Adaptive Multi-modal Tuned Mass Dampers Based on Shape Memory Alloys: Design and Validation

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ABSTRACT

The use of shape memory alloys (SMA) is really promising in the field of vibration mitigation. Indeed, several works are already available in the literature, describing how to exploit the special features of SMAs in order to design and build dampers and tuned mass dampers (TMD).

Regarding TMDs, the features of SMA materials allow to design adaptive TMDs able to change their eigenfrequencies in order to keep the TMD tuned on the primary system to be damped in case of changes of the dynamic features of the primary system (e.g. changes of the eigenfrequency due to thermal shifts). The possibility to ensure the tuning between the TMD and the primary system allows to achieve an optimal damping action.

The adaptive TMDs based on SMAs described in the literature are usually able to work on a single eigenfrequency of the primary system. Conversely, this paper proposes a new adaptive TMD able to change more than one eigenfrequency at the same time with a given level of independence. This allows to work on at least two eigenfrequencies of the primary system, thus realizing a multi-modal adaptive TMD.

The paper explains that this multi-modal adaptive TMD is based on a special configuration made from a system of masses and SMA wires. Particularly, each mass is connected to the adjacent masses by SMA wires. The possibility to tune more than one eigenfrequency is achieved by heating/cooling the different SMA wires independently. Indeed, this allows to change the geometry of the adaptive TMD and, at the same time, the tensile load into the SMA wires. This double effect is suitable for building multi-modal adaptive TMDs.

The paper first describes the working principle of the adaptive TMD. Then, simulations are presented in order to show the effectiveness of the proposed device.

Keywords: Adaptive tuned mass damper, damping, shape memory alloys, vibration, vibration control

INTRODUCTION

The use of smart materials for vibration reduction has been proved to be very promising thanks to their advantageous features. Indeed, piezoelectric materials (e.g. [1,2]), shape memory alloys (SMA) (e.g. [3–9]), magnetic memory alloys (e.g. [10]), and magnetorheological materials (e.g. [11,12]) have been fruitfully employed in damping applications.

In particular, these materials showed to be effective for the design of tuned mass dampers (TMD). TMDs are in general really effective in reducing vibrations but suffer of two main drawbacks:

- their performances decrease significantly when mistuning occurs;
- they are usually effective on a single mode.

As for the first point, smart materials can give significant contributions because their properties are particularly suitable to the design of adaptive tuned mass dampers (ATMD) (e.g. [13]). ATMDs able to adapt their own eigenfrequencies can follow the changes of one resonance frequency of the primary system (PS) to be damped, enabling a constant tuning between the ATMD and the PS, thus having an optimal damping action. Changes of the dynamical features of the PS are a critical issue since they often occur because of a number of possible reasons (thermal shifts, as an example).

Among the various smart materials, this article has its focus on SMAs. Indeed, SMAs have been successfully employed to damp vibrations in light structures, and especially to design and construct ATMDs capable of changing their eigenfrequency, thanks to the unique physical properties of these materials.

Moreover, they are cheap if compared to other materials and can be manufactured with shapes (wires, as an example) which allow to have low weights. This is an important characteristic since it enables to design and build adaptive devices avoiding high load effects in light structures.

