EXPLOITATION OF INHERENT SENSOR EFFECTS IN MAGNETOSTRICTIVE ACTUATORS

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Abstract
The inherent sensor effects in magnetostrictive materials allow in combination with proper measurement and signal processing methods the simultaneous use of a magnetostrictive transducer as both sensor and actuator. Operating in this way the transducers are frequently called self-sensing actuators. This paper presents and evaluates two different methods, a direct and an indirect one, for using these inherent sensor effects with respect to their principal feasibility.

Keywords: Self-sensing actuator, magnetostriction, magnetostrictive actuator

Introduction

The elongation of ferromagnetic crystals due to a magnetic field is called the magnetostrictive effect. Due to this magnetostrictive effect these materials can be applied for the construction of actuators. On the other hand a mechanical load of the material produces a variation of its magnetisation. This behaviour is called the Villary effect and allows the construction of sensors. The inherent sensor effects in magnetostrictive materials facilitate in combination with proper measurement and signal processing methods the simultaneous use of a magnetostrictive transducer as both sensor and actuator. Operating in this way the transducers are frequently called self-sensing actuators and lead to a miniaturised, simpler and cheaper mechatronic system design [4]. At present there exist two different methods, a direct and an indirect one, for using these inherent sensor effects.

Direct and indirect use of sensor effects

Fig. 1 shows the principle of a magnetostrictive transducer. A cylindrical coil surrounds the magnetostrictive rod and generates the magnetic field strength required for the actuation function. If the magnetic field is homogeneous along the axis of length d and the cross-sectional area A of the rod, the magnetic flux ϕ results from the magnetic flux density B according to $\phi(t) = AB(t)$. The relationship between the magnetic field strengh H in the magnetostrictive rod and the magnetomotive force Θ, defined as the product of the winding number n and the driving current I

$$\Theta(t) := nI(t), \tag{1}$$

is given by the magnetomotive force law. With the homogeneous field distribution and assuming an ideal flux guide this law results in $\Theta(t) = dH(t)$. For a given rod length d and cross-section area A the rod displacement s follows from the rod strain S according to $s(t) = dS(t)$ and the mechanical load F follows from the stress T in the rod according to $F(t) = AT(t)$.

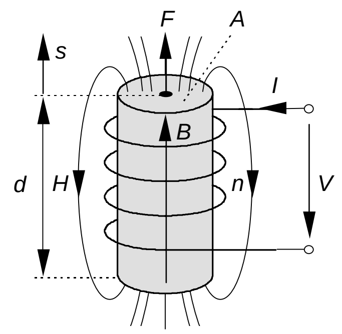

Fig. 1: *Principle of a magnetostrictive transducer*

The voltage across the electrical leads

$$V(t) = n\frac{\mathrm{d}}{\mathrm{d}t}\phi(t) + RI(t)\ . \tag{2}$$

results from the voltage drop across the ohmic coil resistance R and the induction voltage. The magnetomechanical part of the system is determined by the quasistatic transfer characteristics of the magnetostrictive material. These mappings couple the magnetic quantities B and H as well as the mechanical quantities S and T and thus, considering the rod geometry, also the measurable, integral quantities ϕ, Θ, s und F. If the magnetomotive force Θ and the mechanical load F are regarded as independent quantities the magnetomechanical transfer characteristic is given by

$$\phi(t) = \Gamma_S[\Theta, F](t)\ , \tag{3}$$

$$s(t) = \Gamma_A[\Theta, F](t)\ . \tag{4}$$

The mappings Γ_S and Γ_A in the sensor equation (3) and the actuator equation (4) respectively must be interpreted as hysteresis operators which take into account the hysteretic memory in the transfer characteristics of the magnetostrictive material introduced by the domain switching processes.

The direct sensing method makes use of the dependence of the magnetic flux ϕ on the magnetomotive force Θ and the mechanical load F according to (3) and reconstructs the mechanical load F by means of measurements of the magnetic flux ϕ and the magnetomotive force Θ. For this purpose the inverse

$$F(t) = \Gamma_S^{-1}[\Theta,\phi](t)\,, \tag{5}$$

of the ϕ-F mapping with Θ as a parameter must be calculated.

