

# APPLICATIONS OF MAGNETIC SHAPE MEMORY ACTUATORS

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## Abstract:

Magnetic shape memory (MSM) materials offer a new way of producing motion and force. For the time being the most common usage of the materials are in the linear motion actuators. In this paper we present results from three MSM actuator applications: linear motor, valve and pump application. We also discuss the controllability and properties of the MSM actuators in applications generally.

## Introduction

A new mechanism to develop rapid strains in a material has recently been suggested. These strains are based on magnetic-field-induced reorientation of twin variants of the material [1,2]. The first demonstration of that mechanism, called magnetically controlled shape memory (MSM) mechanism, on a Ni-Mn-Ga alloy revealed a strain of about 0.19 % [3]. By now largest measured magnetically controlled strains are already over 10 % [4]. This is about 100 times larger than in other present fast responding actuator materials. For the time being, Ni-Mn-Ga alloys are proven to be the most promising MSM materials and these were used in the applications presented in this article. The MSM effect has been under intensive study by a large number of research groups and many articles describing the mechanism have been published, e.g., [5,6]. Also several applications of the material have been proposed. In this paper we study only the motion generation applications, but different kinds of reverse operations like energy generation or position-, velocity- and acceleration sensors can be implemented with MSM material.

Operating temperatures of the present Ni-Mn-Ga MSM materials range from  $-40^{\circ}\text{C}$  to  $60^{\circ}\text{C}$ . It is expected that new alloy development will increase the operating temperature well above  $120^{\circ}\text{C}$ . The materials development is going on at AdaptaMat Ltd. which is currently the only commercial MSM materials manufacturer.

MSM material's shape change can occur in different modes (see Fig. 1), e.g., axial motion or bending. However, common practical usage of the material is in linear axial motion actuators [7,8]. These have been built for different applications.

The linear MSM actuator and its fundamental properties have been described in [7]. In the present article we concentrate more in specific applications. Benefits of the MSM actuator were found to be fast motion, high operating frequencies, high strains and damping abilities [7].

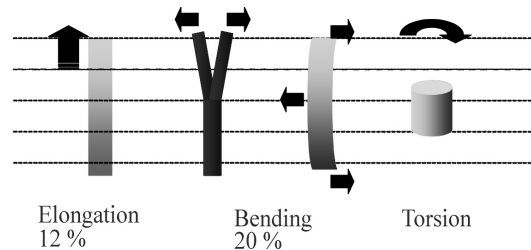


Fig 1: Different forms of MSM shape change.

Two actuator applications are studied in more detail: a linear motor and a valve. Demonstration devices have been built and tested. As an example of different applications we show a pump, where we use two dimensional motion of the MSM element. In addition we discuss the controllability of MSM actuators.

## MSM actuators and control

The most common magnetic circuit topology of the MSM actuators can be seen in Fig. 2. In this topology the MSM element is located in the same magnetic circuit with ferromagnetic core and the magnetic field is generated with the coils. The electric circuit connected to the coil senses this kind of construction as an inductor. The magnetic field strength inside the MSM element is roughly dependent only on the current. The voltage supplied to the coils has a delay before it affects the magnetic field inside the MSM element. Therefore, MSM actuators are best driven with current sources. If driven

with the voltage source, there is extra delay in the operation.

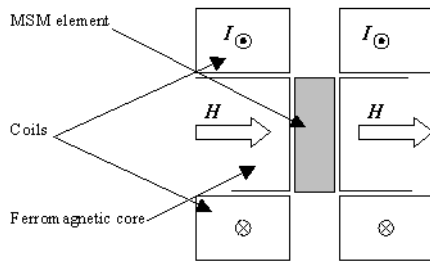


Fig 2: Basic structure of the linear motion MSM actuator

When exposed to magnetic field the MSM element generates stress [5]. Stress is a function of the magnetic field strength which in turn is a function of input current. Hence, when we control the current we can control the MSM actuator's acceleration. This relation affects the position control of the actuator. For position control applications it is beneficial to have an intelligent control algorithm, which takes the relation between current and motion into account.

It is useful to include an external position measurement for position control applications since the motion of MSM actuator depends on the force the MSM element has to work against [7]. A diagram of a control system for a MSM actuator can be seen in Fig. 4. The control system is designed for a linear motor's actuator, but it is generally usable for any MSM actuator used for position control.

The hysteresis of MSM material has to be taken into account in the design of specific MSM actuator application. The hysteresis dampens unwanted mechanical vibrations and higher harmonics of current and in that way ease the control of the application. On the other hand some control application can have trouble with the hysteresis.

