Inherent Sensory Capabilities of Solid State Actuators

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1. Introduction

Solid-state actuators based on piezoelectric and magnetostrictive materials are characterised by forces reaching the range of kilonewton and reaction times going down to the range of microseconds. On the other hand the displacements are low because the maximum strain amounts to 1.5 .. 2 ‰. As a consequence solid-state actuators are mainly driven in large-signal operation and therefore their nonlinear hysteretic and creep transfer characteristic takes strong effects. The technical problems, which can be traced back to this fact, namely the multi-valued static characteristics, can be solved by driving the transducers in a closed loop control. The actual value, e.g. displacements or forces, are measured and fed to a controller, which generates suitable corrective signals for the transducer in accordance with the intended values. Nowadays, the required sensors are discrete components. Their properties have to be adapted to the transducer principle and the respective application.

For some time scientists have attempted to use the sensor effect, an inherent feature of solid-state transducers due to physical laws, which would make external sensors superfluous. These inherent sensory capacities reduce the efforts necessary to carry out the linearizing of hysteresis and make it possible to gain information about the behaviour of the actuator and thus to compensate for the influence of different loads on the static and the dynamic transfer characteristic or to detect dissipation and aging in the transducer at an early stage.

This article aims at presenting the fundamental possibilities of using the capabilities of solid-state transducers to perform sensing and actuation which occur at the same time and the same place. These solid-state transducers are frequently called smart actuators. Our method of describing solid-state transducers is general and based on operators and it will be limited, due to the lack of space, to piezoelectric transducers. Additionally, we would like to present new methods of describing solid-state transducers worked out at the LPA which compensate the hysteresis as well as the creep influences which have been neglected until now.

2. Concept of smart solid-state actuators

Piezoelectric transducers are capable of transforming electric into mechanical energy and vice versa. The electric and the mechanical energy form can be described by the product of two physical quantities, which interact with the electrical and the mechanical environment of the piezoelectric transducer. On the electrical side these are the electric field $\boldsymbol{E}$ and the dielectric displacement $\boldsymbol{D}$ and on the mechanical side the mechanical stress $\boldsymbol{T}$ and the mechanical strain $\boldsymbol{S}$.

In most of the technical applications piezoelectric actuators are used as stack transducers or bending transducers. In this case the vectors of the electric field and the dielectric displacement as well as the tensors of the stress and the strain can be replaced by their scalar components. Which of the two electrical or the mechanical quantities can be regarded as impressed or independent and which one can be regarded as dependent depends on the electrical or the mechanical operation conditions of the transducer. This leads to four possibilities of equal importance to describe the transducer characteristic by mutually linking the physical quantities. The following possibility is used most frequently:

$$D = \Gamma_s[E,T] \tag{1}$$
$$S = \Gamma_a[E,T]. \tag{2}$$

In this set of equation the transfer characteristic of the transducer is described through the operators Γ_s and Γ_a, which attribute in an unambiguous manner, which has to be specified further, to the time signals of the independent electrical or mechanical quantity time signals of the dependent electrical or mechanical quantity. This is a general black-box description of the system characteristic which expresses, even on the level of system theory, the mutual linkage of the electrical and the mechanical quantities and thus the possibility of using the functions of a sensor and an actuator at the same time in one material. The qualitative transfer characteristics of both operators decisively depends on the dynamic range of the transducer. While linear system equations have a good approximation when driven in small-signal operation, in large-signal operation they are mainly determined by hysteresis and creep phenomena.

The basic idea to implement a smart actuator is presented in Figure 1 as an example of using the electric field E and the stress T as independent quantities. While the actuator is in operation the electric field E and the dielectric displacement D are measured by suitable sensors at any instant. These information is meant to help reconstruct the mechanical quantities stress T and strain S, which are considered not measurable. This requires a mathematical model of reconstruction based on the system equations, namely the sensor model (1) and the actuator model (2).