The indirect sensing method uses the dependence of the small-signal inductance, defined as

$$L[\Theta,F](t) := n^2 \frac{\partial \Gamma_S[\Theta,F](t)}{\partial \Theta}\,, \tag{6}$$

on the driving current $I = \Theta/n$ and the mechanical load F. For this purpose the driving current I is divided into a low-frequency signal I_A with large amplitude and a sinusoidal high-frequency test signal I_T with small amplitude. Introducing (3) into (2) and with (6) and

$$\Theta(t) = n(I_A(t) + I_T(t)) = nI(t) \tag{7}$$

follows the relationship

$$\begin{aligned} V(t) = {} & L[\Theta,F](t)\frac{\mathrm{d}}{\mathrm{d}t}(I_A(t)+I_T(t)) \\ & +R(I_A(t)+I_T(t)) \end{aligned} \tag{8}$$

between the clamp voltage V and the driving current I. According to (6) the small-signal inductance L can be interpreted as the effective slope of the ϕ-Θ mapping in the operating point defined by the driving current I and the mechanical load F. If the amplitude of the test signal is sufficiently small the current I_T drives the ϕ-Θ mapping in the linear range and thus produces no high-frequency variation of the inductance L. Therefore the influence of the test signal can be neglected in the argument of L. In this case the coil voltage V consists of a high-frequency part

$$V_T(t) \approx L[I_A,F](t)\frac{\mathrm{d}}{\mathrm{d}t}I_T(t) + RI_T(t) \tag{9}$$

which can be separated from the low-frequency part

$$V_A(t) \approx L[I_A,F](t)\frac{\mathrm{d}}{\mathrm{d}t}I_A(t) + RI_A(t)\,, \tag{10}$$

by means of a bandpass filter. An experimental determination of the small-signal inductance from the measurements of I_T and V_T, i.e. a measurement value L_m, follows from a phase-selective demodulation, a parameter identification or a signal analysis based on a discrete Fourier transformation (DFT). Finally the force reconstruction requires an inversion

$$F(t) = L^{-1}[I_A, L_m](t) \tag{11}$$

of the inductance model $L[I_A,F]$ with respect to the mechanical load F and with the low-frequency driving current I_A as a parameter.

Flux and inductance measurement

The direct method requires the simultaneous measurement of the magnetomotive force and the magnetic flux. The flux measurement can be achieved directly by a Hall element which is integrated into the transducer casing [6]. This option requires the consideration of this additional functionality in the design stage.

The electrical measurement circuit in Fig. 2 allows an experimental determination of the magnetomotive force Θ and the magnetic flux ϕ by means of the coil current I and voltage signal V of the transducer.

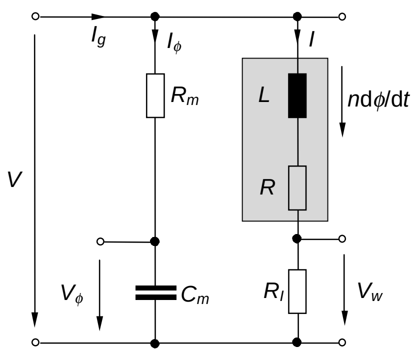

Fig. 2: *Indirect flux measurement with an electrical measurement circuit*

The magnetomotive force follows with (1) immediately from the voltage V_W across the current measurement resistance R_I. The frequency response of the measurement voltage V_ϕ with respect to the magnetic flux ϕ and the driving current I of the transducer is given by

$$\begin{aligned} \underline{V}_\phi(\mathrm{j}\omega) = {} & \frac{\mathrm{j}\omega}{1+\mathrm{j}\omega C_m R_m} n\underline{\phi}(\mathrm{j}\omega) \\ & + \frac{R+R_I}{1+\mathrm{j}\omega C_m R_m}\underline{I}(\mathrm{j}\omega). \end{aligned} \tag{12}$$

According to (12) the magnetic flux determines the measurement voltage V_ϕ for sufficiently high frequencies and is thus a measure for this quantity in this frequency range. In contrast to the flux measurement with the Hall element it is not possible to measure a static magnetic flux with the measurement circuit shown in Fig. 2.

According to (9) the experimental determination of the small-signal inductance L_m with the test signal approach results from an amplitude comparison of the voltage $V_T - RI_T$ across the inductance and the measured driving current I_T at the test signal frequency f_T. The resistance R of the coil windings is widely independent of the operating point of the transducer and the signal frequency and can be determined experimentally with high precision in advance. In this case the small-signal inductance is given by

$$L_m = \frac{1}{2\pi f_T} \frac{\left| \underline{V}_T(\mathrm{j}\omega) - R\underline{I}_T(\mathrm{j}\omega) \right|}{\left| \underline{I}_T(\mathrm{j}\omega) \right|} . \tag{13}$$

The evaluation of this expression requires a band-pass filtering of the current and voltage signals at the test signal frequency as well as a demodulation to transform the high-frequency information into the base band. An alternative for the evaluation of (13) is the DFT-based digital signal analysis [7]. If the sampling frequency f_s is properly chosen the test signal frequency f_T corresponds to a frequency point in the discrete frequency spectrum of the DFT. In this case there is no leakage effect and the value of the discrete frequency spectrum at this frequency point corresponds to the amplitude value of the signals.

