EXPERIMENTAL STUDY OF AEROELASTIC RESPONSE OF A FLEXIBLE HIGH ASPECT RATIO WING WITH PASSIVE SMA ACTUATORS

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Abstract

The search to increase aircraft performance has led to wings with higher aspect ratios. High aspect ratio wings are subjected to aeroelastic instabilities. Consequently, the use of advanced materials added to its structure might be an aeroelastic control strategy. Among the passive and active methods to control and mitigate such structural phenomena, the use of shape memory alloys (SMA) has gained space in aeronautical applications. In such context, the present research aims to analyze the flutter answer of a flexible wing with high aspect ratio with SMA wires as passive controller. First, a research model has been designed, built and tested in a wind tunnel. After being calibrated, SMA wires were installed as a dynamic actuator in such model. The flutter condition was then evaluated through monitoring aeroelastic damping effect and the frequency coupling. The results showed lower peaks of the frequency response function (FRF) for some wire configurations as their critical flutter airspeed was reached. In addition, similar reductions of the limit cycle oscillations (LCO) were also observed.

1 Introduction

Historically, the aeroelastic effects have worried and influenced the aircraft design since the aviation pioneers era. To solve these problems, several control techniques have been applied. The solution traditionally used consists in balancing of mass, stiffness increase or a combination of these two practices. These methods ordinarily result in adding mass to the structure leading to manufacturing problems, lower mission performance and impacting also in terms of operational cost, among other undesired consequences. Refereeing to already established solutions, even being not the best approaches, it is noticeable the work of Von Baumhauer and Koning [1]. The author applied a balancing mass in an aileron, accomplishing to decouple the vibration modes and avoiding structural flutter. Nowadays, recent investigation developed by Tang and Dowell [2] showed the effectiveness of flutter and LCO suppression using this traditional technique by inserting mass with variable center of gravity, shaped as slender body, at the wing tip.

Answering the negative aspects of the traditional techniques, active control technologies (ACT) have been applied using controlling surfaces activated by computers, sensors and actuators. This controlling system uses control laws that can reduce or even eliminate completely the undesired aeroelastic effects without increasing considerably the aircraft mass or reducing its manobrability [3]. The ACT success has already been extensively demonstrated at the literature, as it may be verified at the papers by [4] and [5].

As alternative to sensors and mechanical actuators used by ACT, a new trend of aeroelastic controllers has been tested by researches using the so-called intelligent materials (IM). In IM universe, the shape memory alloys (SMA) has gained notoriety. Quite a lot of authors have emphasized the ability of SMA to control vibrations, as [6] and, [7] who demonstrated its potential to confer damping control and stiffness to the structure.

Nam [8] support that SMA are preferable in static or low frequencies applications, as in shape changing situations associated to morphing technologies done by [9] and [10]. Though this controversial limitation, the applications of such alloys has gained space in aeronautical engineering. Njuguna [11] showed that SMA have applied to aeroelastic control by introducing them in the matrix of composite materials in order to control its stiffness and damping characteristics. Towards this perspective, Ostachowiczand and Kaczmarczyk [12] modeled a composite plate with inserted SMA wires and concluded that the flutter frontier can be extended by using this technique. Following a similar objective, Donadon and De Farias [13] investigated the aeroelastic stability of a composite plate with inserted SMA wires and highlighted that the higher stiffness promoted by the wire heating was able to stabilize the plate recovering it from a flutter condition.

In parallel to the flutter control technologies commented so far, the application of internal forces, concentrated or distributed on the structure, is an alternative way to dissipate energy and reduce the vibrating amplitudes [11]. With this idea on mind and aiming to tackle aeroelastic phenomena, Silva [14] used an experimental apparatus with two degrees of freedom to aeroelastic control by SMA wires. In this case, the SMA wire added stiffness and damping strength only to the torsion degree of freedom. The main results for this wire set up were the reduction of vibration amplitudesbetween 80% and 90% to wind velocities of 14 m/s and 14.6 m/s, respectively. In a similar experimental bench, Sousa [15] applied SMA springs to control the torsional degree of freedom with excellent outcome in terms of oscillation reduction as the spring preliminary load increased. He concluded that this application represents a useful method do passive aeroelastic control.

