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Smart Control Systems for Smart Materials

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Shape memory alloys (SMAs) are thermally activated smart materials. Due to their ability to change into a previously imprinted shape by the means of thermal activation, they are suitable as actuators for microsystems and, within certain limitations for macroscopic systems. Most commonly used SMAs for actuators are binary nickel-titanium alloys (NiTi). The shape memory effect relies on the martensitic phase transformation. On heating the material from the low temperature phase (martensite) the material starts to transform into the high temperature phase (austenite) at the austenite start temperature (A_s). The reverse transformation starts at the martensite start temperature after passing a hysteresis cycle. To apply these materials to a wide range of industrial applications, a simple method for controlling the actuator effect is required. Today's control concepts for shape memory actuators, in applications as well as in test stands, are time-based. This often leads to overheating after transformation into the high temperature phase which results in early fatigue. Besides, the dynamic behavior of such systems is influenced by unnecessary heating, resulting in a poor time performance. To minimize these effects, a controller system with resistance feedback is required to hold the energy input on specific keypoints. These two key points are directly before transformation (A_s) and shortly before retransformation (M_s). This allows triggering of fast and energy-efficient transformation cycles. Both experimental results and a mechatronical demonstrator system, exhibit the advantages of systems concerning efficiency, dynamics, and reliability.

Keywords automotive, control, fatigue, shape memory alloys, simulation, steering

1. Introduction

Shape memory actuators have certain characteristics which are unique in comparison to other actuating principles. Today's competitiveness of micro- and mechatronical systems is determined by precision, cost, quality, and simplifications. Systems driven by shape memory elements can be used for smart actuators which include aspects of flexibility and mass reduction in addition to the above-quoted. The aspect of simplification is related to the system's costs as well. For example, a shape memory actuator driven system generally consists of fewer parts than conventional ones (Ref 1). Furthermore, the reduction of parts often enhances the reliability of the actuating components. Besides, the mass of shape memory systems as compared to other actuators is lower. A striking advantage of shape memory actuators is the significantly higher working capacity in comparison to conventional actuators. These advantages are beneficial, for example, in automotive applications. In spite of these advantages, the broad break-through of actuators driven by shape memory alloys (SMAs) is hindered by polycausal phenomena.

One critical hindrance is the repeatability of standardized SMA actuators, which depends on fatigue effects and thermal variations of ambient conditions. If the ambient temperature rises, the phase transformation will be completed earlier in face of heating with the same current and heating time as compared to lower ambient temperature. Another disturbing effect, causing system damage as well, is overheating of the material by too long current feeds. That overheating even accumulates with increasing numbers of phase transformations because the phase transformation temperatures decrease with every transformation cycle (Ref 2). If a SMA actuator system is only controlled by time-variant current switches, it will be overheated more and more after each transformation and this will cause accelerated fatigue. By electrical activation of shape memory wires, the maximal wire temperature is located at the middle of the actuator's length. This is caused by the electrical connection which commonly is made of materials with a high heat transfer rates. Thus, the thermal field of shape memory wires have a maxima in the so-called mid-section. In this mid-section, the temperature reduces the yield strength so the material becomes more ductile. If an actuator is overheated during actuating cycles (with the coupled mechanical load), the mid-section is elongated more than the rest of the SMA actuator. This additional elongation is partly irreversible and leads after cycling to structural failure. Hence, analysis of proper electrical activation and development of an adequate and simple control system is the first step for minimizing these disturbance variables and for realizing a reliable long-life actuating SMA system.