Several works on adaptive devices based on SMAs are available in the literature to prove the possibility to apply SMA-based devices in real engineering applications. As examples, Mani and Senthilkumar developed an application where an absorber composed by SMA springs damps the vibration of a centrifugal pump with time-varying excitation frequency [14], whereas Zuo and Li showed that SMA dampers are suitable to damp the vibrations of cables [15]. The various works proposed by the scientific community on ATMDs based on SMAs differ in the physical principle employed to adapt the TMD eigenfrequency and for the used control strategy. As an example, Rustighi et al. showed the effectiveness of cantilever beams made from SMA material to implement reliable ATMDs [16]. The principle by which the eigenfrequency of the ATMD is changed is a change of the SMA material temperature, which in turn causes a change of its Young's Modulus. Various approaches for controlling this type of ATMDs are discussed in [17]. Williams et al. developed an ATMD based on a series of cantilever beams made from SMA in [18], using the same physical principle presented in [16]. Furthermore, Williams et al. discussed a non-linear control approach for the same device [19]. A different concept is presented by Savi et al., who studied the behavior of a spring of SMA to be employed for controlling vibrations [20], highlighting its capability to change damping and stiffness properties by changing temperature and using the so-called pseudoelastic effect. A similar device was studied experimentally by Aguiar et al. [21]. Instead, Tiseo et al. showed by means of experiments that an ATMD can be built with a SMA wire with constrained ends and a mass placed at its centre: the eigenfrequency of the system can be thus changed by varying the wire temperature [22]. Even if the effectiveness of this working principle was demonstrated in the paper, no models of the structure, and quantification of the performance in terms of adaptation capability were discussed in this work.

Recently, Berardengo et al. [23,24] proposed a new ATMD based on SMA, which is able to change its eigenfrequency of more than 100% of its initial value, by coupling a SMA wire, a central mass and elastic elements. Moreover, this ATMD configuration showed to have two further advantages if compared to the other SMA-based ATMDs:

- it works properly with any kind of SMA material, therefore without requiring high-performance SMAs (i.e. SMAs with special features like high change of the Young's modulus with temperature);
- it allows to easily add devices able to change the damping level of the ATMD as well. This was achieved in the referenced papers by using an eddy current damper but other systems/principles could be used (magnetic or mechanical devices, as examples).

Although the effectiveness of SMAs in the development of ATMDs is mainly proved by most of the referenced works, the other main drawback of these ATMDs (i.e. they usually act on a single mode, see above) is still an open issue. There is a lack of works in the literature proposing ATMDs based on smart materials able to work at the same time on more than one mode of the PS independently. Hence, the aim of this article is to investigate the possibility to design multi-mode (MM) ATMDs based on SMAs which are able to change more than one eigenfrequency in specific frequency ranges independently (or, actually, with a given level of independency) and at the same time. This would allow to have an ATMD able to recover any possible change of the PS eigenfrequencies, thus assuring a satisfactory damping of the PS vibrations. The design approach and the working principle are the same described in [23] because the device proposed there guarantees an extended frequency range, and high flexibility of the layout if compared to other ATMDs based on SMAs.

The next section recalls the SMA features, while Section 3 recalls the SMA-based ATMD presented in [23], for understanding the newly proposed MM ATMD. Then, the same section discusses the physical principle of the MM ATMD. Finally, Section 4 presents some simulations in order to show the effectiveness of the proposed layout.

SHAPE MEMORY ALLOYS

This section summarizes the main properties of SMA materials [25] which are useful to comprehend the working principle of the proposed adaptive device. SMAs are characterized by transformations among three different solid phases, which occur when the material faces a change of either the applied stress or the temperature value. The solid phase transition leads to a change of mechanical properties (the Young's modulus, as an example) and can lead to a change of the shape of the SMA device. The three phases involved in these transformations are: austenite (AU), twinned martensite (TM), detwinned martensite (DM).

Figure 1 shows the temperature-stress diagram of SMAs, where σ_s is the stress value at which the transformation from TM to DM starts at environmental temperature, while σ_f is the stress value at which the transformation is completed. Moreover, M_s is the temperature value at which the transformation from AU to TM starts at null stress, and M_f is the value at which the transformation is completed, A_s is the temperature value at which the transformation from TM to AU starts at null stress, A_f is the value at which the transformation is completed. C_M and C_A are the angular coefficients of the transformation lines. Table 1 shows the values of the parameters shown in Figure 1 for the SMA materials employed in this paper (identified through experimental tests), which is Nitinol (made from nickel and titanium). In Table 1, α is the thermal expansion coefficient, H_{cur} is the strain due to the change of shape during the change of phase between TM and DM (see the vertical solid arrow in Figure 1), named the current maximum transformation strain. Moreover, $E_{w,AU}$ and $E_{w,DM}$ are the Young's moduli of the AU and DM phases, respectively.

