MULTISTABLE VALVE TECHNOLOGY WITH MAGNETIC SHAPE MEMORY ALLOY AS PASSIVE ELEMENT ACTIVATED BY A BIDIRECTIONAL SOLENOID ACTUATOR

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ABSTRACT

Magnetic Shape Memory (MSM) alloys show a superelastic behaviour with possible deformation rates up to 6% until 12% and a sufficient lifetime performance [1, 2]. In this paper, a passive application for a superelastic Ni-Mn-Ga-alloy is presented by using the MSM element as an accurately defined inner friction in a system of a multistable actuator, in particular a multistable proportional valve. The multistable valve is characterized by a currentless holding of the valve displacement in any position of the stroke. This circumstance makes the concept a very low energy consumption valve, compared to conventional proportional valves with solenoid actuators. The new aspect of a rigid connection of MSM Materials enables an absorption of tension as well as compressive forces. To realize an applicable controlling valve, a simple and effective controlling strategy has been implemented. Due to the stabilizing effect of the MSM element, an accurate controlling of the valve stroke and the usage for example as a pressure-, mass-flow or temperature-controlling valve was made possible. Furthermore, some potential applications in pneumatics as well as in hydraulics are presented.

Keywords: Shape Memory Alloy, MSM, Ni-Mn-Ga, multistability, energy efficient proportional valve

1. INTRODUCTION

Multistable actuators, especially multistable valves, based on magnetic shape memory (MSM) materials have been investigated in several publications [3, 4]. These concepts are using the actuation of MSM and the multistability due to the inner friction of the material. Different control strategies have been implemented to this active MSM principle in a proportional valve to reach a sufficient repetitive accuracy and low energy consumption. For MSM based actuators, often relatively high currents are necessary, which is generally in contrast to the energy efficient target of the multistable valve principle. In this paper a new actuation concept of multistable valves with MSM is presented, a simple and efficient control strategy is shown and aspects relevant for valve applications are discussed.

2. STRESS-STRAIN BEHAVIOUR OF MAGNETIC SHAPE MEMORY ALLOYS

MSM elements are produced from single crystal Ni-Mn-Ga alloys, which show a magnetic anisotropy along two defined crystallographic axes. This anisotropy leads to an elongation of the element in one axis, if the other axis is in the direction of a moderate magnetic field > 0.8 T.

Figure 1: Stroke over field measurement of magnetic shape memory alloys.

The elongation depending on the magnetic field is shown in **Figure 1** for different pre-stresses from 0.1 MPa to 3 MPa. Taking a look at the purely mechanical stress-strain characteristics of MSM materials, one can also observe a hysteretic behaviour. In **Figure 2**, the force-over-stroke curve for a mechanical tension (positive force) and a subsequent compression (negative force) of a $3 \times 5 \times 25 \text{ mm}^3$ sized MSM element is shown, demonstrating the hysteretic and superelastic behaviour.

Figure 2: Passive force-stroke behaviour of a MSM tension and compression cycle.

If the element is deformed mechanically up to 6% in length, it remains in this position. The necessary force to mechanically deform the element is the so-called twinning stress, which can be understood as an inner friction of the material. This force-stroke characteristics is not velocity-dependent and the force rises with increasing stroke, because the twins with the highest mobility (or lowest twinning stress) move first. The twinning stress is between 0.2 MPa and 1 MPa for MSM-elements, which is between 3 N and 15 N for a sample with a cross-section of $3 \times 5 \text{ mm}^2$, which corresponds with a type I twinning stress [5]. Important for the controllability of the passive MSM valve is the fact, that each stroke value is disambiguously linked to a defined force value, i.e. that the force-stroke behaviour is strictly monotonous. If the element is not entirely elongated, the force required for initializing the antagonistic motion is similar like the force for initializing the initial motion, allowing hysteretic minor loops to be performed easily.

For the design of actuator and control system the twinning stress has to be properly modelled. This is done with a piecewise linear fit of the force-stroke curves, which represents most measured curves in a suitable way.

