Experimental and Numerical Analysis of Aeroelasticity of an Aircraft Wing Section with Nonlinear Energy Sink

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Abstract:

Recent works on nonlinear passive dampers present high control efficiency for broadband frequency range with low added mass (order of the percent). This work presents a configuration of a wing where the flap is considered as a Nonlinear Energy Sink tuned mass damper (NES), which adds zero mass and has a cubic stiffness. Two aeroelastic test-benches are created and characterized in linear and nonlinear structural configurations with a subsonic wind-tunnel experimental campaign. The strongly nonlinear hardening stiffness is obtained by using linear springs at large angles. For the nonlinear tests, several Limit Cycle Oscillation (LCO) were observed. Numerical analysis was also carried out for both linear and nonlinear cases using: Unsteady Vortex Lattice Method (UVLM) and Theodorsen theory (low fidelity), Euler (medium fidelity) and Reynolds-Averaged Navier Stokes (high fidelity) methods. The numerical methods present good agreement, within the limits of each approach, and are validated with the experimental data. Using the NES, a gain of flutter speed is reached compared to the linear flap restoring force configuration.

Key words: aeroelasticity, flutter, nonlinear dynamics, limit cycle, energy absorber

1 Introduction

Aeroelasticity, the study of the coupling between a flexible body and aeroelastic forces, remains today a subject of great interest in aircraft design. It includes the study of static aeroelastic effects and the analysis of more complex problems which appear when dynamic systems are considered. Moreover, aeroelasticity is often affected by non-linearities which alter the system's response; it is the subject of active research [1]. These non-linearities have two different sources: structural elements such as freeplay or cubic stiffness [2] can appear alone or simultaneously in any of the degrees of freedom (DOF) of the airfoil and aerodynamic effects which are mainly due to either transonic effects [3] or to aerodynamic effects, such as dynamic flow separation due to large deflections in wings, known as stall flutter [4].

An important phenomenon encountered in dynamic aeroelasticity is flutter. If there are no sources of non-linearities the system can only experience classic flutter which is defined as self-excited vibration of the structure due to energy extraction of the incident airflow. This generally results from the coalescence of two structural modes: pitch and plunge, which reach the same vibration frequency. If the speed becomes greater than the flutter speed, the amplitude of the movement grows exponentially causing structural failure [4].

The presence of nonlinearities can change dramatically the observed behavior as other phenomena, such as limit cycle oscillations (LCOs), can appear in the system's response. During a LCO, the vibration reaches a stable amplitude which remains constant unless the wind speed changes. LCOs can be observed in subcritical or in supercritical regime once flutter speed is passed [5].

In order to increase the system's flutter speed, active methods (energy input) are the most efficient but can be obsolete in emergency cases (ie. lack of power). Tuned Vibration Absorbers (TVA) are a good alternative and are already widely used in civil engineering [6]. The classic linear TVA is simple and efficient but only close to a single frequency. The main drawback is the inefficiency to control an oscillator whose natural frequencies changes with the wind speed (i.e. Aeroelastic wing). Semi-active strategies could solve this problem but the energy dependency is still present. This is the reason why some research studies focus on Nonlinear Tuned Vibration Absorber (NLTVA) [7]. The Nonlinear Energy Sink (NES) [8] is a NLTVA with a purely nonlinear stiffness that presents high vibration absorption skills for a broadband frequency range and a low added mass.

With the objective of controlling passively a wing with a NES for a minimum added mass, the idea of this work is to consider the profile's control surface as a NES *(figure* 1). For a better understanding of the system, an experimental campaign was carried out on a 2 degrees of freedom (DOF) and 3DOF aileron/airfoil typical section with a strong structural nonlinearity at the control surface stiffness. Similarly, pertinent numerical analysis is carried out. The aerodynamic forces acting on the airfoil are computed and these forces together with the equations of motion enable the computation of the fluid-structure effects and, therefore, the resolution of the aeroelastic system. For the aeroelastic analysis, both the linear and the non-linear cases are studied. In the non-linear 2DOF case, cubic stiffness and freeplay gap are applied in the pitch restoring force whereas in 3DOF the flap is modelled to become a NES.

