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# Simulation-Based Design of a Rotatory SMA Drive

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**The design and optimization of a rotatory drive powered by shape memory alloy (SMA) actuators is described in this paper. SMA actuators used in technical applications are parameterized by the use of trial-and-error methods, because there is a lack of computer-aided design tools for this active material. A numerical modeling approach was developed to design and optimize the geometry and the load and heating conditions of SMA actuators in a technical system to achieve a good dynamic and a high reliability. The shape memory effect used in most technical systems is the extrinsic two way effect (2WE). This effect can be simulated with the numerical model which was implemented in MATLAB/SIMULINK. The focus of the model is on the activation behavior of the SMA actuator, which defines its rate of heating and cooling. Different load conditions and various actuator geometries and shapes, e.g. wire or spring actuator, are simulated by the calculation of the energetic balance of the whole system. The numerical model can be used to simulate time variant heating currents in order to obtain an optimal system performance. The model was used to design a rotatory SMA-drive system, which is based on the moving concept of a wave drive gear set. In contrast to the conventional system, which is driven by an electric motor, the SMA drive consists of a strain wave gear and SMA wire actuators that are applied circularly to generate a rotatory movement. Special characteristics of this drive system are a high torque density and a high positioning accuracy.**

**Keywords** mechanical testing, modeling processes, superalloys

## 1. Introduction

Actuators are always series of energy providers and energy transducers. An actuator can be considered a 'new actuator' when its function is essentially based on physical characteristics of new transducer materials [e.g. shape memory alloys (SMAs)] (Ref 1). SMAs show a characteristic property by which the metal remembers a high-temperature shape and reverts to it as a result of a phase transformation between the low temperature phase (martensite, α) and the high temperature phase (austenite, β). This transformation process can be utilized to generate the work load (Ref 2). The characteristic transformation temperatures $M_s$, $M_f$, $A_s$, $A_f$ (where M is martensite, A is austenite, s is start, and f is finish) represent the start and finish temperatures of this phase transformation. The phase change between the two solid phases involves a rearrangement of atoms within the crystal lattice. The fraction of martensite and austenite in the SMA device depends mainly on its actual temperature, its stress condition, and the transformation temperatures which are determined by the chemical alloy composition of the SM material. The results of research presented in this paper are all based on the use of binary nickel titanium (NiTi) as SM alloy.

The fundamental features of shape memory actuators are (i) the high energy density (characterizing the work load to volume ratio) and (ii) the high reversible strain when exploiting the one way effect (1WE). This makes SMAs unique compared to other smart materials that can be used for actuator applications. Cyclic actuator movements of SMAs are often realized by what is referred to as an "extrinsic two way effect" (2WE). The shape memory effect only governs one direction, i.e. the SMA device remembers its shape as it transforms from the low-temperature to the high-temperature phase whereas the backward movement on cooling (which transforms the device back into α) results from an external resetting force, e.g. a biasing spring. Experiments show that extrinsic two-way effects are superior in engineering applications to the so-called intrinsic two-way effect which suffers from being difficult to achieve by thermo-mechanical training, from a lack of stability and from only small exploitable strain amplitudes. In order to use SMAs as switching transducer materials, particularly SMA wires can easily be heated with electric current by the use of their electrical resistance. As the time response of SMA actuators is limited by the velocity in which heat can flow in and out of the material, small devices like thin wires outperform thick section components in this respect.

Although the exceeding properties of SMAs are already known, these materials could not be established in R&D processes so far. A number of problems have limited their success on the market which is partly due to a lack of generally accepted design procedures and difficulties in manufacturing suitable components. In this paper, the design and optimization of an SMA actuator in a technical application based on a numerical simulation of the activation behavior is presented. The simulation is validated experimentally and used exemplary for a SMA powered Rotatory Drive System.