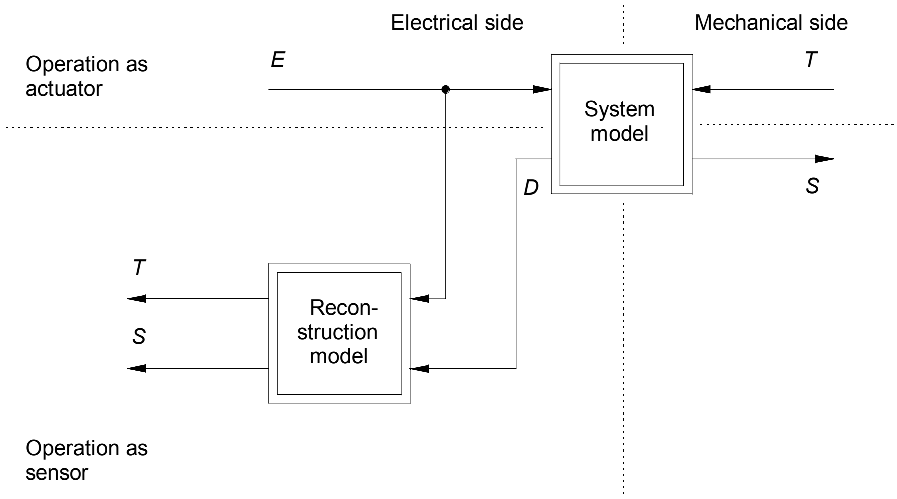


Figure 1: Piezoelectric transducer as a smart actuator

The mechanical quantities are reconstructed in two steps: first, an inverse operator is implemented with respect to the D-T-characteristic by means of the electric field as a parameter based on the sensor model (1). The stress can be reconstructed with the help of an inverse operator by inserting the measured values of the electric field and the dielectric displacement in the inverse operator (3). Then the stress of the transducer is calculated.

$$T = \Gamma_s^{-1}[E,D]. \tag{3}$$

The strain can thus be reconstructed by means of the actuator model (2) by inserting the electric field and the reconstructed stress.

$$S = \Gamma_a[E, \Gamma_s^{-1}[E,D]]. \tag{4}$$

In nonlinear system models the inverse operator and thus the reconstruction model can be determined in an analytical way only under certain conditions, so that as a rule the inversion has to be carried out numerically with the help of iterative calculation procedures. The continuity and the monotony of the *D*-*T*-characteristic are the conditions for the existence and the uniqueness of the inverse system (3) as well as for the convergence of the calculation procedures. The reconstruction models (3), (4) can be implemented for linear system equations by analogue circuit technology. When taking into consideration the nonlinearities occurring in large-signal operation the use of signal processors to implement the model of reconstruction is indispensable.

3 System models for smart solid-state actuators

3.1 Linear system model

In small signal range the operators Γ_s and Γ_a can be approximated by the well-known linear system equations

$$D = \Gamma_s[E,T] = \varepsilon^T \cdot E + d \cdot T \tag{5}$$

$$S = \Gamma_a[E,T] = d \cdot E + s^E \cdot T\ . \tag{6}$$

Here the permittivity ε^T, the coefficient of elasticity s^E and the piezoelectric constant d are the well-known small signal parameters of piezoelectric transduction if the stress and the electric field are imposed in one direction. In this linear case the inverse operator (3) can be derived analytically by an evaluation of (5). Then the linear reconstruction model of the smart actuator results in

$$T = \Gamma_s^{-1}[E,D] = \frac{1}{d}(D - \varepsilon^T \cdot E) \tag{7}$$

$$S = \Gamma_a[E, \Gamma_s^{-1}[E,D]] = d \cdot E + \frac{s^E}{d}(D - \varepsilon^T \cdot E)\,. \tag{8}$$

At first application (7) was used to evaluate the inherent sensor effect of piezoelectric transducers. The substraction of D and $\varepsilon^T E$ was realized by an analog signal processing with a capacitive bridge circuit which a piezoelectric transducer is one bridge element. Then the voltage across the bridge is proportional to the stress T which now can be determined without additional force sensor. With such a smart actuator different mechanical systems were equipped. In a first experiment by Dosch et al. a smart piezoelectric actuator was employed to damp the vibrations of a long cantilever beam [4]. With known values for d and s^E the strain S of the transducer can also be determined with (8). This reconstruction of the strain was used by Jones et al. for precision positioning with a stack transducer [6]. In another application the inherent sensor effect was used by

Vallone et al. for vibration damping in large mechanical structures [16]. Cole and Clark as well as Vippermann and Clark made use of the sensor effect for an on-line control of a stack actuator [2,17]. Another utilization of the sensory effect for a noise reduction of an actively clamped plate was published by Ko and Tongue [8].

