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Simulation-based Design Methodology for Magnetic Shape Memory Actuators

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MSM alloys, especially Ni-Mn-Ga alloys have been studied extensively for almost two decades. Their remarkable properties make them very promising for use in various electromagnetic (EM) devices, notably in actuators and sensors. However, at present there are no well-established design methodologies for MSM-based devises. This paper proposes a design methodology that uses commercially available EM modelling software and just a small amount of experimental data for its implementation. It allows reliable actuator modelling and performance evaluation without needing to calculate the magnetic field-induced stresses.

1 Introduction

The application of MSM alloys in EM devices on micro- and macro-scale have been considered in various studies since the discovery of MSM effect in Ni-Mn-Ga alloys [1,2]. An enormous 6-12% magnetic field-induced strain and magnetically controlled shape memory effect allow MSM alloys to compete successfully with other “smart” materials. However, a complete design methodology for MSM-based devices is yet to be developed. Mathematical models which describe MSM behaviour are usually very complex and also they are not compatible with EM modelling and design software [3]. On the other hand, phenomenological models [4] or models requiring extensive measurement data are applicable only to particular cases. In this paper, we propose a widely applicable design methodology for MSM actuator design, which requires just two sets of experimental data for its implementation.

The first measurement data needed includes the “easy” and “hard” axes magnetisation curves [5]. Second – the data giving the MSM strain as a function of applied magnetic field at different pre-stress levels [6]. Simultaneous measurement of MSM strain and bias magnetic field is essential for capturing the effects arising from varying MSM magnetisation.

2 Modelling approach

An FE-based EM software tool (e.g. Ansys Multiphysics for the approach reported in this paper) is used for modelling and computation of complex magnetic fields associated with non-linear magnetic properties of actuator’s magnetic circuit. The FE modelling of non-homogeneous microstructure of MSM element in an actuator also possesses considerable challenges.

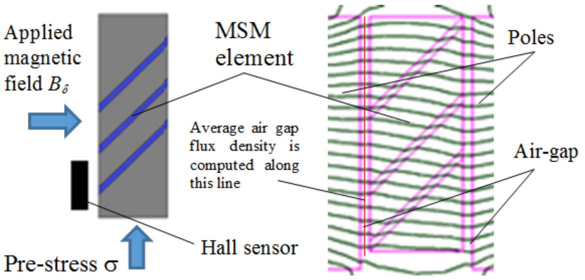

Figure 1. Measurement setup for strain-field measurement (left) and FE model (right) of the MSM element in actuator.

It is important to calculate the magnetic field in the air gap of an actuator so that the modelling results are consistent with the experimental procedure (see Fig. 1). Otherwise, a considerable disagreement is possible due to demagnetisation effects in the MSM element. It should be noted in this context that the permeability of MSM element varies with strain. It is very important to take this into account as well as local effects arising from non-homogeneous MSM microstructure. A modelling approach proposed in [5] is suitable for these purposes.

The air gap magnetic field data obtained from a model is checked against a particular point on a strain-stress curve. Hence, a relationship between an actuator input current and MSM element’s strain/stress output is established. Therefore, a complete displacement versus current curve is calculated for a particular output stress. Design optimisation can also be incorporated into the modelling cycle.

3 Results and discussions

Fig. 2 shows how measurement data are translated into actuator output. The difference in the hysteresis loop size is attributable to the effect of the mechanical return spring in the actuator.

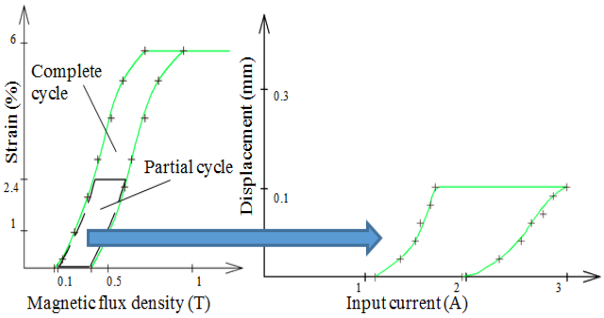

Figure 2. Relationship between the strain-field measurement data of the MSM element (left) and the actuator performance (right) at 2MPa pre-stress.

At present the applicability of the proposed approach is somewhat limited by the available pre-stress data. This is its main drawback. However, this approach allows the computation of actuator performance without needing to calculate the magnetic field-induced stress of its MSM element. Moreover, it is possible to approximate the behaviour of actuator's output force using data from multiple pre-stress curves. For example, a Lagrange interpolating polynomial for an actuator output force, obtained using measurement data at three different pre-stress levels for a particular 2.4% strain is

$$F_{act} = (-6.76 \cdot B_\delta^2 + 11.98 \cdot B_\delta - 3.29) \cdot A_{msm} \qquad (1),$$

where F_{act} is actuator output force, N, B_δ is airgap flux density T and A_{msm} is the cross-section of the MSM element, mm^2. Fig. 3 below shows how the actuator output force varies with its input current. The shape of this curve is very similar to the shape of the MSM blocking stress reported in [7]. A threshold at low currents depends on twinning and compressive stresses.

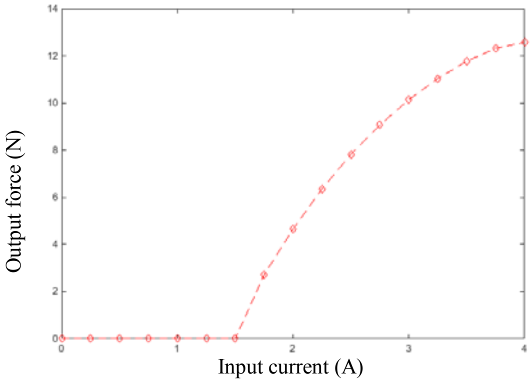

Figure 3. Variation of actuator output force with its input current at 2.4% strain of the MSM element.

4 Conclusions

A design methodology for MSM actuators based on FE simulation and two types of experimental data for the MSM element has been proposed. Its compatibility with modern FE-based EM modelling software allows the application of well-known actuator design and optimisation techniques. Although developed for the primary purpose of MSM actuator design, this methodology can also be used for design and analyses of other magneto-mechanical MSM applications (e.g., pressure or magnetic field sensors).

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