2. Electrical Resistance of Shape Memory Wires

Today, most shape memory systems are designed by trial and error methods. This usually leads to high engineering cost

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and long developing phases. Often the designers underrate the interdependency of SMAs and try to build product prototypes ignoring crucial system interrelationships. One striking interrelating effect of a shape memory actuator is the change of the resistance behavior during activation, which can be used to detect the phase transformation start and finish. In order to analyze the response time in dependence of electrical current and shape memory wire dimension, a test rig was equipped with a resistance detecting unit. Figure 1 schematically shows that test rig, consisting of an air bearing, a distance sensor (detecting the wire contraction Δx as displacement) and a resetting element (bias spring). During heating, the shape memory wire contracts compressing the bias spring. The Young characteristic of the bias spring is insignificant to the actuating tests (nearly 0.08 N/mm) causing load divergences $<2\%$. The resistance is measured by detecting the current and the voltage in the testing circuit. Basically, the resistance of shape memory actuators is a function of temperature and mechanical stress. The tension-dependant resistance change is included in the structural part of the equation. The variable (l_w) is the elongated wire length (for example, by mechanical load). This elongation leads to resistance change.

$$R_A = \rho_{NiTi} \cdot \frac{l_w}{A_w} \cdot [\alpha_{NiTi} \cdot \Delta T + 1] \tag{Eq 1}$$

$$\rho_{NiTi} = \rho_{aus} \cdot \psi(T) + \rho_{mar} \cdot [1 - \psi(T)] \tag{Eq 2}$$

R_A is the electrical resistance, A_w is the wire-actuator cross section, l_w is the elongated wire-actuator length, T is the temperature, α_{NiTi} is the thermal resistance coefficient for NiTi, ψ is the volume ratio of the B2 phase ($0 < \psi < 1$), ρ_{NiTi} is the specific electrical resistance of NiTi (unencumbered): $\rho_{NiTi} = \rho_{mar} = 1.067 \times 10^{-6}\ \Omega\text{m}$ for $\psi = 0$, $\rho_{NiTi} = \rho_{aus} = 1.014 \times 10^{-6}\ \Omega\text{m}$ for $\psi = 1$ (Ref 3).

Figure 2 exemplarily shows the characteristic of the phase transformation by the electrical resistance plotted against the displacement of the wire at load of 200 N/mm^2. In the first activation phase, the material consists of pure martensite. The first increase of the resistance (I) is characterized by conventional metallic resistance change depending on temperature. During transformation (II), the phase-dependant decrease of the specific electrical resistance (ρ_{NiTi}) superseeded by the thermal resistance change (α_{NiTi}). This causes a decline of the absolute resistance in the second segment of the characteristic. When the phase transformation is finished (III), the material completely consists of austenite. The resistance increase of the third phase is again induced by conventional metallic resistance change depending on temperature. Unfortunately, the resistance behavior, as well as the deformation behavior is influenced by material fatigue effects. The cycle-dependant change leads to a relative displacement of the characteristic resistance curve on the ordinate (resistance axis) and by the change of transformation temperatures the resistance feedback hysteresis is limited. All in all, this reduces the possibility to control the activation or deformation behavior of the actuator by its specific resistance values. Clearly, repeatable phenomena of these resistance curves are the local extrema. Considering those extrema the establishment of a control system detecting the time gradient is possible because due to the calculation of these extrema, a transformation start and finish point can be detected.

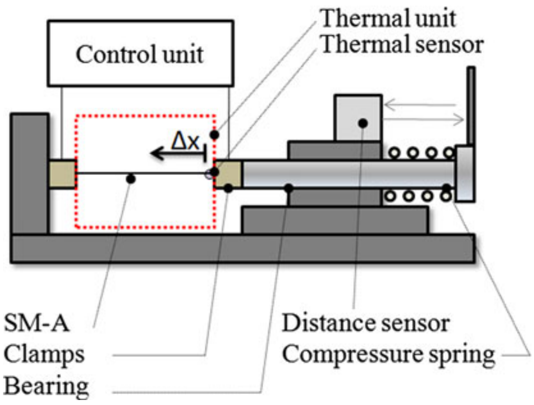

Fig. 1 The test rig for resistance feedback of NiTi-wires

3. Experimental and Numerical Simulation

With the detection of the electrical resistance, a smart control system with automatic current outage can be used for material characterization. Several NiTi-wires with different lengths (from 100 to 300 mm) and different diameters (0.15-0.25 mm) of a Dy90 wire (Dynalloy) were tested with a mechanical load of 200 N/mm^2 on the test rig, Fig. 3 combines results as a characteristic function. Different diameters were accommodated by using a current-area ratio (ampere to cross section). The results clearly point out that within the considered time range the wire length has no noticeable influence.