All this applications have confirmed on the one hand the principle of a smart actuator, on the other hand they have shown that the linear reconstruction model (7) and (8) is restricted on small amplitudes of the electric field and stress. Furthermore the bridge circuit is strongly effected by external disturbances e.g. from temperature leading to a wrong evaluation of the sensory information. A transfer of this principle to magnetostrictive transducers is not easily possible. An external force generates a *B*-field which induces a voltage in the coil. This voltage, however, is superimposed by an induction voltage from the premagnetization of the magnetostrictive rod. Thus experiments with a bridge circuit to evaluate this induced voltage were not successful so that this method to receive sensory information does not seem to be promising for magnetostrictive transducers [14].

3.2 Nonlinear hysteresis-free system model

A further step to extend the validity of the model beyond the small-signal range is a description of the operators with unambiguous static nonlinear multidimensional characteristics *f*().

$$D = \Gamma_s[E,T] = f_s(E,T) \tag{9}$$

$$S = \Gamma_a[E,T] = f_a(E,T). \tag{10}$$

From this description model the linear system equations can be derived as a special case by a linearization in a fixed operating point A deveploment of (9) into a Taylor series at $E = 0$, $T = 0$ under the assumption

$$\frac{\mathrm{d}f_s(E,T)}{\mathrm{d}E} = \varepsilon(E,T)\cdot E \tag{11}$$

$$f_s(0,T) = d\cdot T. \tag{12}$$

results in a nonlinear sensor model

$$D = \varepsilon(E,T)\cdot E + d\cdot T \quad . \tag{13}$$

At the Laboratory for Process Automation the following research dealt with the implementation of a smart actuator based upon this sensor model.

The dependence of the permittivity ε on the electric field E is noticeable already at small amplitudes of the electric field. This dependence was measured at a bending transducer and stored as a characteristic. Hysteresis and creep as well as the dependence of ε on the mechanical stress (cf. (11)) were not considered. The bending transducer was used in vibration damping of a cantilever beam. The dielectric displacement D was measured by a Tower-Saywer circuit and the substraction with $\varepsilon(E)$ was realized by a digital signal processor considering the stored charcateristic for $\varepsilon(E)$. This processor also calculates the phase-inverted driving signal for the transducer. Utilizing this smart actuator the time needed to bring the beam to rest was shortened by factor 60, while the assumption of a constant ε leads only to a reduction by factor 20 [15].

All methods to utilize the inherent sensor effect presented up to now use the generation of a dielectric displacement by an external mechanical force. Another approach is based upon the evaluation of the dependence of the permittivity ε on the stress T, cf. (11). The permittivity ε determines the capacity of the transducer which can be calculated from the current and voltage at the transducer. The dependence of the permittivity ε and consequently the capacity on the electric field E must be considered, too. Experiments have proved that the capacity can be reliably determined by a parameter estimation yielding an unambiguous relation between capacity and external mechanical force. This characteristic can even be linearized in some areas and the calculating effort can be reduced so that the software can be implemented on a microcontroller. Therefore this method is interesting for many practical applications. A direct transfer of the method on magnetostrictive transducers is possible, too [3].

3.3 Nonlinear hysteretic system model

The next step to extend the validity of the system model is carried out by the modelling of hysteretic nonlinearities by the so called hysteresis operators.

In the mathematical literature the notation of the hysteretic nonlinearity will be equated with the notation "rate independent memory effect" [18]. This means that the output signal of a system with hysteresis depends not only on the present value of the input signal but also on the order of their amplitudes but not on their rate in the past. The rate-independent branching transfer characteristic shown in Figure 2 is a typical sign of a system with hysteretic nonlinearities. The past history of the input signal determines in a clear manner which branch of the multi-valued characteristic is valid for an increasing or a decreasing input signal.