With all these observations in mind, the present paper reveals the contributions of a recent research where SMA wires inserted inside a high aspect ratio and flexible wing were used to aeroelastic control purposes. The wires were fixed to the wing structure in order to contribute to its stiffness and damping related to the torsion and bending degrees of freedom. Several wire arrangements have been tested, so as many level of initial load were applied to the wires [16]. Besides that, the conditions of flutter occurrence and the LCO have been analyzed.The technique presented here showed be very promising to lowering vibration amplitudes after the flutter, so as to expand the flight envelope.

2 Experimental wing model and measurements

The research model consists basically of a high aspect ratio wing with a slender body at the wing tip. In addition, it counts with two subsystems: one to preload the wires and another to anchor them. The wing is rectangular with no geometric torsion and flexible in both directions of bending and torsion. It has been build using a rectangular wing stringer (length x width x thickness of 0.457 m x 0.0126 m x 0.003398 m, respectively) of aluminum 6060 with uniform mass distribution. The precision of the wing aerodynamic profile was obtained by a laser cutting process using the coordinates of a NACA 0012 airfoil on a 3 mm thick polystyrene flat plate. The wing sections were then composed by nine airfoil profiles joined side by side. Two brass cylinders (diameter x length of 3.17 mm x 27 mm, respectively) were inserted into these sections along the wingspan and close to the wing leading edge to mass balancing. In a total of 16, the wing sections were uniformly distributed along the wingspan and mounted with 1.0 mm between them, avoiding significant dynamic interference from a section to its adjacent ones.

The slender body that composes the aeroelastic system is symmetrical and 0.16748 m long. With a diameter of 0.00952 m and manufactured in brass, this body presented a 0.0045 m chamfer at its extremities to improve its aerodynamics. Another chamfer like a keyway (0.01915 m long, 0.0034 m high and 0.00476 m deep) allows the displacement of the slender body to control the position of the wing center of mass (CG). The body was fixed by a screw when the CG reached the desired position along the wing chord.

The slender body was designed to produce an aeroelastic system with adequate torsional moment of inertia in order to reduce its torsion natural frequency, turning easier the coupling of the bending and torsional modes of vibration. This mode coupling is mandatory to flutter occurrencefor the air speed range of the wind tunnel used at the experiments. The physical representation of the whole aeroelastic system can be visualized in Fig.1.

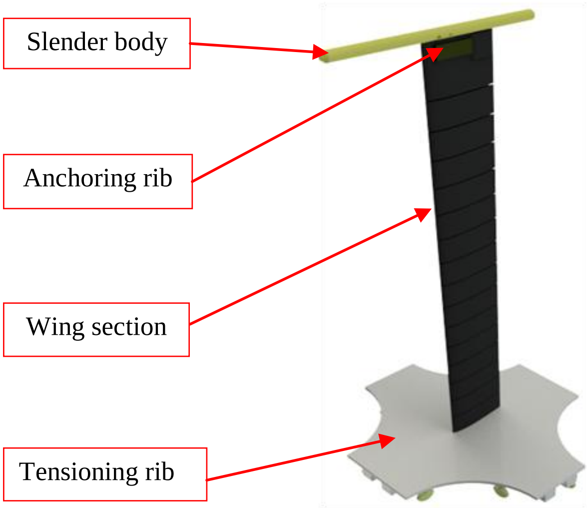

Figure 1. Major components of the flexible wing model.

2.1 Anchoring rib and tensioning rib

The tensioning and anchoring ribs were manufactured in ABS (acrylonitrile butadiene styrene) filament by a 3D rapid prototyping printer.

Figure 2. Anchoring rib.