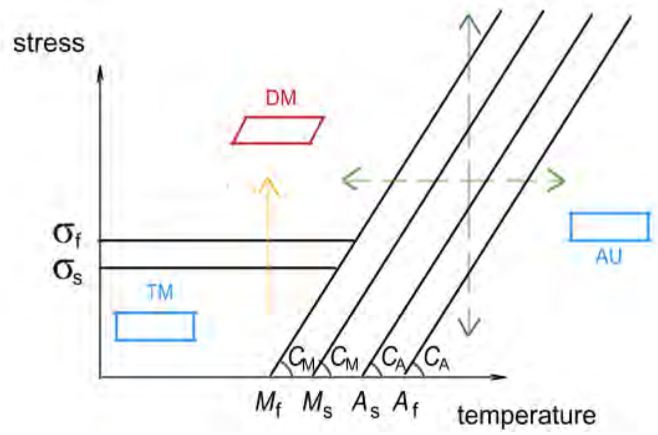

Figure 1: Temperature-stress diagram of SMA materials.

A_s	A_f	M_s	M_f	C_A	C_M	H^{cur}	$E_{w,DM}$	$E_{w,AU}$	α
68.6 °C	78.9 °C	55.2 °C	42.7 °C	9.90 MPa/°C	6.83 MPa/°C	4.39%	32.1 GPa	39.5 GPa	10^{-6} °C^{-1}

Table 1: Data for the SMA material used in this work (identified with experiments).

Figure 1 evidences that the shape of an SMA device can be changed when either transformations from TM to DM occur or the SMA changes phase from DM to AU and vice versa. The shape in the TM and AU phases is almost the same (which is the unstrained shape). Thus, a change of the shape can be achieved applying a stress value higher than σ_s (transformation from TM to DM, see the vertical solid arrow in Figure 1) and the original shape can be recovered by increasing the temperature (transformation from DM to AU). When the SMA is in AU, the shape can be changed using the AU-DM transformation (and vice versa) and therefore changing the applied stress (pseudoelastic effect, see the vertical dashed double arrow in Figure 1) and/or the temperature (temperature-induced phase transformation, see the horizontal dashed double arrow in Figure 1).

As for the strain of the SMA wires ε_w, it can be expressed by the following general relation, according to (Lagoudas, 2008):

$$\varepsilon_\mathrm{w} = \varepsilon_\mathrm{w}^\mathrm{e} + \varepsilon_\mathrm{w}^\mathrm{t} + \varepsilon_\mathrm{w}^\mathrm{th} \tag{1}$$

Here, $\varepsilon_\mathrm{w}^\mathrm{e}$ is the elastic strain component, $\varepsilon_\mathrm{w}^\mathrm{th}$ is the strain component due to the thermal expansion, and, finally, $\varepsilon_\mathrm{w}^\mathrm{t}$ is the strain component due to the thermo-elastic martensitic transformation (which is the strain caused by the change of shape from TM to DM; see Figure 1).

ADAPTIVE TUNED MASS DAMPER

The MM ATMD presented in this work takes advantage from the ATMD proposed by Berardengo et al. [23]. Therefore, it is worth recalling in brief its working principle.

