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Nano- Positioning With Ferromagnetic Shape Memory Alloy Actuators

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Abstract. Ferromagnetic shape memory alloy-based actuators offer distintive features that make them advantageous competitors to traditional electromechanical devices. The production of force and motion without contact is one of the most important features. However, the largely non-linear and hysteretic nature of the response of such materials makes them of little use apart from on-off or continuous actuation.

In this work we present the results obtained in a laboratory prototype of linear position FSMA actuator, where the active element is a 12 mm long Ni-Mn-Ga single crystal. The crystal expands a maximum of 12 micrometers and in control experiments, is commanded to expand and contract alternatively to reach positions at 5 µm and 8 µm. It shows that the commanded position could be controlled within 20 nm.

Introduction

The ability of Ferromagnetic shape memory alloys (FSMAs) to show large magnetic field- induced strains at moderate fields, 5 layered martensites have repeatedly shown about 6% magnetic field-induced strains [2] and in some 7 layered martensites have shown up to 10% field-induced strains [3]. These are comparable to those achieved by other conventional magnetically driven actuators, and make it an attractive actuator material. However one of the main areas that remain unexplored in the application of FSMAs as actuator materials is their controllability. This in principle should not be a trivial undertaking, since they show hysteresis and a non-linear behavior. In this paper we show that, at least at low actuation frequencies, FSMA-based actuators can be controlled with good precision.

FSMA actuator prototype and experimental set-up

The figure 1 shows a real image and a scheme of a laboratory FSMA actuator prototype. The active element is a 12 mm long and 6.25 mm^2 Ni-Mn-Ga single crystal grown by the Bridgeman method at the Ames laboratory in Ames, Iowa and cut with the faces parallel to the {100} austenite planes by spark erosion. The crystal growth process has been described elsewhere [4]. Once the crystal was cut, it was polished and heat treated. The heat treatment consists of heating the sample to 950^o, for 12 h to anneal it, and then cooling to 500^o for 5 h, to allow the alloy to order into the $L2_1$ phase. After this, the sample was cooled to 200^o and a 2 MPa load was added to the sample before it was allowed to cool into the martensite phase.

The actuator consists of an iron-core laboratory electromagnet that is fed by a computer-controllable power supply (Kikusui Electronics Corp) that provides the drive magnetic field. The magnetic field is applied perpendicular to the load direction. The crystal expands against a spring that provides the restoring force. The stiffness of the spring used is such that it can be compressed by the crystal when the field is applied, and the energy stored by the spring is sufficient to recompress the sample once the field is turned off. Motion is transferred by a brass rod in a low-friction bearing, and a brass target at the end is used for the capacitive position sensor (ADE Technologies, 4810) that measures the position. The magnetic field is measured using a Lakeshore hall probe. The experimental set-up is placed on a vibration isolation table in order to minimize vibration noise.

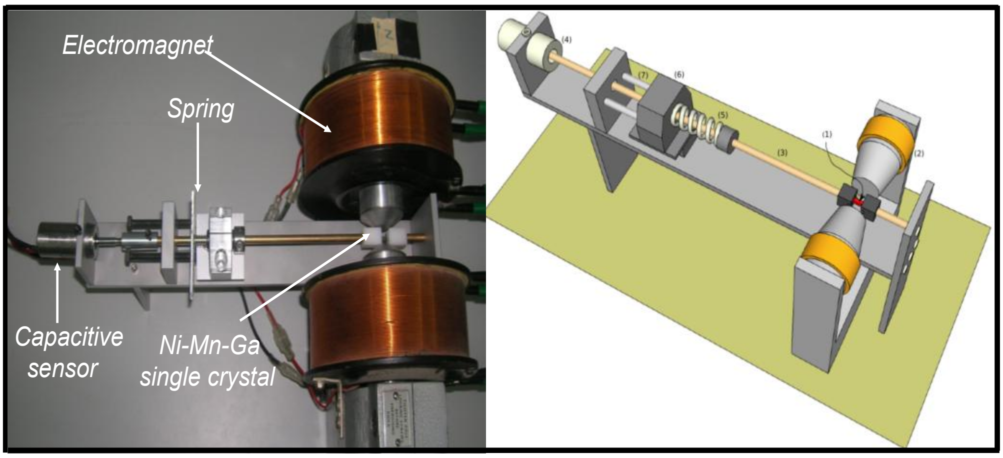

Fig. 1: FSMA actuator prototype and its scheme.

A Proportional-Integral (PI) controller [1] (see figure 2) is implemented using LabVIEW, and the use of this program together with a sourcemeter (KEITHLEY, 2602) connected to a PC through a GPIB interface, handles all the voltage signals involved. The actual position measured by the capacitive sensor is used as the feedback into de controller, and the magnetic field required to achieve the desired deformation of the FSMA crystal is calculated and programmed to the power supply.