The anchoring rib aims to fasten the SMA wires to the wing structure. This fastening was taken by clamping the wire against the wing stringer using a flat steel made bar tightened by three screws that compressed the whole set. As the wire diameters were less than a millimeter, compressing them may lead to high stress concentration and consequent wire rupture. This was avoided by gluing the wires in both sides submitted to the fastening device on plates of cardboard using cyanoacrylate adhesive.Fig. 2 shows a CAD image of the anchoring rib.

On the other hand, the tensioning ribs were responsible to tight the wire and to produce the designed initial deformations in a very accurate way. To do that, threads of guitar strings were used to tight the SMA wires with their endless screw and gear fixed on the tensioning ribs, as shown by Fig. 3.

Figure 3. Global view of the tensioning rib.

2.2 Mounting of actuators on the structures

Graphically represented by the colored straight segments bythe Fig. 4, the wires were mounted and worked in pairs. The first configuration (C1) is identified by the red lines, the second (C2) by green lines and the third (C3) by blue lines. The fourth and last configuration (C4) consists simply of a combination of (C1) and (C2).

The configuration C1 and C2 has been thought to actuate only in bending modes. On the other hand, C3 wire mounting intends to control both bending and torsional modes with a higher focus on torsional vibration, due to the "X" shape configuration presented by the SMA wires. Three preliminary deformations (PD) were imposed to the wires: 1%, 5% and 7.5%. These values were chosen to evaluate the aeroelastic system when the SMA consists exclusively of austenite and when at the superelastic plateau in order to evaluate the particularities of each one of these material phases, so as of a combination between them.

2.3 Thermomechanical characterization of the wires

The SMA wires used by the present research were made of a NiTi (niquel-titanium) alloy provided by Sandinox company. According to this company, the wires with a diameter of 0.127 mm were obtained using the procedures of the ASTM F2063 standard. Before mounting the wires at the wing structure, it was necessary to characterize them thermomechanically and to determine its major characteristics.

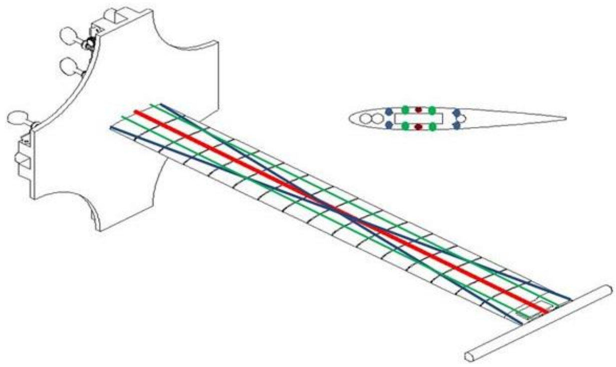

Figure 4. Wire arrangements in the wing model.

The differential scanning calorimetry (DSC) technique was applied to obtain the temperatures of phase transformation of the SMA wires. This allowed to analyze if the alloy would be superelastic (SE) at the working temperature. The equipment used to do so was the TA Instruments® DSC-Q20 model.

After knowing the temperature range of phase transformations, the axial traction tests of the wires were then carried out in a quasi-static way using a mechanical dynamic analyzer manufactured by TA Instruments Inc., model Q800. These tests obtained the critical stresses at the beginning (σ_{Ms} and σ_{As} for austenite and martensite, respectively) and at the end (σ_{Mf} and σ_{Af}, respectively) of phase transformation in function of the wire-environment equilibrium temperature (T) and the wire dissipated energy (E_D). Table 1 show these results.

Before assembling the actuating wires on the research model, a cycling procedure to stabilize the shape memory effect of the wire was carried out. It consists of heating the wire by Joule effect to a temperature higher than A_f limit followed by a cooling until the environment temperature. This process is continuously repeated 250 times with the wire submitted to a constant load of 500 MPa.

Table 1. Temperatures and stresses at the beginning and the end of phase transformation and dissipated energy.