A numerical simulation, using Matlab/Simulink engine has been build up by the authors to describe the activation behavior of shape memory actuators (Ref 4). This simulation calculates the phase transformation of binary NiTi alloys especially with time-variable current profiles and variable load conditions. These parameters cannot or may be inadequately described with simplifying algebraic functions. In order to characterize the activation behavior of a SMA actuator system, all time variant and invariant energy fluxes that pass the system border

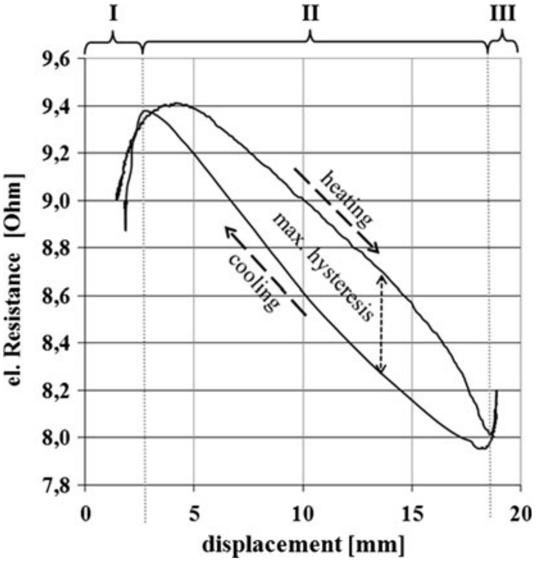

Fig. 2 A resistance curve of a binary NiTi alloy over the actuating displacement

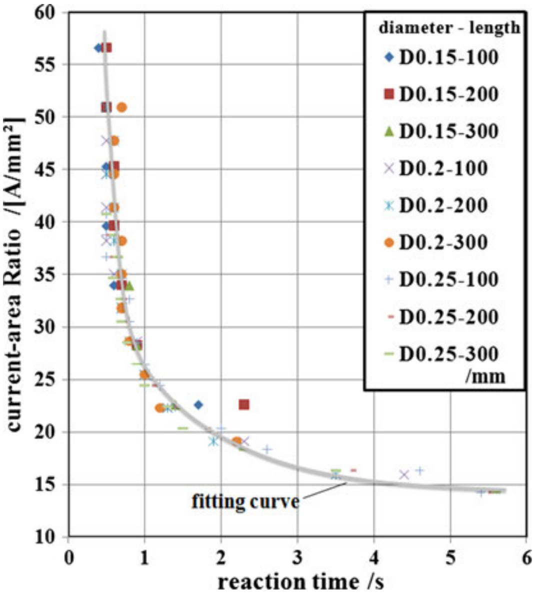

Fig. 3 Results from the activation testing of binary NiTi-wires

have to be balanced. This energy balance of the whole system for a straight SMA wire with a bias spring is exemplarily shown in Fig. 4(a). Figure 4(b) shows the results of the simulation as well as a comparison of those results to the experimental data from Fig. 3. It is obvious that there is a distinct analogy of both, experiment and simulation.

4. Conceptual

As already published in Ref 5-7, it is possible to create PID-controlled systems by detecting of the actuator's electrical resistance. While this method tends to result in stable and applicable systems, the current supplying unit (with fast potential variation) often surpasses the actuator costs, itself. In addition, most SMA actuator applications are confined to binary activations without the need of moving toward an inclined position of the maximal gage. These simple systems are commonly activated over a defined time period (time variant steering) using a constant heating current.

