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HYSTERESIS COMPENSATION OF ELECTROMAGNETS

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Abstract. *Electromagnetic direct drives are charactized by a high energy density and short cycle times but they show a strong non linear behavior especially because of saturation and magnetic hysteresis. Different applications use force and position control. To replace the force sensor by a software solution can reduce costs and influences. For this purpose a hysteresis compensation is required in order to preserve good accuracy. This paper discusses the Jiles-Atherton model as one way to model hysteresis effects and its inversion for the compensation of the hysteresis. The implementation on a 16-bit Digital Signal Controller is presented. The presented work was supported by the German Federal Ministry of Education and Research BMBF (project number TRI 03I2916B).*

Key Words: *Electromagnet, Hysteresis Compensation, Jiles-Atherton Model*

1. INTRODUCTION

In the production technology there are several applications for linear drives with both force and position control e.g. bonding and welding heads. The costs of those devices are determined by the expensive force sensors. In addition, most force sensors reduce the system stiffness and accuracy.

Because of this there is a need for force controlled actuators without force sensors. In the case of closed-loop controlled actuators with a defined transfer function (e.g. the linear current to force ratio in voice coil actuators) a force signal can be achieved by observing electrical signals and a position signal. This reduces costs and system complexity.

Generally, this is also possible in the case of proportional solenoid actuators. Due to the strong mechanical and magnetic hysteresis the achievable resolution and precision are limited.

Hysteresis is a very complex process. Only complicated models describe this phenomenon with satisfying accuracy. The current state of the system depends on all former states.

There are several mathematical approaches to the accurate modeling of hysteresis effects. The hysteresis model describes, how the force F lags behind the evocative current

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I. This is a non-unique function F(I). The implementation of the hysteresis compensation requests high CPU-intensity. It is also difficult to define the model parameters for different applications.

2. Comparison of hysteresis models

There are several ways to approximate hysteresis loops:

a. Analytical functions: superposition of a anhysteretic function (e.g. arctan) with a sign depending deviation function,
b. Numerical interpolation of measured and scaled curves,
c. Integrated approach, e.g. the Preisach model: integration of a distribution function of elementary hysteresis in a phase space,
d. Differential approach, e.g. the Jiles-Atherton model: superposition of an anhysteretic function with a numerically integrated differential term.

These kinds of models differ in their accuracy and the calculation effort. The best accuracy concerning inner and asymmetric loops is reached by the Preisach model and the Jiles-Atherton model.

A crucial difference is the inversibility. Because of the integrated approach of the Preisach model it has to be inverted by an iterative calculation. In contrast, there is a way to invert the Jiles-Atherton model by a straight forward algorithm [2]. This can be applied with several problems, e.g. for FEM or circuit simulation or for inverse transfer functions of systems.

3. The Jiles-Atherton model

D.C. Jiles and D.L. Atherton published a method for modeling hysteresis effects for ferromagnetic materials in 1983 [1]. The approach is closely connected to the real physical processes occurring in the Weiss domains of magnetic material. Due to reversible and irreversible processes resulting from the magnetic field strength H, the magnetization M is defined as a sum of two parts:

$$M = M_{rev} + M_{irr} \,. \tag{1}$$

M_{rev} represents the reversible component. M_{irr} is caused by irreversible processes. For the irreversible part applies:

$$\frac{dM_{irr}}{dH} = \frac{M_{an}(H_e) - M_{irr}}{k \cdot \mathrm{sgn}\left(\frac{dH}{dt}\right) - \alpha \cdot (M_{an}(H_e) - M_{irr})}\,, \tag{2}$$

M_{an} represents the anhysteretic magnetization which is approximated by:

$$M_{an} = M_S \cdot \left[\coth\left(\frac{H_e}{a}\right) - \frac{a}{H_e}\right], \tag{3}$$

H_e is the effective field strength and k, a and α are material constants. The irreversible component of the magnetization M_{irr} is calculated by the integration of (2).

