Design of a smart magnetostrictive actuator by sensing the variation of magnetic flux

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Abstract
An essential reason for the increasing interest in magnetostrictive materials is the capability to perform collocated and simultaneous sensing and actuation due to the inherent sensory capability of the material. This dual function predestines the material for application in mechatronic systems. Operating in this way these solid-state transducers are frequently called smart actuators. They favour a miniaturized, simpler and cheaper mechatronic system design and are therefore regarded as a key technology in the 21st century. The focus of the present paper is the realisation of a smart magnetostrictive actuator by sensing the variation of the magnetic flux in the material. For this purpose, a hall sensor has been integrated into the casing of the magnetostrictive actuator. A central task of the smart magnetostrictive actuator is the separation of the sensing information from the actuation information contained in the magnetic flux measurement signal. In practice, however, due to the high input amplitudes undesired complex hysteresis and saturation nonlinearities appear making a separation of sensing information from actuation information impossible with linear actuator models. In this article a novel control and signal processing method based on hysteresis and superposition operators is applied to the smart magnetostrictive actuator. This method allows the compensation of these simultaneously occuring nonlinearities in real-time and with it a linearisation and decoupling of sensor and actuator operation.

1 Introduction
Rods of magnetostrictive materials have been found in industrial use in the form of actuators for many years due to their ability to convert electrical into mechanical energy. As shown in Figure 1 a coil is located around the rod which produces the necessary magnetic field for actuation operation. For a defined field production and field reduction the coil is driven with a given driving current I.

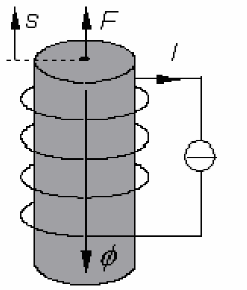

Figure 1: Principle structure of a magnetostrictive actuator

Due to the magnetostrictive effect in the material the rod produces a displacement against the surrounding mechanical structure. Magnetically the rod reacts with a current-dependent variation of its magnetic flux. Due to the current-dependent displacement the surrounding mechanical structure reacts with a force F against the rod. Beside the current-dependent displacement and magnetic flux variation, this force produces an additional force-dependent displacement due to the elasticity of the material and an additional force-dependent magnetic flux variation due to the so-called Villary effect. The latter effect is the cause for the inherent sensory capability of the magnetostrictive material. So far, the separation of the sensing information from the actuation information which is necessary for the realisation of a smart actuator was based on linear actuator models [PF93]. In practice, however, due to the high input amplitudes undesired complex hysteresis and saturation nonlinearities appear which make a separation of sensing information from actuation information impossible with linear actuator models. In [KJ02] a new control and signal processing method based on hysteresis and superposition operators was presented for a piezoelectric actuator which allows the compensation of these simultaneously occuring nonlinearities in real-time and with it a linearisation and decoupling of sensor and actuator operation. The goal of the present paper is to investigate whether this newly developed control and signal processing method is also well-suited to archive a smart actuator with magnetostrictive material.

2 Design and construction

Due to the quite low permeability of about $\mu_r = 5 \ldots 10$ magnetostrictive materials are not effective flux guiding elements in the construction of a magnetostrictive actuator. In fact, the surrounding structure has to assure guiding and focussing of the magnetic field so normally highly permeable iron is used for flux guidance. The lower end of the magnetostrictive rod is a mechanical fix point while the upper end is axially freely movable. As shown in Figure 2 the upper part of the fixture is freely movable and attached to two metal membranes forming an elastic suspension.

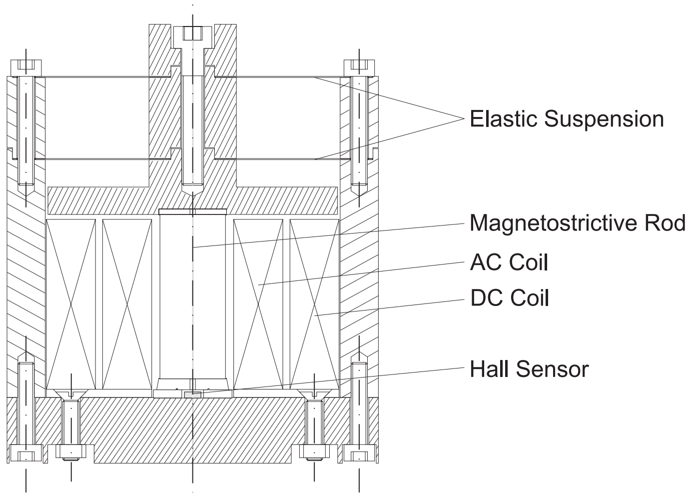

Figure 2: Magnetostrictive actuator with electrically generated magnetic bias field