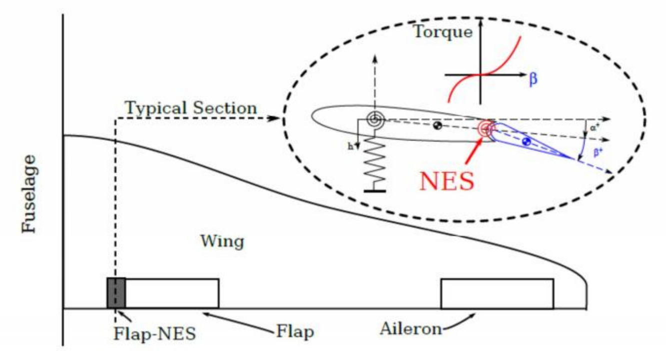


Figure 1: Configuration of wing with NES with zero added mass

2 Experimental approach

2D experimental setup

For the first setup, the wing is rigid with an aileron which goes all along the wingspan and a modular mechanism which lies above and below the wind tunnel and enables its movement. There are three possible degrees of freedom which can be independently blocked: plunge, pitch and aileron deflection. The mechanism also enables the stiffness of each degree of freedom to be varied by changing the springs associated to each movement. Not only can this stiffness be modified, but it is possible to replace the torsion spring of the aileron, which gives rise to linear stiffness, by a traction spring placed perpendicular to the airfoil's and the flap's rod *(see figure 2)* in order to create a cubic stiffness. This is used to turn the flap into a NES and study the system's response.

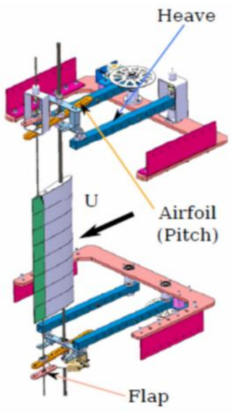


Figure 2: a) Rigid wing with flap and modular mechanism CAO b) Cubic nonlinearity with traction spring between the airfoil and the flap rods

In order to start a test, an initial condition must be imposed to one or more DOF. This is done by a system of electromagnetic breaks which enable us to fix the position of the wing and to release it at the start of a test. These breaks also have a security function and serve to stop the tests when required.

Three types of sensors are used: position sensors, acceleration sensors and aerodynamic speed sensors. *Figure 3* shows the position of the sensors. In this figure, the position sensors which measure the angle of rotation, acceleration sensors and the electromagnetic brakes are represented.

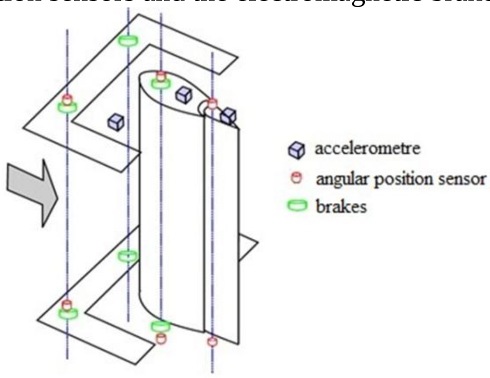


Figure 3: Diagram of the sensor distribution

Firstly, different degrees of freedom were blocked in order to characterize the rigidities of each DOF, then, the linear behavior was studied for 2DOF and 3DOF configurations and, lastly, the non-linear configuration where a cubic stiffness was introduced in the aileron was tested. The tests were made by fixing all the other parameters and setting a different inlet velocity. The initial conditions were also varied. For each case, like in the preliminary numerical results, different regimes where observed. The vibrations were either damped or they presented interesting aeroelastic behavior. Each of the tests was repeated at least twice for repeatability.

