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Design and Modeling of a self-sufficient Shape-Memory-Actuator

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ABSTRACT

In machine tools several time and position varying heat sources causes complex temperature distributions. The resulting problems are varying thermal deformations which cause a loss of accuracy as well as non optimal drive conditions. An option to deal with that issue is to use structure integrated SM-actuators which use the thermal energy accumulated by machining processes to yield an actuator displacement. That creates a structure inherent control loop. There the shape-memory-elements work as sensing element as well as actuation element. The plant is defined by the thermal and mechanical behaviour of the surrounding structure. Because of the closed loop operation mode, the mechanical design has to deal with questions of stability and parameter adjustment in a control sense. In contrast to common control arrangements this issues can only be influenced by designing the actuator and the structure.

To investigate this approach a test bench has been designed. The heat is yielded by a clutch and directed through the structure to the shape memory element. The force and displacement of the actuator are therefore driven directly by process heat. This paper presents a broad mechanical design approach of the test bench as well as the design of the SM-actuator. To investigate the thermo-mechanical behaviour of the structure-integrated actuator, a model of the test bench has been developed. The model covers the thermal behaviour of the test bench as well as the thermo-mechanical couplings of the shape memory actuator. The model has been validated by comprehensive measurements.

Keywords: shape-memory-alloy, actuator, self sufficient, structure integrated, adaptive, ball-screw-drive

1. INTRODUCTION

In machine tools there are several heat sources that vary in time and position. Combined with changes in the environmental conditions complex temperature distributions occur. The resulting problems are varying thermal deformations. Common machines are optimized for using under defined conditions. If these conditions differ, the thermal deformations cause a loss of accuracy as well as non optimal drive conditions

A well distinguished and a common realized way to avoid such irregularities is using the machines CNC-control unit to compensate thermal deformations. There are different approaches for realization. For instance, it is possible to use a thermal model of the machine to determine the thermal deformations as well as using additional sensors. The basis of these approaches is to use the main drives to compensate the deformations. This is an adequate and simple solution if the deflection occurs in the actuating direction of the main drive. But it is rather complex to use it to compensate multi-axial deformations or deformations that differ from the main drives moving direction.

A suitable way to deal with this problem is to design thermo-stable structures. If deformations occur on a part of the structure where they directly effect to the Tool-Center-Point, the deviation of the TCP is often multi-axial and differs from the directions of the main drives. To compensate these deformations it is necessary to integrate additional components that enable to react against the forces caused by thermal extensions. These devices can be either hydraulic, electromechanical or piezobased components. Even though these devices work seemingly well, the principle is not applicable in all cases. There are limitations caused by the complex design, the limited forces and the system costs. A recent approach to design thermo-stable or thermo-adaptive structures is to use thermal Shape-Memory-Alloys (SMA).

Thermal SMAs offer the special ability to “remember“ and re-assume their original shape following permanent plastic distortion below a specific critical temperature by means of heating up above this temperature. A reversible austenite-martensite phase transformation is required for the development of the shape memory effect. Analogous to steel the high temperature phase of the material is also described as austenite and low temperature phase α as martensite. In an ideal

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situation the austenite β phase is converted into the martensite α phase as a result of shear. Due to diffusion-free rearrangement processes in relation to the atoms this generates a change in the stacking sequence of the crystal lattice levels and therefore enabling a change in the structure of the crystal lattice. Consequently, two different stress-strain-curves exist as shown in Figure 14. In the low-temperature phase a small Hook region is followed by a so-called plateau-stress. in this case, the material can be easily deflected almost without increasing the applied external stress. After setting the stress to zero, a plastic deflection remains to the material. Heating the material causes the described phase transformation and results in a completely different stress-strain-behaviour. During the phase transformation from martensite to austenite (heating) the material is able to perform mechanical work. The amount of work depends on the mechanical boundary conditions. The normal operation mode is to use the material in an arrangement with a spring, as it is shown in Figure 1 (a) or a mass.

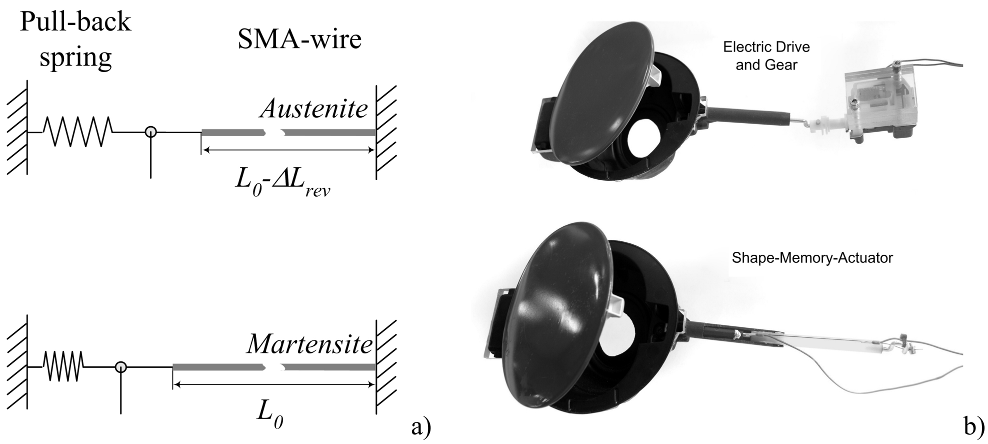


Figure 1: Common working principle of a SMA-actuator (a), application example of a SMA-wire actuator: fuel gap (b)

The currently focused actuation approach is to use SMA-wires to design actuators which replace electric drives as shown in Figure 1 (b). Such wire actuators use the contraction of the wire resulting by the phase transformation, to create movements. Due to the required electrical energy and the system dynamics, this approach is limited to actuators with small cross sections. Therefore the achievable forces are less than 100N. The benefits of this approach are significantly smaller, lighter and cheaper drives. Plenty of effort is spent in research to obtain a level that allows realizing serial applications. Especially the automotive industry and the consumer product industry push this work.