In order to analyze the fatigue damage caused by overheating and to develop a simpler and cheaper system for common shape memory actuators, the resistance feedback control has been used. The aim was to avoid unnecessary overheating and to generate a system which automatically cuts off energy discharge after reaching complete material transformation. In addition, the system reacts to temperature changes and gives feedback on its transformation status. For that purpose, the test was equipped with a microcontroller system (smart control system) with a simple resistance detection circuit (Fig. 5). There are two logic states at the SMA connection: low and high. During the low phase, the current is set to constant 20 mA, which is insufficient to cause a shape memory activation but sufficient for resistance detection. If the controller unit sets the circuit on high, a second current supply with a constant current of 1200 mA is activated. The controller detects the SMA's voltage by the pulse wide modulation (analog input port) with a frequency of 50 Hz. This measuring signal passes a noise filtering processor and is calculated by using Ohm's law and the two possible current levels to the SMA's resistance. For simple position holding applications, there is the possibility to integrate a two-level controller, so after having passed the complete transformation, the controller can hold the resistance level slightly over the reverse transformation starting point (M_s) using binary control pulses. This enables the holding of the maximal displacement position for differing time periods without the risk of system damage by electrical overheating.

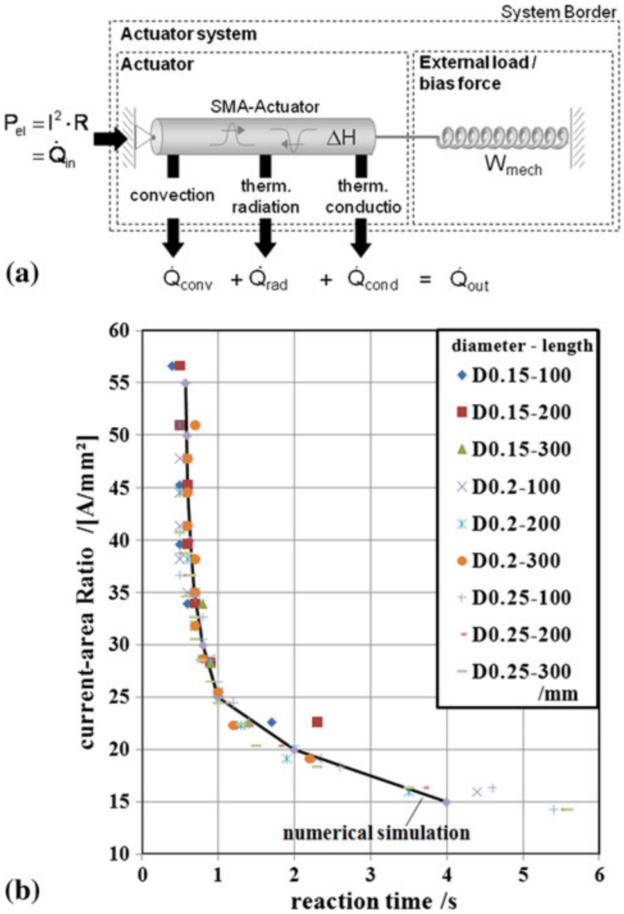

Fig. 4 (a) Energy balance of a NiTi-wire for the numerical simulation of the activation behavior. (b) Results from the numerical simulation of activation time in comparison to the tested results