The MSM element is the central part of the MSM actuator. The magnetic field induced force of an element depends on its cross-sectional area. The stroke in turn depends on the length of the MSM element. These affect the measures of the actuator. For the time being AdaptaMat's MSM actuators produce strokes up to 5 mm and forces up to 2 kN, using MSM elements up to 100 mm in length. Also larger actuators can be done.

Since the MSM shape change is relatively large, the motion can often be used directly without any mechanical amplification. Hence, the structure of

the actuator is simple and reliable. An example of this type of application is an MSM valve. When very large stroke is needed, a mechanical system to amplify motion is useful. This can be done by using the linear motor structure discussed in the following.

### Application 1: MSM linear motor

The linear motor consists of three parts: actuator, front clamp and back clamp. The design of the motor was based on a variation of inchworm principle. Similar principle has been used for magnetostrictive motors [9]. The structure of the linear motor can be seen in Fig. 3. The actuator is connected to the back clamp, and it moves the front clamp. In forward motion the back clamp opens and the actuator moves the closed front clamp forward and the axis of the motor moves. Then the back clamp closes locking the axis to its new position and front clamp opens and the actuator moves it backward to its original position. By repeating this motion sequence the axis changes its location. By changing the order of the sequence the direction of the motion is changed. The linear motor system can be used also as an actuator. An inductive position measurement system (LVDT) was also integrated to the motor. The basic operation specifications of the motor can be seen in Table 1. Average speed of the axis is 40 mm/s and force 1 N.

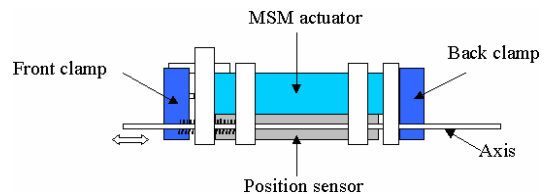


Fig. 3: Basic structure of the MSM motor

Table 1: Maximum ratings of the motor.

Average speed (no-load)	40 mm/s
Force	1 N
Range of LVDT position sensor	25.5 mm

Since the operation of the motor needs synchronous movement of three different electromechanical components, the system has to have a control system. This also makes possible the position control. Each component, two clamps and the actuator, move on their selected phases. By controlling the actuator's electric current during its motion phase we can control the position.

The diagram of the control circuit of an MSM linear motor's actuator is presented in Fig. 4. As

can be seen there are two closed loops in the control system: the current control and the position control loops. The current control is realized by the integrated circuit in the power electric circuits. The position controller is programmed using the LabView software.

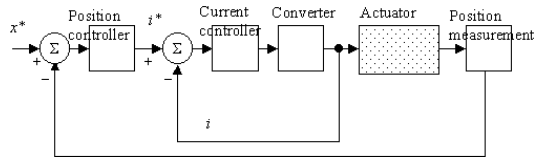


Fig. 4: Diagram of the control system of the linear motor's actuator

Several tests were performed for the linear motor system. Main interest was in the positioning accuracy. For position measurement we used two different position sensors: the LVDT sensor, which was integrated to the linear motor and external laser sensor. LVDT sensor had a higher range, but lower accuracy of the position than laser sensor. The basic operation of the motor without load can be seen in Fig. 5, where the stepping action of the motor can be seen.

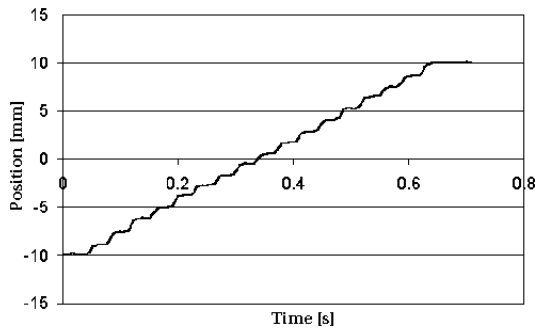


Fig 5: Motion curve of the axis measured with the LVDT sensor

The results when the motor was moving a mass of 70 g can be seen in Fig. 6. At the start of the measurement there is a jump due to the opening and closing of the front clamp. During testing these mechanical effects caused by the clamps were considerably affecting the motion of the motor. The moving mass causes delay and the code uses heavy filtering to improve the position measurement accuracy. The target position was approached slowly because of these issues. Measurements in Fig. 6 show that the positioning accuracy is the same as is the position measurement accuracy. This was less than 1  $\mu\text{m}$ .