An even more unexplored approach is the integration of SMA-actuators into mechanical structures for compensating thermal deformations. In this paper we present two different working principles of structural integrated SMA-actuators. The mechanical design process is demonstrated at the example of an adaptive ball screw drive. The thermal modelling of the structure integrated SMA-actuator is another important task. Here we present a nodal based modelling approach to describe the thermal behaviour.

2. WORKING PRINCIPLE OF SELF SUFFICIENT SMA-ACTUATORS

The requirements for designing thermostable structures using SMA are completely different compared to conventional SMA actuators. Depending on the structure forces of several kilonewtons up to several ten kilonewtons are necessary. However, the generated displacements have to cover a range between several microns and 1 mm. Therefore the actuator geometry has to be changed completely from the wire to a more compact body. Heating by means of electrical current as it is done in the case of wire actuators is not possible. There are rather two different operation modes for these actuators.

2.1 The fully-adaptive approach

The application of electric current is not possible due to the increased diameter of the actuator. A more convenient solution is the application of area oriented heat mechanisms like heating foils or electrical resistors mounted at the surface. An alternative but usually more complex approach is the application of induction heating systems. However, in all cases the actuator is fully controllable. An adaptive ball screw drive as an example of such system design is shown in Figure 2 b).

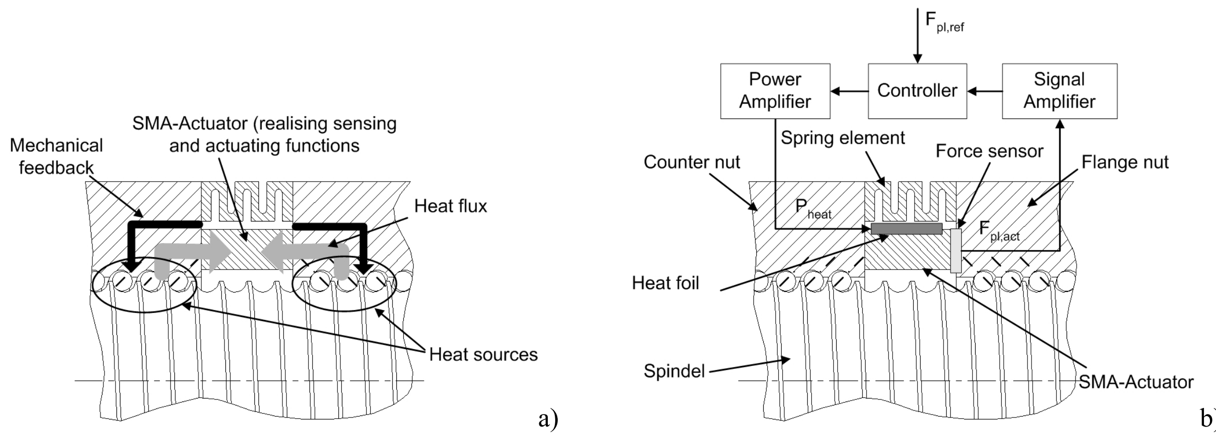


Figure 2: Ball screw drive with integrated SMA-actuator: fully adaptive approach (a) and self-adaptive approach (b)

The design process of external heated actuators is focused on the mechanical design and the design of the heating and sensing component. The thermal characteristic of the structure is less important at this operation mode compared to the autonomous system. However, it must be ensured that the heat transfer to the actuator does not influence the surrounding structure. This can be achieved by implementing some layers or elements with minor heat conductivity to avoid a heat flow in the surrounding structure.

2.2 The self adapting approach

Another way to operate structural integrated SMA-actuators is to use thermal energy which is accumulated by machining processes. Typical sources are friction in bearings or the heat produced by electrical drives. This approach is especially suitable if this waste heat causes thermal deformations which influence the machine behaviour.

A possible system design is shown in Figure 2 a). The heat produced by friction is guided through the structure to warm up the SMA-actuator. When the actuator reaches its transformation temperature, it contracts and causes a mechanical feedback to the friction mechanism. In this operation mode the SMA-element realises actuation function as well as sensing functions. According to the thermal and the mechanical transfer path a closed loop, similar to a control loop, is created. The closed loop is an inherent part of the structure. There is no need for external control devices. That means that the system can be thermo-stable if it is designed properly. Every heat input causes an actuator displacement which acts back at the thermal deformation caused by the heat input.

Compared to the fully-adaptive approach described in chapter 2.1 the thermal transfer behaviour gets more important. Due to the fact that the system behaves like a control loop, the stability issue has to be focused in the design process. The thermo mechanical behaviour and the stability of the system can only be adjusted by designing the mechanical structure. This involves the thermal behaviour of the structure, like convection, conduction and the heat capacity, as well as the mechanical behaviour. Of course the thermo-mechanic parameters of the actuator, like transformation temperatures, stiffness an so on, are considered significantly. Over all, very complex interactions during the design process have to be regarded. Understanding these interactions is one of the objectives of the project "Self-sufficient Self-Adaptive Systems based on Shape-Memory-Alloys" within the Cluster of Excellenz "eniPROD".