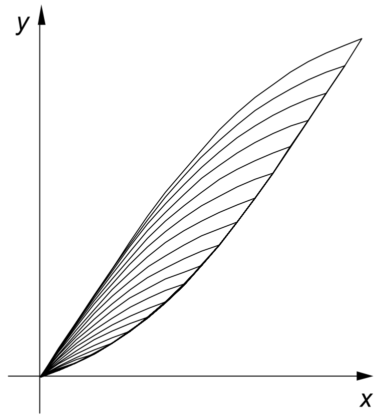


Figure 2: Hysteretic transfer characteristic

If a piezoelectric solid-state transducer is used as a smart actuator, it will be driven by two input signals, see Figure 1. These are either the electric field E or the dielectric displacement D and either the stress T or the strain S. In this case the past history of the vectorial input signal will not only be determined by the order of its amplitudes but also by the direction of the vector in the two-dimensional space. Thus the trajectory of the input vector in the two-dimensional space contains all the information about the past history of the vectorial input signal. Therefore, a model for the description of vectorial hysteretic nonlinearities should be able to consider the dependence of the output signal on the trajectory of the vectorial input signal [1].

Because of its phenomenological character the concept of hysteresis operators developed by Krasnosel'skii and Pokrovskii in the 1970's allows a very general and precise modelling of hysteretic system behaviour [10]. The basic idea consists of the modelling of the real hysteretic transfer characteristic by complex hysteresis operators. These are build up by the weighted superposition of many elementary hysteresis operators, which differ dependent on the type of the elementary operator in one or more parameters. With such a complex hysteresis operator *H* an operator based system model, which describes complex hysteresis phenomena very precisely, can be developed:

$$D = \Gamma_{\mathrm{s}}[E,T] = H_{\mathrm{s}}[E,T] \tag{14}$$

$$S = \Gamma_{\mathrm{a}}[E,T] = H_{\mathrm{a}}[E,T]. \tag{15}$$

A reconstruction model, which is able to consider the hysteretic nonlinearities in the large-signal transfer characteristic of a piezoelectric transducer, has first been introduced by Jones and Garcia in 1997, see Figure 3 [7].

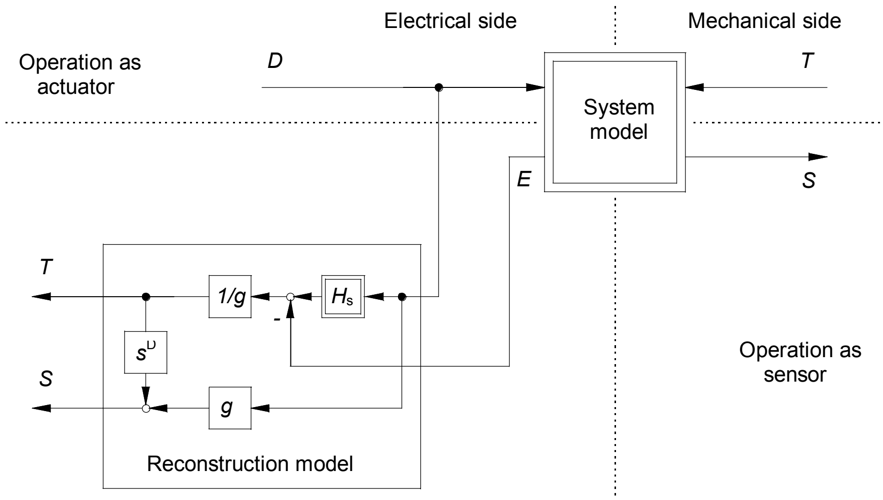


Figure 3: Smart solid-state actuator of Jones and Garcia [7]

In their application Jones and Garcia use a charge amplifier instead of a voltage amplifier to drive the piezoelectric smart actuator. Therefore, the dielectric displacement *D* must be regarded as the independent quantity and the electric field *E* as the dependent quantity. This leads to the operator based system equations

$$E = \Gamma_{\mathrm{s}}[D,T] \tag{16}$$

$$S = \Gamma_{\mathrm{a}}[D,T]. \tag{17}$$

The operator based system model of Garcia and Jones can be described in detail by

$$E = H_{\mathrm{s}}[D] - g \cdot T \tag{18}$$

$$S = g \cdot D + s^{\mathrm{D}} \cdot T. \tag{19}$$

In this model only the scalar hysteretic relation between the electrical field *E* and the dielectric displacement *D* will be considered by the scalar complex hysteresis operator H_s[]. The relation between the stress *T* and the electric field *E* is assumed to be linear. Therefore, the influence of the large-signal amplitudes on the stress, which leads to the vectorial hysteresis effects, will not be considered. For that reason this model is only valid for small amplitudes of the mechanical stress. The strongly nonlinear creep phenomena, which have an influence on the transfer characteristic worth to be mentioned, will not be considered either. The advantage of this piecewise linear model lies in the fact that the reconstruction model can be developed analytically from the system model.