The parameters of the setup were adjusted to ensure that flutter was within the mentioned wind speed, and each case was tested between 0 and 15 m/s. The natural frequencies of the different degrees of freedom were calculated by mechanically blocking the rest of DOF and measuring the free response in 0 wind conditions. H and Alpha degrees of freedom were tested 6 times with 2 different initial conditions and Beta was tested 3 times by manually imposing a flap deflection. The signals where filtered and the natural frequencies and damping frequencies were obtained via FFT and curve fitting (see Figure 4).

FFT				
DOF	Natural Frequency (Hz)	RMS error (%)	Damping	RMS error (%)
h	1,38	2,49	x	x
alpha	2,63	3,71	x	x
beta (linear)	3,95	5,23	x	x
Curve Fitting				
DOF	Natural Frequency (Hz)	RMS error (%)	Damping	RMS error (%)
h	1,38	3,06	0,085	10,83
alpha	2,6	1,06	0,04	19,42
beta (linear)	4,09	0,64	0,093	20,48

Figure 4: Natural frequencies and damping ratios of each DOF and their RMS errors calculated via FFT and curve fitting

The setup was observed to be able to capture the aeroelastic phenomena of interested. Different LCO were identified having different amplitudes and either a constant or a periodic behavior.

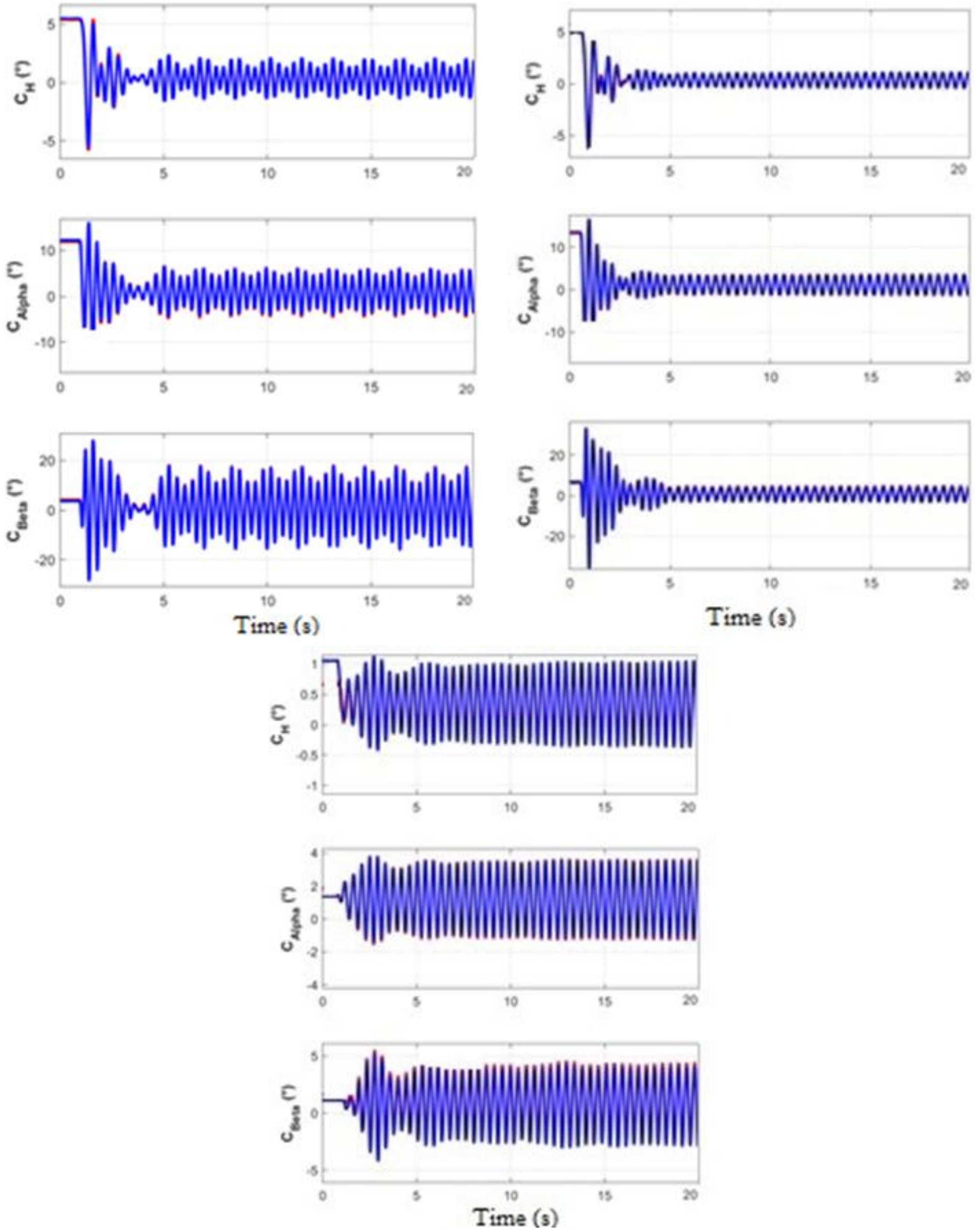


Figure 5: Time signals of position sensors showing LCOs

The nature of the setup makes capturing linear flutter difficult due to its large deflections which cause flow detachment and therefore a nonlinear aerodynamic effect. This means that while testing structurally linear cases the observed behavior was nonlinear due as LCO were accounted for. As a consequence, the numerical analysis for this setup at large deflection will have to be carried out using URANS simulations to correctly capture the aerodynamics present.

As a further note, it is not ideal to have the NES along the whole wingspan (although it is obviously the only solution in a 2D case) because the nonlinearity becomes too strong. With the objective of developing a more robust setup with a localized flap-NES and which will enable a more realistic aircraft wing to be tested: a 3D experimental setup was built.