3. APPROACH OF AN ADAPTIVE BALL SCREW DRIVE

Ball screw drives are commonly used in today's machine tools to convert rotary to linear motion. Due to the demands of high accuracy and rigidity, balls screw drives are usually preloaded to avoid backlash. However, preloading also determines durability, friction and therefore heat generation and noise. The basic setup for a ball screw drives is always a conflict of aims between high precision and rapid manufacturing.

Operating a ball screw drive with high preload causes an increase of friction. The friction causes a heat flux into the surrounding components, like the nuts and the spindle. Due to the rising temperature thermal deflections occur. That causes negative effects regarding durability and accuracy due to an increasing backlash. This problem can be solved by varying the preload during operation. Currently known approaches range from conventional systems using servo drives [3] to systems using piezoceramic actuators [1], [2]. However, these solutions necessitate implemented actuators that are, considering the efforts quite honestly uneconomic.

According to the approaches discussed in chapter 2.1 and chapter 2.2 there are two different system designs using SMA-actuators. The fully controllable approach, as shown in Figure 2 a), uses heat foils for heating the actuator and a force sensor to measure the pre tension. With a suitable controller it is possible to follow a defined value of pre tension. Due to the required actuator mass, the bandwidth of the control is strictly limited. Nevertheless, it is possible to react on changes at the environmental conditions.

The self-adapting approach, shown in Figure 2 b) does not necessitate any external element. The control loop is closed by the structure of the ball screw drive, the SMA-actuator and the friction heat. As it was mentioned in chapter 3 the system design rather has to be focused on the thermo-mechanical behaviour of these elements instead a control algorithm. Even though an active control of the pre tension is not possible, the approach ensures a constant pre tension independent from environmental and temperature changes of the ball screw drive. Both approaches are currently under investigation.

4. MECHANICAL DESIGN OF SMA-DRIVEN ADAPTIVE BALL SCREWS

There are several approaches to achieve a predetermined preload of the ball screw e.g. a single nut with lead offset, pitch-shift or ball oversize and a double nut with adjusting washer or spring element. To adjust the preload several attempts with piezoelectric actuators have been made and were discussed in [1], [2]. They all have in common that a double nut was chosen due to high demands. Mutuality is the adjusting element which was placed between load carrying nut and preloading nut.

An important influence on rigidity of the whole assembly is the contact between balls and grooves in shaft and nuts. For this reason it is highly nonlinear. The general correlation between an external load and a deflection is described in [4]. A load change will cause a preload depletion in one nut and a preload raise in the other one as shown in Figure 3. Installing an additional element, e.g. the actuator, between the nuts, will influence the rigidity of the ball screw. Thus the preload chart has to be enhanced to reflect the changing mechanical properties. In Figure 3 the actuator is referred to the load carrying nut and therefore the characteristic is flatter. The elimination of asymmetrical behavior – equal amount of pressure and tension leads to unequal deflections – has been discussed in [1].

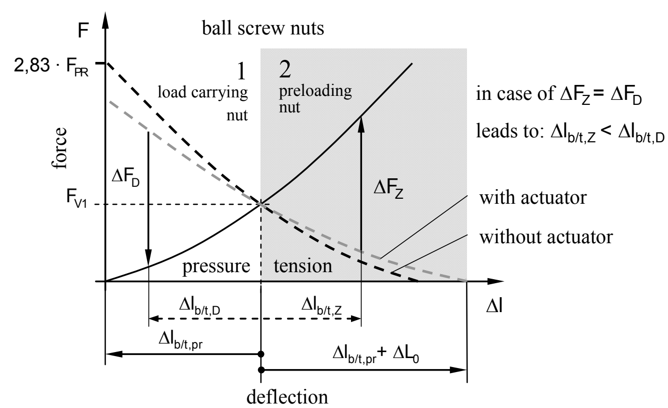


Figure 3: Preload chart of a ball screw with and without actuator

Due to the fact that using an actuator made of shape memory alloy, which is characterized by nonlinearities, and the nonlinearities of the ball screw, a rough estimate has to be done under simplified boundary conditions. One linearization method is to connect the corner marks at maximum pressure and maximum tension for each nut (Figure 4-I). Another variation (Figure 4-II) is specified in [4]. However this method is not convenient due to the fact that calculations will lead to a less required actuator deflection than really necessary.

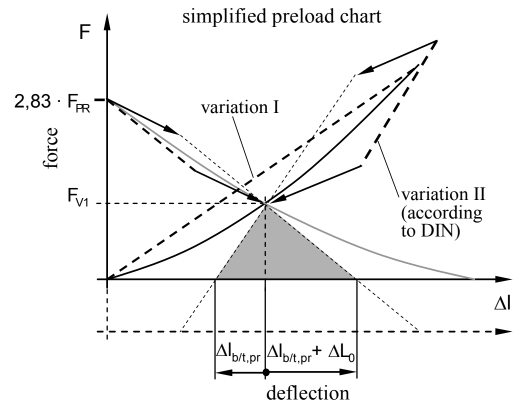


Figure 4: Simplified preload chart of a ball screw

A simplified mechanical model of a adaptive ball screw with a double nut and actuator is shown in Figure 5, regardless of fully-adaptive approach or self adaptive approach. The adjusting washer has been replaced with the actuator. The actuator consists of a SMA-element and a spring to reset the SMA-element's initial shape.

