Magnetic Shape Memory (MSM) Actuators in Practical Use

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Abstract. Limited practical applications of MSM actuators motivates the authors to start experimental and theoretical research in the field of multifunctional materials. The authors present a concept of using MSM actuators for control, altering and tuning of forced vibrations of a rotor. The main goal of their experimental research is to show how the activation of MSM actuators can influence forced vibration responses of a rotor system in terms of altering and tuning selected rotor resonant frequencies and vibration amplitudes. Experimental results show that MSM actuators can be successfully applied for vibration reduction and vibration control in the case of rotor systems.

1. Introduction

In recent years a considerable increase has been observed in scientific interest in the properties, development and applications of new structural materials of controllable mechanical properties. Because of the exceptional and controllable properties such materials like: piezoelectrics, electro and magnetorheological fluids, and most of all shape memory alloys (SMAs) are of the highest interest. Within the shape memory alloys (SMAs) two special types of alloys can be distinguished:

- Shape Memory Alloys (SMAs) are the alloys that ‘remember’ their shape and after deformation can return to the low temperature shape by heating and subsequent cooling.
- Magnetic Shape Memory Alloys (MSMAs) are the ferromagnetic alloy exhibiting large changes in their shape and size under applied magnetic field.

Exceptional physical properties of the shape memory alloys (SMAs) allow them to be integrated within other materials in order to achieve properties that cannot be produced by any conventional technological processes. In such a way new multifunctional materials of fully controllable properties can be made, which next integrated with elements of structures enable one to control their static or dynamic characteristics. By the use of the shape memory alloys (SMAs), as such multifunctional materials, static and dynamic characteristics like: static deflection and shape, critical loading and stability, natural frequencies and modes of vibrations, resonant frequencies and amplitudes of forced vibrations, or structural damping can be controlled, altered or tuned. Investigations on rotor systems equipped with smart bearings utilising shape memory alloys (SMAs) were reported in the literature [1-3], however the use of magnetic shape memory alloys (MSMAs) for that purpose has not been investigated.
2. Magnetic shape memory effect

For the first time the magnetic shape memory effect (MSME) was observed and reported by Ullakko in 1996 [4]. MSMAs as materials that undergo large and completely reversible non-linear deformation influenced by an external magnetic field have been known for a relatively short time. However, since that time many theoretical models have been developed and used for modelling their quasi-static behaviour, magnetic-field-induced strains, all related with the MSME [5, 6].

The MSME can be considered as a significant and completely reversible non-linear deformation in the martensitic phase driven by an external magnetic field. Full understanding of the MSME behaviour requires investigation at micro and macro scale levels. Both scales should be examined because the macroscopic deformation observed in this kind of alloys is strictly connected with certain changes at the micro scale level.

Until now the most known MSMA is the alloy of NiMnGa (nickel, manganese and gallium). In MSMAs the crystallographic structure of the martensitic phase is tetragonal (unit cell length $a$ and $c$) and the austenitic phase is regular (unit cell length $a_0$) – see Fig. 1. In the martensitic phase three martensitic variants can be marked out. Each of them is magnetised along a preferred crystallographic direction named the magnetic easy axis. This direction is aligned with the short edge $c$ of the tetragonal unit cell. Magnetisation can be oriented in either positive or negative direction of the easy axis and aligned with the direction of the external magnetic field vector.

![Figure 1. Crystallographic structure of NiMnGa alloy variants [6]](image_url)

Let us consider a sample made out of a MSMA that initially in the austenitic phase and is cooled down under constant and compressive stress $\sigma_{xx}$ such that $\sigma_{sv} < \sigma_{xx} < \sigma_{b}$. The symbol $\sigma_{sv}$ is the minimum stress value necessary to obtain a single variant martensitic configuration and $\sigma_{b}$ is the blocking stress above which the MSME is not observed. As a result of the acting compressive stress $\sigma_{xx}$ and the martensitic transformation a single martensitic variant is obtained in the alloy – variant 1 – and the sample is slightly shortened. At the micro scale, due to cooling, several magnetic domains can be distinguished in the single variant state as it can be seen in Fig. 2a. The direction of the magnetic polarisation $M$ is connected with the direction of the acting stress $\sigma_{xx}$. Subsequent application of an external magnetic field $H_y$ orthogonal to the applied stress $\sigma_{xx}$ starts the nucleation and growth of variant 2 by the motion of magnetic domain walls, reorientation, and migration of twins. The growth of variant 2 occurs at the cost of variant 1 and causes strain reorientation and elongation. This process is named as the magnetic field-induced martensitic variant reorientation in MSMAs.

