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A SHAPE MEMORY ALLOYS BASED TUNEABLE DYNAMIC VIBRATION ABSORBER FOR VIBRATION TONAL CONTROL

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This paper examines a novel model of an Adaptive Tuneable Dynamic Vibration Absorber (ATDVA), based on the use of Shape Memory Alloy materials (SMA). Being adaptive, the absorber is able to track variation of the structural dynamic response.

The absorber architecture is extremely simple: it consists of a clamped SMA wire and a concentrated mass. Two reference structures have been considered: a typical aeronautical aluminium panel and a fibreglass panel. In the first part, the investigated concept is introduced with a short presentation about the SMA main properties. The realisation and experimental characterisation of the device are then presented. Its implementation, a report on the experimental campaign and the presentation of the attained results conclude the work, together with a discussion on the achieved results and the next investigation steps.

Key words: ATDVA, SMA, vibration control

1. Introduction

Vibrating environments are a common experience in the all-day life. When a structure is undergoing some form of vibration, there are a number of ways in which this vibration can be controlled. Passive control involves some form of structural interventions, often including the use of springs and dampers, that leads to reduction of the vibration levels, while active control uses sensors, actuators and electronic control systems, aimed at reducing the measured response.

This study investigates the use of ATDVA, based on shape memory alloy materials, to control structural vibration.

A Dynamic Vibration Absorber (DVA) is essentially a secondary mass, attached to the main system generally via a spring and a damper. The natural frequency of the DVA may be tuned to the eigenfrequency of unwanted vibration. In this case, its action produces a split of the response peak. If it matches with the disturbance frequency, a specific absorption of the structural vibration occurs, extracting energy from the primary system.

The application of DVA's has been investigated by many authors (Hartog, 1956). Among the most significant examples, the work of Dayou and Brennan (2002) can be recalled. They investigated how to use vibration neutralizers to control global vibration of structures and the influence of certain parameters in the control of kinetic energy. Huang and Fuller (1997) examined the effect of DVA on the forced vibration of a cylindrical shell and its coupled interior sound field.

Traditional vibration absorbers have limited applications for its narrow frequency bandwidth; in fact, the DVA must be tuned very accurately to a specific frequency value, in order to obtain substantial vibration reduction.

The use of a tuneable device instead of a classical one, allows changing the frequency at which it can operate. A significant example of implemented tuneable DVA is the one at the Arsenal Football Club (Texas), where the structure is particularly excited by the crowd jumps that happen at a rhythm near to its resonances (TDVA..., 2008). The device was chosen to be tuneable, to satisfy the structure in case the initial experimental test campaign characterisation was not correct.

"Adaptively tuned" refers to the capabilities of the DVA to change its internal properties to take into account changes or follow variations of the vibrating structure.

Mechanical components are however hard to be adapted. Dealing with systems that may be intrinsically adaptive is fashionable and may lead to simplified control architectures.

SMA's are a kind of smart materials whose physical properties change as a function of temperature. This effect can be exploited to build tuneable and adaptive devices.

One of the first studies carried out on the subject is due to Baz (1990) who demonstrated the feasibility of using SMA in controlling flexural vibrations of a beam. Rustighi, Brennan and Mace first designed an SMA-based vibration absorber and implemented a control algorithm for its real time adaptation (Rustighi *et al.*, 2005b), Williams *et al.* (2002) investigated the use of SMA to build an adaptive-passive absorber. Elahainia (2005) presented a tuned vibration absorber, based on SMA wires working as adaptive stiffness elements and taking advantage of the elastic modulus variation.

This paper presents an ATDVA, based on the use of SMA wires that exploits its capabilities through a proper architecture. Its arrangement is extremely simple: it consists of an SMA clamped wire and a concentrated mass placed in its middle. It works as a tensioned spring whose stiffness is controlled by varying the electrical current through the wire. Two effects are taken advantage of: the change of the material phase from martensite to austenite that induces an increase of the Young modulus and the adopted wire constraint that causes an increase of the internal tension as the transformation occurs. In this way, the natural frequency of the absorber may be adjusted in a wide range to match one of the targeted frequencies.

Further the traditional DVA's advantages, the proposed device presents benefits as extremely low cost, simplicity of implementation and integration, with its architecture being very simple and compact. For instance, it could be easily embedded in the core of a honeycomb panel. It would result in a completely self-standing active vibration insulating element that could be integrated within existing aircraft, replacing the already installed panels.

