrate theoretical models, to highlight and explore their limits, to recommend the necessary modifications and future pertinent investigations. The objective of this paper is to provide the authors' point of view on a consistent scaling procedure applicable when investigating the flutter stability of a full-size high aspect-ratio composite wing structure by means of an economical laboratory wind tunnel test model. Sizing and technological development aspects are discussed along with a detailed design procedure to gather the necessary data for the model manufacture. To exemplify the procedure a wooden model is fabricated and used to provide insight into the scaling procedure and verify the acquired data. Finally a dynamically scaled composite model is defined for a wind tunnel aeroelastic test.

INTRODUCTION

Aeroelastic instabilities always constrain the flight envelope and thus they have to be considered fundamental during the design process. These instabilities need to be evaluated to both its consequence on the aircraft wing integrity and on the airworthiness requirement included into the regulation. The objectives of the A2-Net-Team Project is multifold: 1) To develop multidisciplinary analysis methods appropriate to unconventional highly flexible aircrafts 2) To develop design tools capable of predicting the effects of uncertainties on the behaviour of an aeroelastic system. 3) To propose innovative control techniques to dynamic aeroelastic control of a highly flexible wing. 4) To integrate theoretical analysis with commercial structural (FEM) and aerodynamic tools (CFD). 5) To design and manufacture a test article to be used for experimental aeroelastic investigations 6) To validate theoretical and numerical results by vibration and aeroelastic wind tunnel tests. The three year A2-Net-Team project was in response to the FP7-PEOPLE-2010-IRSES funded by the European Commission through the Seventh Framework Programme. The Marie Curie International Research Staff Exchange Scheme (IRSES) aims at strengthening research partnerships through short period staff exchanges and networking activities between European research organizations and research organizations from countries with which the Community has an S&T agreement and countries covered by the European Neighborhood Policy. The A2-Net-Team is composed by five partners that will move Experienced Researchers and Early stage researchers for a total of 69 Man Months: 1) Politecnico di Torino-IT 2) Clarkson University-US 3) Institute of Mechanics of the National Academy of Sciences of Armenia-AM 4) Budapest

University of Technology and Economics-HU, and 5) University of Ljubljana-SI.

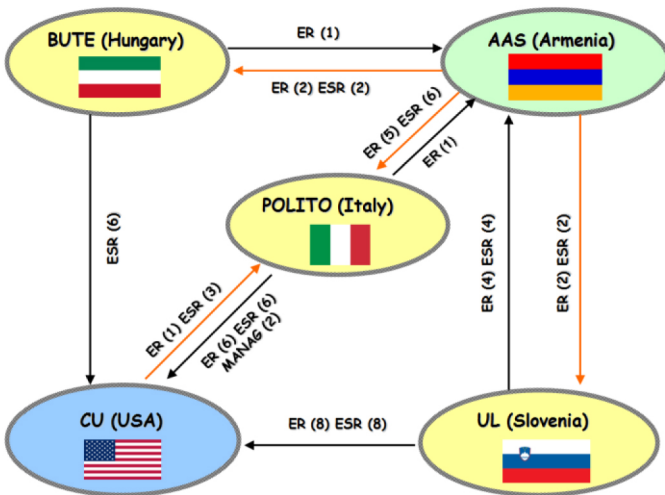


Figure 1. The scheme of the network. The numbers stand for the duration of the exchange (man months) and ER (Experienced Researcher) ERS (Early stage researcher). Only eligible exchanges are used to quantify the total amount of months for each group.

This project addresses important challenges in new aircraft preliminary and conceptual design. It is especially important in a new type of unmanned aircraft configurations and aircraft made from composite materials. The scientific approach will combine theoretical analytical work with experimental testing, something clearly lacking from the literature for this class of vehicle. Testing activity ensures that knowledge gained is actually applicable and theoretical models validated. This paper shows some preliminary results as part of the main objectives of the A2-NetTeam group at Politecnico di Torino (Italy) and at Clarkson University (US). Long endurance UAVs usually employs high aspect ratio flexible wings to reduce weight and power in order to achieve extended flight operation. There are advanced concept designs for aircraft that will sustain autonomous operations for months or even years. The increased wing flexibility can lead to large structural deflections for trimmed flight states. These large elastic deformations within the static equilibrium state of the vehicle can induce aeroelastic instabilities quite different from their rigid counterparts. Therefore, it is imperative to perform a flutter analysis which considers the trimmed large amplitude deformed state as a reference point. Considering the complexity of the system under investigation, the aeroelastic flutter analysis process usually includes an experimental test phase for verification purposes. In this respect, wind tunnel test models provide the opportunity to modify and calibrate theoretical models, through a process of model updating. Two general areas are pertinent to the field of aeroelastic testing. When no airstream is present, static and ground vibrating testing are conducted to

