SELF-SENSING SOLID-STATE ACTUATORS

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Contents

Summary

Actuators interface the information processing part of automation systems and the processes that are to be controlled and hold therefore a key position, which is similar to the sensor technology. An essential reason for the growing interest in piezoelectric, magnetostrictive and electrostrictive materials as well as in shape memory alloys is their capability to perform sensing and actuation tasks simultaneously. With these inherent sensory capabilities, the materials can adopt both sensing and actuation functions in mechatronic systems.

Operating in this way the combination of these solid-state transducers with an information processing unit is frequently called self-sensing actuators. They favor a miniaturized, simpler and cheaper mechatronic system design and are therefore regarded as a key technology in the 21st century. Until recently, the actuation information necessary to achieve a self-sensing actuator has been separated from the sensing information on

the basis of linear actuator models. In practice, however, undesired complex hysteresis nonlinearities appear in all smart materials due to the high driving amplitudes. These highly nonlinear effects make it impossible to distinguish between sensing information and actuation information by means of linear actuator models.

This article presents novel control and signal processing methods based on hysteresis operators. They allow the compensation of these nonlinearities in real time and consequently the linearization and decoupling of sensor and actuator operation. The practical application of these control and signal processing concepts to a simple one-degree of freedom micropositioning system with a piezoelectric actuator shows that the actuator's performance in terms of the control error improves by up to one order of magnitude in comparison to the uncontrolled operation of the system.

1. Introduction

Mechatronics is the synergetic integration of mechanical engineering with electronics and intelligent computer control via sensors and actuators in the design and manufacture of products and processes. The embedded intelligence may vary from programmed behavior to self organization and learning. Its key function is measuring the characteristic process quantities with sensors, which are then sent to the electronic information processing module. Actuators, on the other hand, are connectors between the information processing part of process control and the mechanical process and have therefore a key function similar to that of the sensors.

Whereas up to now, actuators and sensors in most cases have been separately implemented and integrated into a mechanical structure, the use of solid-state transducers based on piezoelectric, electrostrictive and magnetostrictive materials permits the integration of actuator and sensor technology within one single component. The coexisting actuator and sensor properties of the active material are the basis for this multifunctionality. The intrinsic sensing property of the solid-state actuator results in a dependence of the electrical quantity on the mechanical load, which is thermodynamically dual to the electrical control quantity. In piezoelectric and electrostrictive actuators, the thermodynamically dual quantity which contains the sensory information is given by the electrical charge q if voltage U is controlled and by the electrical voltage U if charge q is controlled.

Accordingly, the sensory information in magnetostrictive actuators with current control is provided by the magnetic flux ϕ through the magnetostrictive material, and in those with flux control it is provided in the coil current I. In order to give a uniform notation, the electrical control quantity will be represented by the electrical input parameter X, whereas the thermodynamically dual electrical quantity which contains the sensory information will be represented by the electrical output parameter y.

Ideal solid-state actuator: According to Figure 1, an ideal solid-state actuator has the function of transforming the desired displacement s_d given by the superior control system into the actual displacement s without regarding the current mechanical load situation described by the physical quantity force F. A further goal is to feed back the momentary load situation, which is dominant at the mechanical interface between the actuator and the mechanical structure, to the superior control system in the form of the reconstructed force F_r and the reconstructed displacement s_r during actuator operation. In that sense, the actuator represents a bidirectional interface between the information processing part of process control and the mechanical process. In addition to the precise implementation of control tasks, it also allows implementing such functions as adjusting, diagnosing and controlling in the superior control system.

Conventional solid-state actuator: The conventional solid-state actuator consists of the sub-systems conventional feedforward controller, power electronics and solid-state transducer, see Figure 2a. By means of the desired displacement s_d, the conventional feedforward controller consisting of a rate-independent, linear transfer-characteristic with a constant k_s produces an electrical input signal X_i for the power electronics. The power electronics, consisting of a controlled voltage, charge, current or magnetic flux source, generates the energy carrying output signal X for the solid-state transducer from the information carrying electrical input signal X_i. The solid-state transducer transforms the electrical energy signal X into a displacement s against a force F. However, even in quasi-static operation the actual displacement and desired displacement usually do not correspond.