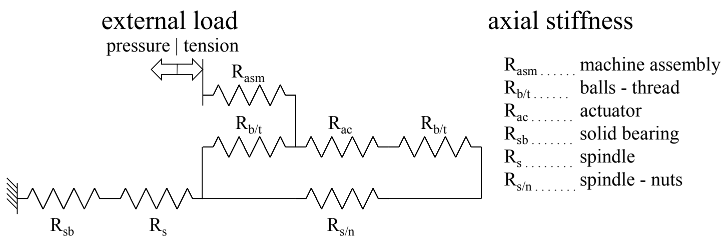


Figure 5: Simplified mechanical model of a ball screw drive with actuator

The total axial stiffness R_{ges} of a ball screw drive (where one end is supported with a double bearing and the other end is supported with a single bearing) and an actuator system is defined as:

$$R_{ges} = \frac{1}{R_{sb} + R_s + R_{asm} + \dfrac{1}{\dfrac{1}{R_{s/n} + R_{ac} + R_{b/t}} + R_{b/t}}} \tag{1}$$

If a critical temperature is reached, the SMA-actuator in the autonomous system will sense it and reduces its length. Hence the preload decreases and thus affects friction and therefore wear. It also has an impact on the stiffness, since the stiffness of the balls $R_{b/t}$ is nonlinear. Compared to a ball screw without a smart washer the preload will increase the hotter the nuts get. However, compared to the piezoelectric actuator system it will not be possible to use a SMA-driven mechanism for increased positioning accuracy because of its low dynamics.

5. THERMAL MODELLING OF STRUCTURE INTEGRATED SMA-ACTUATORS

In contrast to actuator systems, which are externally heated, like shown in Figure 1, the mechanical design of self-sufficient actuators have to deal with thermal as well as mechanical questions. Therefore, the force and deflection provided by the actuator is only one aspect of the design process. However, the mechanical design is only a static task and can be done with the formulas described above.

An important task, especially for the self adaptive approach, is the dynamic modeling of the structure. Due to the neglectable mechanical influence of the dynamical behavior, dynamical modeling has to deal with the thermal aspects of the structure only. A way to describe the thermal behavior is to use FE-models. Even though this results in a very detailed definition of the system's behavior, there are several other problems. The strongly nonlinear behavior of the SMA-material needs huge effort to build an exact model of the SMA-actuator. Especially in transient simulation, which is needed for describing the feedback behavior, the effort is very high. Another aspect is the adjustment of the feedback parameters. Like described in Chapter 2.2, the structure integrated actuator behaves like a negative feedback loop. Therefore the design rules for such feedback loops have to be noticed. Due to the structure inherent feedback loop, an adjustment of control parameters is not as easy as in conventional controllers. The only way to adjust these parameters is to change the thermal behavior of the structure and the actuator. For extracting the relevant design parameters and to estimate the influence of them related to the thermal behavior, a nodal model of the thermal behavior is even more suitable than a FE-model.

5.1 Thermo-mechanical modelling of self-sufficient actuators

To describe the dynamic properties of the shape memory alloy actuator (SMA actuator), it is necessary to develop a thermal model of this actuator. This task is considered to be very challenging if the thermodynamic basic laws and constraints are used. Thus it is advantageous to use the analogy between thermodynamic and electrical systems. That possesses to transform the thermodynamic behavior into an electrical network of resistors and capacitors. The conductive and transmission resistances (thermal) correspond with the electrical resistances. The heat flow and the thermal potential correlate with their electrical analogies of current and electrical potential. The network consists of finite primal cuts of the desired physical model and describes the properties of the corresponding section by single node points. Every section is assumed to be homogenous, i.e. in all sections a constant thermal field across the length of the part exists. Figure 6 shows the general correlations.

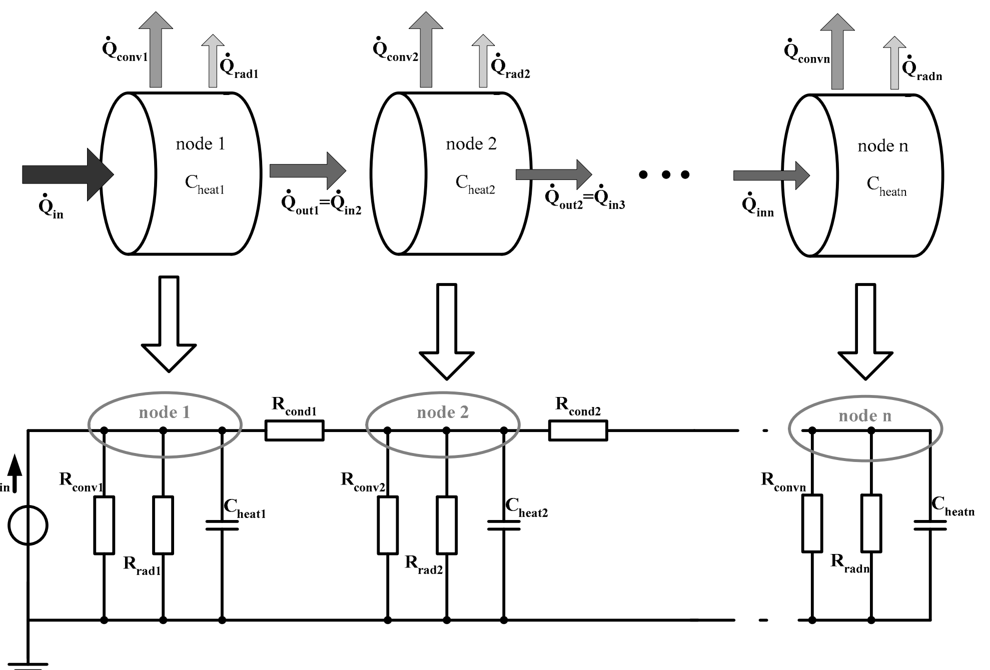


Figure 6: Schematic view and general electrical network

The heat balance of the finite elements yields the resulting heat flow of the sections to:

$$\dot{Q}_{out} = \dot{Q}_{in} - \left(\dot{Q}_{cap} + \dot{Q}_{radiation} + \dot{Q}_{conv}\right) \tag{2}$$

$$\dot{Q}_{out} = \dot{Q}_{in} - \left(C_{th} \cdot \dot{\vartheta} + \alpha_{rad} \cdot A_{rad} \cdot \Delta\vartheta + \alpha_{conv} \cdot A_{conv} \cdot \Delta\vartheta\right) \tag{3}$$

The objective of the work is to calculate the temperatures of each element in the actuator module. Therefore it is necessary to know the parameter of the objects for rendering radiation, convection, conduction and heat capacity. They are defined by its geometry and by the properties of the material, especially by its specific heat capacity and conductivity. The challenge is to calculate sufficient parameters, because the SMA-module is mechanically complex, consisting of disk springs and the SMA-actuator. For this reason it is necessary to develope a sufficient approach for further calculations. The conductivity of the SMA mounting in the actuator is averaged by the cross section of the surrounding material (copper, steel). The conductivity of the module including disk springs for resetting the SMA and the SMA-element itself is also influenced by its surface. Due to the variable cross section area of the springs and its dependency of the deflection of the SMA actuator it is approximated to a quarter of the real cross section area. The parameters of the remaining module components are ascertainable because parameters like diameter, material, surface and length are definite. Further it is necessary to implement a calculation of convection and radiation, because these parameters heavily depend on the current temperature.

The known nodal analysis of the electrical network possesses to calculate the temperatures in detail and allows to build a model of the object to be used it in Matlab/Simulink®. This method yields a system of differential equations as described by:

$$\begin{pmatrix} C_1 & 0 & 0 & 0 & 0 \\ 0 & C_2 & 0 & 0 & 0 \\ 0 & 0 & C_3 & 0 & 0 \\ 0 & 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & 0 & C_n \end{pmatrix} \cdot \begin{pmatrix} \dot{\vartheta}_1 \\ \dot{\vartheta}_2 \\ \dot{\vartheta}_3 \\ \vdots \\ \dot{\vartheta}_n \end{pmatrix} + \begin{pmatrix} \sum\limits_{nodal\,1} G & -G_{cond\,1} & 0 & \cdots & 0 \\ -G_{cond\,1} & \sum\limits_{nodal\,2} G & -G_{cond\,2} & \cdots & 0 \\ 0 & -G_{cond\,2} & \ddots & \cdots & \vdots \\ \vdots & \vdots & \vdots & \ddots & -G_{cond\,(n-1)} \\ 0 & 0 & \cdots & -G_{cond\,(n-1)} & \sum\limits_{nodal\,n} G \end{pmatrix} \bullet \begin{pmatrix} \vartheta_1 \\ \vartheta_2 \\ \vartheta_3 \\ \vdots \\ \vartheta_n \end{pmatrix} = \begin{pmatrix} \dot{Q}_{in} \\ 0 \\ 0 \\ \vdots \\ 0 \end{pmatrix}, \tag{4}$$

or in short form:

$$\underline{C} \cdot \underline{\dot{\vartheta}} + \underline{G} \cdot \underline{\vartheta} = \underline{\dot{Q}} . \tag{5}$$

Now it is relatively easy to ascertain the transfer functions. Converting equation 5 by using the Laplace transformation shows, that the elements can be described by a first order lag element. However, a model with lots of control loops is to complex to handle with. Hence it is suitable to describe the system in state space description as defined by:

$$\begin{aligned} \underline{\dot{x}} &= \underline{A} \cdot \underline{x} + \underline{B} \cdot \underline{u} \\ \underline{y} &= \underline{C} \cdot \underline{x} + \underline{D} \cdot \underline{u} \end{aligned} . \tag{6}$$

Transforming equation 4 results in:

$$\begin{aligned} \underline{\dot{\vartheta}} &= -\underline{C}^{-1} \cdot \underline{G} \cdot \underline{\vartheta} + \underline{C}^{-1} \cdot \underline{Q} \\ \underline{\vartheta} &= \underline{I} \cdot \underline{\vartheta} + \underline{0} \cdot \underline{Q} \end{aligned} . \tag{7}$$

This nodal model is implemented in Simulink by using the “Embedded Matlab Function” that possesses to calculate inside the matrices. To calculate the convection and radiation parameters it is estimated that there is unforced convection around the actuator. Therefore the equations according to [6] for unforced convection are valid and will be used in the the calculation. For the simple reason that Matrix A is plugged with the temperature signal it is realized inside the Matrix A.