Magnetostrictive material is normally used with a magnetic bias and under mechanical prestress so that by changing the magnetic field the variation in length of the rod in this operating point is most significant. Working under these these conditions the magnetostrictive material is used at its best resulting in the most strain for a given excitation amplitude. The magnetic bias can be realised with permanent magnets or electromagnetically. When using the electromagnetic method the static field can be generated by adding a second coil or by overlaying an offset current in the dynamically used coil. With regard to the dynamic behaviour the generation of the magnetic operating point with two separate coils should be preferred allowing the magnetic field to be changed more rapidly because of the lower inductance of the coil. Another advantage of the electromagnetically approach is the easily changeable magnetic operating point.

A special feature in the design of the presented actuator is a Hall sensor allowing measurement of the variation of magnetic flux with respect to the mechanical load and the electric current. If the actuator is operated in current-control mode, the magnetic flux in the magnetostrictive material represents the physical variable containing the sensor information. Therefore, quantitative knowledge about the flux is basic for the realisation of a smart magnetostrictive actuator.

3 Operator-based control und signal processing concepts

To generate worthy displacements in actuator operation the magnetostrictive rod is driven by magnetic field amplitudes which excite domain switching processes in the magnetostrictive material and thus produce hysteresis and saturation effects in the electromagnetic and actuator transfer characteristics. Additionally in actuator operation the magnetostrictive rod is exposed to mechanical load which leads to mechanically excited domain-switching processes and produces hysteresis and saturation effects also in the sensory and mechanical transfer characteristics. Moreover the hysteresis and saturation characteristic of the transfer paths with the current as input signal depends on the present mechanical load and vice versa. In principle the coupling about the inner domain-switching processes requires a mathematical modeling of the coupled system characteristics using vectorial hysteresis operators. But if we limit the electrical and mechanical input signals to amplitude ranges for which the dependence of electromagnetic and actuator hysteresis on the mechanical load and the dependence sensory and mechanical hysteresis on the driving current is negligible the vectorial hysteresis operators can be replaced in a first-order approximation by a linear superposition of scalar hysteresis operators. From this point of view follows the operator sensor equation

(1) $$\phi(t) = \Gamma_E[I](t) + \Gamma_S[F](t)$$

and the operator actuator equation

(2) $$s(t) = \Gamma_A[I](t) + \Gamma_M[F](t)\,.$$

The transfer paths in the sensor equation (1) and the actuator equation (2) can be modelled in a sufficiently precise way by so-called modified Prandtl-Ishlinskii hysteresis operator [Kuh03]. The identification of the modified Prandtl-Ishlinskii hysteresis operators with measured input-output data of the corresponding transfer paths is carried out using a computer with a special model and compensator synthesis procedure, which is explained in detail together with the foundations of the modified Prandtl-Ishlinskii approach in [Kuh01] and [Kuh03].
For the magnetostrictive actuator introduced in chapter 2 the electrical range of validity of the models (1) and (2) is about 40% of the electrical full amplitude range and amounts to about ± 0.5 A at an electrical operating point of 1.25 A. The mechanical range of validity is about 50% of the mechanical full amplitude range and amounts to about ±100 N at a mechanical operating point of -500 N. The mechanical full amplitude range is defined in the present example as the force amplitude which compensates the current-dependent displacement of the actuator produced by maximum current amplitudes of ± 1.25 A. This force is called the clamping force of the actuator and amounts to ±200 N in the given operating point. Figures 3a-d show the measured hysteresis characteristics of the actuator, electromagnetic, sensory and mechanical transfer paths as a grey line and the corresponding modified Prandtl-Ishlinskii hysteresis operators Γ_A, Γ_E, Γ_S and Γ_M as a black line. In contrast to the characteristics of the operator models, Figures 3a-d show the characteristics of the best linear approximations as dashed lines. A comparison of the relative model errors of the diffferent transfer paths, defined by

(3) $$e_{yx} = \frac{\max\limits_{t_0 \le t \le t_e}\{|\Gamma[x](t) - y(t)|\}}{\max\limits_{t_0 \le t \le t_e}\{|\Gamma[x](t)|\}},$$

leads to the results in Table 1.