determine the accuracy of the stiffness distribution, natural frequencies, and mode-shapes. In the presence of airstream the critical and post critical aircraft wing behavior, such as flutter and limit cycle oscillations can be investigated. An experimental aeroelastic slender wing model can be designed using a scaling procedure. By expressing the aeroelastic governing equations in dimensionless form, it is possible to relate the behavior of a scaled model to that of a full-scale. Consequently, the correctness of the parameters representing the characteristics of the full-scale system can be verified and, when required, a model updating can be performed. In this work, a numerical method is introduced to expedite the analysis required during the preliminary design process. A Typical HALE wing is considered and its aeroelastic behavior is investigated while a model identification procedure is required to develop a wind-tunnel component suitable for experimental test campaigns. An advanced experimental test-bed is proposed and a preliminary wooden model is prepared in order to have a rough evaluation of the wing behaviour under aerodynamic loading condition.

AEROELASTIC MODELS

This section discusses a range of structural models for aeroelastic analysis with the purpose of determining the level of physical fidelity to predict the flutter boundary of a composite high aspect ratio wing configuration. The simplest model of an aeroelastic system with bending torsion instability is the classical typical airfoil section model based on linear springs, which can be considered the first term of comparison [1]. It is essentially an elastic structure constrained in the pitch (ϕ) and plunge, (h). Despite its simplicity, it continues to be a test bed for investigations of nonlinear stiffness [2], flutter and limit cycle oscillations, dynamic stall [3] as well as structural uncertainty effect on classical wing flutter characteristics [4].

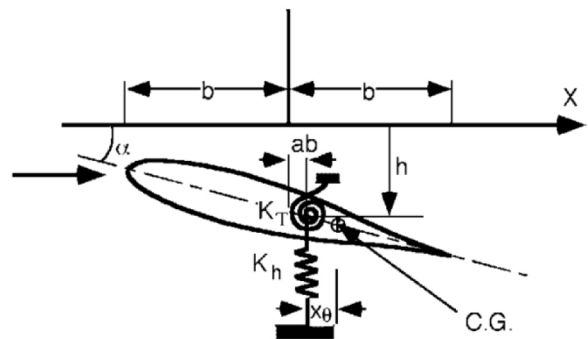


Figure 1. Typical airfoil section model.

A more realistic wing model for composite structures can be obtained introducing a bending-torsion coupled stiffness K by using a wing-box model for the wing cross-sections. The introduction of composite material originates a coupling effect in the constitutive equations introducing a

displacement field slightly different from the isotropic counterpart. A first simple method to study the Flutter of a composite finite aspect ratio wings is the model that consider uniform cantilevered beam approximation with only vertical bending and torsion DOFs. The linear partial differential equations (1) governing the dynamics of the flexible beam can be reduced to a typical section model (Fig 1) applying Galerkin's condition to the residuals:

$$\begin{cases} m\ddot{w} + c_3\dot{w} + me\ddot{\phi} + EI_2 w'''' - K\phi''' = q_w \\ j_1\ddot{\phi} + c_4\dot{\phi} + me\ddot{w} - GJ_1\phi'' + Kw''' = q_\phi \end{cases} \quad (1)$$

The stiffness expressions can be derived from a procedure similar to Armanios and Badir [5,9], starting from the constitutive equations in terms of stress resultants and by expressing the torsional Moment M_x , and bending moment M_y as follows:

$$M_x = GJ\phi_{,x} - Kw_{,xx} \quad M_y = K\phi_{,x} - EIw_{,xx} \quad (2)$$

GJ , EI , K can be calculated based on the properties of each segment of the box-geometry by integration along its cross sectional circumference as follows:

$$GJ = \frac{4\Omega^2}{\oint (1/C(s)) ds} ; \quad K = 2\Omega \frac{\oint (B(s)/C(s)) z ds}{\oint (1/C(s)) ds} ;$$

$$EI = \oint z^2 \left(A(s) - \frac{B^2(s)}{C(s)} \right) ds + \frac{\left[\oint (B(s)/C(s)) z ds \right]^2}{\oint (1/C(s)) ds} \quad (3)$$