The last step is to implement the hysteresis model, which describes the activation behavior of the SMA actuator. It is realized by a state machine, which alternates between 3 states depending on the martensite ratio of the SMA and is described in [5]. The model calculates the deflection of the SMA body for the elements and adds them to the total contraction of the actuator. Though it is achievable to develop a control system, which controls the injected heat. The final system is further extended by a thermal expansion model which simulates the property of expansion caused by heating material. To control the injected heat the actuator should be able to compensate the expansion completely. The model allows to simulate and test different scenarios before the practical realization. Figure 7 shows the developed model. The dotted line box covers the thermo dynamic properties of the structure. The output y are the temperature of the nodes. The dashed-dotted line box covers the thermal deflections, caused by the temperature rising, of the structure. It can be seen, that this deflections cause a positive feedback and would make the system instable. The SMA actuator (dotted line box) brings a negative feedback in this arrengement because of the contraction during the phase transformation. Due to this, the SMA-actuator is able to compensate the expansion and therefore able to control the system. Comparing the model with a conventional control loop shows that the SMA actuator works as a controller and the injected heat acts as a disturbance. The control parameters are defined by the geometrical and material properties of the SMA-element and the surrounding structure. To validate this modeling approach a test bench was designed.

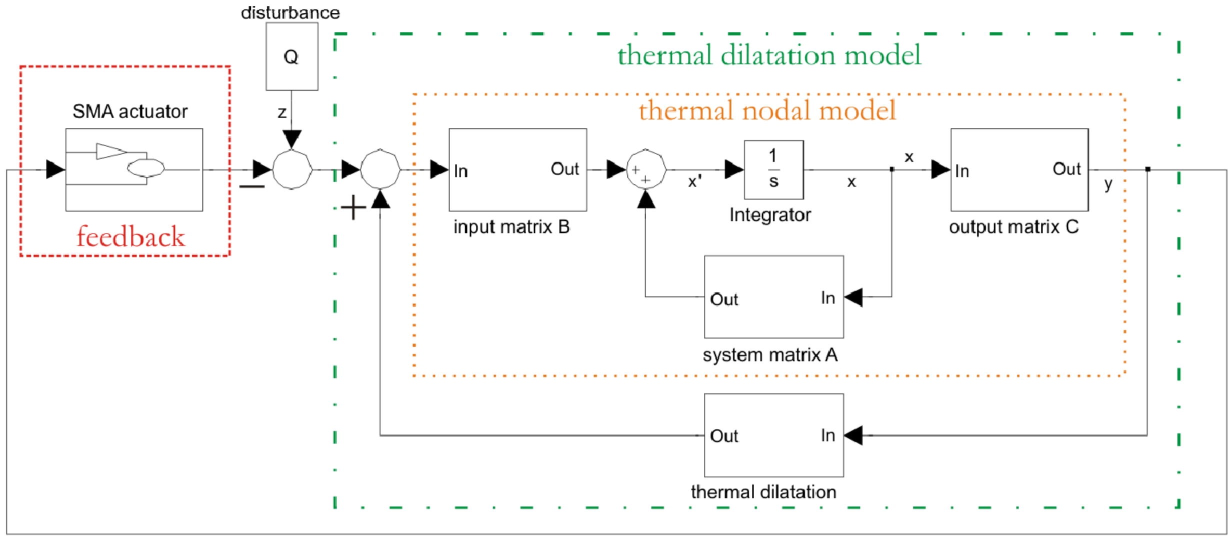
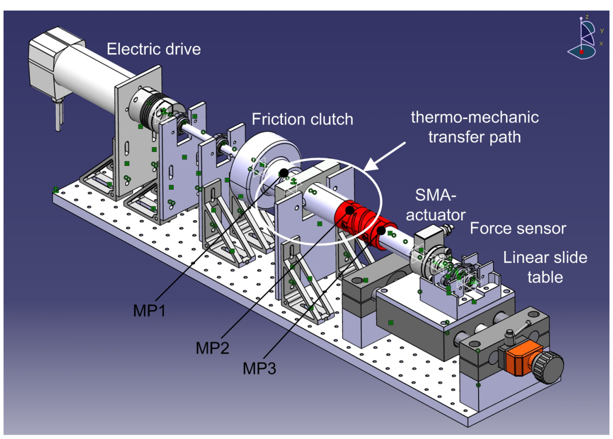


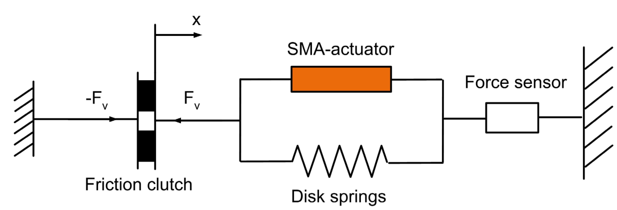
Figure 7: Control scheme of the structure inherent feedback loop

5.2 The test bench

The described application of an adaptive ball screw drive has very complex interactions between the actuator and the thermo-mechanic behaviour of the ball screw drive and the operation process. To achieve a more general knowledge of the mechanisms that are important for designing self-sufficient actuators, a test bench, shown in Figure 8 a) was designed. It consists of an electric drive, a clutch and a thermo-mechanical transfer path. The electric drive creates a rotational motion in the left side of the test bench, while the right side remains standing. The resulting relative movement in the clutch causes a frictional power which induces a heat flux into the right side of the test bench. The two parameters for adjusting the induced thermal energy are the rotational speed of the motor and the axial force of the clutch. The speed of the electrical drive is set to be constant due to the accurate speed control of the drive. The axial force can be adjusted by the linear slide table and can be measured by force sensor. A simple mechanical scheme is shown in Figure 8 b).