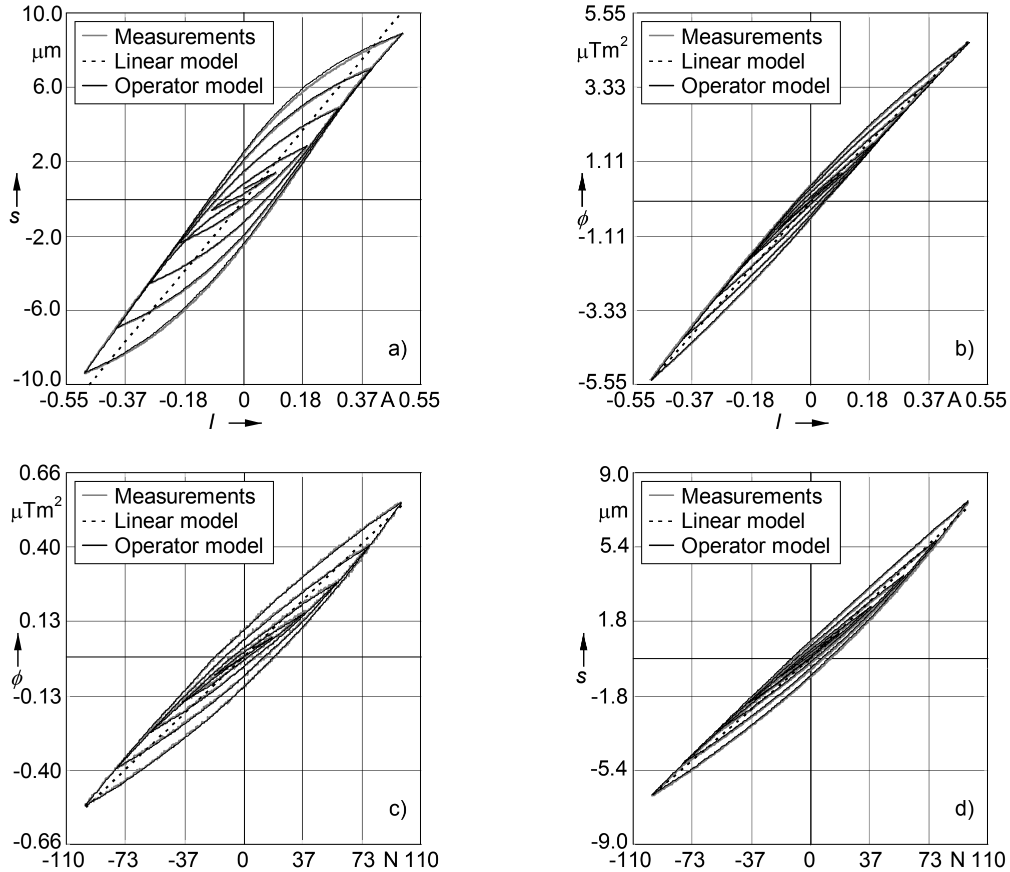

Figure 3: Hysteresis characteristics of the magnetostrictive actuator in the operating point for limited driving and loading amplitude ranges

The results show a reduction of the relative model error of the operator models of about one order of magnitude in comparison to the relative model error of the best linear approximations.

Model error	$e_{\phi I}$	e_{sI}	$e_{\phi F}$	e_{sF}
Linear model	10.47%	25.03%	20.99%	13.34%
Operator model	1.19%	1.94%	2.94%	1.82%

Table 1: Relative model errors e_{yx} of the operator models and the corresponding best linear models

Following the procedure in [KJ02] we can derive an operator-based controller concept for the magnetostrictive actuator in the limited driving and loading range which compensates the hysteresis and saturation effects in the actuator transfer path. For this purpose, we augment the magnetostrictive actuator with a compensation filter which fulfils the operator equation

(4) $$I(t) = \Gamma_A^{-1}[s_c](t)\,.$$

To obtain information about the real displacement s of the magnetostrictive rod during actuator operation the electrical current I and the magnetic flux variation $\Delta\phi$ are measured. The goal is the reconstruction of the present displacement only with these measurement values and without using an external displacement sensor. The corresponding reconstruction filter can be derived by resolving the operator-based sensor equation (1) and integrating the result into the operator-based actuator equation (2). From this follows the reconstruction filter equation

(5) $$s_{rec}(t) = \Gamma_A[I](t) + \Gamma_M[\Gamma_S^{-1}[\phi - \Gamma_E[I]]](t)\,.$$

Figure 4 shows the signal flow chart of the combined control and signal processing concept.