According to (1) the resulting magnetization M is then:

$$M = (1-c)\cdot M_{irr} + c\cdot M_{an}(H_e) \tag{4}$$

with reversibility coefficient c. From magnetization M and field strength H the magnetic induction B is calculated:

$$B = \mu_0 \cdot (H + M)\,. \tag{5}$$

4. THE INVERSE JILES-ATHERTON MODEL

In [2] a method to invert the Jiles-Atherton model is introduced, which was originally intended for FEM simulations. Magnetic induction B is stated as an independent argument. Starting from the derivative of (3):

$$\frac{dM_{an}}{dH_e} = \frac{M_s}{a}\cdot\left(1-\coth^2\left(\frac{H_e}{a}\right)+\left(\frac{a}{H_e}\right)^2\right) \tag{6}$$

and

$$\frac{dM_{irr}}{dB_e} = \frac{M_{an} - c\cdot M_{irr}}{\mu_0\cdot k\cdot \operatorname{sgn}\left(\frac{dH}{dt}\right)} \tag{7}$$

with saturation magnetization M_S, effective induction $B_e = \mu_0 H_e$ and material parameter a, the following differential equation is derived:

$$\frac{dM}{dB} = \frac{1 - c\cdot\frac{dM_{irr}}{dB_e} + \frac{c}{\mu_0}\cdot\frac{dM_{an}}{dH_e}}{1+\mu_0\cdot(1-c)\cdot(1-\alpha)\cdot\frac{dM_{irr}}{dB_e} + c\cdot(1-\alpha)\cdot\frac{dM_{an}}{dH_e}}\,. \tag{9}$$

Magnetization M is calculated by integrating (9). Together with magnetic induction B magnetic field strength H yields:

$$H = \frac{B}{\mu_0} - M\,. \tag{10}$$

5. APPLICATION AT FORCE HYSTERESIS

The magnetic B-H hysteresis is the reason for the force-current (F-I) hysteresis of electro-magnets. The idea is to use the Jiles-Atherton model directly at the F-I hysteresis. The problem is that there is a nonlinear relation between flux density B and force F depending on the concrete construction of the solenoid, the position of the armature and the excitation. By means of a coordinate transformation (shifting, scaling) the F-I hysteresis can be mapped onto the point of origin. Then it acquires a shape similar to the one of the B-H hysteresis. The following experimentally gained transformation equations are applied:

$$H = c_H \cdot I \tag{5}$$

$$F = c_B \cdot B^2 \tag{6}$$

Due to the transformation, the *F-I* hysteresis is mapped onto the *B-H* hysteresis model. Therefore the five Jiles-Atherton model parameters a, M_S, α, k and c become abstract values, which cannot be assigned to certain characteristics of the *F-I* hysteresis loop. Yet to simplify matters, the original denotations are retained, although it is formally incorrect.

Finally a coordinate transformation leads to an inverse model for the force-current hysteresis.

6. PARAMETER DETERMINATION

6.1. Simple Parameter Search

There is no direct way to measure all of the five model parameters a, M_S, α, k, c of the original Jiles-Atherton model (2)-(4). Applying it to the force-current hysteresis two more parameters c_H and c_B have to be determined. This has to be done with measured hysteresis loops.

Exemplarily the F-I hysteresis loops of a solenoid actuator are measured for several air gap lengths (reference points) and currents. With optimization algorithms we search for a set of parameters that minimize the deviation from the model to the measurement.

To define the quality of a parameter set, the sum of deviations between calculated and measured hysteresis curve at certain measuring points is determined by:

$$Q_{JA} = \min\left[\sum_{j=1}^{j_{ges}} \left|F_{calc,j} - F_{meas,j}\right|\right], \tag{11}$$

where j_{ges} denotes the number of measuring points. For higher accuracies also inner hysteresis loops are included in the parameter identification. The optimization algorithm tries to minimize this quality criterion.

In [3] some optimization algorithms are investigated with regard to their applicability for this task. The possible solution space is first narrowed by the evolutionary optimization algorithm according to Schwefel in a very efficient way. Then for a more exact optimum localization the Nelder-Mead Simplex algorithm is executed starting with the parameter set found by the evolutionary search procedure.

With the obtained parameter sets the measured F-I hysteresis can be reproduced at the reference points in a highly accurate way. Yet, a parameter interpolation for air gap lengths between the measured reference points does not lead to physically reasonable results (see Fig. 1). The hysteresis loops calculated with interpolated parameters do not run between the loops evaluated for the adjoining reference points, but rather incoherent. Further optimizations with seven free parameters show similar results. The reason is that the parameter shows quite a random distribution, for example parameters k and c_H in Fig. 1. Such a distribution comes from quality function Q_{JA} which has a great number of small local minima because of discrete calculations.