a)

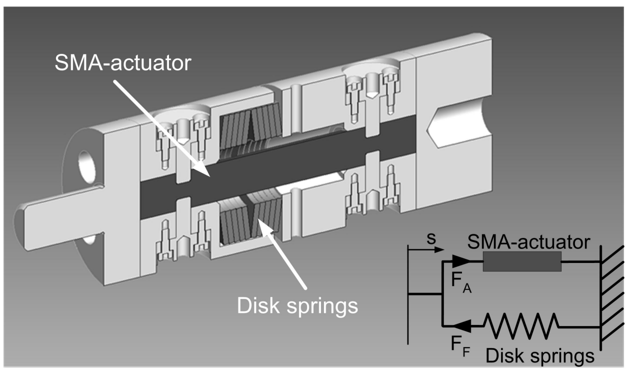


b)

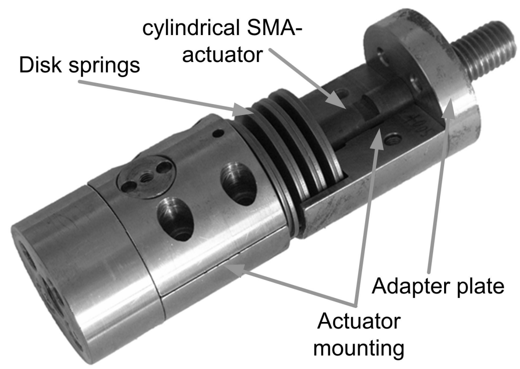
Figure 8: Test bench for testing the self-sufficient SMA-actuator (a), mechanical model of the test bench (b)

During operation the thermal energy created in the clutch heats the mechanical structure of the test bench. That leads to a thermal deformation of the structure. Due to the axial fixing created by the slide table, the force in the clutch is rising. Hence a rising frictional power and therefore a further increasing thermal energy is the result. The mechanism acts like a positive feedback as shown in the control scheme in Figure 7. The integration of a SMA-element in this structure cuts the positive feedback. Heating the structure creates a thermal deflection as well, but now also the SMA-element is heated up. When it reaches its transformation temperature, the phase transformation gets started and the element contracts. Due to that, the thermal deflections of the structure are compensated. Nevertheless the positive feedback is separated, the integration of the SMA-element creates a negative feedback loop as shown in Figure 7. Even though the model is developed for a test-bench it is also valid for all systems which have a direct feedback loop from the heat source (frictional force) to the SMA-element and back again to the heat source (frictional force).

The actuator designed for the adaptive clutch is shown in Figure 9. It consists of an adapter plate at each end of the actuator module to possess a simple integration into the test bench. The SMA-actuator itself is made of a cylindrical shaped semi finished SMA-element and is placed in the centre of the module. The SMA-element is fixed at both sides to a steel body. Due to the connection between the SMA-element and the steel bodies has to carry a vast amount of tensile force the connection is ensured by a combination of force closure and form closure. Several disk springs are located between both halves of the steel body to provide a preload to the SMA-element. The massive form of the actuator module is not only related to the task of carry a lot of force, it also transmits the heat flux of the surrounding structure into the SMA-element. The SMA-actuator module generates a movement of 0.9mm and a usable force of almost 7kN. It is realised by a cylindrical SMA-actuator of 10mm diameter and a free length of 40mm. The force-displacement characteristics of the module can be adjusted by choosing the diameter and the free length of the actuator that it meets the demands of the structure.



a) Mechanical design of the actuator



b) structure integrated actuator

Figure 9: Structure integrated SMA-actuator for actuation of adaptive clutch

5.3 Measurements Results

To validate the nodal modal results measurements with the described test bench was done. Hence an experiment using a speed controlled servo drive was realized. It injected frictional heat into the system by a clutch. Using the speed control it is possible to investigate the reaction of the injected heat resulted by the thermal expansion. During the experiment the temperature of the structure and of the SMA-element was measured at different locations (see MP1, MP2 and MP3 in Figure 8 and Figure 10. Also the axial force in the clutch, deflection of the structure and the electrical power of the servo drive was measured.

The results of the measurement are shown in Figure 10. The experiment starts with an electrical power of 50W. Due to the induced heat flux the temperature is rising. This causes a slightly rise in the deflection as well as in the axial force. The phase transformation of the SMA-element starts at an actuator temperature of 40°C (MP2 see Figure 8). Due to the contraction of the SMA-element the deflection of the structure is strongly over compensated. This yields to a strong decline of the axial force and also of the drive power. The drive power almost reaches zero. Because of the reduced heat input the structure and the SMA-element cool down. After 3000 seconds the SMA-element reaches the re-transformation starting temperature. The re-transformation is not fully accomplished and stops at a mixed lattice state. The system gets stationary. The testbench behaves exactly like a non-optimal adjusted control loop. The question to answer is, which design parameters (heat conductivity, heat capacity, convection) have to be changed to get an optimal behavior of the feedback loop.

However, it is visible in Figure 10 that only very small differences between simulation and the experimental results occur. This differences are caused by the fact that there is not just unforced convection due to the engine rotation. Furthermore friction exist inside the actuator module that avoids to contract as fast as the simulation model. This effect gets especially obvious regarding the expansion of the actuator after cooling down. Hence there are some neccessary improvements to do in the simulation model. However, the result shows that it is possible to approximate the dynamic behavior of an SMA actuator using a relatively simply thermal nodal model.