2.1. One-dimensional model of the magnetic shape memory effect

Experimental observations reported in the literature allows one to make the following simplifications in the phenomenological modelling of MSMAs:

- value of magnetic anisotropy can be assumed as infinite [6],
- strains connected to magnetostriction can be neglected,
- MSME depends only on the process of martensitic variant reorientation.
The total macroscopic strain $\varepsilon$ related to the MSME can be expressed as a sum of the thermoelastic strain $\varepsilon^{te}$, the reorientation strain $\varepsilon^{r}$, and the transformation strain $\varepsilon^{tr}$:

$$
\varepsilon = \varepsilon^{te} + \varepsilon^{r} + \varepsilon^{tr}
$$

(1)

The thermoelastic strain $\varepsilon^{te}$ is a sum of the thermal strain $\varepsilon^t$ and the elastic strain $\varepsilon^e$:

$$
\dot{\varepsilon}^{te} = \dot{\varepsilon}^t + \dot{\varepsilon}^e = \dot{\varepsilon}^e - \frac{\Theta(\xi)}{E(\xi)} \dot{T} = \dot{\varepsilon}^e + \alpha(\xi) \dot{T}
$$

(2)

where $T$ is temperature, $\Theta$ is a thermal coefficient, $E$ is Young’s modulus and $\alpha$ is a linear expansion coefficient. In MSMAs the reorientation strain $\dot{\varepsilon}^{r}$ associated with the MSME is proposed as proportional to the rate of changes in the martensitic variant volume fraction [6, 7]:

$$
\dot{\varepsilon}^{r} = -\frac{A(\xi)}{E(\xi)} \dot{\xi}_s^{(2)} = \varepsilon_r \dot{\xi}_s^{(2)}
$$

(3)

where $A$ is a reorientation coefficient, $\varepsilon_r$ is the maximum elongation connected with martensitic variants reorientation and $\dot{\xi}_s^{(2)}$ is the stress-induced variant 2 martensitic phase. Similar to thermal SMAs the transformation strain $\dot{\varepsilon}^{tr}$ is proposed as proportional to the rate of changes in the strain-induced martensitic phase $\dot{\xi}_s^{(2)}$ [7]:

$$
\dot{\varepsilon}^{tr} = -\frac{\Omega(\xi)}{E(\xi)} \dot{\xi}_s^{(2)} = \varepsilon_l \dot{\xi}_s^{(2)}
$$

(4)

where $\Omega$ is a transformation coefficient and $\varepsilon_l$ is the maximum elongation connected with martensitic transformation driven by temperature. In the phenomenological model proposed here the constitutive equation describing changes in the stress $\sigma$ is postulated as analogous to thermal SMAs [7-9]:

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**Figure 2.** Schematic diagram of the magnetic shape memory effect in a NiMnGa alloy [6]
\[
(\sigma - \sigma_0) = E \left( \epsilon - \epsilon_0 \right) + \Theta \left( T - T_0 \right) + \Omega \left( \xi_s - \xi_{s0} \right) + A \left( \xi_s^{(2)} - \xi_s^{(3)} \right)
\]  

(5)

where \(\sigma, \epsilon\) and \(\xi_s\) denote the stress, strain and relative volume fraction of the martensitic phase, \(E_m\) is Young’s modulus of the martensitic phase and ‘0’ denotes a certain starting level. Assuming that the martensitic reorientation process takes place under constant temperature and that a state of single martensitic variant orientation has been established the thermal effects, as well as the effects due to the martensitic transformation, can be neglected. Because of that Eq. (5) can be rewritten in a simpler form:

\[
(\sigma - \sigma_0) = E_m \left( \epsilon - \epsilon_0 \right) + A \left( \xi_s^{(2)} - \xi_s^{(3)} \right)
\]  

(6)

This form of equation can be used as a base form of the constitutive relation for changes in the stress \(\sigma\) connected with the MSME.