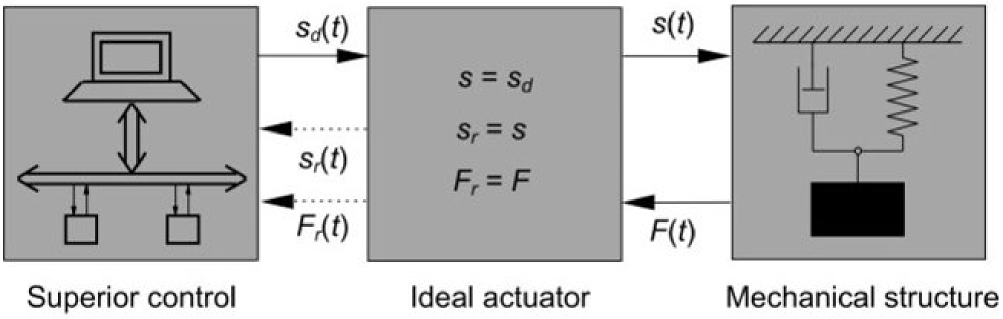

Figure 1: Process control of mechatronic systems with ideal actuators

Internal imperfections - such as complex hysteretic nonlinearities described by the operator Γ_A in Figure 2 - and external influences - such as load reactions via the surrounding mechanical structure - are the main reasons for the deviation between the desired and actual values. The former imperfection provokes ambiguities between the input and output of the transducer; the latter one causes an additional deviation in the actual displacement from the desired value due to the finite stiffness of the solid-state transducer.

Intelligent solid-state actuator: According to general usage, solid-state actuators are called intelligent when their transfer characteristic is determined by a functionally allocated and electronically integrated “intelligence”, if necessary, with sensor support. Such intelligent actuators can recognize deviations from the desired transfer characteristic, which result from the hysteretic nonlinearities as well as from load feedback, and correct them automatically. The position controlled actuator in Figure 2b is an example of such an actuator type. With this principle, the compensation of internal imperfections and external disturbances is achieved by a linear controller $\underline{G}_\mathrm{R}$, which receives information about the actuator output from an external displacement sensor.

With the reconstruction of force by means of the inverse filter $\mathit{\Gamma}_\mathrm{A}^{-1}$, it is possible in this case to give feedback about the actuator’s current load situation to the superior control system. An electrical circuit for the measurement of the electrical quantity X is necessary for the implementation of this additional function. Such an electrical measurement circuit is usually an element of the power electronics. The actuator concept in Figure 2c is sometimes used in piezoelectric transducers.

It has clearly a higher measure of integration. In this case, some of the stack’s ceramic disks in Figure 3 are used as sensors in order to measure the force, whereas the major part of the stack operates purely as an actuator. For the accurate measurement of the force, the hysteretic transfer characteristic of the integrated sensor must be compensated within the electronic signal processing part by an inverse filter $\mathit{\Gamma}_\mathrm{S}^{-1}$. In this case, the displacement can be reconstructed with the filter $\mathit{\Gamma}_\mathrm{A}$ from the electrical quantity X and the measured force F . Hysteretic nonlinearities and loading feedback emerging during actuator operation can be compensated by implementing the inverse filter $\mathit{\Gamma}_\mathrm{A}^{-1}$.