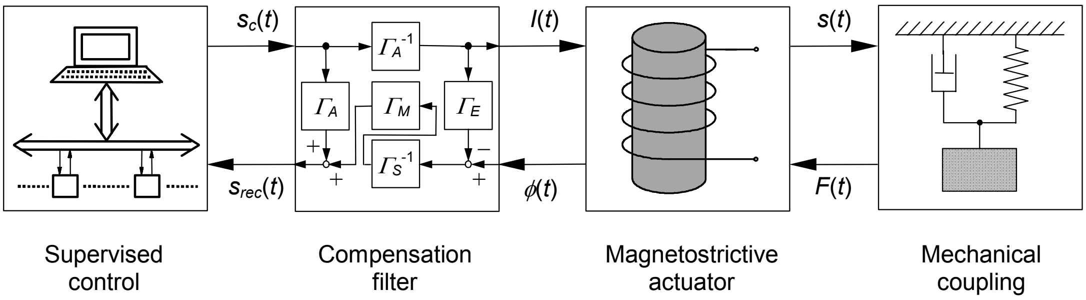

Figure 4: Inverse feed forward controller with reconstruction of the rod displacement

4 Control and reconstruction results

To show quantitatively the performance of the inverse feed forward controller with displacement reconstruction as shown in Figure 4, the system of Figure 4 is driven with a given displacement signal s_c traced in Figure 5a.

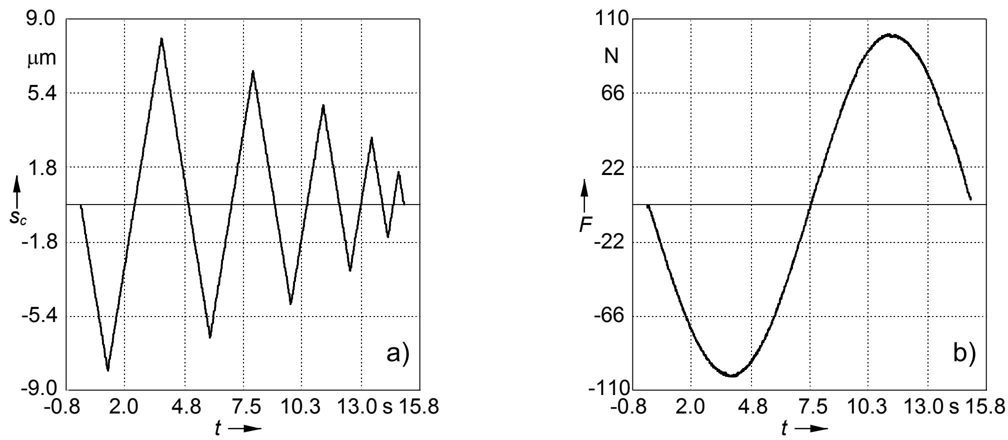

Figure 5: Driving and loading signals: a) Given displacement $s_c(t)$, b) Loading force $F(t)$

Figure 6a shows in grey the s-s_c trajectory of the system in the case that the inverse operator Γ_A^{-1} is based on the best linear approximation for the actuator transfer path and the magnetostrictive actuator is mechanically unloaded. As expected the I-s_c trajectory of the inverse operator Γ_A^{-1} shown in Figure 6b as a grey line has a linear characteristic. Thus the s-s_c trajectory of the complete system shows the hysteretic and saturated characteristic of the actuator transfer path of the magnetostrictive actuator. The relative control error, defined as

(6) $$e_{ss_c} = \frac{\max\limits_{t_0 \le t \le t_e} \{|s_c(t) - s(t)|\}}{\max\limits_{t_0 \le t \le t_e} \{|s_c(t)|\}},$$

amounts to 25.6% in this case. Figure 6a shows in black the s-s_c trajectory of the system for the operator-based model of the actuator transfer path. In this case the I-s_c trajectory of the inverse operator Γ_A^{-1} is represented by the characteristic shown in Figure 6b as a black line. As a result of augmenting the inverse operator Γ_A^{-1} to the actuator transfer path the s-s_c trajectory of the system in Figure 4 displays an extensively hysteresis and saturation free characteristic. The compensation effect of the filter results in a relative control error of about 4.6%.