T(°C)	Stress for transformation (MPa)				E_D (MJ/m³)
	σ_{Ms}	σ_{Mf}	σ_{As}	σ_{Af}	
35	449,65	464,79	280,94	257,69	13,65
45	488,57	505,01	329,49	309,94	12,75
55	545,67	564,19	389,26	371,93	12,60
65	608,17	628,25	452,74	438,16	12,70

Temperature for transformation (°C)			
R_s	R_f	A_s	A_f
19,85	-6,48	0,499	**26,47**

2.4 Tests in the wind tunnel

Aeroelastic tests were performed in an open circuit blower type subsonic wind tunnel with a 0.7 m long and 0.6 m high and wide test section. Its maximum nominal air velocity is of 33 m/s. The tunnel has a Pitot tube coupled to a digital gauge, a Testo 512-0560-5128-3 model, installed in the test section. This pitot tube provides the measurement of total pressure from where the flow velocities can be obtained.

After mounting the actuatorsin the wing model, this set was clamped to an inertial base positioned in the test section,. The model is trimmed to avoid loads normal wise direction, at zero angle of attack.

A Polytec® laser vibrometer, CLV-2534 model, was used to monitor the output speed of the wing model as it was excited by a PCB Piezotronics® impact hammer, model 086C03. In such tests, a LMS SCADAS® system was used to register the dynamic parameters.

The wing model was submitted to air velocities of 12, 13 and 14 m/s, being these values sometimes exceeded to verify how much the aeroelastic response of the structure had been improved. These values were chosen based on the flutter critical velocity of the present model of approximately 14 m/s and 29.25 Hz coupling frequency, as shown by Fig. 5 and Table 2. Also note that the coupled modes were first and then degrees of flexure. For additional information about the design of the research model, it is suggested to consult the details reference [17].

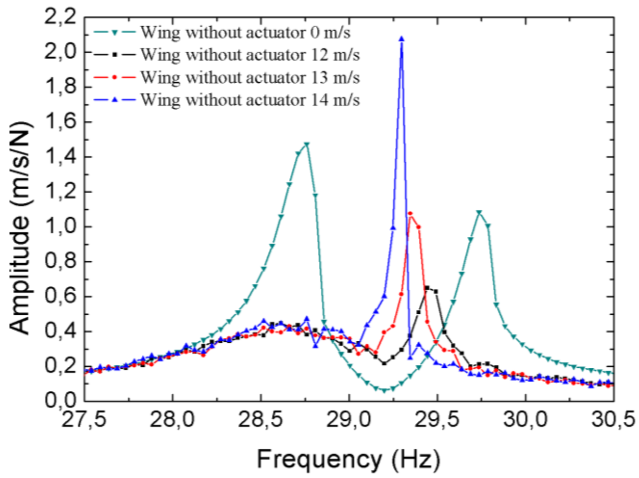

Figure 5. Wing model GVT results without wires.

In addition, ground vibration test (GVT) of the model was performed with the actuators in different configurations. Settingthe previously selected PD (preliminary deformations)levels and without the aerodynamic load, the behavior of frequencies and displacement amplitudes were monitored and the coupling frequencies were identified.

Table 2. Damping and coupling frequency of torsional and bending modes versus air velocity.

V (m/s)	6	8	10	12	13	14
Damping (%)						
Torsional	0.73	0.78	0.98	1.26	1.34	1.55
Bending	0.74	0.54	0.39	0.22	0.12	0.05
Frequency (Hz)						
Torsional	28.79	28.80	28.70	28.62	28.65	28.60
Bending	29.70	29.64	29.57	29.46	29.36	29.27

Imposed the preliminary deformation to the actuators and stabilized the flow velocity in the wind tunnel, the structure was then excited by the impact hammer. This allowed the measurement of the wing model FRF's.

With the FRF's, a data extraction technique (PoliMAX) was used to evaluate the modal parameters of the system. This analysis revealed how the natural frequency and the damping effect behave as the air velocity increases, allowing consequently to assess the flutter velocities empirically.