Because of the thermal nature of activation, these SMA-based devices may be used to follow slow structural-related variations like turboprop rotation regimes, different stationary conditions (i.e. electrical machinery working at different rpm).

This research builds upon past works (Tiseo *et al.*, 2005), where the feasibility of the concept and preliminary experimental studies were performed, aimed at verifying the functionality of the proposed device to control noise and vibrations.

In the first part of the paper, the investigated concept is introduced, with a short presentation of the SMA materials. Then, details about the two herein considered reference structures, the realisation and experimental characterisation of the device are presented. The experimental campaign and the presentation of the attained results conclude the work, together with a discussion on the achieved results and the next investigation steps.

2. One-DOF system controlled by tuned vibration absorber

Vibration absorbers are a valuable tool used to suppress vibrations due to harmonic excitation in structural systems.

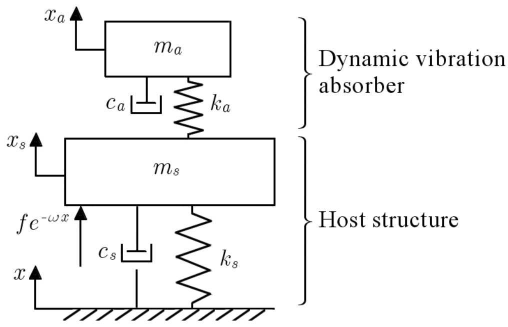

Fig. 1. Schematic of Dynamic Vibration Absorber attached to a host structure

The concept of the dynamic vibration absorber is fairly old and consists in a simply mass-spring system attached to a vibrating host structure, which can be modelled as in Fig. 1. The inertia of the absorber mass reduces the net force and hence the response of the host structure. According to Estéve (2004), the analytical model of a dynamic vibration absorber attached to a single-degree-of-freedom host structure is described by the following equations of motion

$$\begin{aligned} &m_s\ddot{x}_s + (k_s + k_a)x_s - k_a x_a + (c_s + c_a)\dot{x}_s - c_a\dot{x}_a = f(t) \\ &m_a\ddot{x}_a + k_a(x_a - x_s) + c_a(\dot{x}_a - \dot{x}_s) = 0 \end{aligned} \tag{2.1}$$

The impedance of the host structure without the dynamic vibration absorber is given by

$$Z_s(\omega) = \frac{m_s(\omega_s^2 - \omega^2 - 2\mathrm{i}\omega\omega_s\xi_s)}{-\mathrm{i}\omega} \tag{2.2}$$

The impedance of the dynamic vibration absorber is defined as the reacting force through the spring and damper exerted on the primary system due to unit velocity of its attachment point. Using Eqs. (2.1), the absorber impedance is given by

$$Z_a(\omega) = m_a\frac{\mathrm{i}\omega\omega_a^2 + 2\xi_a\omega^2\omega_a}{\omega_a^2 - \omega^2 - 2\mathrm{i}\xi_a\omega\omega_a} \tag{2.3}$$

Therefore, the effect of the dynamic vibration absorber on the host structure vibration is a function of the ratio of the absorber impedance to the impedance of the structure at its attachment point since

$$\dot{x}_s = \dot{x}_0\Big(1 - \frac{Z_a}{Z_s}\Big)^{-1} \tag{2.4}$$

The bigger the impedance mismatch between the dynamic vibration absorber and the structure, the more the absorber affects the response of the structure.

Dynamic vibration absorbers are used in two different ways. When tuned to a specific vibration of the hosting structure, usually driven by a broadband excitation, they act as tuned dampers. When they are not tuned to a mode but to a specific excitation frequency usually encountered in rotating machines, dynamic vibration absorbers are designed to present a large impedance at their attachment points in a very narrow band around the excitation frequency, and therefore the absorber damping is kept as small as possible.

The idea herein presented deals with using SMA as adaptive spring elements. The architecture is made of an SMA wire, clamped at the edges, with a concentrated mass placed at its geometric centre. Because the SMA material have variable properties, the device may present different configurations in terms of the mechanical response. In detail, the absorber design consists of a trained NiTi wire. To let it modify its dynamic behaviour, it was heated by an electrical current (Joule effect), forcing the internal tension to change, and then attaining a controlled frequency shift.