Ω is the enclosed area of the cross section and parameters $A(s)$, $B(s)$ and $C(s)$ are given below.

$$A(s) = A_{11} - \frac{A_{12}^2}{A_{22}} ; \quad B(s) = A_{16} - \frac{A_{12}A_{26}}{A_{22}} ;$$

$$C(s) = A_{66} - \frac{A_{26}^2}{A_{22}} \quad (4)$$

In the above equation, A_{ij} are derived from the coefficients of stiffness matrix $[A]$ of the thin-walled anisotropic closed-section beam. For the laminated composite wing box structure as illustrated, the stiffness matrix $[A]$ depends on the laminate properties and layup of the wing box skin and spar web laminate along the circumference cross-section.

The resultant equations of motion can be expressed in dimensionless form as:

$$\begin{bmatrix} 1 & \bar{x}_\alpha \\ \bar{x}_\alpha & \bar{r}_\alpha^2 \end{bmatrix} \begin{Bmatrix} \ddot{w} \\ \ddot{\phi} \end{Bmatrix} + \begin{bmatrix} c_{11} \frac{\theta \bar{r}_\alpha^2}{\lambda^2} & c_{12} \frac{\bar{K} \bar{r}_\alpha^2}{\lambda} \\ c_{21} \frac{\bar{K} \bar{r}_\alpha^2}{\lambda} & c_{22} \bar{r}_\alpha^2 \end{bmatrix} \begin{Bmatrix} w \\ \phi \end{Bmatrix} = \begin{Bmatrix} -\frac{1}{\mu} C_L(\hat{t}, a, k^*) \\ \frac{2}{\mu} C_M(\hat{t}, a, k^*) \end{Bmatrix} \quad (5)$$

where:

$$k^* = \frac{\omega_r b}{U} ; \quad \lambda = \frac{L}{b} ; \quad \mu = \frac{m}{\pi \rho b^2} ; \quad \bar{K} = \frac{K}{G J_t} ; \quad \theta = \frac{E I}{G J_t} ;$$

$$\bar{X}_\alpha = \frac{e}{b} ; \quad \bar{r}_\alpha = \frac{r_\alpha}{b} \quad (6)$$

and c_{11}, c_{12}, c_{22} are coefficients dependent on the shape functions used for the 2 D.O.F. model reduction. Lift and moment coefficients are determined through an external unsteady aerodynamic model. Generally speaking, the models used for the calculation of unsteady aerodynamic loads can be divided into three groups: a) analytical models such as Theodorsen's function, Wagner's function, Kussner's function, strip theory, piston theory etc. b) models based on the Euler/Navier-Stokes equations, which might be extremely demanding as far as computing resources are concerned; c) models based on singularity elements such as vortex-lattice methods or vortex-panel methods. During the preliminary design phase, when parametrical studies and comparisons of on different configurations have to be performed, a time-saving procedure can be of strategic importance. For this reason analytical models are usually favored at this stage, especially if expressed in the state-space formulation, particularly useful for control applications. Wagner's function or Roger's approximation are thus preferred as they accurately transforms the unsteady aerodynamic forces from frequency to time domain. It is important to noticed that, when the values of the angle-of-attack become significant, the aerodynamic nonlinearities could play an important role in the critical and post-critical aeroelastic behaviour, modifying consistently the flutter characteristics. To take into account this effect, semi-empirical dynamic stall models for example there is the model developed at the ONERA research center [3] or the Beddoes [6] model, later extended by Leishman and Beddoes [7], among the others. The aerodynamic model considered in this paper omits the stall model, which limits the analysis to a basic flutter prediction.

The more complex model of Fig. 2 can be obtained using a set of nonlinear beam equations, which highlight the bending-torsion elastic coupling due to two different effects: 1) the composite coupling due to the CAS configuration; 2) the coupling deriving from the second-order geometric nonlinearities [8,9].