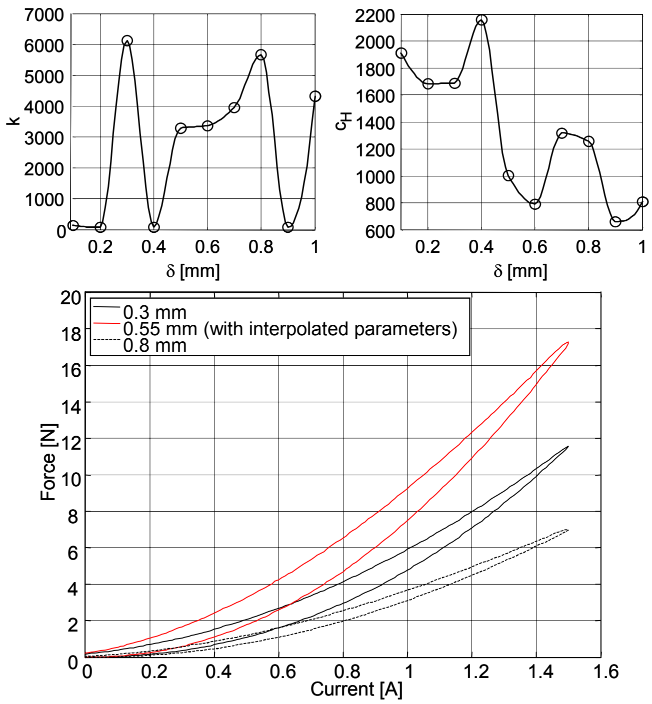

Fig. 1. A simple parameter determination causes interpolation problems because of the incoherent parameters (a, M_S, α, c, c_B not shown)

6.2. Advanced Optimization Procedure

The idea to overcome the interpolation problem is that the parameters should not show the distributed behavior because natural material parameters mostly show continuous or constant behavior.

For this reason the parameter optimization procedure is modified to enable a realistic reproduction of the F-I hysteresis for every possible air gap length at the electromagnet. Thereby it is aspired to keep constant as many parameters as possible and thus to reduce the number of position depending parameters.

A proceeding with several optimization cycles, where the number of the position depending parameters is reduced step by step and the remaining parameters are kept constant as shown in Fig. 2, is successfully investigated. The best result is gained with c_H as the only depending parameter. For $c_H(x)$ a continuous, almost quadratic curve arises (Fig. 3).

For the optimization procedure shown in Fig. 2 a MATLAB-program is developed, which automatically computes and saves the parameters needed for the hysteresis model.

To verify the results, again hysteresis loops for air gaps between the reference points are calculated (see Fig. 3). Now these hysteresis loops run exactly between those for the reference points.

The usage of c_H as the only free parameter implicates the advantage, that the Jiles-Atherton model can be computed with the same inner model parameters for all air gap lengths. Subsequently the result is scaled through a multiplication by c_H.