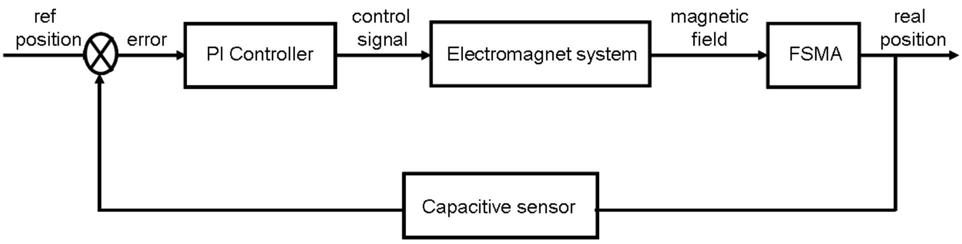

Fig. 2: Simplified scheme of the control loop.

Experimental results

The FSMA materials show a non-lineal and hysteretic response that makes difficult to accurately control their deformation. The figure 3 shows an hysteretic response of 12 mm long and 6.25 mm^2 section Ni-Mn-Ga single crystal.

The response of the crystal was tested by applying a field ramp from 0 to 1 T and then back to 0 T, the single crystal shows a threshold field of 0.2 T, and for a field of 1 T, a 12 μm deformation. Note that this is not the maximum deformation the crystal can achieve, because the spring that was added to the experimental set-up to provide the restoring force, in this case, also limits maximum deformation. The wide hysteresis of the sample is clearly visible in the figure 3.

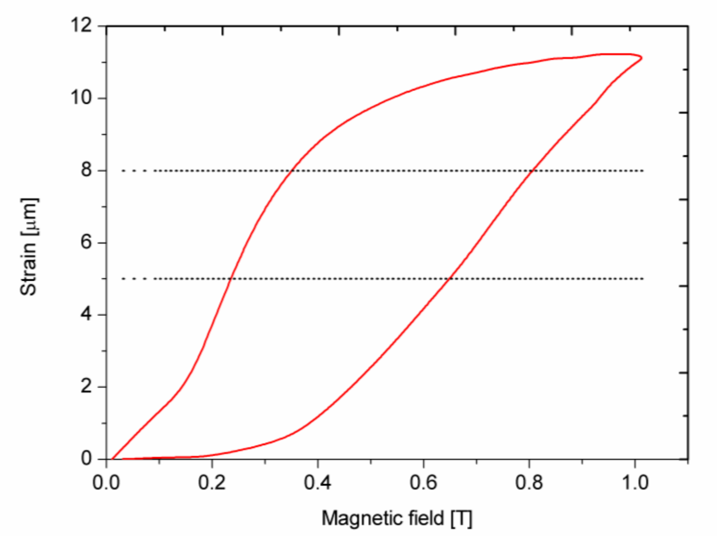

Fig. 3: Hysteresis cycle of the NiMnGa single crystal.

To test the applicability of these materials as position-controllable actuators, two intermediate deformations within the FSMA deformation range were chosen for the position control experiments (5 and 8 µm, shown as the two dotted horizontal lines shown in figure 3). The crystal is commanded to expand and contract alternatively to reach those positions. Figure 4 shows the results for the control experiments.

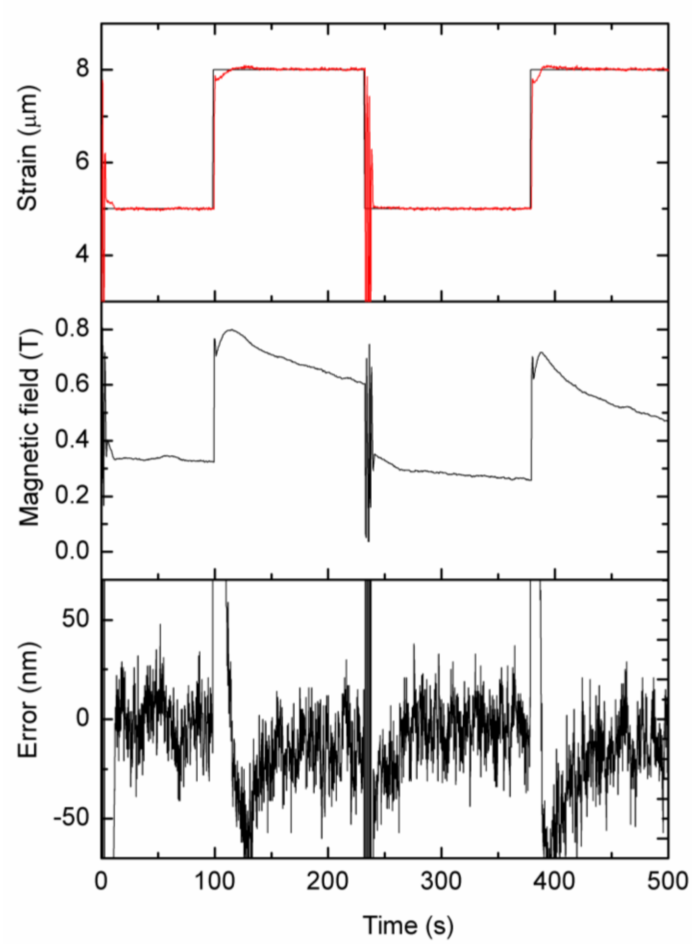

Fig. 4: Control results. *Top*: Reference strain signal (black) and real strain (red); *Middle*: Control signal, the magnetic field applied to the crystal; *Bottom:* Error between reference signal and measured position