All these tests were developed at the facilities and laboratories of the Federal University of Campina Grande (UFCG) and Technological Institute of Aeronautics (ITA). The global characteristics and physical parameters of the wing model are listed at the Tab. 3.

Table 3. Experimental wing model data.

Wing		
Span (m)		0.457
Chord (m)		0.05823
Elastic axisposition		31% chord
CG position		26.04% chord
Slender Body		
Diameter (m)		0.00952
Length (m)		0.16748
Mass (kg)		0.0941753
Momentsof inertia (10^{-6} kg.m²)	I_{XX}	1.065
	I_{YY}	211.909
	I_{ZZ}	211.895
Material		Brass
Offset (mm)		3.8
Stringer		
Length (m)		0.4570
Width (m)		0.0126939
Thickness (m)		0.0033981
Material		Al 6060
Modulus of Elasticity (GPa)		59.5
Poisson Coefficient		0.33
Density (kg/m³)		2607.54

3. Results and Discussion

To evaluate the wire effect on the wing vibration,the wing without and with aerodynamic loading are first shown. All the wire configurations and PD levels have been tested with both load conditions and the dynamic answersare registered here.

3.1 GVT without aerodynamic load

Analyzing the results of Figure 6 [(a) PD = 1%; (b) PD = 5%; (c) PD = 7,5%], it is possible to infer that the three preliminary deformations values applied to C1, C2 and C3 configurations generated a fairly similar behavior. The addition of the wires caused an increase of the torsional frequency, while the bending one remained around the same value. By analyzing the peaks of the FRFs for C1 and C2 arrangements, there was an increase of the damping, practically in the same intensity for all preliminary deformations.

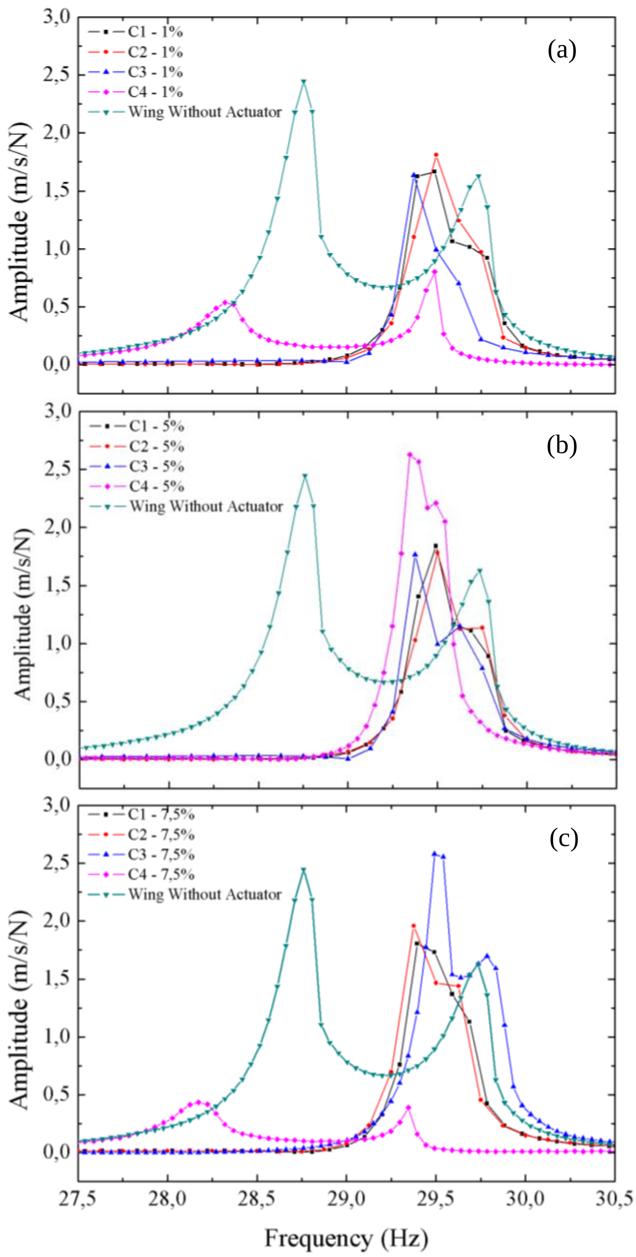

Figure 6. GVT amplitude x frequency for wing without aerodynamic load for three PD's.