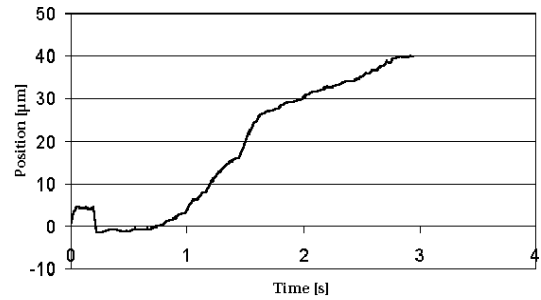


Fig 6: Example of the motion of the axis from 0 to 40  $\mu\text{m}$  measured with laser position sensor.

## Application 2: proportional MSM valve

The MSM actuator was used in a proportional valve to control airflow. A simplified construction of this valve is given in Fig. 7.

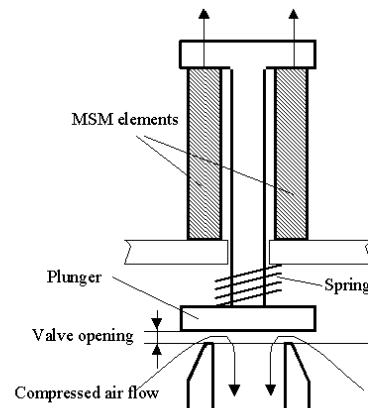


Fig.7: Basic structure of the proportional MSM valve.

Fig. 8 shows the operation of the valve at 40 Hz frequency, when the valve is opening and closing the airway. In valve application the fast ( $< 4$  ms) response of the MSM actuator is utilized. Because the material shape change is large the valve opening is also large without amplification. This makes the structure more robust and easy to manufacture. The magnitude of valve opening can be controlled with the coil current.

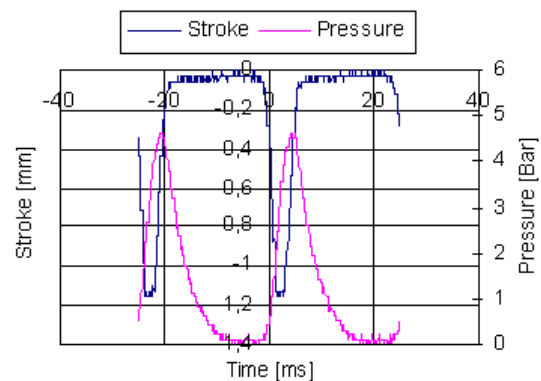


Fig. 8: Pressure behind the valve and stroke of the valve as a function of time.

### Application 3: MSM pump

Third application of our study is an MSM pump. The two other actuator applications presented previously utilize only one direction of the motion of the MSM material. The MSM pump application demonstrates the possibility to use both directions of the motion of the MSM material. The MSM element in this pump application can be seen in Fig. 9.

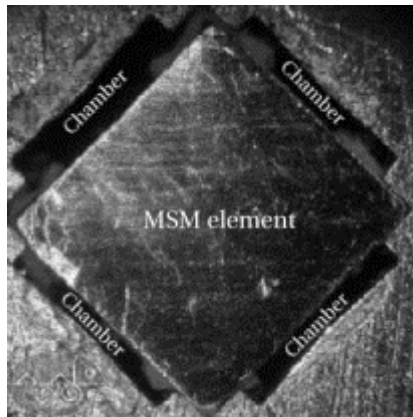


Fig. 9: MSM element inside the pump.

The pump system consists of three parts: the pump itself (shown in Fig. 9) and two valves. As can be seen in Fig. 9 the pump has four separate chambers. The MSM element empties and fills these chambers in turns. With this procedure it can generate pressure. There are several possibilities how to use the valves and chambers to implement the pump. One simple way is to use only the opposing chambers and open and close the valves in turns.

### Conclusions

We discussed the control of MSM actuators and their three specific applications. Clear benefits of the MSM material are high positioning accuracy, short rise time and high strains. The high strains enable robust and simple design of the actuator.

Hysteresis of the MSM material reduces mechanical harmonics and high harmonics of the current, but in some control applications hysteresis can be a problem. In position control applications current directly affects the stress rather than the produced strain of the material. This effect can be solved using advanced control algorithms.

Increasing the operating temperature range of MSM material will increase the potential of MSM technology, e.g., to engine applications. Also the size of the core and coils needed for

field generation have to be taken into account. The study of these issues is proceeding, and more optimal forms of magnetic circuits and MSM materials are being generated.

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