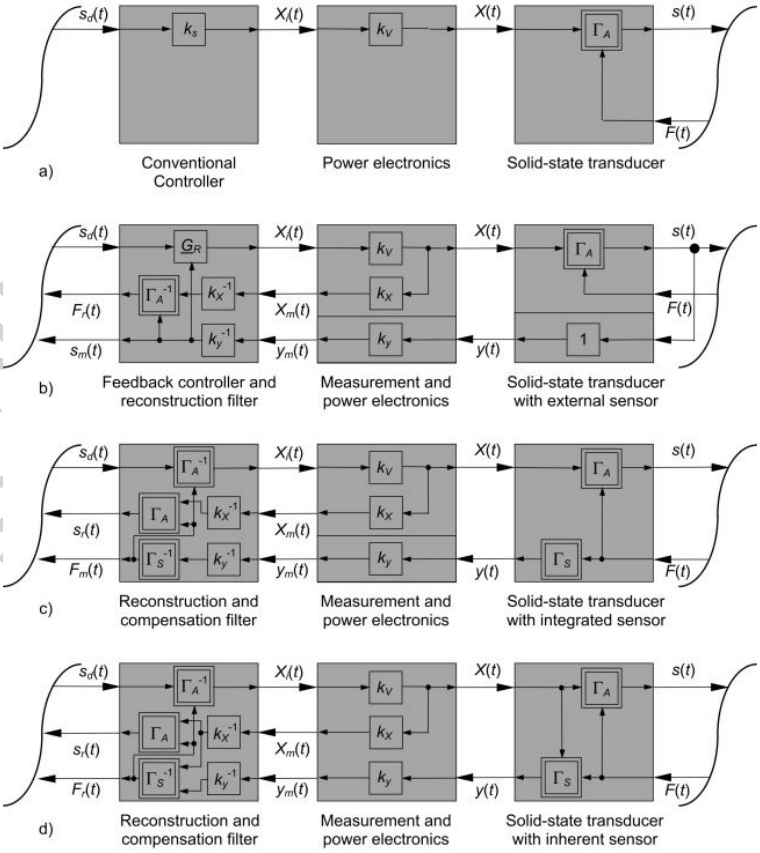

Figure 2: Bidirectional actuator concepts with a growing measure of integration

Self-sensing solid-state actuator: The self-sensing solid-state actuator shown in Figure 2d has the highest measure of integration and the simplest and thus economical construction. However, its bidirectional function requires also the most complex mathematical and electronic signal processing unit. Characteristic of self-sensing actuators is the simultaneous utilization of actuator and sensor properties of the active material. In contrast to the intelligent concepts in Figure 2b and Figure 2c, they have a power electronics which contains the electronic circuits for measuring the given electrical quantity X and the dual electrical quantity y carrying the sensory information.

The central function of the signal processing unit, which is responsible for the bidirectional function, is in this case the linearization and decoupling of both sensor and actuator operation. Especially the decoupling of both sensor and actuator operation for force and displacement reconstruction according to Figure 2d is the main difference to the intelligent actuator concepts depicted in Figures 2b and 2c. In the former case the output y of the sensory path is strongly influenced by the driving quantity X of the solid-state transducer and must be regarded as an external disturbance for the sensor operation. This is shown in the right block in Figure 2d. In the latter cases the output y of the sensor path is not influenced by the driving quantity X of the solid-state transducer. Therefore in these cases a model-based decoupling of the sensor and actuator operation is not necessary.

2. Solid-state Transducers

Solid-state transducers are elements whose behavior is based on the properties of crystalline bodies, e.g. piezoelectric, magnetostrictive and electrostrictive materials and shape memory alloys. Because of the limited space, the following explanations will merely go into the first two mentioned types of solid-state transducers.

2.1. Piezoelectric Transducers

Principle: Certain crystals, as for example quartz, which have no center of symmetry with regard to the positive and negative crystalline ion in the lattice, show a physical interaction between the mechanical force and the electrical charge. This effect is called a direct piezoelectric effect and forms the basis for sensor constructions. If, however, an electrical voltage is applied to the piezoelectric material, the thickness will change due to the so-called inverse piezoelectric effect. This property allows the construction of actuators. Nowadays, ceramic, polycrystalline materials, e.g. lead-zirconate-titanate, are mainly used.

Due to their strong piezoelectric effect, these materials are employed for the production of transducers and can be fabricated in the shape of sheets or disks up to a thickness of several millimeters. In contrast to piezoelectric transducers, electrostrictive transducers exhibit with equal displacements and forces a quadratic dependence of strain on the electrical field strength. The Curie temperature of electrostrictive materials in use till now, is the temperature above which electromechanical coupling does not occur, lies within the range of room temperature. Therefore in contrast to piezoelectric transducers, electrostrictive transducers are currently of little practical importance.