3. Magnetic Shape Memory (MSM) Actuators in Practical Use

3.1. Concept of a special rotor rig with a MSM actuator

A Bently Nevada Rotor Kit 4RK is a high quality machine unit enabling observation and investigation of transverse vibrations of rotating machinery. The main parts of the Bently Nevada Rotor Kit 4RK are: base on which the driving motor (1) is mounted, helical coupling (3), 560 mm long and 10mm of the diameter shaft (4) with standard (5) and ‘smart’ (6) bearings – for more details refer to Fig. 3 and Fig. 4.a.

![Figure 3. A special rotor rig with a smart bearing support](image)

The motor run is controlled by a driving unit (2) that allows to achieve the rotation speed of 10000 rpm for at a given speed ratio. The shaft is attached to the motor by the helical coupling that compensates all misalignments resulting from the rotor assembly. Additionally it is possible to attach two mass wheels (9) – 75mm external diameter, 10mm internal diameter, 25mm width, 800g weight. The position and mass unbalance, in the range from 0.1 g to 2.0 g, can also be fully controlled and modified. By standard the shaft is supported by two self-lubricating sliding bearings. For the purpose of the experimental research one shaft support with the sliding bearing has been replaced by ‘smart’
bearing support (6) – Fig. 3 and Fig. 4.a – equipped with a MSM actuator (7) presented in Fig. 4.b. The MSM actuator is driven and controlled by a generator unit (8) and a time module controller (10). The smart bearing support controls the vibrations of the rotor in the horizontal plane, while the vibrations in the vertical plane are uncontrolled. The position of each bearing can be altered and modified.

**Figure 4.** Smart bearing assembly (a) with the AdaptaMat(MSM) actuator (b)

In order to measure the transverse vibrations of the shaft a set of 2 proximity probes (11) were used. The signals from the probes were observed via oscilloscope or computer thanks to the use of a proximitor assembly unit (12). During operation the rotation speed of the rotor can be changed and this may result in multiple passes through the resonance regions of high vibration amplitudes. In these cases the use of the smart bearing support helps to control the level of the vibration amplitudes or to reduce them to a safe level.

### 3.2. Experiment

The custom modified rotor rig described above allowed the authors to carry experimental measurements. The transverse vibrations of the rotating shaft were observed and tuned by the use of the MSM actuator.

The experiment was conducted for the shaft with one additional mass wheel placed at the mid-span of the shaft for the following three different settings: (a) shaft with one mass wheel rotating at the speed of \( n = 1000 \) rpm, which is equal to frequency \( f = 16.67 \) Hz, (b) shaft with one mass wheel rotating at the speed of \( n = 1750 \) rpm, which is equal to frequency \( f = 29.17 \) Hz, (c) shaft with one mass wheel rotating at the speed of \( n = 4600 \) rpm, which is equal to frequency \( f = 76.67 \) Hz.

All measurements were performed in the following manner. By the use of the motor driving unit the required shaft rotating speed was established. Next the working frequency of the MSM actuator work was selected by the use of the generator and the time module controller. The frequency of the MSM actuator could vary from 10 Hz to 350 Hz with a step of 10 Hz. The activation time was chosen as \( t = 8 \) s. Changes in rotor vibration characteristics due to activation of the MSM actuator were observed on the oscilloscope.

Figure 5 shows the obtained amplitude-frequency characteristics of the shaft with one mass wheel. It indicates the regions of the resonant frequencies in \( u \) and \( v \) direction. The dashed line denotes the frequencies for which the experimental measurements were carried out.