In addition, higher torsional frequency resulted in a greater proximity with the bending frequency or, alternatively, in a small wind-off. This phenomenon is a promoting element of flutter, since a wind-off reduction demands a smaller critical velocity (V_{crit}) to its occurrence. On the other hand, at PD of 7.5% and C3configuration, there was a less severe coalescence of the vibration modes, while damping remained almost unaltered.

For C4 assembly and a preliminary deformations of 7.5%, a significant increase in damping effect is observed and higher wind-off value in comparison to the wing without the actuators, both effects contributing to higher V_{crit}. On the other hand, a PD of 5% promotes the torsional stiffness and slightly reduces the bending stiffness of the wing, resulting in the coalescence of the modes.Moreover, a reduction of the damping was also experienced for this combination. These two behaviors fall on the same drawbacks of C1 and C2. Therefore it can be concluded that the best configuration was the C4 with preliminary deformations of 1 and 7.5%.

3.2 GVT with aerodynamic load

Observing the effect of the actuators over the wing dynamic behavior, C1 and C4 wire assemblies were chosen to be analyzed under aerodynamic loading with PD's of 1, 5 and 7.5%. Using the procedure mentioned previously, it was possible to extract the FRFs.

Observing the profiles of Fig. 7 (a), the behavior of C1-PD1% combination is similar to the wing without the wires. There is an increase in the damping and a reduction in the frequency of both vibration modes. To the torsional mode, this reduction is less pronounced when compared to that of the bending mode. This reduction of frequencies is attributed to the fluid flow around the aeroelastic model, as it can be seen that the stiffness and damping of the system as a whole is dependent on the flow velocity. Note that both structural stiffness and damping decrease when the wing is subjected to the fluid flow.

The effect of the wires in C1-PD1% setup was almost imperceptible since this deformation does not take the SMA to the superelastic plateau. Therefore, there is no energy dissipation and the wires are providing only stiffness to the modelat this condition. Comparing Fig. 7 (a) with Fig. 5on flutter velocity (V ~ 14 m/s), it can be seen that the amplitude is practically the same. For lower speeds,all frequency peaks were considerably reduced. Table 4 brings together the values of damping and frequency for the C1 configuration.