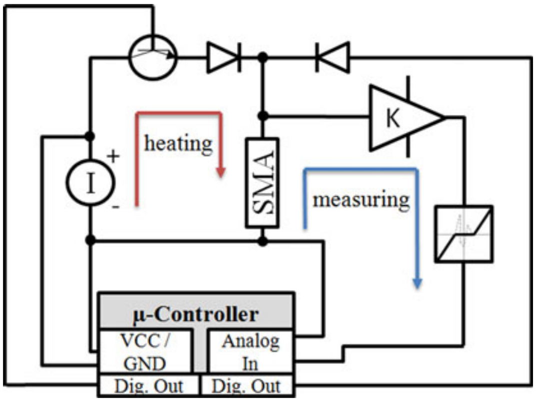

Fig. 5 Resistance detection circuit with filters and signal gains

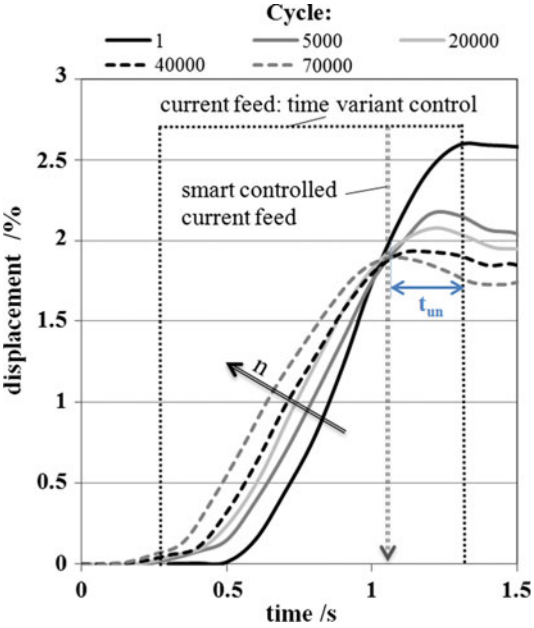

Fig. 6 Dynamic behavior of time-variant controlled NiTi-wire. The smart control system is exemplarily shown as the arrow, which cuts automatically the current of after completing the phase transformation

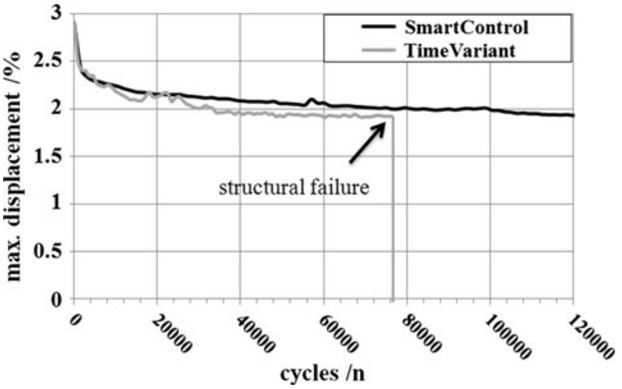

Fig. 7 Fatigue comparison of time-variant and smart-controlled NiTi-wires. The time-variant controlled wire failures after 77 thousand cycles. The smart-controlled wire was activated more than 120 thousand cycles without failure