Construction: In the most prevalent construction, the transducer's active part consists of a multiplicity of thin ceramic disks with metallic electrodes for applying the operating voltage, see Figure 3. The disks are stacked up and affixed to each other in pairs with alternating polarization and are then hermetically sealed against external influences (stack design, translator). Due to this stack design the the single ceramic disks work mechanically in series and thus generate with the same electrical voltage amplitude a much higher displacement as a single disc. A mechanical pre-stress, which can be applied using a screw and a slotted tube spring, allows the transducer to be used for tension as well as compressive forces.

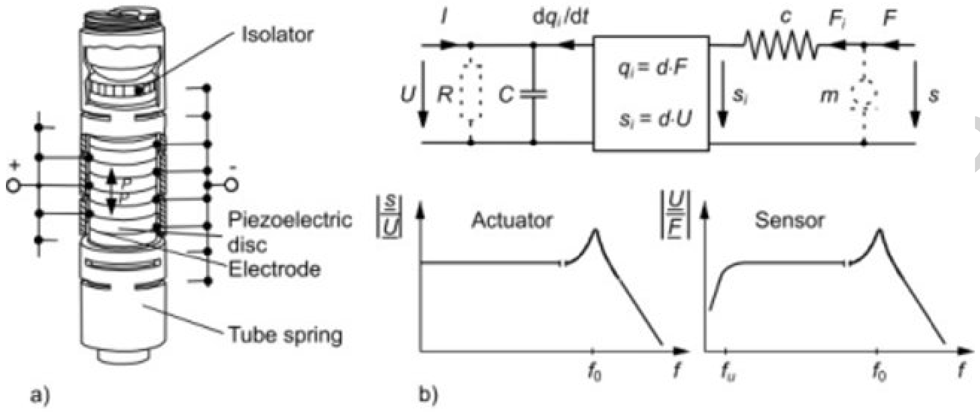

Figure 3: Piezoelectric stack transducer: a) Construction, b) electromechanical equivalent circuit diagram and amplitude responses of actuator and sensor transfer characteristic in small signal operation

Large-signal characteristic: The voltage-induced displacement s and the polarization charge q of a piezoelectric transducer are composed of a linear and a hysteretic part and display the rate independent branching characteristic as shown in Figure 4. Loading the transducer mechanically causes also a displacement and polarization in the ceramic. The consequence is a change in displacement s and in polarization charge q. This is recognizable by means of the curves in Figure 4, which are parameterized by different loads.

Operation region and operating point: The maximum achievable displacement of piezoelectric ceramics is limited by saturation and depolarization. In practice, usually only the operating region of the displacement-voltage characteristic which is grey-shaded in Figure 4 is employed. For special applications, it is also possible to expand the operating region to the light grey-shaded area.

However, the negative operating voltage may not exceed about 30% of the maximum voltage, as otherwise an electrical repolarization will occur. In order to achieve bipolar operation of the piezoelectric transducer, the transducer is electrically biased by a constant voltage at about half of its operating range. The mechanical operating point is given by the mechanical pre-stress of the material in the transducer casing.