3. SMA background general overview

SMA's show a reversible change in the crystalline structure depending on temperature or internal stress variations. At low temperatures, the SMA material structure is in a martensite phase, characterised by low stiffness and high damping values. When the alloy is heated up, the phase changes into austenite, stiffer (around three times higher) and slightly damped; it also recovers eventual residual strain the alloy underwent when martensite. If the SMA is a one-way type, by reversing the process, the material transforms into a pseudo martensite phase, called "twinned" with no further strain recovery. If a load is applied, the material transforms into de-twinned martensite and may restore the original shape, depending on the load combination and other factors. Generally speaking, under a pre-load, a cycle may be aroused. If the SMA is a two-way type, the strain is recovered in both directions, austenite to martensite and vice versa. This last phenomenon, however, does not demonstrate symmetry in the two directions in terms of strength.

Another interesting property is the so-called super-elastic (or, after certain authors, pseudo-elastic) effect. If the environmental temperature is higher than the one that allows complete transformation into austenite, the material will fully recover spontaneously, when unloaded, large strain fields (magnitude

105 strain) that led its internal structure from austenite to martensite phase (Fig. 2).

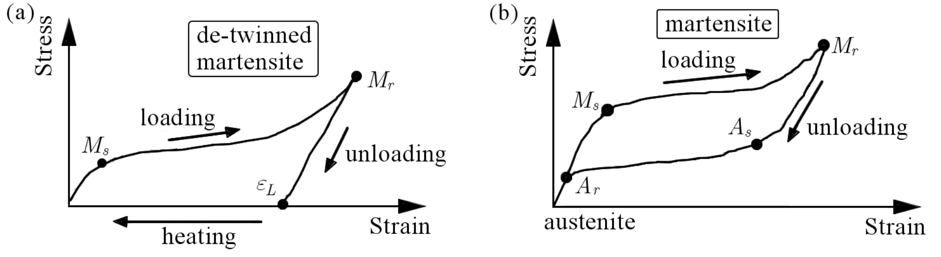

Fig. 2. Stress-strain curve for a generic SMA; (a) – shape memory effect, (b) – superelastic effect

Summarising, the SMA material, deformed by an external load, changes its internal structure from austenite into martensite displaying very high strain (around 10%), that is fully recovered when the material itself is heated (shape memory effect) or simply unloaded (super-elastic effect).

SMA's show a good potential for vibration control, linked to their property of changing their elastic modulus, showing different levels of damping and recovering large strains (Otsuka and Waymann, 2002). Because the transition from martensite to austenite is continuous and because it can be represented through a well-sketched relationship with respect to its intrinsic composition (see the models of Tanaka *et al.*(1986) or the one of Liang and Rogers (1990), for instance), SMA wires can be easily used as continuously adaptive tensioned spring elements. A DVA that incorporates such devices could continuously control the vibration field of a structure in a large band around a specific frequency (tonal control). Another possibility is to switch from a frequency to another if the reference system is characterised by the possibility or the necessity to work at different frequencies.

4. SMA-based ATDVA

Standing on the characteristic properties of the SMA, a novel concept of DVA is introduced, able to be tuned to a prescribed frequency, inside a determined band, without any external mechanical device. This device is therefore an Adaptive Tuneable DVA and is referred to as an ATDVA. The architecture is extremely simple. The absorber consists of a pre-stressed Ni-Ti wire, clamped at the edges, with a concentrated mass placed in its geometric centre. It is heated by an electrical current (Joule effect), so that the internal stress field is forced to change (strain is inhibited), attaining a large controlled eigenfrequency shift. The design is completed by a sustaining frame that hosts the wire (Fig. 3).

Fig. 3. ATDVA basic architecture

Such a kind of a device is able to track slow variations of the structural vibration response and provide tonal vibration attenuation. It does not require tight tolerances and may be easily applied when the characteristic external forces vary into a definite range or assume finite different values (different working regime).

The design frequency range is computed through an approximated relationship that can be derived from the formula valid in the case of a non-massive string with a concentrated mass at its centre, and the formula which refers to the case of a massive vibrating string (Blevins, 1979; Imman, 1989)

$$f = \sqrt{\frac{T}{(\pi^2 M_c + 4M_w)L}} \tag{4.1}$$

In (4.1), f is the resonance frequency, M_c – concentrated, M_w – total wire mass, L – wire length and T the force per unit of area acting on the SMA wire (internal stress).

5. Referred applications

In order to preliminarily evaluate its capabilities, the proposed ATDVA has been tested on two reference structures that are both of certain interest for aeronautical applications.