3. DESIGN OF MULTISTABLE MSM-ACTUATORS

Compared to previous multistable MSM actuators [3, 4] a modified design has been developed with the aim to increase control quality and to minimize current consumption. The design is based on a superelastic or passive use of the MSM element, which has been introduced in chapter 2 and has been also discussed in other publications yet [6, 7, 8]. To transfer both compression and tension forces between the MSM element and the actuator, it requires a rigid connection with the housing on one side and with the plunger or armature at the other side. This connection is made by laser welding, which has been proven a robust solution.

The actuation is then realized by a bidirectional solenoid actuator, which has a very accurate horizontal force-stroke behavior at every current level. This is advantageous for the controlling behavior of the actuator. Different solenoid systems have been tested, one of them is schematically illustrated in **Figure 3**. Two coils are used, to induce a force in both directions, deforming the MSM element and opening or closing the valve in a proportional way. On the left side of the plunger in **Figure 3**, the valve can be attached, which is presented in the following chapter.

Figure 3: Schematic design of multistable valves with magnetic shape memory alloy as passive element.

In this study, two different valve designs are considered. Both designs are 2/2 proportional seat valves with a nominal stroke of 1 mm. The first design is completely pressure balanced, which makes it suitable for pneumatic as well as

hydraulic applications at higher pressure rates on both sides. The second one has the same design but is not pressure balanced at the outlet, and is, thus, primarily suitable for pneumatic applications with low outlet pressures. The pressure balanced system is tested with a nominal diameter of 10 mm, the other one with a nominal diameter of 3 mm.

The valve stroke of 1 mm requires a MSM element length of 25 mm at a strain of 6%, which takes into account that around 0.2 mm of the potential stroke are lost by the pinning of the twin boundaries at material zone influenced by the laser welding process. The cross-sectional area of the element depends on the twinning stress and, furthermore, determines the level of absorbed force. If we assume fluid forces up to 10 N, the required element area is about 15 mm² for an initial twinning stress value of 0.7 MPa. Experiments with the non-balanced design demonstrated, that lower twinning stresses with an initial force of 5 N also compensate the fluid forces sufficiently at an inlet pressure of 5 bar and a flow up to 100 l/min. This can be explained by additional friction forces of the sealing.

4. ENERGY EFFICIENCY

The current consumption of this type of multistable valves is considered in this chapter. Generally, the valve only consumes current during changing the position of the valve piston. The huge benefit is a current-free holding of any valve stroke under stationary force conditions. The average power consumption P_{mean} is the quotient of the required duty cycle time t_{DC} and the time between consecutive adjustments t_{period} multiplied with the nominal current and voltage of the actuator as follows:

$$P_{mean} = U_N * I_N * \frac{t_{DC}}{t_{period}} \quad (1)$$

While the nominal voltage and the control dynamics, represented by t_{period} in Equation 1, are mainly determined by the application of the valve, the current consumption and the switching time are design parameters. To analyze the influence of these parameters, the boundary values and the average power consumption at different time periods are compared in **Table 1** and **Table 2** for two different actuator concepts.

Table 1: Parameters actuator type II @ $U_N = 24$ V.

Nominal current I_N	1.2 A
Duty cycle time t_{DC}	250 ms
Power consumption P_{mean} @ $t_{period} = 1$ s	6 W
Power consumption P_{mean} @ $t_{period} = 5$ s	1.2 W
Power consumption P_{mean} @ $t_{period} = 20$ s	0.3 W

Table 2: Parameters actuator type II @ $U_N = 24$ V.

Nominal current I_N	8 A
Duty cycle time t_{DC}	10 ms
Power consumption P_{mean} @ $t_{period} = 1$ s	1.9 W
Power consumption P_{mean} @ $t_{period} = 5$ s	0.38 W
Power consumption P_{mean} @ $t_{period} = 20$ s	0.1 W

The valve type II (**Table 2**) exhibits a significantly lower average power consumption compared to valve type I (**Table 1**) due to a lower duty cycle time and smaller dimensions even though it requires a nearly seven times higher nominal current.