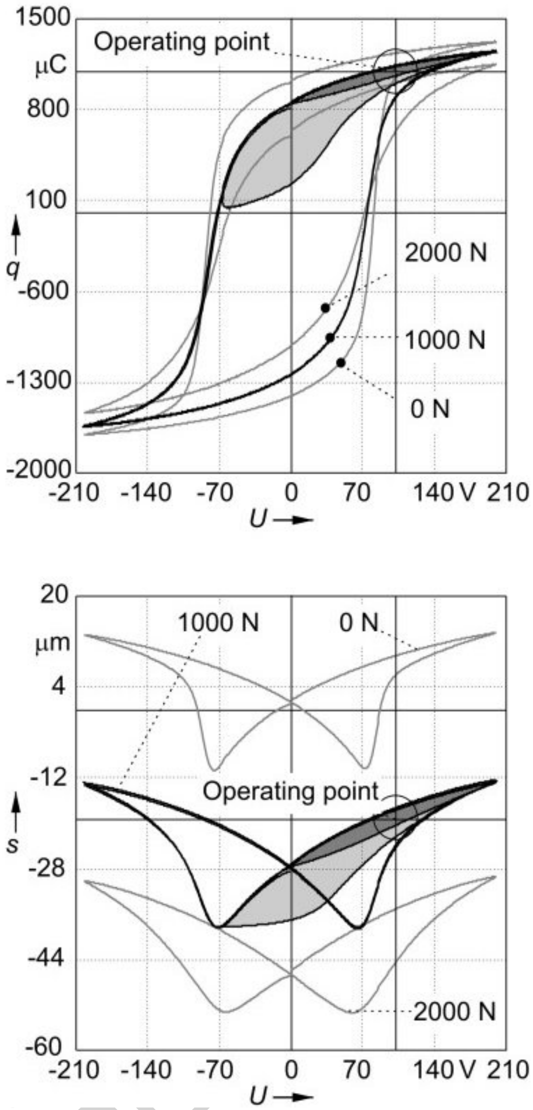

Figure 4: Typical hysteretic characteristics of a piezoelectric stack transducer for different loads with marked operating regions and operating points

Small-signal equivalent circuit diagram: During small-signal operation, the piezoelectric transducer displacement *s* and polarization charge q display merely voltage- and force-induced components. Subsequently, its transfer characteristic can be described by the electromechanical equivalent circuit diagram, shown in Figure 3.

Accordingly, the input of a piezoelectric transducer can be considered as an electrical capacitor with the capacitance C and its output as a mechanical spring with the stiffness c. As in reality C is always lossy and c has always a mass, the amplitude response $\left|\underline{U}/\underline{F}\right|$ of the piezoelectric transducer has a definite lower cut-off frequency f_u and a mechanically determined natural frequency f_0 for an open electrical port ($I = 0$), and the amplitude response $\left|\underline{s}/\underline{U}\right|$ has a mechanically determined natural frequency f_0 for an open mechanical port ($F = 0$).

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Bibliography

Bergqvist, A.: *On magnetic hysteresis modeling*. Doctoral thesis, Royal Institute of Technology, Electrical Power Engineering, Stockholm, 1994. [This book discusses some vectorial hysteresis problems in magnetomechanical elements like magnetostrictive transducers]

Brokate, M.; Sprekels, J.: *Hysteresis and Phase Transitions*. Springer-Verlag, New York, Berlin, Heidelberg, 1996. [This book presents the basics of scalar complex hysteretic nonlinearities]

Dosch, J.J.; Inman, D.J.; Garcia, E.: *A self-sensing piezoelectric actuator for collocated control*. J. of Intell. Mater. Syst. and Struct., Vol. 3, 1992, pp.166-185. [This article describes an application of the self-sensing effect in piezoceramics]

Pratt, J.; Flatau, A.B.: *Development and analysis of a self-sensing magnetostrictive actuator design*. Proceedings SPIE Smart Structures and Materials 1917, Albuquerque, USA, 1993, pp. 952-961. [This article describes an application of the self-sensing effect in magnetostrictive transducers]

Janocha, H.(Ed.): *Adapronics and smart Structures*. Springer-Verlag, Berlin, Heidelberg, New York, 1999. [This book presents the basics of adaptronics and smart structures]

Janocha, H.; Quinten, R.: *New Power Amplifier Concept for Piezoelectric Actuators*. Actuator 2002, Proc. 8th International Conference on New Actuators (Bremen 10.-12.06.2002), pp. 462-465. [This article deals with new power electronic concepts for piezoelectric actuators]

Janocha, H.; Stiebel, C.; Würtz, T.: *Power amplifiers for piezoelectric actuators*. Responsive Systems for Active Vibration Control, NATO Science Series, II. Mathematics, Physics and Chemistry, vol. 85, Dordrecht 2002, Kluwer Academic Publishers, pp. 379-391. [This article deals with switching, hybrid and analog power electronic concepts for piezoelectric actuators]

Jones, L.; Garcia, E.: *Novel approach to self-sensing actuation*. SPIE Smart Structures and Materials Conference, 3041, SPIE, 1997, pp.305-314. [This article describes an application of the self-sensing effect in piezoceramics with hysteresis modeling]