In order to show the effectiveness of the MSM activation an indicator parameter has been defined and used. In the case of all results of numerical calculations presented below the indicator \( I \) is used defined based on the following formula:
\[
I = \frac{A_1}{A_2}, \quad A_i = \int_0^{f_N} P_i(f)df, \quad i = 0, 1
\]  

(7)

where \(f_N\) denoting the frequency, \(P_i\) is the signal power, 0 and 1 denote the case of inactive and active MSM actuator, respectively.

Figure 5. Amplitude-frequency characteristic for the shaft with one mass wheel

Results for the shaft with additional mass wheel rotating at the speed of \(n = 1000 \text{ rpm}\)
Figure 6 shows the effectiveness of the MSM activation as a function of the activation frequency \(f\) and changes in vibration reduction.
Minimal vibration reduction was achieved for the MSM actuator activation frequency equal to \(f = 30 \text{ Hz}\) and maximal for \(f = 120 \text{ Hz}\).

Results for the shaft with additional mass wheel rotating at the speed \(n = 1750 \text{ rpm}\)
Figure 7 shows the effectiveness of the MSM actuator activation as a function of the activation frequency \(f\) and changes in vibration reduction. Minimal vibration reduction was achieved for the MSM actuator activation frequency equal to \(f = 40 \text{ Hz}\), and maximal for \(f = 260 \text{ Hz}\).

Results for the shaft with additional mass wheel rotating at the speed \(n = 4600 \text{ rpm}\)
Figure 8 shows the effectiveness of the MSM actuator activation as a function of the activation frequency \(f\) and changes in vibration reduction. Minimal vibration reduction achieved for the MSM actuator activation frequency equal to \(f = 10 \text{ Hz}\), and maximal for \(f = 190 \text{ Hz}\).

Figure 6. Indicator \(I\) changes as a function of the MSM actuator activation frequency \(f\) and minimal (a) and maximal (b) vibration reduction
3.3. Comparison of experiment and numerical simulation

Numerical simulations were made for the shaft with one mass wheel and for 3 different rotating speeds. The FEM has been applied for the analysis of the effectiveness of the MSM actuator activation. For shaft modelling 10 beam finite elements were used with 2 nodes and 4 degrees of freedom per each node. The mass wheel was modelled a rigid body with 6 degrees of freedom.

Figure 9. Amplitude-frequency characteristic obtained from experimental measurements and from numerical simulations

First comparison is connected with the amplitude-frequency characteristic. Figure 9 shows the amplitude-frequency characteristic obtained from the experimental measurements (grey) and from the numerical simulations (black). Only the horizontal direction was considered because this direction was the direction of work of the ‘smart’ bearing.
Second comparison is connected with the effectiveness of the MSM actuator activation. Figure 10 shows the effectiveness of the MSM actuator activation obtained from experimental measurements (grey) as well as for numerical simulations (black). It is shown in terms of the indicator $I$ defined by equation (7) in the following way. Starting from left results for the shaft with one mass wheel rotating at the speed of $n = 1000$ rpm are presented, next for the shaft with one mass wheel rotating at the speed of $n = 1750$ rpm, and finally for the shaft with one mass wheel rotating at the speed of $n = 4600$ rpm.

![Graph showing the effectiveness of MSM actuator activation](image)

**Figure 10.** Changes in indicator $I$ as a function of the MSM actuator activation frequency $f$ obtained from experimental measurements and from numerical simulations

### 4. Results

The obtained result from experimental measurements and numerical simulations allow the authors to formulate the following general conclusions:

- **MSM actuators can be successfully used for reduction of forced vibrations of rotor systems.**
- Both experimental and numerical results show that activation of the MSM actuator significantly influences forced rotor vibration responses.
- In certain cases the observed effectiveness of the MSM actuator activation is lower. This is when the MSM actuator activation frequency is equal to a multiple of the natural frequency of the rotor.
- In certain cases the MSM actuator activation cause an increase in the forced vibration amplitudes of the rotor. This happens when the MSM actuator works as an additional source of excitation.

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