Another alternative for the determination of the inductance is offered by means of the discrete-time approximation

$$V_T(k) - RI_T(k) = L_m \frac{1}{T_s} (I_T(k) - I_T(k-1)) \tag{14}$$

of the differential equation (9) with the sampling time T_s. An immediate evaluation of (14) with respect to L_m becomes crucial for small current changes occuring in particular for high-frequency sampling and due to the high sensitivity to external disturbances as for example signal noise. A suppression of these effects requires measurements of the current and voltage signal over several, i.e. $k = 1 \,.\,.\, N$, sampling points. Accordingly, the identification of the inductance results from the solution of the overdetermined system of linear equations

$$\begin{pmatrix} I_T(1) - I_T(0) \\ I_T(2) - I_T(1) \\ \vdots \\ I_T(N) - I_T(N-1) \end{pmatrix} \frac{L_m}{T_s} = \begin{pmatrix} u_T(1) - RI_T(1) \\ u_T(2) - RI_T(2) \\ \vdots \\ u_T(N) - RI_T(N) \end{pmatrix} \tag{15}$$

which can be solved either directly or recursively [2,3].

Force reconstruction and system inversion

In the last step, the use of the self-sensing effect requires an inversion of the ϕ-F mapping according to (5) in the case of the direct approach and an inversion of the L-F mapping according to (11) in the case of the indirect approach. Therefore, above all we have to specify the precondition for a successful inversion and thus a successful reconstruction of the mechanical load. This object should now be discussed representatively by means of the ϕ-F mapping.

At time t the force reconstruction unit determines that force value $F(t)$ which generates the measured magnetic flux value $\phi(t)$ for the measured magnetomotive force value $\Theta(t)$. This can be done with the sensor model (3) by means of solving the implicit equation

$$\phi(t) - \Gamma_S[\Theta, F](t) = 0 \tag{16}$$

with the simultaneous measurements $\Theta(t)$ and $\phi(t)$. This implicit equation possesses a unique solution for time t if and only if the continuous ϕ-F mapping is strongly monotone for all Θ. This is shown in Fig. 3 for a hysteretic mapping Γ_S which is typical for solid-state transducers.

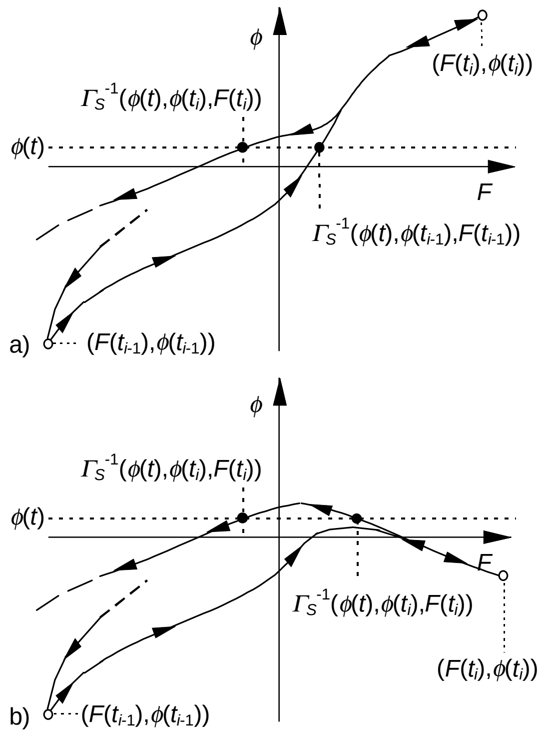

Fig. 3: *Solution of the implicit equation for a given time t for: a) a strongly monotone characteristic b) a non strongly monotone characteristic*

At first glance, due to the hysteretic ϕ-F mapping there exists a multivalued solution in Fig. 3a. But the different solutions differ in the history of the system which is given here by the couple $(\phi(t_i),F(t_i))$. With t_i we denote the time of the last extreme value of the force signal [1,5]. As a consequence we can calculate the inverse mapping (5) by the numerical solution of (16). According to Fig. 3b in the case of a non strongly monotone ϕ-F mapping we have amplitude ranges for ϕ with a multivalued solution for the same history of the system and thus an unique inverse mapping Γ_S^{-1} does not exist.