The ATMD presented in [23] relies on the use of two (or more) SMA wires, a central mass and some elastic elements (see Figure 2a). The elastic elements link this ATMD to the PS to be damped and allow to apply a pre-stress (and thus a pre-strain) to the wires. The value of this pre-stress is set above σ_f (refer to Figure 1) to have the SMA wires in the condition of DM. Hence, a further change of the shape (i.e. the length mainly) of the wires can be obtained through a temperature variation, thanks to the transformation between DM and AU. Being the wires connected to the PS by the elastic elements, this change of shape allows to change the axial tensile load F in the wires, which in turn enables to have a change of the eigenfrequency of the ATMD [26–28]. The basic working principle of the ATMD can be thus summarized as: a temperature change causes a shape change and thus even a change of stress in the SMA wires occurs. More in detail, when the wires are heated, they change their phase from DM to AU, and this implies that they recover their initial shape (refer to Figure 1) and therefore their length decreases. This causes a stretch of the spring and an increase of the axial load. On the other hand, when the wires are cooled form AU to DM, their length increases and thus the springs shorten and the axial load decreases. As said, the axial load changes cause changes of the ATMD eigenfrequency (if the axial load increases, the eigenfrequency increases; while if the axial load decreases, the eigenfrequency value decreases). Such a configuration, that is mostly based on changes of the axial load of the wires rather than the change of their Young's moduli, enables changes of the ATMD eigenfrequency of more than 100% of the starting value, does not require high current values to heat the wires with Joule's effect, can be easily coupled to devices for adapting also the ATMD damping, and does not require any special feature of the SMA material employed [23]. All these features make such a layout very attractive, and, for this reason, this paper further develops the concepts presented in [23] to the aim of developing an MM ATMD.

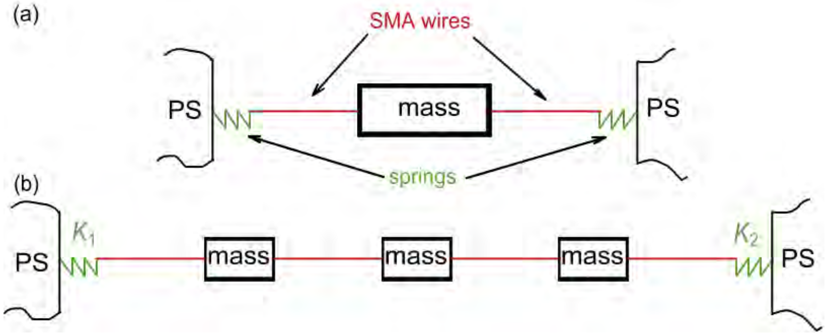

Figure 2: Layout of the original ATMD (a), and of the MM ATMD (here, an example with three masses is shown) (b).

The idea presented in this paper is to design the ATMD with more than one mass (a number of masses higher than/equal to the number of the ATMD eigenfrequencies to be adapted; see, as an example, Figure 2b) connected each other by an SMA wire. Then, each wire is heated/cooled independently from the others. Indeed, the eigenfrequency of the first q modes of an adaptive TMD with q masses (that are the modes with significant eigenvector components at the degrees of freedom of the masses [29]) can be changed in two ways: changing the axial load, as already discussed (see previously), and changing the ATMD geometry. Both these effects are obtained through a change of the temperatures of the SMA wires.

The decrease/increase in the axial load changes all the ATMD eigenfrequencies at the same time, while heating the different wires independently can result in changes of the ATMD geometry and therefore of its eigenfrequencies. With this combined effect, the value of one eigenfrequency is not expected to be completely linked to the value of the others.

NUMERICAL SIMULATIONS

The MM ATMD has been tested numerically. This was possible by using the model describing its behavior. This model is composed by three different models which run in sequence: a thermal model which allows to calculate the temperatures of the wires, given the currents flowing in the wires (which are set by either a user or a controller), the model of the material which links the wire temperatures to the length of the wires and the stress acting along them, and, finally, a dynamic model which finds the eigenfrequencies and the mode shapes of the ATMD starting from the outputs of the model of the material.

The whole model is not described here. It comes from the model presented in [23] and its is completely developed in [30].

A simulation of an ATMD with two masses (one equal to 100 g and the other to 200 g) and three wires is presented here. The global length of the ATMD is 40 cm and all the wires have at environmental temperature the same length.