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## 2. Numerical Simulation of Shape Memory Actuators

The activation of SMAs, defined as the stroke-time-relation of the actuator within transformation, is solely specified by the velocity of cooling and heating the material. Many factors determine the dynamic behavior of SMA actuators: the chemical alloy composition, the actuator's geometry, the position and width of the hysteresis, the electrical heating current (DC) I and its cycle I(t), the mechanical load and the number of cycles as well as the environmental conditions. Especially with time variable current profiles and also variable load conditions, these parameters cannot or only inadequately be 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 have to be balanced. This energy balance of the whole system for a straight SMA wire with a bias spring is shown in Fig. 1.

The only energy source during the heating phase is an external electric current that heats the wire by using its ohmic resistance. Regarding the heat transmission for the cooling process of the actuator, three effects are distinguished in thermodynamics: convection, thermal radiation, and thermal conduction (Ref 3). The heat transmission caused by free air convection is about 90% and by heat radiation about 10% of the total emission.

The low influence of heat conduction due to the clamping of the wire can be neglected. Similarly to the consideration of the emitted heat flow, the required mechanical energy, resulting from the returning device and external loads as well as the integral latent heat for transformation from martensite to austenite has to be quantified.

The latent heat for transformation is considered proportional to the derivation of the volumetric martensite fraction $\xi$. Its value for the applied SMA actuators was specified by a differential scanning calorimetry (DSC) measurement to about 24000 J/kg. According to the first law of thermodynamics, the caloric state equation for the actuator′s inner energy can be described for heating and cooling by differential equations.

These non-linear first order differential equations cannot be solved definitely with analytic methods. Therefore, the solution curve for one unknown parameter, as the wire temperature $T_w$ for instance, has to be calculated numerically by using an approximation procedure. Besides the solvability of the problem at all, the main advantage of using a numerical method is the possibility of implementing time-variable parameters that depend on the mixture between martensite and austenite and thus have an impact on the phase transformation. These

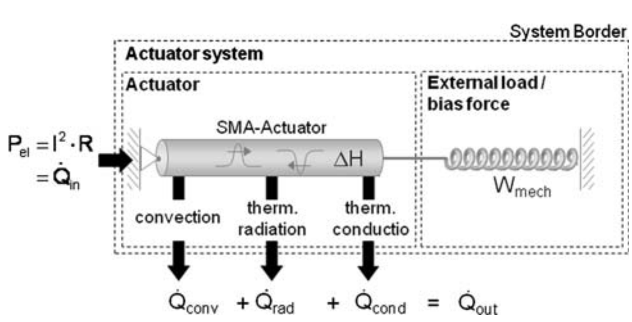


**Fig. 1** Energy balance of a SMA actuator system

mixture-dependent parameters are the convective heat-transfer coefficient, the thermal expansion, the elastic elongation, the geometry and the ohmic resistance of the SMA actuator. Thereby the quality of the generated model can be enhanced.

All these parameters are influenced by the geometric shape of an actuator. The most common SMA actuator shape is a thin wire. For this shape the stress behavior under load conditions can easily be described, as well as the change of the geometry and the ohmic resistance. For some applications SMA spring actuators are used. The behavior of a spring-shaped actuator is different to a wire actuator. The convective heat-transfer coefficient is temperature dependent, on the one hand, but on the other hand, the shape generates interdependencies between the sections of the spring which have a huge influence on the numerical model. A complete uncompress spring behaves like a wire-shaped actuator whereas a fully compressed spring can be described as a hollow cylinder. Between these two states of the spring a linear transformation is assumed. The stress condition differs as well. A wire actuator is loaded by axial stress only, which is constant over the cross section. A spring actuator shows a completely different condition with shear stress and a cross section related increased maximal stress that can be described with a known parameter *k*.

For the analytic description of the SMA's characteristics during phase transformation, an interconnection with a hysteresis model that has to be parameterized by the input of specific actuator attributes is necessary. For this purpose a simple hysteresis model from Liang and Roger (Ref 4) that segmentally defines the characteristic hysteresis curve of a SMA with trigonometric functions in the different temperature ranges is implemented into the numerical model. With an extension of this hysteresis model it is possible to describe not only the outer hysteresis routes, but also inner hysteresis route (Ref 5). On these routes the actuator is not heated up to or over the temperature where the transformation into austenite is completed or the heating of the actuator is started before the back transformation into the martensitic phase is finished. These activation strategies can be used to increase the dynamic of the actuator system.