The differences between these two valve concepts are dominated by the reduced inductance of the magnetic circuit and the reduced mass of the armature and valve piston. Therefore, an optimization problem between switching time and nominal current results. In the above case, the reduction of the switching time by more than 10 times has a larger influence than the higher nominal current.

In order to find the optimized actuator design for very low energy consumption a holistic optimization study would be required, while the design focus in the present study has been on the horizontal force-stroke characteristics of the actuator to allow a good control behavior.

5. CONTROL STRATEGY

Conventional valves with a mechanical spring typically have a perfect proportional behaviour due to the linearity of the spring which leads to a linear dependency of valve stroke on current. This characteristic is compatible with familiar controllers, like a PID-controller.

However, the output of the multistable valve depends on the current of two coils. Furthermore, the hysteresis and the tolerances of force-stroke behaviour of the MSM elements lead to a dependence on temperature and cycle number. These circumstances make it very difficult to control the valve with model based controlling

methods, which are often applied to conventional proportional valves.

In order to guarantee a stable system, a new simple and effective control strategy has been developed which is based on the stable behaviour of an alternatingly compressed and strained MSM element as discussed in chapter 2. A monotonously increasing twinning stress is required.

Figure 4: Passive force-stroke curve with a noisy plateau in the marked section.

This is given for the majority of the MSM elements measured with few exceptions such as presented by the blue curve in **Figure 4**. A noisy plateau between stroke of $\sim 0,65$ mm until $\sim 0,85$ mm leads to an undefined position at a force level of 10 N, illustrated by the circle in **Figure 4**. This may cause an overshoot of the valve stroke and can be a problem which must be accounted for by the controller. In contrast to the noisy blue characteristic, a well monotonously increasing twinning stress is figured by the red curve, which corresponds to a $3 \times 5 \times 20$ mm³ sized MSM element.

Figure 5: Control behaviour with a target position of 0.5 mm and a flat force-stroke curve.

The control strategy is a simple ramp profile of the current as long as the actual position is deviating from the target position. In our experimental setup, a laser triangulation sensor measures the position as control input. In case of an overshoot, e.g. due to a non-monotonous force-stroke behaviour of the MSM material, the antagonistic coil has to be activated with the same control strategy until the overshoot is within the tolerance. The influence of the different force-stroke characteristics of the MSM material twinning stresses in **Figure 4** is compared in **Figure 5** and **Figure 6**.

Figure 6: Control behaviour with a target position of 0.3 mm and a steep force-stroke curve.

The force-stroke curve of the MSM element used in **Figure 5** has large slope for low strains and a subsequent plateau with a weak force increase (blue curve in **Figure 4**). This causes the tendency of frequent overshoots until reaching the target position of 0.5 mm. In contrast, the force-stroke curve of the element used in **Figure 6** has a constantly increasing force (red curve in **Figure 4**), which reduces the probability of an overshoot to a minimum.

In both measurements an error $< \pm 1\%$, hence $< \pm 10$ μm , can be achieved by using the laser triangulation sensor. The measurement quantity in an industrial fluidic system typically is a fluidic parameter such as pressure or flow rate, thus the control accuracy is significantly influenced by the measurement accuracy.

6. SENSITIVITY ANALYSIS OF INFLUENCE PARAMETERS FOR CONTROL DESIGN

In order to analyze the stabilizing influences of various parameters in this control strategy a 1D transient model of the valve has been developed. A sensitivity study of the overshoot depending on

different parameters has been performed using the software optiSLang®. The model describes the inertia of the plunger, a friction term and the modelled nonlinear force-stroke curve and the modelled actuator force. The resulting differential equation

$$m\ddot{x} + d\dot{x} + F_{TW}(x) = F_{act}(x, t) \quad (2)$$

is solved numerically. The twinning force of the material is modelled by two linearized sections as introduced in chapter 2. The force-stroke-dependence of the actuator is taken into account and the time dependent ramping profile is implemented. The considered parameters including their boundary values are listed in **Table 3**. The output value is the error between the target value and the overshoot after a current pulse excitation.