In order to test the behavior of the ATMD, the temperatures of the three wires were initially set at the environmental temperature and the stress into the wires was 50 MPa. The model discussed previously was used to calculate the eigenfrequencies of the ATMD at environmental temperature. The temperature of the first wire was then increased of 2 °C and the eigenfrequencies were calculated again. The temperature of the first wire was then changed step by step of 2 °C up to 120°C, which is a temperature higher than that at which the wires complete the transformation in AU at a stress value of 200 MPa (which is the maximum target stress in these simulations). The temperature of the wire was then decreased again to the environmental temperature in steps of 2 °C. At each step, the eigenfrequencies of the ATMD were calculated.

After this cycle, the temperature of the second wire was increased of 2 °C and the cycle for the temperature of the first wire was then repeated. When also the second wire had completed the temperature cycle (i.e. the second wire was finally cooled again to ambient temperature), the temperature of the third wire was changed by 2 °C and the previous procedure was then repeated. The simulations ended when also the third wire had completed a temperature cycle.

This simulation allows to build a diagram with all the possible pairs of values of the first two eigenfrequencies of the ATMD. The plot obtained is shown in Figure 3 and it presents the resulting percentage plot for the ATMD. The symbol Θ indicates the percentage change of the eigenfrequencies. The reference values for calculating the percentage values are the eigenfrequency values with all the wires at environmental temperature in DM.

The plot of Figure 3 confirms that it possible to obtain two different values for the second eigenfrequency, when the first eigenfrequency is at a given value, and vice versa. This is made possible by the working principle presented in the previous section (i.e. the combined effect of the change of the axial load and of the change of the geometry of the ATMD).

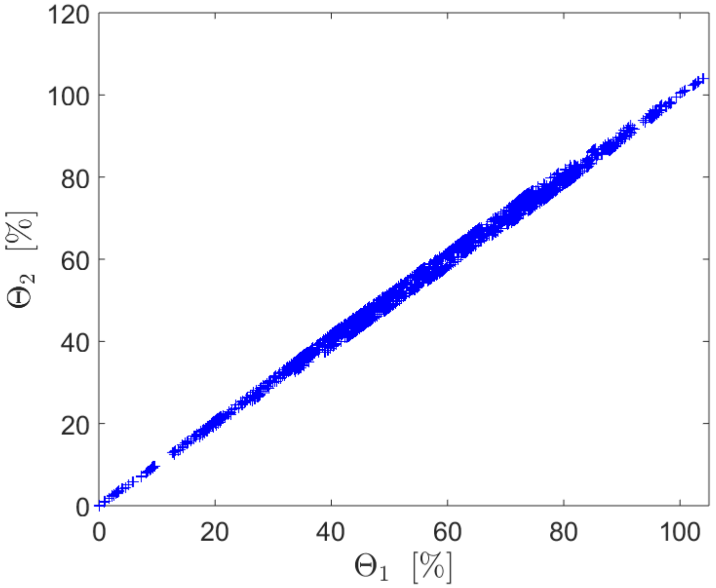

Figure 3: Adaptation plot: percentage change of the second eigenfrequency (Θ_2) as function of the percentage change of the first eigenfrequency (Θ_1). The blank spaces are due to the step used for the simulations (i.e. 2 °C). A narrower step would fill the spaces.

CONCLUSION

This paper has discussed an MM ATMD based on SMAs. The simulations carried out confirm that it possible to achieve two different values for one eigenfrequency, when another eigenfrequency is at a given value. This is made possible by the working principle presented (i.e. the combined effect of the change of the axial load and of the change of the geometry of the ATMD).

Therefore, the simulations confirm that it is possible to change the eigenfrequencies of the proposed ATMD with a given level of independence. This enables to recover the changes of two (or more) eigenfrequencies of the PS with the ATMD. This is made possible by the special features of the SMA materials, and setting independently the temperatures of the different wires of the ATMD.

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