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Wind tunnel flutter tests of a strut-braced high aspect ratio wing

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Abstract. Increasing the wing aspect ratio is one way to improve aircraft aerodynamic efficiency. This reduces the induced drag term but, at the same time, produces an increment of the wing loads, hence an increase of the structural weight. One design solution to reduce the wing root bending moment, which is the main driver of the weight of the wing, is the addition of a strut. This work deals with the experimental identification of the flutter behavior of an ultra-high aspect ratio (19) strut-braced wing in a wind tunnel. The inherent non-linear behavior of such a structure that has two different effects on the wing when loaded in compression and in tension is coupled with large deformations due to its extreme flexibility. From here derives the extreme importance of experimental tests to understand how different parameters of such a design can impact its aeroelastic behavior.

Introduction

New aircraft configurations such as the strut-braced wing require experimental studies, as results coming from simulations are less trustworthy than those regarding traditional and well-tested configurations. Data should be collected to assess both static and dynamic aeroelastic behavior, with the ultimate goal of validating numerical models and techniques. After a scaling process of a typical strut-braced wing reference aircraft provided by ONERA, a 1:10 scale model for wind tunnel testing is designed by Polimi and IBK allowing for some variations in the geometry and kinematics of the strut. A pneumatic system is designed for the excitation of the model inside the wind tunnel when turbulence is not enough. The dynamic response is measured both in terms of accelerations and displacements, using accelerometers and an optical system to track the motion of some markers on the model.

Reference aircraft

Reference aircraft is an Onera concept [1,2]. Typical mission and fuselage use an Airbus A321 as a baseline. It’s a strut-braced configuration with an aspect ratio of 19. This results in a 55 m wingspan. Two engines are mounted on the rear of the cabin, the empennage layout is a T-tail. The connection between the strut and the main wing is not straight, but the strut is bent in a way that allows it to enter the wing perpendicularly, improving its aerodynamic behavior at transonic speeds.

Description of the model

The test model consists of a scaled left-wing clamped at the root and mounted in a vertical position. A constant Froude scaling approach was adopted with a geometric scale factor of 1:10.

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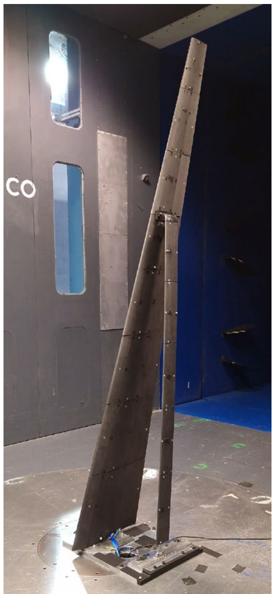

Figure1 Wind tunnel model

The design of the structure is decoupled from the aerodynamics. For the main wing, a single glass fiber spar is used. It is obtained by milling a thick glass fiber plate with full rectangular cross-sections defined at 9 spanwise locations to correctly match out-of-plane and in-plane bending stiffnesses. The resulting torsional stiffness is representative of the correct one. The aerodynamic shape is obtained with 8 3D printed sectors attached to the spar at just one point spanwise so that they can transfer the aerodynamic loads to the structure without contributing to the overall stiffness.

For the strut, two options were designed: one stiffer than the reference with a full rectangular section aluminum spar and 3D printed aerodynamic sectors; and a second one with the correct stiffness obtained with a steel wire, but no aerodynamics attached. From here on we will refer to these two configurations as the “Aero” configuration and the “Wire” configuration. Both struts are hinged to the ground, the axis of rotation being parallel to the fuselage direction. A parallel hinge is also used to connect the strut to the wing. A rail on the floor and a plate at the connection with the wing allow 4 different chordwise positions for both strut configurations. This is done with the goal to obtain a sensitivity regarding this design parameter.