In the first case, a thin aluminium plate $(480 \times 760 \times 1.5\,\mathrm{mm})$ has been selected, representing a classical fuselage panel. A $1.2\,\mathrm{mm}$ diameter SMA (Ni-Ti) wire, $100\,\mathrm{mm}$ long has been adopted. The wire has been clamped at both the extremities to a circular steel frame. The complete device has been then bonded to the plate.

In the second case, an advanced adaptive-stiffness panel was referred to, in order to evaluate the investigated device (SMA-based ATDVA) capabilities to further affect the dynamic response of such a next generation structural element (Ameduri *et al.*, 2005). More in detail, the adaptive panel is made of four, $0.3\,\mathrm{mm}$ thick fibreglass plies; on the middle plane, 17 SMA wires are embedded, oriented along the panel widest dimension and $1\,\mathrm{cm}$ spaced. By driven variations of the SMA properties (by heating, for instance), the dynamic response of the panel may be affected. The ATDVA architecture is basically the same as the previous one. However, a ligther solution was tested: a rectangular aluminium frame was used and a $0.76\,\mathrm{mm}$ diameter SMA (NiTi) wire, $80\,\mathrm{mm}$ long was adopted (Fig. 4).

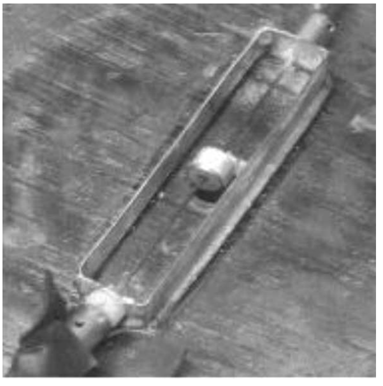

Fig. 4. ATDVA lighter architecture

To check different control strategies, in the first case, the current, travelling through the SMA wire, measured through an amperometer, has been chosen as the control parameter; in the second case, the wire temperature, measured through a thermocouple. A feedback controller has been implemented to stabilise the selected parameters. In particular, temperature appeared to be strongly dependent on both environmental conditions and the current.

The objective of the work has been the assessment of a single-DOF system aimed at reducing the dynamic structural response at certain resonances. This can be seen as a first step before moving towards to the control of generic tone excitations (e.g. sinusoidal periodic excitation).

6. ATDVA architecture and characterisation

The design phase of the SMA-based absorber has needed some previous operations aimed at characterising the structural element to be controlled.

Having fixed the SMA length and diameter, the absorber mass has to be varied to match a proper range around the chosen structure eigenvalue.

Firstly, an experimental campaign has been addressed to characterise an isolated SMA wire. It has been pre-strained, using a dedicated stretching device that has also provided the desired constraining conditions. Pre-strain ensures a starting eigenfrequency different from zero. Then, the wire has been heated to pass from the initial martensite to the austenite phase. The wire vibration has been measured by using a laser vibrometer.

The working temperatures range has been set to: 25°C (room temperature) – 38°C.

Seventy-five temperature cycles have been enforced. A large eigenfrequency shift has been measured, resulting in about 140 Hz as shown in (Fig. 5) where only some of the cycle results are reported, for the sake of clarity.

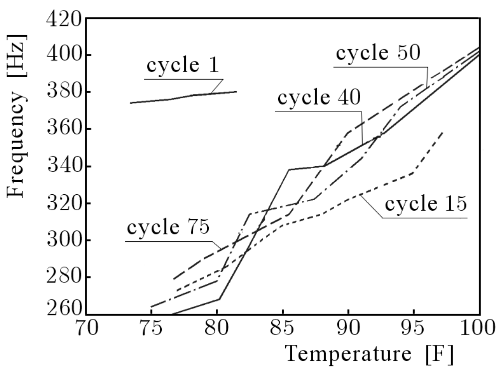

Fig. 5. Thermal test on a constrained SMA wire; first modal frequency vs. wire temperature

The graph also shows a drastic variation of the SMA behaviour between the first and the next cycles after which clear behaviour stabilisation occurred.

At this point, a wire with a concentrated mass and hosted in the abovementioned frames has been experimentally characterised. This device represents the studied ATDVA.