## 3. Numerical Model

The computer-aided computation of the differential equations and the relevant process parameters in order to simulate the time response of a SMA actuator during phase transformation is implemented in MATLAB/SIMULINK. The complete SMA actuator system was built in SIMULINK (Fig. 2) as a block diagram consisting of data sources and sinks, algebraic functions, logic operations and customized subsystems. Important inputs for the SIMULINK model (e.g. length and diameter and number of coils of the actuator, constant of the opposed bias spring(s), environmental conditions) are separately combined in a MATLAB script for easy parameterization. By using virtual switches (upper left) the heating current can be defined (constant value, sine wave, ramp, arbitrary sequence…). The energy sinks (convection, radiation, latent heat for transformation, mechanical energy) are defined in subsystems and added to the model. In the loop shown, the wire's temperature, the mechanical stress, the transformation temperatures depending on the stress and the martensite fraction are calculated. The change in the ohmic resistance of the actuator, as a

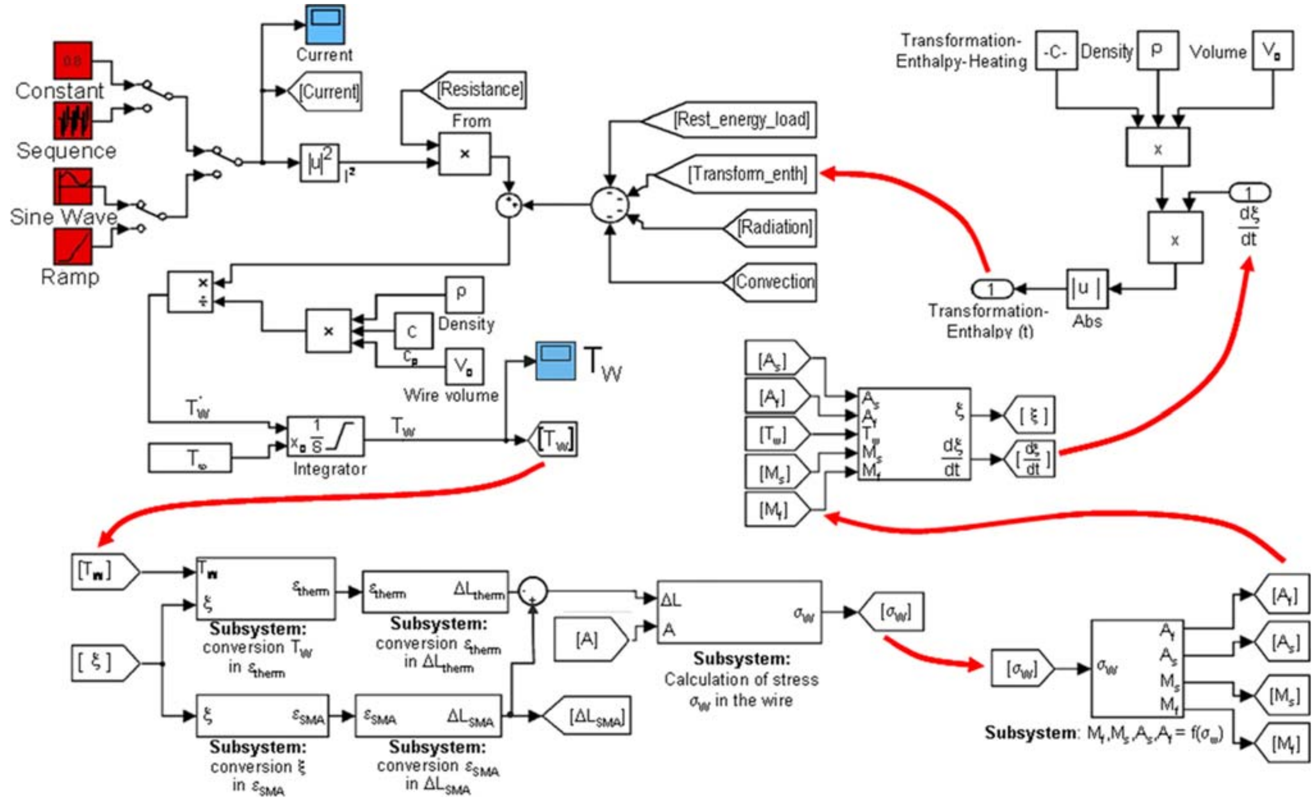


**Fig. 2** Simulink flowchart: heating stage

function of the temperature and the geometry of the wire, is calculated in the subsystem *Resistance*. These values—each interdependent—can be visualized by the use of scopes that can be placed at any position in the model.