$$T = \frac{1}{g}(H_s[D] - E) \tag{20}$$

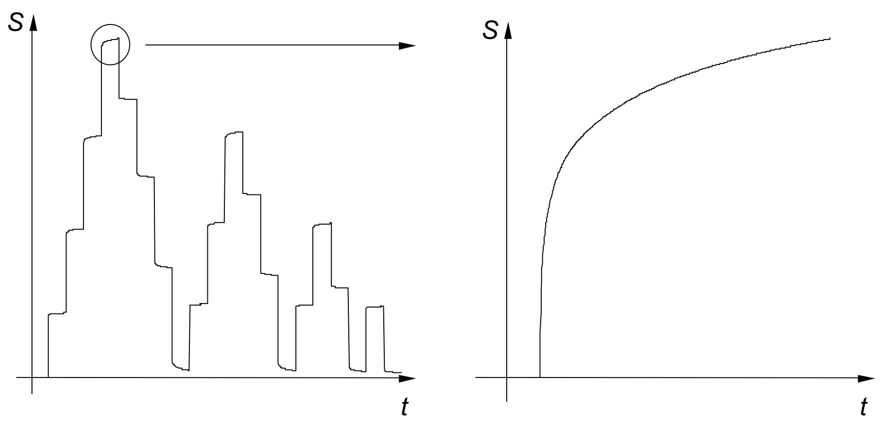
$$S = g \cdot D + \frac{s^D}{g}(H_s[D] - E). \tag{21}$$

Therefore the mechanical quantities need not be calculated by iterative procedures and so the computational effort will be clearly reduced.

3.4 Nonlinear creeping system model

The notation of creep originally comes from the field of solid-mechanics and describes the time-variant deformation behaviour of a body due to a sudden mechanical load [9,12]. It is a strongly damped, dynamic phenomenon, which can be found in a similar manner in the field of ferromagnetism and ferroelectricity and which is there closely related to the notation of the magnetic and electric after-effect.

Like hysteresis phenomena the creep effects have a considerable influence on the large-signal transfer characteristic of a piezoelectric transducer, see Figure 4. If the creep phenomena are linear, they can be described, analogously to the hysteresis modelling process, by a complex linear creep operator, which is made up by a weighted superposition of many elementary linear creep operators with different creep eigenvalues. In this case the elementary linear creep operators represent the solutions of linear exponentially damped first order differential equations [11].



a) b)

Figure 4: Hysteretic and creep transfer characteristic of a piezoelectric transducer
a) Strain S as a system response due to a staircased excitation with an electric field E.
b) Detailed representation of an electrically generated creep process

The creep transfer characteristic of a piezoelectric transducer depends on the past history of the input signal in a similar manner as the hysteretic transfer characteristic [5]. This dependence of the past history on the input signal will not be considered by the complex linear creep operator so that it is only a crude approximation for the real nonlinear creep transfer characteristic. By the serial connection of an elementary hysteresis operator and an elementary linear creep operator an elementary nonlinear creep operator can be constructed, which considers the dependence of the creep effects on the past history of the input signal.

Like in the hysteresis modelling process a complex nonlinear creep operator can be built up by elementary nonlinear creep operators. With the help of such a complex nonlinear creep operator K an operator based system model, which describes the real creep transfer characteristic very precisely, can be developed:

$$D = \Gamma_{\mathrm{s}}[E,T] = K_{\mathrm{s}}[E,T] \tag{22}$$
$$S = \Gamma_{\mathrm{a}}[E,T] = K_{\mathrm{a}}[E,T]. \tag{23}$$

Up to now no method for the implementation of a smart actuator is known, which is able to consider the hysteresis as well as the nonlinear creep effects. For a smart actuator which is meant to produce reliable measurement values for a long time, the consideration of the creep effects in the system model are inevitable. In connection with the description of the creep and hysteretic transfer characteristic of a piezoelectric stack transducer by scalar complex creep and hysteresis operators methods were recently developed and experimentally tested. They can be used to compensate for these nonlinear effects [11].