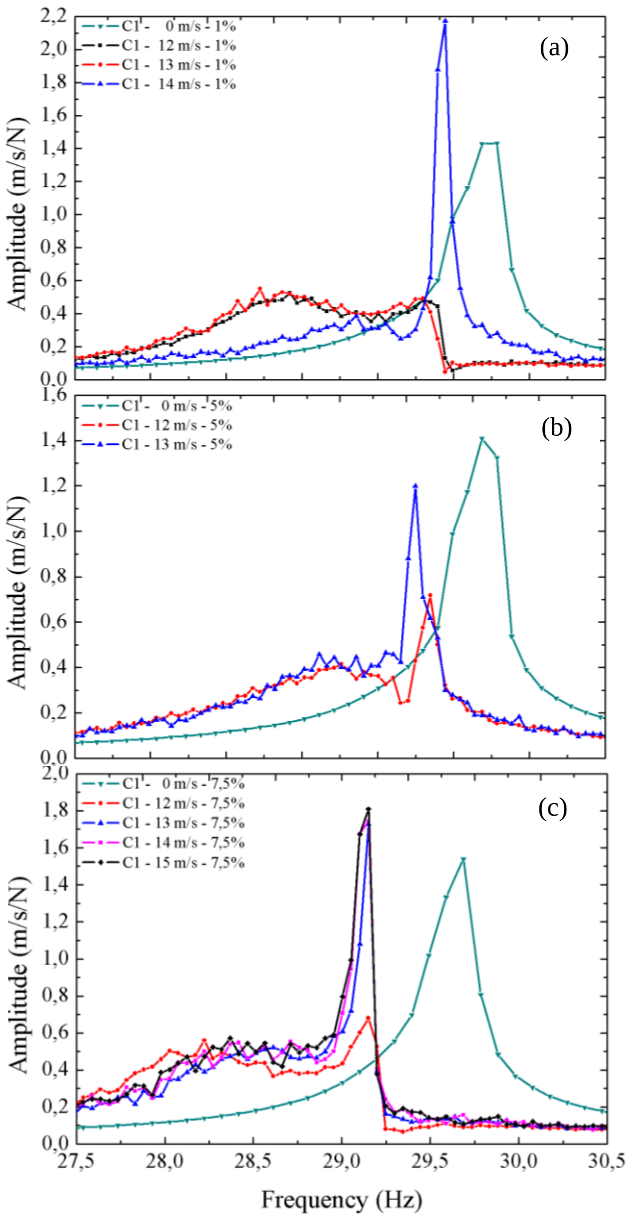

Figure 7. Wing GVT with aerodynamic loading for C1 wire configuration.

There was a surmising behavior for C1 at 5% PD, since a higher V_{crit} was expected due to the supposed larger power dissipation conferred by the wires. Otherwise, it was observed an opposite effect: the model presented flutter with severe oscillations at 13 m/s. This behavior was attributed to the coalescence of the modes that practically showed a single peak. This effect can be ascertained in Fig. 7 (b) and confirmed by the values of the tab. 4.

Shown in Fig. 8, the results obtained for the C4 with 1% of PD indicate that $V_{crit}$is higher than 14 m/s for this case. On the other hand, the amplitudes at the critical velocity for these modes are approximately 73% lower. For C1-5%PD combination, the model experienced a reduction of 86% range and did not flutter even at 18 m/s increasing V_{crit}in more than 28%. Since this is the velocity limit of wind tunnel used, the flutter velocity was not obtained for this setup.

Table 4. Measured damping effect and frequency peaks of C1 configuration.

1% PD				
	Damping (%)			
V (m/s)	12		13	14
Torsional	1.46		1.65	1.67
Bending	0.51		0.57	0.089
	Frequency (Hz)			
Torsional	28.36		28.33	28.89
Bending	29.34		29.25	29.42
5% PD				
	Damping (%)			
V (m/s)	12		13	-
Torsional	1.45		1.38	-
Bending	0.18		0.096	-
	Frequency (Hz)			
Torsional	28.79		28.71	-
Bending	29.33		29.25	-
7.5% PD				
	Damping (%)			
V (m/s)	12	13	14	15
Torsional	1.37	1.67	1.64	1.50
Bending	0.40	0.075	0.058	0.059
	Frequency (Hz)			
Torsional	28.18	28.44	28.44	28.32
Bending	29.15	29.15	29.13	29.13

Finally the C4 assembly with 7.5%PDwhereflutter was observed at 14 m/s with the characteristic behaviors presented in other settings. However, this structure showed FRF peaksapproximately 33% lower and a very significant drop of the LCO amplitudes. The main results of the dynamic behavior in these conditions are listed in Tab. 5.

4. Conclusion

Analyzing the results, it was possible to conclude that the number and the arrangement of the wires incorporated into the structure is important to their effect on the dynamics of the structure. The more proeminent results in terms of structural benefits are: reduction of the FRF peaks of the two coalescing modes in flutter state by up to 86%; and increasing V_{crit} by 28%. Note also that in certain arrangements there was a worsening behavior, reducing the speed of flutter in approximately 15% and increased the energy of the coupling modes. This leads to the conclusion that there must be an accurate design of the SMA wing actuator in order to get the desired effects on the wing dynamics.