Description of measurement system

Two quantities are measured during the tests: accelerations and positions: 17 accelerometers are installed inside the main wing, all reading accelerations in the out-of-plane direction. 2 accelerometers are installed on the strut in the Aero configuration. All the wires pass inside the model and through a hole in the floor of the test chamber, where signals are acquired by a SCADAS acquisition system. Acquisitions and postprocessing are performed using Simcenter Testlab. As a main source of excitation for the structure, the turbulence inside the wind tunnel is used, which is near to a white noise excitation. In addition, a compressed air pulse is also available to get an impact-like effect. The high-pressure line of the wind tunnel (8 bar) is linked to a small tube passing inside the model to reach the 7th aerodynamic sector (near the tip of the wing). A hole in the lower skin allows the air pulse to act perpendicular to the chord exciting the out-of-plane bending of the wing. Since the hole is positioned towards the trailing edge, a partial excitation of the torsion is obtained, too. A button in the control room opens a valve allowing for remote control of the pulse excitation. This system is used both to excite the structure in the no-wind conditions and to tune the optical system. This consists of 6 infrared cameras which track the position of 53 optical markers placed on the model (only 32 in the wire configuration).

Testing procedure

Wind tunnel tests were carried out at the large wind tunnel facility at Politecnico di Milano (GVPM). The test section is a 4 m by 4 m square, top speed is 54 m/s (near the scaled cruise dynamic pressure).

Static aeroelastic assessment was performed changing the angle of attack and measuring the deformed shape with the optical system. This was done at low speeds (10 m/s and 20 m/s) with angles ranging from -3° to +5° with 1° increments.

Dynamic characteristics of the structure were assessed with modal analysis at different airspeeds. Operational Modal Analysis was used to identify frequency, damping and shape of the normal modes of the structure for wind speeds between 10 m/s and 54 m/s (maximum speed of the wind tunnel) with 5 m/s increments. Air pulse was used to identify normal modes at 0 m/s.

The first test consisted in changing the angle of attack to evaluate the influence of the prestress in the strut on the aeroelastic response. Three angles were tested: 0°, 1° and 2°. The chordwise position of the strut was fixed, and its configuration was too (aero). The second test consisted in changing the chordwise position of the strut and its configuration. 8 tests were performed at a fixed angle of attack (1°) to investigate all available options (4 chordwise positions and 2 strut configurations). As a third and last test, the aero configuration was modified to block the hinge connecting the strut and the wing. Data were collected for just one chordwise position at the usual angle of attack (1°) to be able to compare the aeroelastic response in three different conditions for the strut.

Results: Static Aeroelasticity

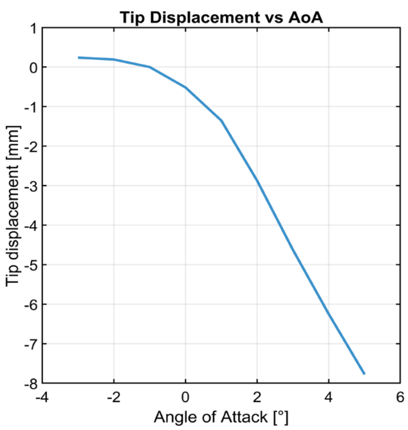

Figure 2 Tip displacement VS AoA

The measured displacement of the tip of the wing is reported in Fig.2

This is obtained at a fixed airspeed of 20 m/s and a range of angles of attack from -3° and +5°. The behavior is linear just in a small range of angles of attack. When the strut is compressed, the nonlinear trend is evident, but also at the upper bound of the tested range, the concavity of the curve starts to change.

Results: Dynamics and Flutter

As a first way to interpret the results, all chordwise positions for the same strut configuration are plotted overlapped, just to see the general trend of the curves and the dispersion of the data. In both the strut configurations, we can see a convergence of the frequency of the 3rd bending mode and the first torsional mode. The damping of the bending mode changes concavity and tends to the zero-damping axis. We can't conclude that this will result in a flutter condition, but this behavior is typical of a pre-flutter condition. Results from the wire configuration are less scattered than those coming from the aero configuration, both for the absence of the aerodynamics on the strut and for the absence of hybrid modes coming from the coupling between the wing and strut bending with different phases. Lower frequency modes are far less consistent, especially around 30 m/s where results become very scattered. At some speeds, modes

