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Finite Element Modeling of a Novel Magnetic Shape Memory Alloy Based Energy Harvester Using a Corrugated Beam and Investigating the Effective Parameters

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ABSTRACT: In recent years demand for mobile electrical power has been increased and due to this application, energy harvester systems have been developed to convert mechanical energy into suitable electrical energy using smart materials. In this investigation, a novel arrangement of a new energy harvester using magnetic shape memory alloys is developed. Elements of smart materials ($Ni_{50}Mn_{28.5}Ga_{21.5}$) are attached to a corrugated beam and their roots are fixed to the base support. The reason for using the corrugated beam is to increase the stiffness of the structure in less thickness and also to increase the effective strain field in smart material elements. This feature reduces the length of the system and the occupied volume. The way of harvesting energy from this system is based on the conversion of vibrational energy to the magnetic flux gradient. That is to say; there is a number of copper coils wrapped around the elements in a constant magnetic field. If strain or stress field is applied to the smart material elements, some variants in a specific direction are changed and as a result, the electrical current is induced to the coils. The alternating current voltage is produced as a result of the change in the magnetic flux of the surrounding coil according to Faraday's Law. The problem is studied with simulations in Abaqus using user material code for modeling behaviour of magnetic shape memory alloy elements. Also, to simulate the material properties of smart material substance, Kiefer and Lagoudas nonlinear model is used. It will be shown the effect of various parameters on the output voltage value.

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1- INTRODUCTION

Today, corrugated structures are playing a key role in different industries, e.g., aerospace, marine, and automotive. For instance, in modern airplanes, most parts of the wings and tails are made of corrugated beams. These structures undergo vibrations due to interaction with the environmental loads. Vibration energy is one of the common energy types in nature. The vibration energy in the environment is a potential source for energy harvesting and converting it to electrical low power type for application in remote devices that require microwatt and mill watt energy scales [1, 2]. All kinds of Magnetic Shape Memory Alloys (MSMA) energy harvester systems can be divided into two categories named force driven and velocity driven [3]. In the force-driven one, the direct force is applied to the MSMA components. A force driven MSMA-based energy harvester was studied by Karaman et al. [4]. They utilized the martensitic variant reorientation mechanism under applying a slow uniaxial load field and 1.6T bias magnetic field. A thermodynamic based constitutive equation for MSMA together with Faraday's law of induction was implemented by Bruno et al. [5] to study the same energy harvester system. Also, a novel inertial energy harvester using MSMAs has been implemented by Askari-Farsangi et al. [6]. Application of MSMA elements used for harvesting vibrational energy from a simple beam was studied and the relation between the strain field and magnetization was shown. Various parameters like pre-strain, number of MSMA elements and bias magnetic field were surveyed in detail. Although several works have been carried out in energy harvesting methods and application of MSMA materials, to the knowledge of the authors there is almost no work on the investigation of parameter's effect and the fraction of harvested voltage per volume. In this paper, it will be shown that the size of the developed MSMA based energy harvester arrangement can get smaller using corrugated structures. This is an important achievement for using this kind of MSMA energy harvester in small-sized consumers and the charging of such remote devices.

2- METHODOLOGY

For harvesting electrical voltage from the vibrational motion of a corrugated cantilever beam, MSMA elements are attached to the top of the corrugated beam. The reason for choosing this point for attaching the MSMA elements goes back to its maximum strain. This way, the maximum capacity of the system could be exploited. MSMA materials have two types of recoverable strain: Thermoelastic strain, and Pseudo elastic strain resulting from the reorientation of the martensite variants. The total retrievable strain is [7]:

$$\varepsilon = \varepsilon^{r} + \varepsilon^{te} \quad (1)$$

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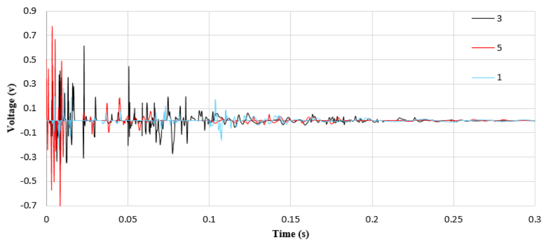

Fig. 1. Comparison of output voltage vs. time for 1, 3 and 5 MSMA elements, 3% pre-strain and 0.6 T bias magnetic field

$$\varepsilon^{r} = -(1-\varepsilon)\varepsilon^{(r,\max)} \tag{2}$$

Four possible configurations of magnetization are described below [7]:

$$\begin{aligned} M_1 &= \text{-}M^{sat}[\cos(\theta_1)\varepsilon_x + \sin(\theta_1)\varepsilon_y] \\ M_2 &= \text{-}M^{sat}[\cos(\theta_2)\varepsilon_y - \sin(\theta_2)\varepsilon_x] \\ M_3 &= M^{sat}[\cos(\theta_3)\varepsilon_x + \sin(\theta_3)\varepsilon_y] \\ M_4 &= \text{-}M^{sat}[\cos(\theta_4)\varepsilon_y + \sin(\theta_4)\varepsilon_x] \end{aligned} \tag{3}$$

Each equation expresses a magnetization of M^{sat} in a direction θ_i determined by the rotation of the magnetization vector about its magnetic field direction.