A comparable block diagram which can be parameterized by the input of the initial values for the start temperature TW_start and the start martensite fraction ξ_start was generated for the cooling phase.

This model was designed to simulate the time behavior of a SMA actuator, depending on the boundary conditions, like the bias force and the heating current. Within the model the heating current, the stress depending transformation temperatures ($M_f$, $M_s$, $A_s$, $A_f$) and the wire temperature TW are calculated. Using the hysteresis model the current martensite fraction ξ during phase transformation is computed. With the martensite fraction ξ the current stroke of the actuator ΔlW is calculated.

## 4. Experimental Validation and Simulation Results

In order to validate the SIMULINK model, an SMA actuator is analyzed experimentally and compared numerically. For simulation and experiment, the applied load, the heating current profile, and the boundary conditions were the same.

An experimental setup has been developed, shown in Fig. 3. It was built to analyze the time response of straight SMA actuator wires or spring actuators. The SMA actuator (5) is clamped between a force transducer (6) on the one side and an aerostatic motion slide (3) that is connected with the bias load (1) and a measuring plate for the ultrasonic displacement transducer (7) on the other side. The programmable power

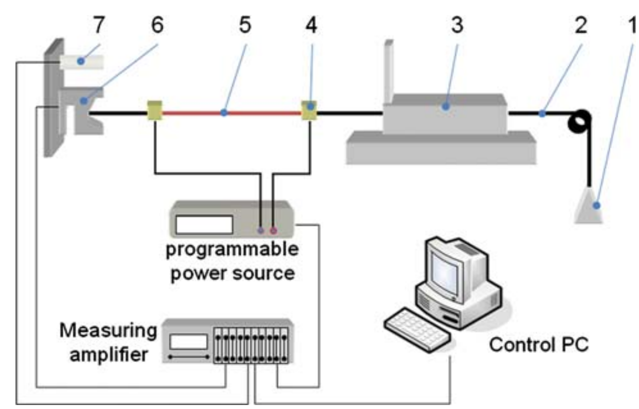


**Fig. 3** Experimental setup for a constant load

source enables the generation of a totally arbitrary heating current that is switched over to the actuator with a relay.

Figure 4, showing an uncompleted cycle of only a third of the maximum stroke with the heating stage on the left and the cooling stage on the right, confirms the physically good implementation of the actuator's properties and its behavior in the SIMULINK model exemplary. The used NiTi wire actuator came from Memory Metalle, Allow Dy90, and had a diameter of 0.25 mm with a length of 800 mm. A constant bias force of 5 N was applied and the heating current was set to 0.6 A.

It is evident that the computed stroke-time curves match the measured curves well. Differences between the measured and the simulated process can be detected at the beginning of the transformation and at the end of the cooling phase. These differences may occur as a result of the simplified, but wrong