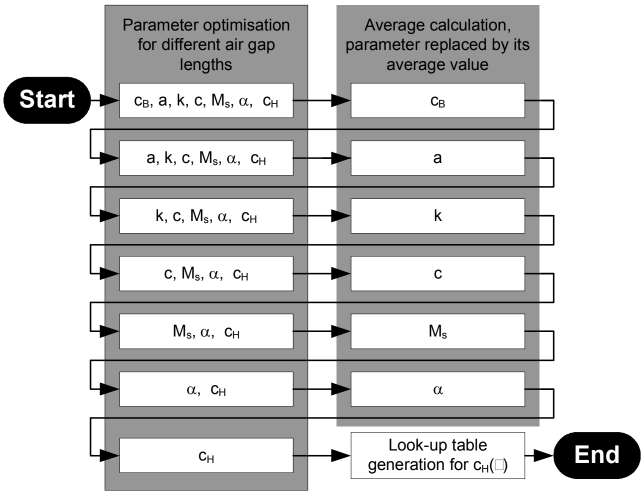

Fig. 2. Parameter optimization procedure

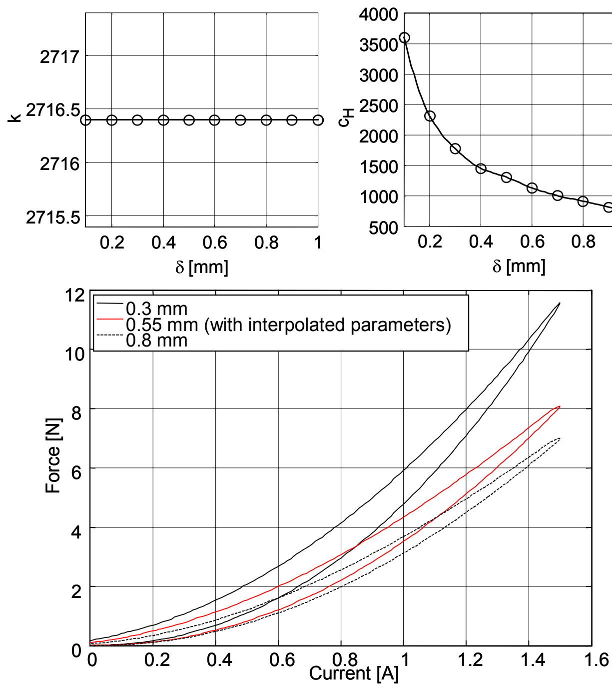

Fig. 3. Parameter Determination Using the Adapted Algorithm Shows a Correct Interpolation in the Hysteresis Simulation (compare to Fig. 1)

7. MICROCONTROLLER IMPLEMENTATION OF A SIMPLIFIED COMPENSATION ON A 16-BIT DIGITAL SIGNAL CONTROLLER

The inverse Jiles-Atherton model allows a compensation of the electromagnets force-current hysteresis.

The Jiles-Atherton model is based on the solution of a differential equation. Thus it is suited for implementation on a digital signal processor. In this case the inverse Jiles-Atherton model is programmed for a Freescale MC56F8322 DSP, which uses fixed-point arithmetic.

In order to use the inverse Jiles-Atherton model for a real-time compensation, the adaptation on the limitations of the fixed-point arithmetic is crucial.

The original models (3) and (6) use the hyperbolic cotangent (coth). This function cannot be implemented directly but it has been proved that equation (3) can be approximated with a sufficient accuracy by a linear equation for small values. In the same way equation (13) can be approximated by a constant value:

$$M_{an} = K_2 + K_1 \cdot H_e \,, \tag{14}$$

$$\frac{dM_{an}}{dH_e} = K_1 \,. \tag{15}$$

The inverse Jiles-Atherton model with approximation is verified by simulation. The accuracy of the compensation is not affected. Furthermore, the approximation leads to a better stability and eliminates initial value problems.

7.1. Experimental Results

The implemented open-loop force control, which sets force according to supplied current, shows good succession behavior both for constant and variable air gap lengths.

Fig. 4 shows the structure of the hysteresis compensation.

The model parameters are calculated for the stroke end position and implemented in the controller program. A serial communication is used for sending the desired force values from PC to the embedded controller. The desired force values and the measured force signals are recorded. The same desired force signal is used as input for a MATLAB simulation. In addition, the proportional solenoid is controlled without the compensation. In this case it is assumed that the actuator has a constant current-force ratio.

Fig. 5 shows the results of this experiment. The measured force signal with activated hysteresis compensation shows only small differences to the desired force curve and the simulated one.

In the next step the parameters of the model are adapted to the armature position. This is done in order to achieve a position-independent force control. For this purpose position-dependent look-up tables for the model constants are used.

The functioning of this approach is tested by measuring the force output for a triangular desired force signal for different discrete positions. Fig. 6 shows the results of this experiment.