The top of frame of figure 4 shows in black the programmed strain and in red the measured position. It can be seen that after a sufficiently large setting time has passed (~50 s), the measured position tracks the programmed position quite well. The middle of the figure shows the magnetic field required to control the corresponding deformation. The deformation in these materials has long been known to be the result of twin boundary motion [5], the decrease observed in the magnetic field required to maintain the position observed in figure 4 is most likely the direct result of the twin finding the lowest energy configuration of them getting pinned on the many non-uniformly distributed defects in the crystal [6]. As the control system tries to maintain a position and the magnetic field oscillates about a given value, the twins will move from one defect to another until the find the minimum external field configuration for the twins to rest at the highest energy defects. Finally, the error in the position can be seen in bottom of the figure. The controller is capable to obtain precisions about 20 nanometers.

Alternative FSMA based actuator prototype

Given the encouraging results obtain for this material a new actuator design based on two orthogonal fields is under development. This alternative approach to FSMA-based actuators is shown in figure 5 and detailed in the next paragraph.

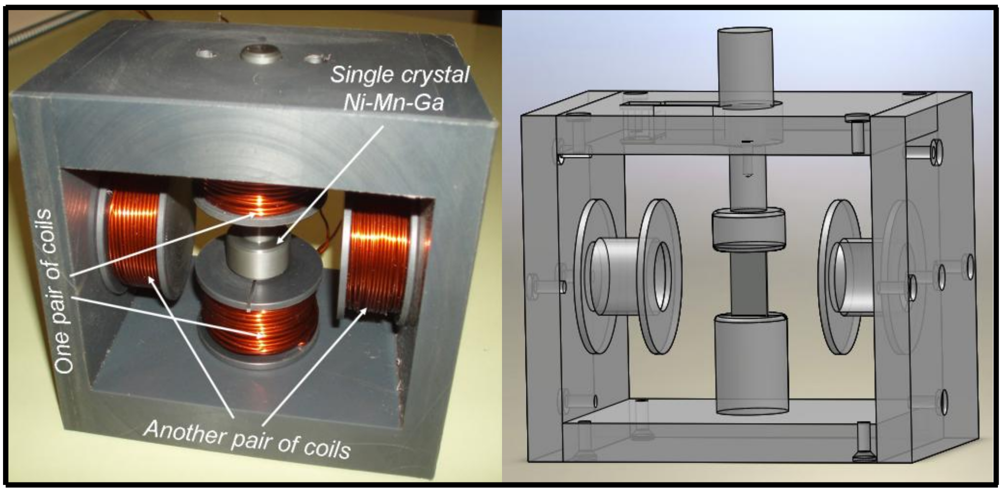

Fig. 5: Alternative FSMA actuator prototype and its scheme

The new actuator consists of two pairs of air coils instead of one iron core magnet and a reset spring. In this way, one of them provides the magnetic field in one of the crystal´s actuation directions, and the other one in the transversal direction, allowing the crystal to be returned to its starting dimensions without the need for a restoring force. If this configuration is used, the transverse magnetic field provides the drive field, while the parallel field provides the reset field. This way the actuator can be used in a “set and forget” mode, that is, once the desired position is reached, the actuator is turned off an the position is held without the need of any applied field, as long as the load on the actuator is below the twining threshold, requiring less energy to hold a position.

The dimensions of the coils are considerably smaller than the previously used one, because the coils are operated in a pulsed mode. This allows for higher currents to be used since the duty cycle is relatively low. The intrinsically digital control mode required for this type of actuator implies will require more work than the simple PID control used in the previously shown results.

Conclusions

The difficulty in accurately controlling the motion of twin boundaries in FSMA has made them of little use for applications other than on-off actuation. However, the initial results obtained in this laboratory prototype of linear position FSMA actuator, show that, despite of the hysteretic response of FSMA materials, even with a simple proportional-integral control strategy, the actuator position can be controlled within ± 20 nm, proving that they can be used as precision actuator in nanopositioning.

Interestingly, the defect structure plays a fundamental role in achieving such performance. The stochastically distributes defects determine a progressive diminution of the magnetic field strength required to maintain the control.

This is a very promising start considering the large room for improvement for the next iterations. Two of those cited improvements related with the actuator design have been presented in a new actuator prototype. Moreover, more sophisticated control strategies would be used to obtain better results.

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