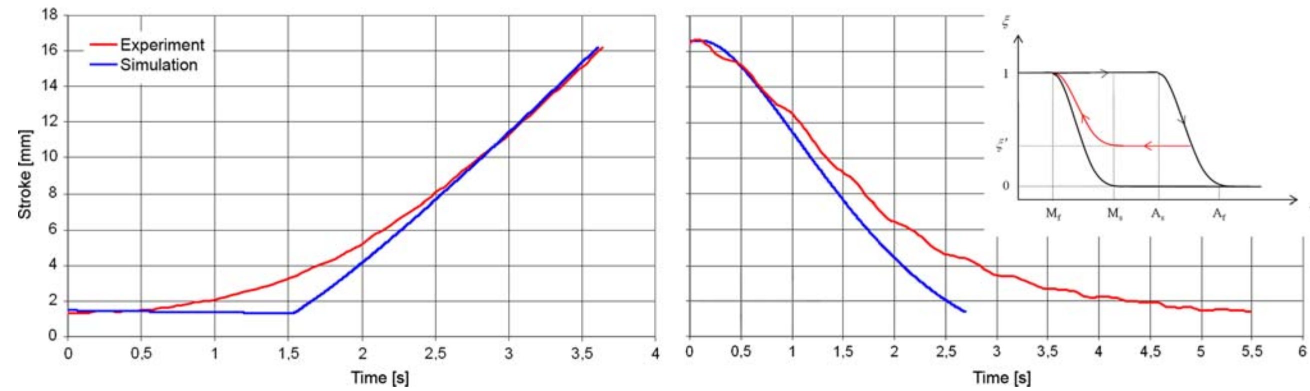


**Fig. 4** Simulation vs. experiment: results of an inner hysteresis route

simulation boundary condition of a constant surrounding temperature in the direct actuator proximity and the friction of the direction change mechanism for the bias force occurring mainly during the cooling phase.

Even better results were obtained for a complete transformation with not only constant heating currents, but also ramp or step current curves. To match the loading conditions of the application described in the next section, the experimental setup can be changed and resetting forces can be generated by installing a bias spring or a pneumatic force generator, which can create variable forces by a regulating valve that controls the volume flow rate blown on a piston connected to the aerostatic motion slide.

## 5. Simulation-Based Design

Based on the results gained by the numerical analysis of the SMA actuator's activation behavior, a rotatory stepping motor powered by SMA actuator wires has been developed. By using the numerical model and its simulation results, the properties of the stepping drive were optimized.

The drive system with straight SMA actuator wires that is presented in this paper is based on a harmonic drive (HD) gear (Ref 6). A conventional HD gear consists of three components: the drive is executed by the Wave Generator, a thin-raced ball bearing that is fitted onto an elliptical plug. The Flexspline is a flexible steel cylinder with external teeth. The Circular Spline is a solid steel ring with internal teeth and has one to two teeth more than the Flexspline. When the elliptical Wave Generator rotates, the pivotable Flexspline shifts within the Circular Spline in a rotatory motion free from slippage. As Flex- and Circular Spline have different numbers of teeth and therefore different circumferences, a relative movement occurs. The gears reduction ratio results from the different number of gear teeth. The functional principle of the HD gear was adopted for the design of a rotatory drive system and enhanced with an actuator component: the Wave Generator is left out and the deformation of the Flexspline is realized by external forces that are provided by eight electrically driven double laid straight SMA actuator wires (see Fig. 5). In this setup, the bias force, which is needed to reset the actuator during the cooling phase, is provided by the elastic properties of the Flexspline which is made of aluminium and the deforming force of the other activated actuators.

With this basic concept the numerical model was used to calculate the optimal diameter of the SMA wires and the

**Fig. 5** SMA-powered Rotatory Drive System

constant heating current, which can be applied with two opposing strategies to generate a movement in both clockwise and anticlockwise direction. The optimization process works in an iterative way. A start set of actuator and boundary parameters is computed. With the fast and modular simulation tool a quick change and calculation with a variation of single parameters is possible. Although this iterative optimization method is a fast and inexpensive way to simulate and design a broad range of technical SMA actuator systems, actual research is focused on the development of a design tool, which uses special algorithms to automatically select and parameterize an optimal SMA actuator.

## 6. Conclusion

Based on an energy balance calculation of the actuator system a numerical model for the activation behavior of SMA actuators (wire and spring shaped) was presented. The model features a simple way to parameterize the actuator system and is therefore well suited for the design and layout of technical solutions with SMA actuators. It includes different environmental conditions, temporally variable heating currents as well as different time variable loads. In addition, inner transformation routes can be simulated. The qualitatively good implementation of the system's properties was proven experimentally. Using the gained results, a stepping drive with straight SMA wires was developed, which was optimized by use of the simulation model.

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