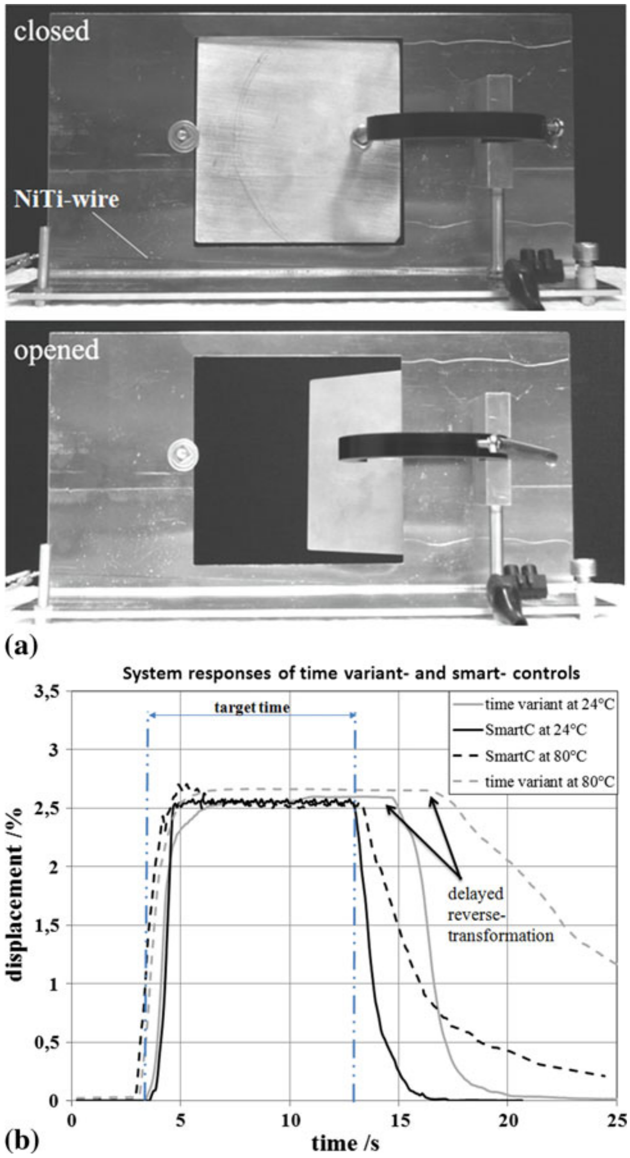

Fig. 8 (a) Comparison of both control systems at different boundary temperatures; (b) demonstrator for automotive application: automatic fuel door opener. A small NiTi-wire opens the fuel door repeatable, with no delay of the reverse starting time and at different ambient temperatures. In addition, it opens for an uncertain time without the risk of overheating

5. Fatigue Testing and Results

Further experiments investigate the dynamical system response over the actuator's life. While the time-variant controlled system (Fig. 6) overheats the actuator over an unnecessary heating period (t_{un}) the smart-controlled system cuts of the energy automatically. An interesting system response, which first seems to be unimportant, is revealed in Fig. 6 too. Directly after the phase transformation, the displacement slightly declines. This is a hint for the thermal strain of a pure austenitic material caused by additional heating after passing the austenite finish temperature. This effect reduces the displacement up to 10% of the possible contraction (total: 0.2% of wire length).

Regarding the material fatigue at room temperature, Fig. 7 shows testing results of resistance-controlled activation in comparison with a time-variant control system. This figure shows the maximal displacement curves (in percent of the actuator's length) of a trained (Smartflex) NiTi alloy wire with a diameter of 0.25 mm. The mechanical load for this experiment was 400 N/mm^2, which approximates a tension force of more than 19 N. This load approximates the maximal possible loads for cycling applications due to Ref 8. The results show that the time-variant system fails after 77 thousand cycles. The smart-controlled system has been ended by the authors after 122 thousand cycles without failure.

6. Application and Conclusion

In order to build reproducible actuating systems, several solutions can be chosen. On one hand, an actuator can be protected from overheating by choosing the right electrical powering in combination with the adequate heating time. A proper steering method (especially for systems with many actuating cycles) is a resistance-controlled system. Another advantage of those systems is the decoupling of the activation phase from boundary temperature gradients. The change of the ambient temperature field is typical in automotive applications. Automotive systems have to operate properly in a temperature range from 220 to 370 K for more than 100 thousand cycles. With a small microcontroller a universal and low-priced control unit can be integrated in a demonstrator system like an automatic fuel door opener. Figure 8(a) shows the real demonstrator. The small NiTi-wire (diameter 0.25 mm, length = 180 mm) opens a fuel door at different ambient temperatures without the risk of damaging the material. The door can be activated for a manually triggered period (target time) which can be set by a wireless remote control. The reaction time to start the reverse transformation is not influenced by the ambient temperatures in this system.

In contrast the time-variant control only enables the activation of the transformation for a certain target time, and furthermore it has a longer reaction time after current cut off (Fig. 8b). The mechanical load of 400 N/mm^2 grants a martensite finish temperature of nearly 350 K, while every 1000st cycle is at $T_e = 350$ K. Examining Fig. 8(b), the system's response (start of back-transformation) is delayed after energy cut off. The delay at $T_e = 350$ K is significant in comparison to the smart-controlled system, which stays nearly identical to the room temperature test.

In general, this work proves that the electrical activation of shape memory wire actuators is not as trivial as often seen due to many considerable boundary parameters, but can be handled by resistance-controlled systems. Such systems enhance the repeatability of SMA actuators' work at differing thermal boundary conditions and fatigue effects.

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