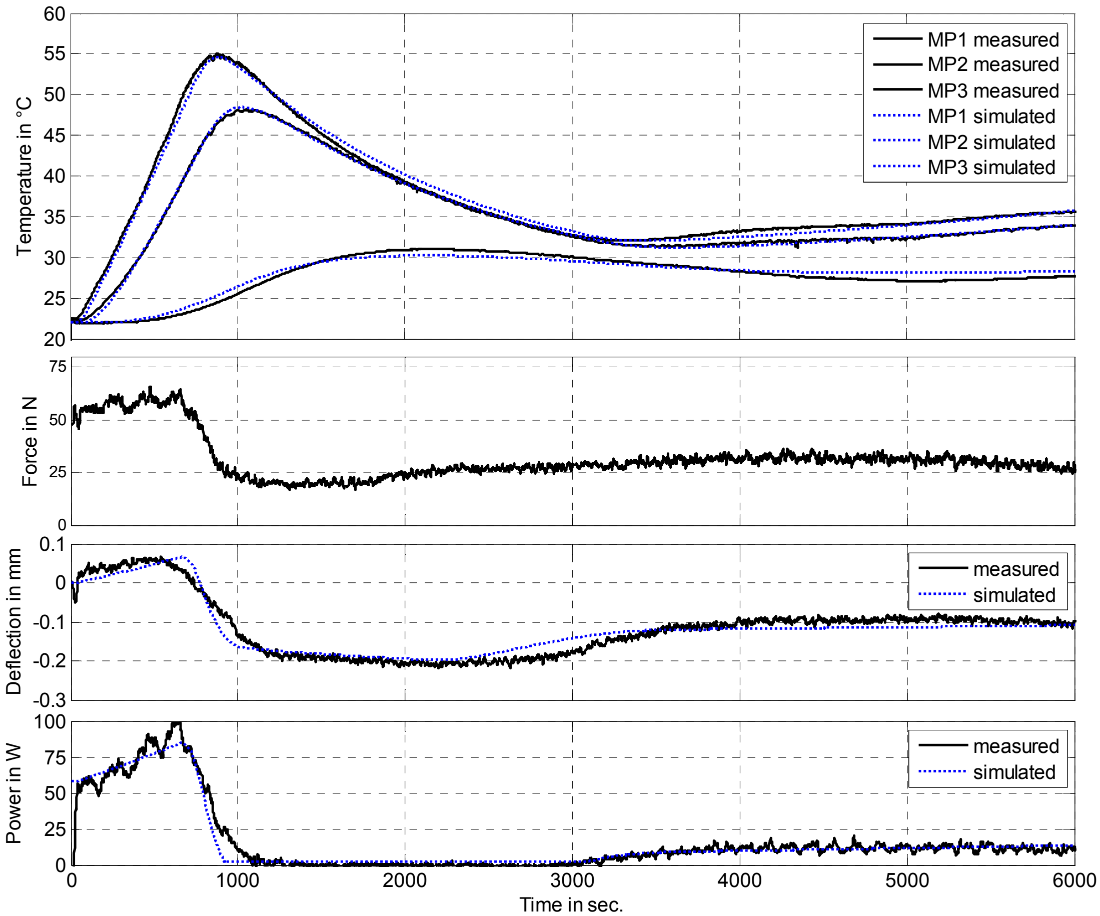


Figure 10: Verification of the thermo-mechanical model

6. SUMMARY AND OUTLOOK

Mechatronic approaches possess a supreme development methodology for machine tools. The future developments considering the basic structure – mechanics/ materials, transformation systems – sensor/actuator systems and data processing will characterise the development of "intelligent" machine tools. Within the next few years, the significance of the emerging trends like self-optimising adaptronic components or more efficient control systems for model supported compensation of machine errors and process control will increase multi-fold.

In the past, huge efforts were made in developing piezo-based components to increase the accuracy and productivity of machine tools. As a result there are numerous application solution available as for instance, the actuator-sensor-unit or the adaptive spindle support. However, the applications for commercial available machines are sparse. The main reasons therefore are the harsh industrial environment and the higher costs of piezo components. The reliability of machine tools is one of the main issues for machine manufacturers. Despite thorough investigations, the reliability of piezo components is not sufficient. Although the number of suppliers which offer commercial actuators and amplifiers increased in the last years, the costs of these components are still the essential cost drivers of adaptronic systems. The resulting system costs are not tolerated by the machine manufacturers. The prospective work has to deal with these aspects in order to transfer piezo applications from the laboratory to industrial applications.

The approaches for thermal compensations using thermo sensitive materials like SMA's are rather unexplored. The main research is therefore currently focused on discovering the interactions between the active material and the thermo-mechanical structure. It is a mighty challenge because the level of integration is even higher than it is for the piezo systems. Especially the aspired self adapting systems which use the process heat are extremely complex. The absence of any external energy source and control component decreases the system costs but increases the demands on engineering complexity. The challenge is to exploit the full capabilities already in the early design phase. The design tools for these adaptronic systems cannot be reduced to the sum of modelling, simulation of individual domains and securing appropriate exchange of data. A closed work chain has rather to be developed. Therefore a complete exploration of the thermo-mechanical interactions as well as the material behaviour and the aspects of designing a structure-inherent control loop are necessary. Achieving this scientific level is the main issue of the prospective work.

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