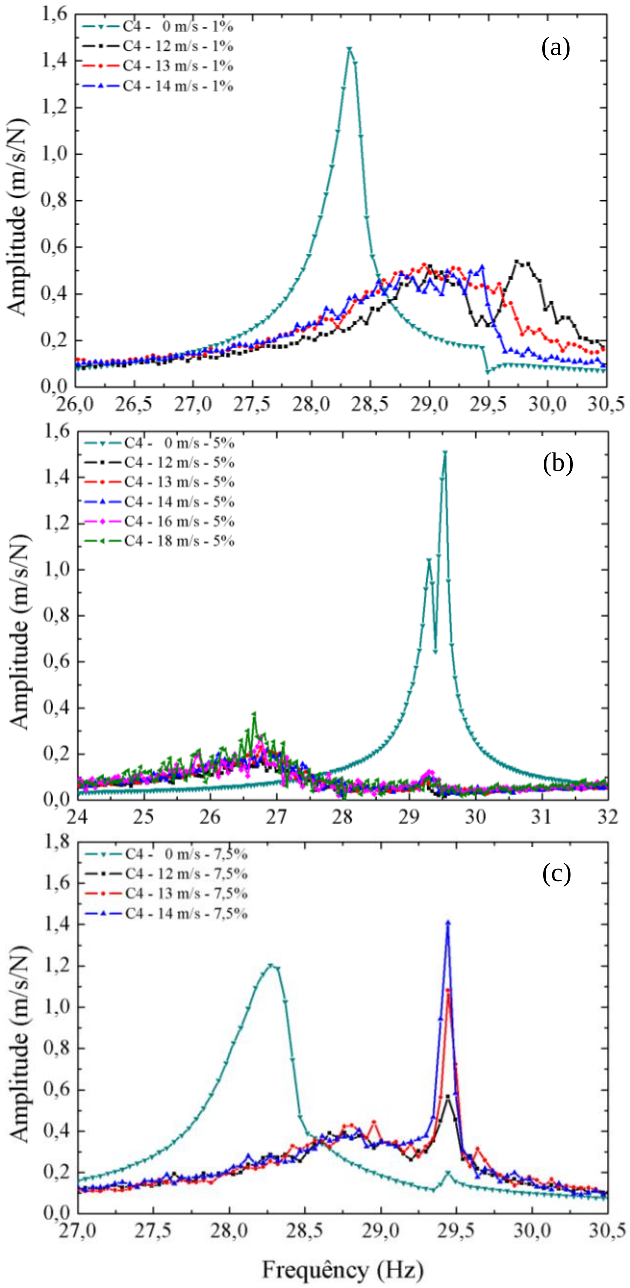

Figure 8. Wing GVT with aerodynamic loading for C4 wire configuration.

Another improvement observed at the wing model with actuators was the lowering of LCO amplitudes. This is so because the wire deformations activate the pseudoelastic related damping mechanism. Therefore such kind of actuator may benefit LCO response which also may lead to structural fatigue related failure.

Table 5. Measured damping effect and frequency peaks of C4 wire configuration.

V (m/s)		12	13	14	16	18
Mode	PD(%)	Damping (%)				
Torsional	1	1.59	2.06	2.25	-	-
	5	1.91	2.02	1.72	1.91	2.03
	7.5	1.57	1.37	1.71	-	-
Bending	1	0.71	0.37	0.23	-	-
	5	0.27	0.23	0.38	0.39	0.55
	7.5	0.21	0.10	0.08	-	-
Mode	PD(%)	Frequency (Hz)				
Torsional	1	29.23	28.86	28.77	-	-
	5	26.85	26.87	26.27	26.74	26.63
	7.5	28.79	28.96	28.76	-	-
Bending	1	29.69	29.56	29.47	-	-
	5	29.34	29.32	29.30	29.33	29.35
	7.5	29.43	29.45	29.42	-	-

From the results obtained, it can be stated that the use of this aeroelastic control technology is quite promising. Even passively as in present study, it allows an improved behavior of the structure adding a practically neglegible mass to the wing structure (0.8129 g), corresponding to 0.3532% of total mass.

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