Tuning vibration frequencies with shape memory alloys in precision engineering applications

Roderick Melnik[1], Ali Sebetci[2], and Linxiang Wang[3]
[1]*M²NeT Laboratory, Wilfrid Laurier University, Waterloo, ON, Canada*
[2]*Department of Mechanical Engineering, Mevlana University, Konya, Turkeyy*
[3]*Department of Ocean Science and Engineering, Zhejiang University, China*
rmelnik@wlu.ca

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Abstract

Shape memory alloys (SMAs) are used widely in a range of applications, including precision engineering, state-of-the-art bio-medical and nanotechnologies. In precision engineering, these materials are used, for example, for automatic alignment of optical systems. In SMA actuators, we often use hysteresis compensation for high-precision positioning, so that SMAs can be applied for control and vibration tuning of various structures. In vibration tuning in many of these applications, it is often necessary to apply supplementary oscillators to absorb the vibration energy input into the primary system. In this contribution we highlight how, due to the thermo-mechanical coupling, the vibration characteristics of the supplementary oscillator can be tuned by changing its temperature. The basis is our dynamic nonlinear model of SMA oscillator which has been simplified for the vibration analysis. At low temperatures, the SMA oscillator behaves as a regular damper by using its dissipation due to mechanically induced phase transformations.

1. Coupling primary and adaptive systems

The limitation of the linear mass-spring oscillator used for the vibration absorption and in similar technological applications lies with the fact that it only works when the excitation frequency is known and close (or, ideally, equal) to the natural frequency of the primary system. For many engineering structures, both such frequencies might not be known a priori [1,2]. In such cases, adaptive oscillators with adjustable stiffness would be beneficial in order to tune (and ultimately to control) the vibrations so that the natural frequency of the oscillator can be adjusted to match the resonance frequency of the primary system. Due to their thermo-mechanical coupling properties, shape memory alloys are promising materials for these purposes.

These advanced materials have already been applied to the adaptive vibration absorption (e.g., [2,3] and references therein), in precision engineering, and in nanotechnological applications [4]. The unique properties of SMAs lead to hardening the elastic modulus of the material at higher temperature (in the austenite state) and to its softening at lower temperature (in the martensite state). When the temperature is continuously adjusted, the elastic modulus of the material will be changing accordingly. Therefore, the thermo-mechanical coupling of SMAs provides a way to adjust the frequency response of vibration absorbers for adaptive vibration tuning. Previous results on the technological applications of SMA (composite) beams showed that the frequency of the oscillator using such beams can be adjusted in a range of 15% (see [3] and references therein).

Up to date, most studies in this field relied on mono-frequency or harmonic assumptions. If one considers the vibration tuning in more realistic situations, where the excitation frequencies may not necessarily be mono-frequency or harmonic and the primary system itself may be nonlinear, then the adaptive vibration absorber designed according to the standard frequency analysis might not be a suitable choice. Indeed, in this case vibration tuning should be implemented by taking energy dissipation into account, ensuring stability and robustness of the system, because of the energy dissipation driven vibration attenuation. In order to exploit the application potential of SMAs in vibration tuning, precision engineering and similar applications, in this contribution we take into account both key SMA properties: the thermo-mechanical coupling and the hysteresis induced by phase transformations. The main ideas are explained on an example of a SMA rod with an end-mass as a vibration absorber [3]. We emphasize that when supplementary oscillators are used in the applications of interest here, we often have to deal with a situation where the primary vibration frequency is not known a priori. In such cases, we have to design a robust supplementary oscillator such that it is able to operate in a rather wide range of frequencies. A SMA-based oscillator is an ideal candidate for these purposes. Hence, we propose a dynamic nonlinear model and its numerical realization for using SMA oscillators as vibration absorbers and in other relevant applications. To model the vibration tuning, the vibration of the primary system and the attached oscillator should be considered simultaneously. To do so, we formulate the governing equations for the entire system as in [3].

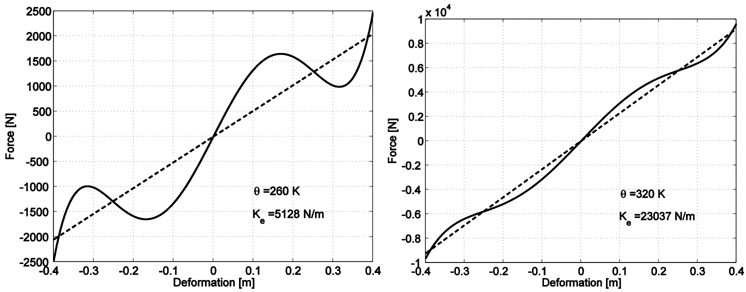

Fig. 1: Typical force-deformation relations of a SMA rod (260K and 320K).

2. Shape memory alloy dynamics for precision enegineering applications

In order to make the dynamic problem tractable in engineering applications, a dimensional reduction of the fully coupled dynamic three-dimensional model for shape memory alloys has been proposed (see [3] and references therein). The reduced model was approximated by a system of differential-algebraic equations and was applied to the modelling of SMA-based devices such as actuators.

The dependency of the dynamics of the mechanical field on the temperature is included in the proposed formulation. Recently we demonstrated that this model is able to capture the thermo-mechanical coupling effects and the first order phase transformations in SMA rods (see [3] and references therein). However, the main difficulty in applying this model to the analysis of vibration tuning in the context of our present problem is that the dynamic response simulation (accompanied by the simulation of phase transformations and wave propagations in the SMA rod) is computationally too costly for most engineering problems. Following [3], we explain here how to overcome this difficulty.

When the primary system is vibrating with unknown multiple frequencies, supplementary oscillators normally will not perform well by tuning their own natural frequencies in this case, because one supplementary oscillator can absorb only the vibration energy of a single frequency component which matches with the supplementary oscillator, with no effects (or very minor effects) on other frequency components. When the SMA oscillator is used in this case, it could be tuned to work in its low temperature range in which the martensite transformations could be induced. However, such martensite transformations and martensite re-orientations are always accompanied by mechanical energy dissipation, and as a result, abroad-band vi- bration attenuation might be induced. In this case, the mechanism of vibration suppression will be different from that of attaching supplementary oscillators. The interested reader is referred to [3] (and references therein) for further discussion on vibration damping by using the mechanically induced phase transformations in SMAs in a situation described above.

The important results of our study include our proposed dynamic nonlinear model for SMA-based oscillators in the vibration absorption and precision engineering applications, as well as the evaluation of the performance of such oscillators. An essential part of such oscillators - the SMA rod - is modelled on the basis of the Ginzburg-Landau theory. The resulting nonlinear model accounts for both thermo-mechanical coupling and hysteresis effects induced by phase transformations. Numerical simulations, carried out for various excitation frequencies, demonstrate that the SMA vibration absorber could be adaptive in a sense that it could be adjusted to match different frequencies by changing its temperature. In particular, based on estimated values of temperature for the vibration absorption, our results show that the vibrations of the primary mass block are successfully attenuated by using the SMA absorber. In the general case, due to nonlinearity of the force-deformation relation (see Fig. 1), the best temperature for the vibration absorption should be found by using an appropriate optimization procedure. We conclude by a discussion of SMAs in nanotechnological applications in the context of [4].

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