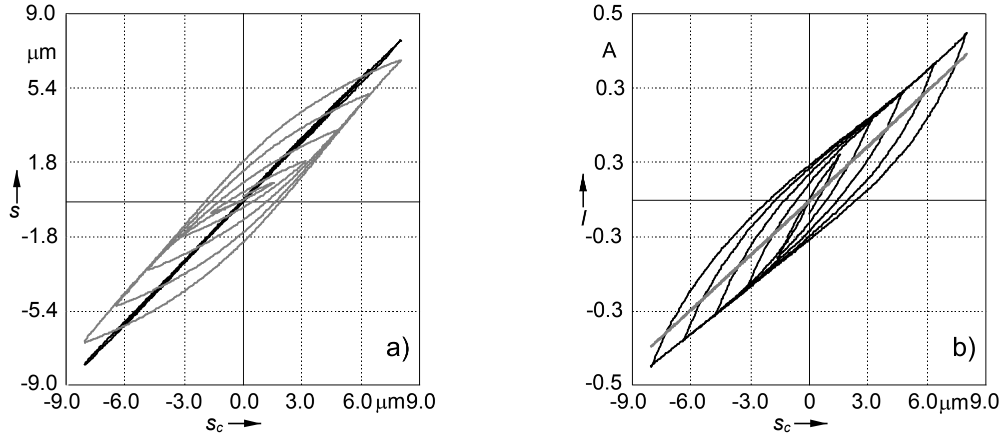

Figure 6: Linear (grey) und operator-based (black) inverse controller without loading force: a) s-s_c trajectory, b) I-s_c trajectory

Figure 7a displays the s-s_c trajectory of the system in case of a linear feed forward control as a grey line and the operator-based inverse feed forward control as a black line under additional mechanical load as presented in Figure 5b. Due to the finite stiffness of the magnetostrictive actuator, mechanical forces cause an additional displacement so the difference between the real s-s_{coll} trajectory and the ideal s-s_c trajectory becomes significant and in consequence, the relative control error increases to 135.7% in the linear control mode and 123.5% in the operator-based control mode.

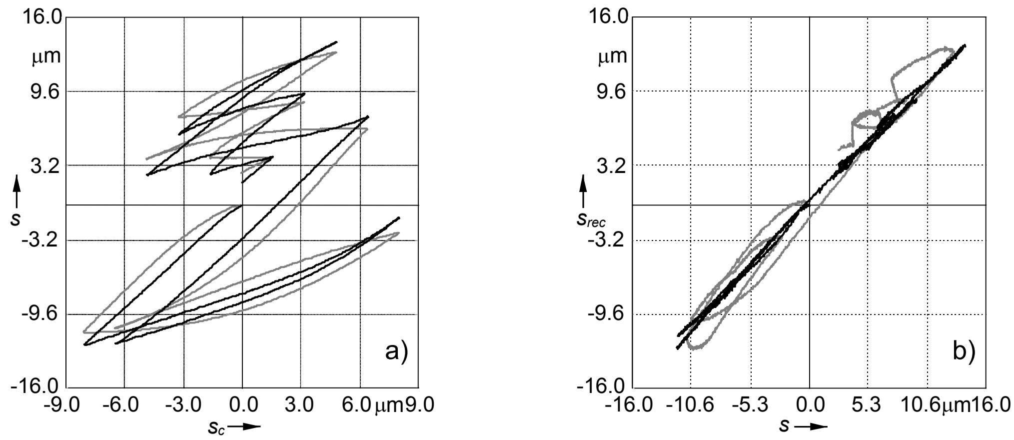

Figure 7: a) Inverse linear (grey) and operator-based (black) controller with loading force: s-s_{coll} trajectory,
b) Performance of the linear (grey) and operator-based (black) reconstruction filter for the displacement: s_{rec}-s trajectory

Nevertheless, the additional compensation of the mechanical load-dependence of the actuator displacement is feasible by using the reconstructed actuator displacement srec in a proper feedback loop. Figure 6b displays the result of the displacement reconstruction with a linear reconstruction model as a grey line and the result of the displacement reconstruction with an operator-based reconstruction model -

as a black line for the driving signal shown in Figure 5a and the loading signal shown in Figure 5b as a s_{rec}-s trajectory. The relative reconstruction error, defined as

(7) $$e_{s_{rec}s} = \frac{\max\limits_{t_0 \le t \le t_e}\{|s(t) - s_{rec}(t)|\}}{\max\limits_{t_0 \le t \le t_e}\{|s(t)|\}},$$

amounts to 25.9% for the linear reconstruction model and 7.3% for the operator-based reconstruction model.

5 Summary and prospects

The present paper describes the realisation of a smart magnetostrictive actuator by sensing the variation of the magnetic flux in the material. For this purpose a Hall sensor is integrated into the casing of the magnetostrictive actuator. A central task of the smart magnetostrictive actuator – namely the separation of the sensing information from the actuation information contained in the magnetic flux measurement signal – is carried out using a novel control and signal processing method based on hysteresis and superposition operators. This method allows the compensation of the simultaneously occuring hysteresis and saturation effects in the characteristic of the magnetostrictive material in real-time and with it an extensive linearisation and decoupling of sensor and actuator operation. Especially the high-quality displacement reconstruction allows in future works the implementation of a smart displacement feedback controller for the additional compensation of force-dependent variations of the displacement due to the finite stiffness of the magnetostrictive material.

Acknowledgements

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