3D experimental setup

The setup consists of a flexible wing which is clamped on one side and free on the other. The wing has a wingspan of 600 mm and the profile is a NACA0020 with a 200 mm chord. The wing has two flaps *(figure 6)* the nearest to the wing tip is equipped to act as a NES and the other has the double function of exciting the structure, for it to become unstable, and also to stop the instability if the NES fails to work. The NES is smaller in this setup to ensure a more localized nonlinear effect which was not possible to achieve in the previous setup and it is placed at the wing tip to ensure the fluid structure interaction as previously explained.

The ribs are printed in ABS, the spar is made of aluminum and has a rectangular cross section. The wing skin is made of composite material composed of an epoxy resin reinforced by glass fibers via contact impregnation. The material is made up of two layers of tissue with fibers woven with one another at 0° and 90°. Although it is not easy to estimate, there was around 55% fiber deposited for 45% of resin in mass. Since analytical approaches for this type of tissues are quite approximate, the material's was characterized experimentally through traction tests.

Similar to the previously presented experimental setup, the objective of this wing was to study the aeroelastic behavior of the system and evaluate the passive control of flutter using the so called flap-NES. Again, in order to create the cubic nonlinearity required for the NES conception, extension springs were placed strategically in the flap. This time as the structure is flexible only accelerometers were used and placed along the wingspan on the ribs. A balance to measure forces is placed above the wing. Strain gauges were also placed near the clamped side of the wing in order to deflect, via a micro controller, the security flap at 90° to stop the movement whenever the deformation becomes higher than a given value.