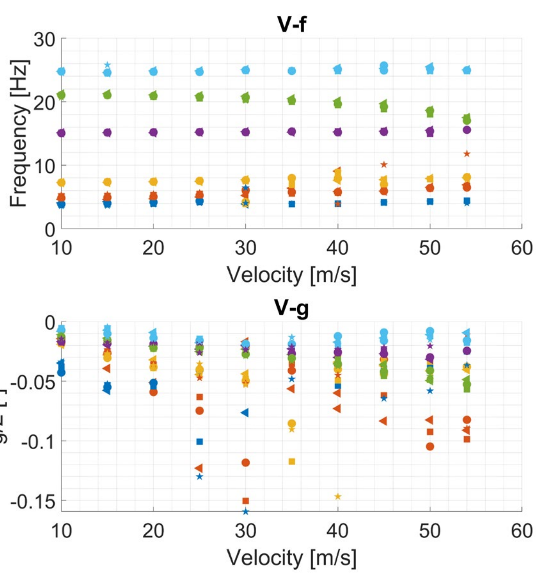

Figure 3 Wire configuration Vf-Vg

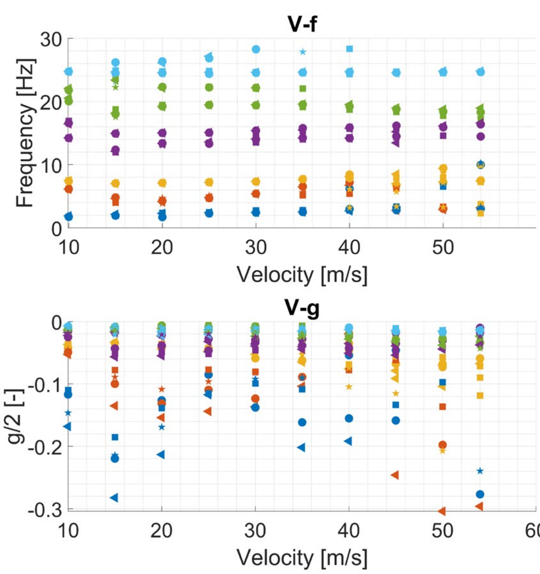

Figure 4 Aero configuration Vf-Vg

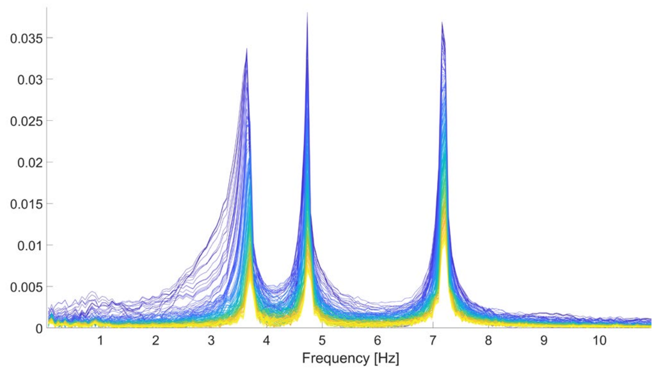

Figure 5 Zeroed Early-Time Fast Fourier Transform

with the same shape as the second bending mode appear both at their expected frequency and at the frequency of the first bending mode. This is a behavior found in nonlinear modes, where frequency and damping depend on vibration amplitude and modal shapes are not unique anymore. A test is performed to check if the modes of this kind of structure can be nonlinear. It is the Zeroed Early-Time Fast Fourier Transform [3]. At least the first mode appears to be nonlinear.

Conclusions

Data was collected for different configurations of the strut at different airspeeds. Initial analyses of the static deformations show a clear nonlinear behavior. Flutter analyses show a potential flutter condition inside the flight envelope of the reference aircraft. A nonlinearity of the normal modes was detected.

Summary

A clamped wing in a strut-braced configuration was tested at Politecnico di Milano in its large wind tunnel facility to gain insights into its static and dynamic aeroelastic behavior. This was achieved using accelerometers for the dynamics and an optical system for the statics. Both static and dynamic characteristics appear to be nonlinear.

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