Two values of the mass have been set, respectively equal to 1 and 1.5% of the main system mass. The wire has been connected into an electrical circuit, with the aim of heating it up. The global system (made of the wire, mass and the ring frame) has been bonded on a heavy steel block. It has been excited through impulsive forces by an instrumented hammer, as the internal excitation current was varying between 0 and 2.5 A. Different wire internal stress levels have then been obtained and consequent different values of the absorber vibration frequency have been measured. The laser vibrometer, the other sensors (thermocouples), the actuator and the excitation devices have been connected to a 36-channel acquisition system (LMS SCADAS III).

In the 1% concentrated mass configuration, the absorber natural frequency proved to vary between 50 and 80 Hz from the cold (0 A) to the hot state (2.5 A), roughly corresponding to a 60% frequency shift. When the mass is increased (1.5% mass configuration), the natural frequency varies from 34 Hz (0 A) to 42 Hz (2.5 A), roughly corresponding to a 25% frequency shift. The results are reported in (Fig. 6). Of course, the larger the mass, the larger the expected capability of the device in attenuating the vibration in the selected range. However, rising the mass value, a narrower frequency variation is expected, also according to simplified expression (4.1).

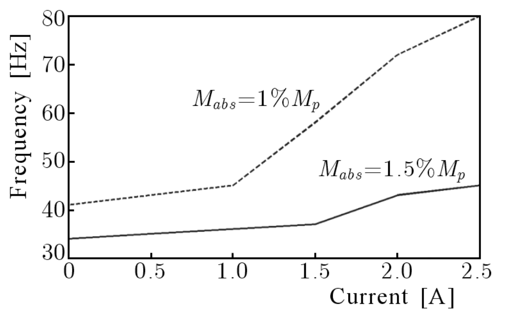

Fig. 6. Experimental characterization of isolated ATDVA: eigenfrequency [Hz] vs. current [A]

7. ATDVA: implementation results

7.1. Aluminium panel

A preliminary numerical simulation has been performed, aimed at estimating panel mode shapes and frequencies for the configurations with and without the ring frame. All the panel edges were not constrained. The ring mass implied a significant panel response modification in terms of eigenfrequencies, while the eigenvectors modifications were negligible. This is easily understood by considering that the frame acts as a concentrated mass located at the centre of the plate. In the low frequency range, it then affects the modal mass for the odd modes without varying their shape, while it is simply non-effective for the even modes. The selected placement came up from the necessity of having large displacement for the considered frequency and then, a large potential energy dissipation.

Experimental modal analysis has been then carried out on the set-up illustrated in (Fig. 7a), confirming the early numerical predictions. The ATDVA working frequency range has been set to the one around the first eigenmode at 66 Hz, (umbrella mode, Fig. 7b). Table 1 reports a comparison of the natural frequencies for the numerical (with and without frame) and experimental results (installed frame).

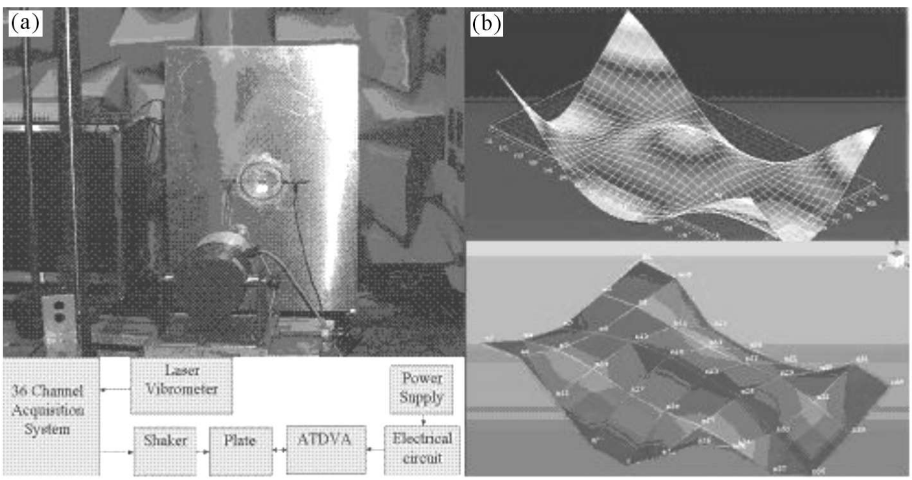

Fig. 7. (a) ATDVA on the aluminium panel: experimental setup and block diagram; (b) mode shape comparison (66 Hz): numerical vs. experimental results

The experimental setup has been made of the following main equipment:

- shaker (Gearing and Watson) as the excitation device, with the associated electronics (amplifier);
- laser vibrometer (Polytec) as the velocity sensor;
- power supply (Delta) to drive the SMA wire;
- acquisition and generation system (LMS SCADAS III).