Table 3: Model parameters and their boundaries

Time to switch on	$t_{ein} = 1 \dots 50 \text{ ms}$
Slope of force-stroke curve of actuator	$s = -10 \dots 10 \text{ N/mm}$
Deviation from target value	$x_{Ziel} = 0.05 \dots 0.9 \text{ mm}$
Plunger and armature total mass	$m = 0.005 \dots 0.2 \text{ kg}$
Duration of current ramp	$t_{Rampe} = 5 \dots 500 \text{ ms}$
Maximum twinning force of MSM material	$F_2 = 6 \dots 25 \text{ N}$

Figure 7: Influence of the model parameters on the displacement error

A sensitivity analysis based on 100 different designs within the parameter range of **Table 3** is performed and the resulting dependence of the overshoot on the parameters is compared in **Figure 7**. A positive dependence value means

that an increase of the respective parameter causes an increase of the overshoot and vice versa.

The maximum twinning stress F_2 and thus the slope of the force-stroke behavior has the largest influence on the overshoot with a high value being beneficial for a reduced overshoot. This corresponds with the analysis of the stability for two different characteristics a in **Figure 5** and **Figure 6**. The second and third important parameters are the ramping time and the mass of the plunger, which affect the dynamic behaviour. A higher mass and a lower switching time increase the inertia forces and cause a higher probability of an overshoot error.

The forth relevant parameter is the deviation of the stroke from the target value. The distribution in **Figure 8** shows that deviations from target $x_{Target} < 0.2 \text{ mm}$ cause only small contributions to the overshoot probability which can be expected.

Figure 8: Error distribution depending on the target displacement.

7. APPLICATIONS

As mentioned in chapter 3, pneumatic as well as hydraulic applications can be realized with the proposed type of multistable valves. Such valves are designed for applications, in which a constant mass or volume flow is preserved for longer periods and which require a very low power consumption. If the application requires high control dynamics, the valve can be used due to its fast switching.

The restricting parameter is the time between consecutive adjustments of the fluid flow. If this time becomes too small, the advantage of the multistability is lost. The minimum useful time

depends on the size of the valve and the flow parameters and thus from the application.

The most common controlled quantities in fluidics are a mass or volume flow or a pressure. In contrast to the plunger position used as control input in this study, this requires a measurement signal with the necessary accuracy. The pressure can be controlled at the inlet or outlet and the measurement signal should have a low noise level, to avoid that the controller and the fast actuator start oscillating. An analog problem may occur, if a mass-flow controlled valve has a fluctuating inlet pressure, which leads to frequent control adjustments if the error range for is too narrow. Further potential control quantities are a fluid temperature or fill level.

Different fields of application can be considered. Power plants like fuel cells or combined heat and power generation systems, whose efficiencies are diminished by the power consumption of any system component, are often driven in stationary conditions which makes them attractive candidates for energy efficient multistable valves. The same argument holds for air-conditioning systems with various coolant fluids. For mobile medical care devices, a multistable valve can be suitable, too. Such systems are often electrically supplied from a battery, so that an energy efficient and compact system contributes to their maximum independent operation time without recharging the battery.

8. CONCLUSION AND OUTLOOK

In this paper, recent progresses in the development of multistable valves with MSM have been presented. Therefor an optimization of the entire design concept has been done compared to previous designs and two different actuator types have been investigated. The focus of research was on the controllability and the energy efficiency of the valve. A new control strategy has been implemented, which leads to a stable behaviour, due to the combination of an aligned bidirectional solenoid actuator and the typical characteristic of a passive deformed MSM element. The energy efficiency of two different actuator types is regarded. A comparison has shown, that a reduction of the switching time has a greater influence on the energy consumption reduction than lower nominal current rates. To optimize the energy consumption, the actuator

design has to be investigated holistically. Furthermore, the average power consumption of the multistable valve with passive MSM utilization will always depend on the application and its control requirements.

Future investigations will be done on the improvement of the control strategy with respect to the measurement and control of a fluidic value. Another topic of investigation is the usage of high temperature alloys, which could make applications with temperatures higher than 80°C possible.

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