3.5 Nonlinear hysteretic and creeping system model

A system model which considers hysteresis as well as nonlinear creep effects can be constructed by the parallel connection of a complex hysteresis operator and a complex nonlinear creep operator.

$$D = \Gamma_{\mathrm{s}}[E,T] = H_{\mathrm{s}}[E,T] + K_{\mathrm{s}}[E,T] \tag{23}$$
$$S = \Gamma_{\mathrm{a}}[E,T] = H_{\mathrm{a}}[E,T] + K_{\mathrm{a}}[E,T]. \tag{24}$$

Investigations at the Laboratory for Process Automation have shown [11] that the additive superposition of a scalar hysteresis model and a scalar nonlinear creep model is a good approximation at least for the scalar S-E-transfer characteristic and the scalar D-E-transfer characteristic due to an electrical large-signal operation. So the system model can be described by

$$D = \Gamma_{\mathrm{s}}[E,T] = H_{\mathrm{s}}[E] + K_{\mathrm{s}}[E] + d \cdot T \tag{26}$$
$$S = \Gamma_{\mathrm{a}}[E,T] = H_{\mathrm{a}}[E] + K_{\mathrm{a}}[E] + s^{\mathrm{E}} \cdot T. \tag{27}$$

In this case the complex nonlinear creep operator $K[]$ was not generated by a superposition of elementary nonlinear creep operators. It was made up by a serial connection of a complex hysteresis operator $H[]$ and a complex linear creep operator $L[]$.

$$K_{\mathrm{s}}[E] = L_{\mathrm{s}}[H_{\mathrm{s}}[E]] \tag{28}$$
$$K_{\mathrm{a}}[E] = L_{\mathrm{a}}[H_{\mathrm{a}}[E]]. \tag{29}$$

With the operator based system model (26) and (27) a reconstruction model can be easily developed, see Figure 5.

$$T = \frac{1}{d}(D - H_s[E] - K_s[E]) \tag{30}$$

$$S = H_a[E] + K_a[E] + \frac{s^E}{d}(D - H_s[E] - K_s[E]). \tag{31}$$

Since no vectorial hysteresis and creep phenomena can be described by the system model this reconstruction model is also, like the model of Garcia and Jones, only valid for small-signal amplitudes of the mechanical stress.

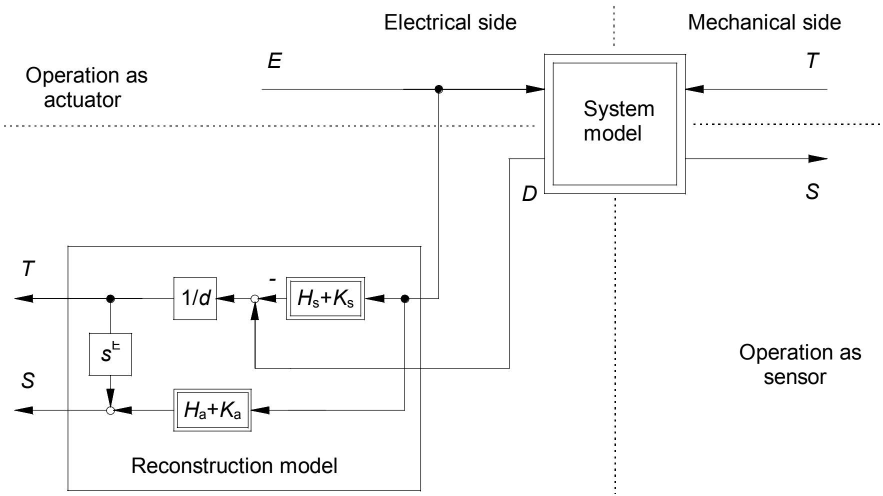


Figure 5: Smart solid-state actuator considering scalar hysteresis and creep effects

4 Conclusions

This article aims at presenting the fundamental possibilities of using the capabilities of solid-state transducers to perform sensing and actuation which occur at the same time and the same place. Our method of describing solid-state transducers is very general and based on operators, which consider multi-valued nonlinearities like hysteresis and rate dependent creep phenomena in large-signal operation. These operators include the well-known linear and single-valued nonlinear system models as a limit case and can therefore be regarded as a logical extension of these classical mathematical descriptions. All system models for the implementation of smart actuators presented in literature up to now as well as in this article first result from this general approach as a special case. In future work at the Laboratory for Process Automation the creep and hysteresis operators will be extended to the vectorial case considering the influence of large stress amplitudes on the transfer characteristic of a piezoelectric transducer.

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