The block diagram is reported in Fig. 7a.

The exciter has been driven by a chirp signal having a frequency content between 0 and 500 Hz; the plate Frequency Response Function (FRF) has been

Table 1. Modal analysis – numerical-experimental eigenfrequencies comparison

Natural frequencies [Hz]		
Numerical plate	Numerical plate + ring	Experimental plate + ring
13.1	12.3	9.5
29.1	29.5	25.1
34.8	31.6	30.1
36.3	35.7	38.4
44.7	43.4	47.3
54.6	54.9	50.3
62.2	58.1	54.4
64.0	67.4	66.2

acquired in the range between 0 and 75 Hz. In Fig. 8, single-point FRF's are presented around the targeted frequency (66 Hz). They have been acquired for different values of the current running along the SMA wire. The measurement point has been the one at the middle of the plate, the most representative in the selected range. Because of the presence of the dynamic absorber, at the target frequency band two new peaks have appeared instead of the original one; an anti-resonance in between can also be seen. The absorber is perfectly tuned for a 1.9 A current. The maximum velocity attenuation of around 20 dB has been attained at 66 Hz.

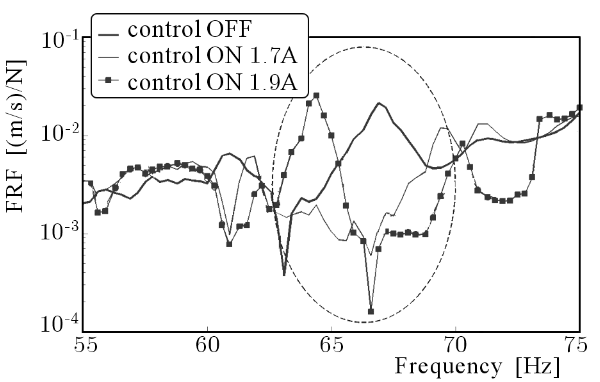

Fig. 8. Case 1 – single point FRF acquired at different current

Global results are instead reported in Fig. 9, where a measure of the vibration energy has been evaluated as the mean value of the velocities, recorded in 40 points and homogeneously distributed on the plate. In this case, the attained attenuation at 66 Hz is also evident (a 10 dB reduction can be appreciated) as well as the appearance of other two peaks.

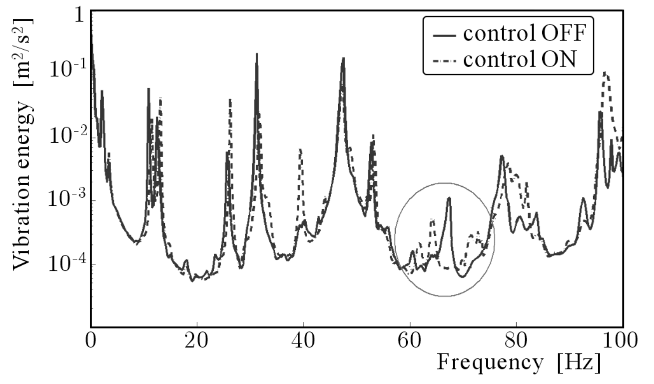

Fig. 9. Case 1 – structural vibration energy (40 measurement points): non-activated vs. activated ($I = 1.9$ A) ATDVA

7.2. SMA-embedded fibreglass panel

The plate has been left free on the longest and clamped along the shortest edges, through a specific device aimed at fixing its embedded wires, too. First, an experimental campaign has been carried out without activating the embedded SMA wires. As expected, the presence of the absorber, placed once again at the plate centre, has not significantly affected the panel response in terms of both mode shapes and natural frequencies, due to the limited amount of added mass and stiffness. A very light ATDVA system has been in fact implemented in this case.

FRF's have been then evaluated. With respect to the former experimental setup, a hammer has been used instead of the shaker (Fig. 10). A single-point excitation has been performed and the system response in terms of velocity $v(t)$ has been acquired over 117 points, uniformly distributed (Fig. 10), through a laser vibrometer and normalised with respect to the input force $F(t)$. The absorber has been then activated through a current. The target system resonance frequency has been set at 196 Hz. As before, the related mode shape has associated with a large displacement at the middle of the plate.