Experimental results

Fig. 4 shows the experimentally determined L_m-F characteristic of a magnetostrictive transducer with n = 1200 coil windings for different low-frequency driving currents I_A. Here and in Fig. 5 below tension forces are defined as positive loads.

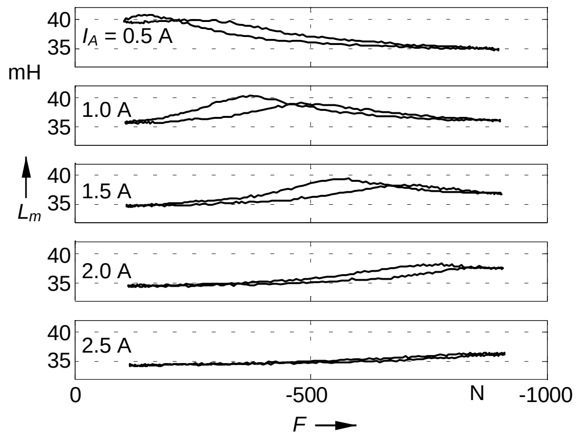

Fig. 4: *Current dependent L_m-F characteristic of a magnetostrictive transducer (indirect approach)*

Beside the hysteretic behaviour, this characteristic exhibits certain ranges of non monotonicity with respect to the mechanical load. Moreover, the location of the maximum value on the force axis depends clearly on the current operating point. Due to this property a unique reconstruction of the mechanical load is not possible even for a perfect model of the L_m-F mapping. Therefore, the proposed indirect approach is not suited for the realisation of a magnetostrictive self-sensing actuator.

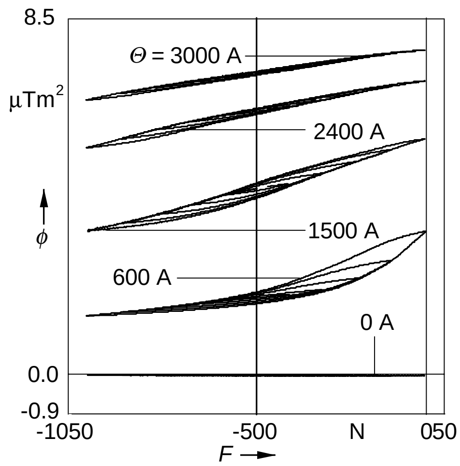

Fig. 5: *Magnetomotive force dependent ϕ-F mapping of a magnetostrictive transducer (direct approach)*

In contrast the experimentally determined ϕ-F mapping in Fig. 5 illustrates a monotone characteristic independently of the magnetomotive force operating point for $\Theta > 0$. Therefore, a force reconstruction and thus a realisation of a magnetostrictive self-sensing actuator is at least in principal possible using the direct approach. But this task requires a sufficiently precise modeling of the measured ϕ-F mapping by means of mathematical models which consider the magnetomotive force dependent hysteresis characteristic in the inherent sensor effect.

Summary and prospects

This paper presents and evaluates two different methods for using the inherent sensor effects with respect to their principal feasibility. As the main result the indirect approach based on the measurement of the small-signal inductance leads to fundamental difficulties for the realisation of a magnetostrictive self-sensing actuator which arise from the non invertibility of the current-dependent inductance-force characteristic. In contrast, the direct approach based on the measurement of the magnetic flux provides a strongly monotone flux-force characteristic which allows at least in principal the unique reconstruction of the mechanical load.

References

[1] Brokate, M.; Sprekels, J.: Hysteresis and phase transitions. Springer-Verlag, Berlin Heidelberg New York, (1996).

[2] Clephas, B.: Untersuchung von hybriden Festkörperaktoren. Doctoral Thesis, Saarland University, Herbert Utz-Verlag, München (1999).

[3] Iserman, R.: Identifikation dynamischer Systeme. Springer-Verlag, Berlin Heidelberg New York, (1988).

[4] Janocha, H. (Editor): Actuators - Basics and applications. Springer-Verlag, Berlin Heidelberg New York, (2004).

[5] Kuhnen, K.: Modeling, identification and compensation of complex hysteretic nonlinearities - A modified Prandtl-Ishlinskii approach. European Journal of Control, Vol. 9, Nr.4, 2003, pp. 407-418.

[6] 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, Nuremberg, May 2003, pp. 267-272.

[7] Schommer, M.; Janocha, H.: Rekonstruktion der Belastung eines magnetostriktiven Aktors durch Signalanalyse. ETG-Fachbericht of the ETG-/GMM-Fachtagung 2004, Darmstadt, March 2004, pp. 189-194. (CD-ROM)