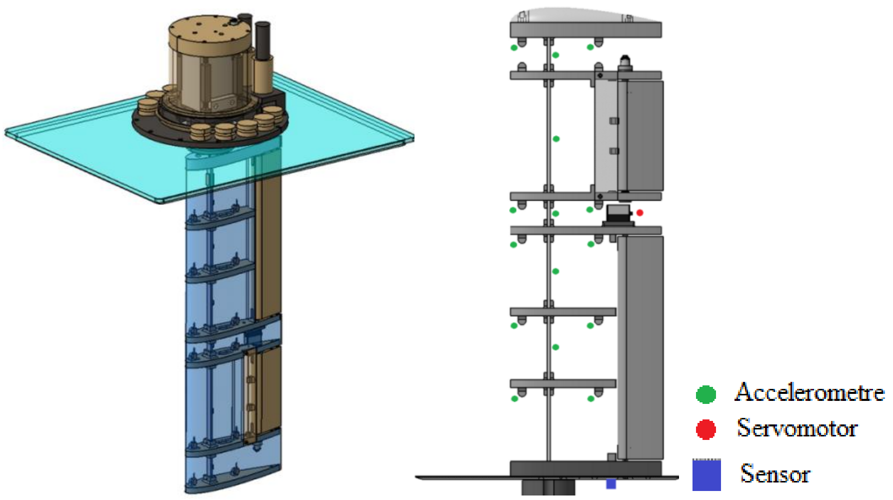
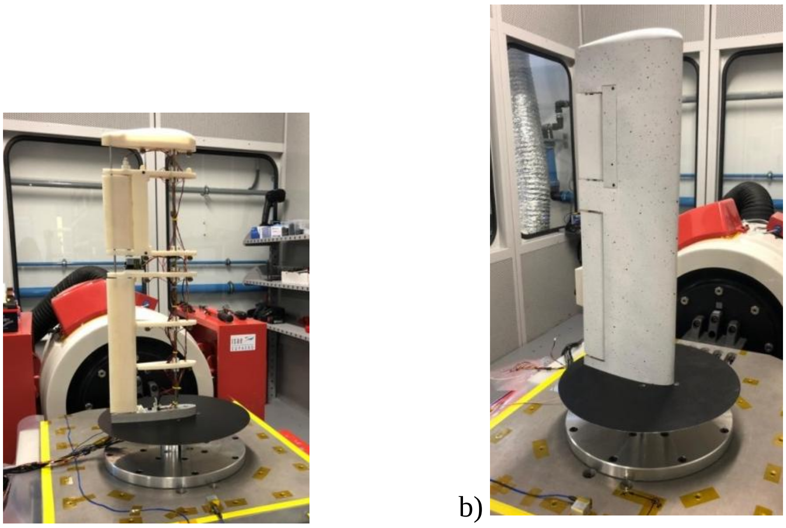


Figure 6: a) Flexible wing setup CAO b) Instrumentation of 3D wing

The wing is equipped with 15 accelerometers (PCB Piezoelectronics 352A74), 10 in the lift and 5 in the drag direction. The flap closest to the wing root is actioned by a servomotor control and there is a rotation sensor placed below the wing *(figure 6).*

Before the wind tests, modal analysis is carried out by placing the wing on a shaker. The effects of the skin on the response are analyzed *(figure 8).*



a) b)

Figure 8: 3D setup without mounted on shaker a) without skin b)with skin

References

[1] F. Afonso, J. Vale, E. Oliveira, F. Lau, A. Suleman, Non-linear aeroelastic response of high aspect-ratio wings in the frequency domain. The Aeronautical Journal, 2017.

[2] E. Breitbach, Effects of structural non-linearities on aircraft vibration and flutter. Tech. rep. DTIC Document 1978.

[3]J.P. Thomas, E.H. Dowell, K.C. Hall, Nonlinear Inviscid Aerodynamic Effects on Transonic Divergence, Flutter and Limit-Cycle Oscillations. AIAA Journal, 2002.

[4] R.L. Bisplinghoff, Aeroelasticity. Dover, 1996.

[5] S.H. Strogatz, Nonlinear Dynamics and Chaos with application in physics, biology, chemistry and engineering. Addison-Wesley Publishing Company, 1994.

[6] J. Mesenguer, et al., Aerodinamica Civil: efectos del viento en edificaciones y esttructuras. Ibergarceta Publicaciones, SL, Madrid, 2013.

[7] G. Habib and G. Kerschen, Suppression of limit cycle oscillations using the nonlinear tuned vibration absorber. In Proc. R. Soc. A. The Royal Society 2015. 471.

[8] Y.S. Lee, et al., Passive non-linear targeted energy transfer and its applications to vibration absorption: a review. Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics., 2008.