Krasnosel'skii, M.A.; Pokrovskii, A.V.: *Systems with Hysteresis*. Springer-Verlag, Berlin, Heidelberg, New York, London, Paris, Tokyo, 1989. [This book presents the basics of scalar hysteretic nonlinearities]

Krejci, P.: *Hysteresis, Convexity and Dissipation in Hyperbolic Equations*. Gakuto Int. Series Math. Sci. & Appl. Vol. 8, Gakotosho, Tokyo, 1996. [This book presents the basics of the modified Prandtl-Ishlinskii method for the modeling, identification and compensation of complex hysteretic nonlinearities and the application of this method to smart piezoelectric actuators]

Kuhnen, K.: *Inverse Steuerung piezoelektrischer Aktoren mit Hysterese-, Kriech- und Superpositionsoperatoren*. PhD Thesis, Saarland University, Shaker, Aachen, 2001. [This book presents the basics of the design of scalar hysteretic ad creep nonlinearities]

Kuhnen, K.; Schommer, M.; Janocha, H.: *Design of a smart magnetostrictive actuator by sensing the variation of magnetic flux*. Proc. of the 11th Int. Conf. Sensor 2003, Nürnberg, Mai 2003, S. 267-272. [This article describes partly the application of the self-sensing concept to magnetostrictive transducers]

Mayergoyz, I.D.: *Mathematical Models of Hysteresis*. Springer-Verlag, New York, 1991. [This book presents the basics of scalar and vectorial Preisach hysteresis operators]

Sawyer, C.B.; Tower, C.H.: *Rochelle Salt as a Dielectric*. Physical Review, Vol. 35, 1930, pp. 269 - 273. [This article presents an experimental method for the simultaneous measurement of voltage and electrical charge of dielectric probes]

Stiebel, C.: *Leistungsverstärker zur verlustarmen Ansteuerung von kapazitiven Lasten.* PhD Thesis, Saarland University, Shaker, Aachen, 2002. [This book presents the basics of the design of power electronics for the control of capacitive loads with low power losses]

Schugt, M.: *Aktor-Sensorverhalten von Piezoelementen in Kfz-Diesel-Einspritzsystemen.* PhD Thesis, Shaker, Aachen, 2002. [This book presents the realisation of a smart piezoelectric actuator in a diesel injection system]

Visintin, A.: *Differential Models of Hysteresis*. Springer-Verlag, Berlin, Heidelberg, 1994. [This book presents the basics of scalar and vectorial hysteretic nonlinearities]

Webb, G.; Kurdila, A.; Lagoudas, D.: *Hysteresis Modeling of SMA Actuators for Control Applications.* Journal of Intelligent Material Systems and Structures, Vol. 9, No. 6, 1998, pp. 432-448. [This article presents the basics of the Preisach method for the modeling, identification and compensation of complex hysteretic nonlinearities and the application of this method to an actuator with shape memory alloys]

Biographical Sketches

Klaus Kuhnen, born in 1967, received the Dipl.-Ing. degree in electrical engineering at the University of Saarland in 1994. Following graduation, he has been working there as a scientific collaborator at the Laboratory for Process Automation (LPA) in the fields of solid-state actuators and control of systems with hysteresis and creep. Since 2000 he works as scientific assistant at the Laboratory for Process Automation (LPA) in the fields of self-sensing solid-state actuators, active vibration damping with active material systems and adaptive identification and compensation with convex constraints. He received the Dr.-Ing. degree in engineering sciences at the University of Saarland in 2001. His research interests are in the mechatronic systems with active materials, the control of systems with hysteresis and creep, adaptive control theory and nonlinear signal processing.

Hartmut Janocha, (Prof. Dr.-Ing. habil.) born in 1944, studied electrical engineering at the University of Hanover. Since 1989, he has been head of the Laboratory for Process Automation (LPA) at the University of Saarland in Saarbrücken, Germany. Here, the main fields of work are unconventional actuators with system and signal-processing concepts, calibration methods for improving the positioning accuracy of industrial robots and measurement of 3D- geometry using CCD video cameras.