Again, the internal tension of the wire has been controlled through variation of its temperature, induced by a current. In this case, the feedback control loop has been based on temperature information, acquired by the thermocouple.

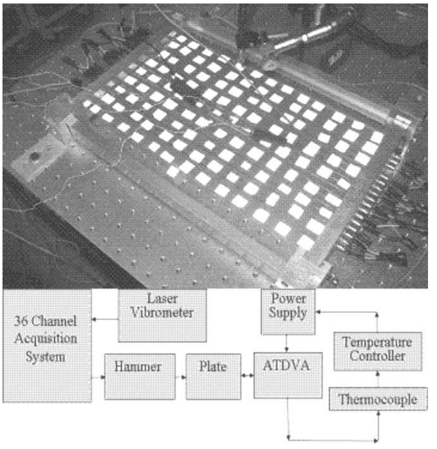

Fig. 10. Case 2 – fibreglass panel: test rig and measurement points; experimental setup block diagram

As the wire-mass system eigenfrequency approaches the panel resonance, its contribution to the structural response at that band, as expected, becomes more and more evident. This effect is maximized at the "tuning frequency", where the isolated mass-wire system and the main structure exhibit the same eigenvalue. Zooming on 196 Hz (Fig. 11), the ATDVA-induced response peak moves towards higher values as a function of the growing temperature. The figure refers to a single acquisition point (central point of the plate).

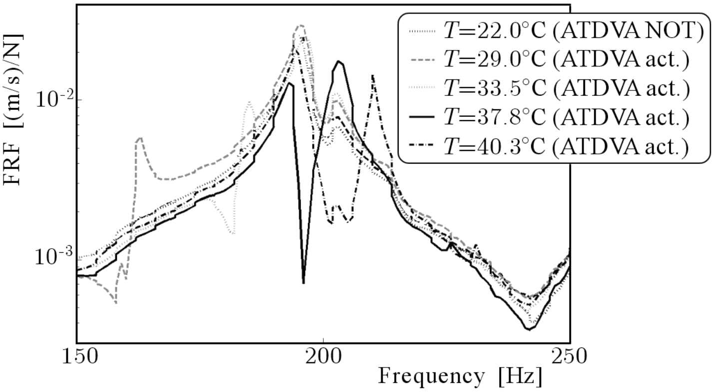

Fig. 11. Case 2 – single point FRF acquired at different wire temperatures

After that, the plate kinetic energy (measured over the aforementioned 117 acquisition points) is computed (Fig. 12). The global energy attenuation level may be estimated in around 5 dB in the narrowband 186-206 Hz (roughly corresponding to the ATDVA influence band). If the half-power bandwidth is considered, the attenuation rises to more than 10 dB.

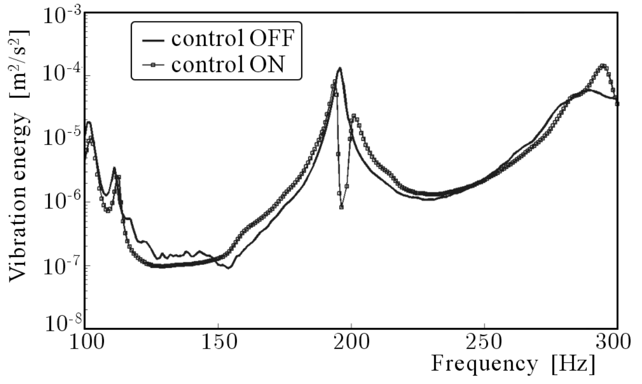

Fig. 12. Case 2 – structural vibration energy (117 measurement points): non-activated vs. activated ATDVA

At the end, in order to verify the effect of the proposed semi-active control device on the smart panel when it is activated, another test has been performed. It has been aimed at evaluating the capabilities of the ATDVA to further affect the dynamic response of such an adjustable stiffness structural element, whose characteristics and behaviour are detailed in bibliography.