To explain the effective magnetic field exists in X and Z directions inside MSMA materials, Eq. (4) is used:

$$\begin{pmatrix} H_x^{eff} \\ H_z^{eff} \end{pmatrix} = \begin{pmatrix} H_x^{app} \\ H_z^{app} \end{pmatrix} - \begin{bmatrix} D_{xx} & 0 \\ 0 & D_{zz} \end{bmatrix} \begin{pmatrix} M_x \\ M_z \end{pmatrix} \tag{4}$$

Kiefer and Lagoudas calibrated their model by performing an experiment at constant compressive stress and examining the applied magnetic field-strain graph to identify the applied magnetic field values at which the reorientation started and finished [7]. This equation is as follows [7]:

$$\pi^{\xi} = \sigma\varepsilon^{r,\max} + \frac{1}{2}\Delta S\sigma^2 - \mu_0 M^{sat}\begin{bmatrix} (\cos(\theta_3)+\sin(\theta_4))H_x^{eff} + \\ (\sin(\theta_3)-\cos(\theta_4))H_y^{eff} \end{bmatrix} + \rho K_1(\sin^2(\theta_3)-\sin^2(\theta_4)) - \frac{\partial f^{\xi}}{\partial \xi} \tag{5}$$

3- RESULTS AND DISCUSSION

As mentioned before, a corrugated structure is used which is connected to three MSMA elements in top of the beam. In the following, the behavior of the energy-harvester system is represented.

Fig. 1 depicts the effect of the number of MSMA elements on the system output. This Figure consists of 3 modes with 1, 3, and 5 MSMA elements. As you can see, as the number of MSMA elements increases from 1 to 3, the output voltage amplitude increases. As the number of elements increases from 3 to 5, although the output voltage amplitude is higher at the beginning of the diagram, it decreases rapidly, due to increased structural stiffness and a decrease in the effective strain field. In other words, with increasing structural stiffness, the strain field does not reach the maximum usable amount and practically the mean square root of the output voltage decreases relative to the 3 element model.

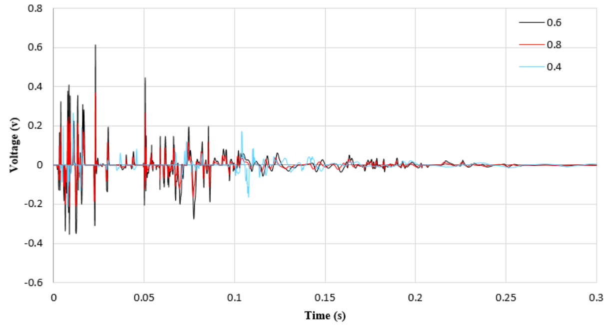

Fig. 2. Comparison of output voltage vs. time for 3 magnetic fields 0.4 Tesla, 0.6 Tesla, and 0.8 Tesla

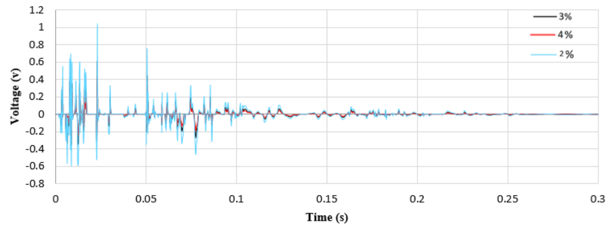

Fig. 3. Comparison of output voltage vs. time for 3 pre- strains 2%, 3%, and 4%

Fig. 2 depicts the effect of the bias magnetic field on the system output. In this case, 3 MSMA elements are used. According to the results, the simulations at 0.4 Tesla field show that the copper coil is not properly stimulated and the output voltage has a maximum amplitude of about 0.2 Volts. By increasing the bias field and reaching 0.6 Tesla, the system voltage output effectively increases to a maximum of 0.6 Volts. As the bias field continues to rise to 0.8 Tesla, the output voltage amplitude is again reduced, because the pseudoelastic behavior of the MSMA materials, in this case, starts at 0.6 Tesla.

Another parameter affecting the output voltage is the pre-strain of the MSMA elements. Fig. 3 depicts the effect of this parameter. As you can see, the increase of the pre-strain from 2% to 4% reduces the output voltage. Due to the structural limitation of the MSMA materials, by increasing the strain to 4% the strain field applied to the elements exceeds the permissible limit (6.4%) and part of the hysteresis loop becomes continuous and does not generate energy. Although the 2% pre-strain appears to produce more voltage, it is observed that sometimes the strain field has a positive magnitude, which in turn causes fracture in the elements and not practical for real applications.

4- CONCLUSION

In this study, a new arrangement of energy harvester system was established that uses MSMA elements in the corrugated beam structure. Firstly, the theoretical concepts of the problem were studied. Then, a geometry of the structure was modeled and the mechanical properties of the MSMA materials were added to this model that was formed as a UMAT subroutine in Abaqus software. Numerical results showed that due to vibration of the beam, magnetization along its longitudinal direction was varied and led to the generation of electrical current according to Faraday's law of induction. The amount of this voltage was reduced over time due to the hysteresis behavior of the MSMA elements. After that, the effect of element numbers, pre-strain and bias magnetic field on output voltage were investigated. According to the results, the root means square of the output voltage in the corrugated beam is about 15% higher than in the simple beam. Also with this arrangement, we were able to reduce the occupation volume by 30%. Ultimately, this arrangement is capable of producing $1.05 \mu W / cm^3$ energy density per impact force.

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