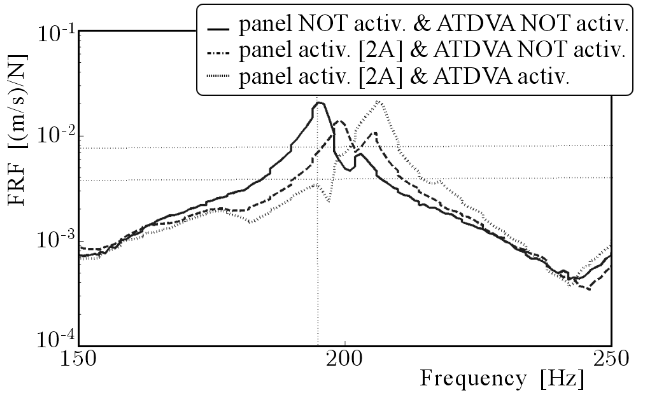

Fig. 13. Case 2 – action of ATDVA on the activated smart panel

Before, a selected panel natural frequency has been shifted, by heating the panel embedded wires: the panel natural frequencies have been globally moved towards higher values. In detail, by considering a 2 A current, a frequency increase of about 4 Hz has been achieved. The ATDVA has been then tuned at the target frequency with the purpose of attaining a further tonal mitigation (Fig. 13). The eigenfrequency at 196 Hz has been again considered as the reference one.

8. ATDVA: conclusion

In this paper, the design and implementation of an SMA-based ATDVA have been investigated. This device uses an SMA wire as a tensioned adaptive spring element. By heating it up, a change in the structural stiffness occurs and a concomitant device frequency shift is attained. The current is generally used to activate the system. The absorber architecture is completed with a concentrated mass placed at the middle of the wire.

Two absorber configurations have been implemented and tested on two different reference structures that are both of interest for aeronautical applications: an aluminium and a fibreglass smart plate, instrumented with SMA wires. A feedback control has been implemented to stabilise the absorber temperature, resulting it strongly dependent on the environmental conditions.

Promising results have been achieved in both the applications. In the first case, an energy attenuation of about 10 dB at the targeted frequency has been attained. Similar results occurred in the second case.

To verify the ATDVA, its effect on the activated smart panel has been of a certain interest, dealing with a variable stiffness structure. After the embedded SMA wires have produced a suitable panel natural frequencies shift, the ATDVA still showed its capability in further modification of the structural dynamic response and achievement of the desired tonal response reduction.

The compact, simple and light system herein presented, easily embeddable in complex structures like honeycomb plates, has shown good potentialities for practical applications.

Further investigation activities should be addressed towards deeper comprehension of the effects, recorded also far from the targeted frequency band. In fact, relevant FRF variations appeared as the device has been turned on. Optimisation of the architecture may be another point of interest; design parameters to be taken into account are the wire length and diameter, the concentrated mass value, the supporting frame structure and configuration, and so on. Also, multiple systems for multi-tone control can be addressed in further examinations. In the end, some complications could arise if, for certain experiences, nonlinear behaviour of the device would be detected. In the current investigations, standing the low levels of excitation produced, in order to attain repeatable results from the experimental point of view and then avoid any kind of non-linearity, these effects were not evident. It is to say that low vibration levels are the typical operative conditions where these objects are thought to be applied for practical applications. On the other hand, the employed SMA material elements are reliable and have shown good and predictable performance in different applications, investigated by the authors. Specific high actuation level tests could be designed in order to face this eventual aspect.

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Zastosowanie adaptacyjnego dynamicznego eliminatora drgań ze stopem z pamięcią kształtu do tonalnego sterowania drganiami

Streszczenie

W pracy omówiono nowy model adaptacyjnego i dostrajalnego eliminatora drgań (ATDVA) opartego na wykorzystaniu stopu z pamięcią kształtu (SMA). Posiadając właściwości adaptacyjne, eliminator taki umożliwia śledzenie jakościowych i ilościowych zmian w odpowiedzi dynamicznej układu, do którego został zastosowany. Architektura eliminatora jest wyjątkowo prosta: konstrukcja zawiera obustronnie utwierdzony drut SMA i masę skupioną. Dla celów porównawczych rozważono dwa układy

drgające: aluminium panel stosowany w aeronautyce i kompozytowy panel zawierający włókna szklane. Pierwszą część artykułu poświęcono omówieniu zaproponowanej koncepcji sterowania drganiami i prezentacji najważniejszych właściwości stopów z pamięcią kształtu. Następnie przedstawiono sposób realizacji badań i charakterystykę układu do eliminacji drgań w kontekście zaplanowanych doświadczeń. Ostatecznie opisano praktyczne wdrożenie eliminatora, przybliżono przebieg wykonanych eksperymentów i zaprezentowano otrzymane wyniki analizy, opatrując je dyskusją i wskazaniem dalszych kroków badawczych.

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