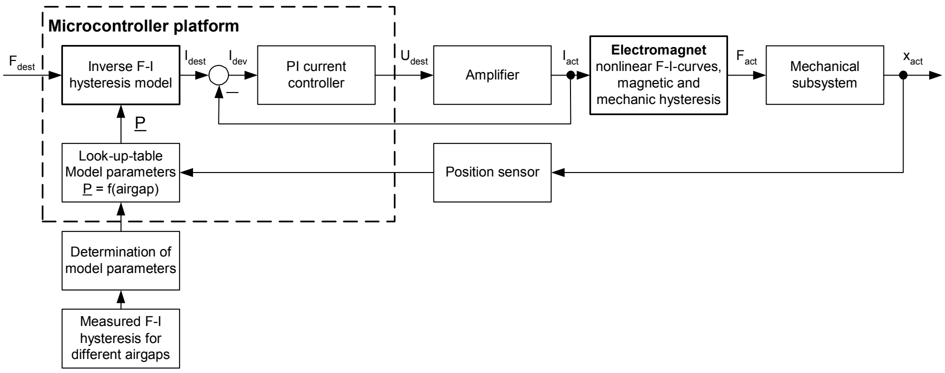

Fig. 4. Parameter optimization procedure

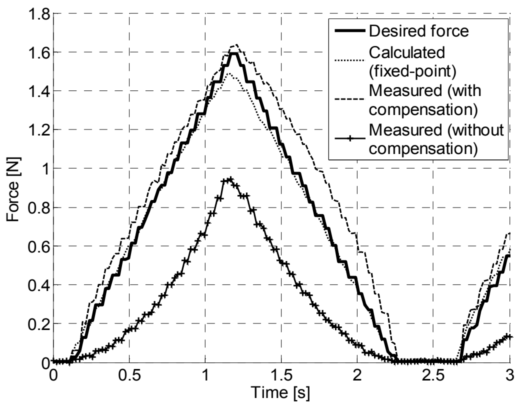

Fig. 5. Verification of the Hysteresis Compensation (fixed position)

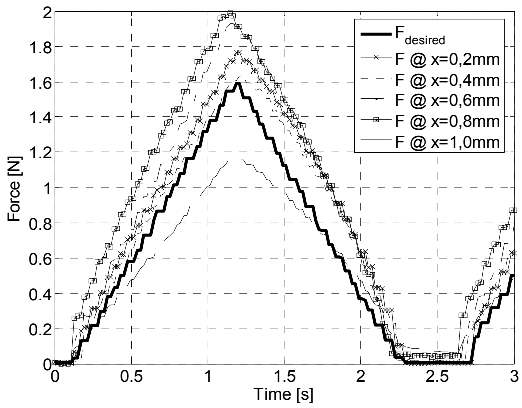

Fig. 6. Verification of the Hysteresis Compensation (different positions)

The triangular signal shape is achieved over the whole stroke. The force is controllable with a maximum relative error of 30 %. Without compensation the signal shape differs strongly with respect to the desired triangular waveform.

8. Hardware Integration

In order to set-up a compact linear actuator with both force and position control the required electronics are integrated together with a proportional solenoid. Electronic modules according to the Match-X standard [4] are used.

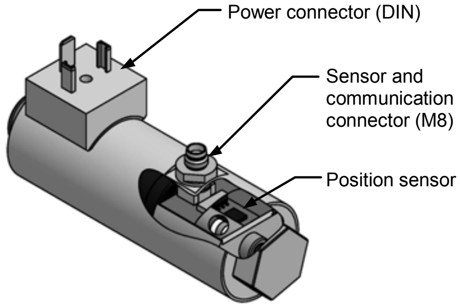

Fig. 7 CAD Image of an Integrated Actuator (Ø 45 mm, maximum force 70 N, stroke 6 mm)

9. Conclusion

In experiments with a solenoid actuator it is exemplarily shown that the Jiles-Atherton model can be applied for the compensation of the F-I hysteresis.

The model parameters can be computed in such a way that only the scaling parameter c_H depends on the air gap length and the remaining parameters are constant. The accuracy of the compensation depends strongly on the quality of the solenoid current control. Optimizations of the current control electronics will allow for a relative force error less then 10 % in the future. This is a sufficient value for several applications in the field of industrial automation. Computational hysteresis compensation permits the use of a solenoid actuator without an additional force sensor in this accuracy range. Thus, the costs for a force controlled drive can be reduced dramatically.

The Jiles-Atherton model can be used furthermore for the simulation of magnetic effects in the design process of electromagnets.

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HISTEREZISNA KOMPENZACIJA ELEKTROMAGNETA

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Direktni pogoni elektromagnetom se karakterišu velikom gustinom energije i kratkim vremenskim intervalom ciklusa, ali i pokazuju izrazito nelinearno ponašanje, naročito zbog zasićenja i magnetnog histerezisa. Za različite primene koriste se sila i upravljanje položajem. Zamena senzora sile primenom softvera može da smanji troškove i neželjena dejstva. Za ovu svrhu je neophodna histerezisna kompenzacija da bi se zadržala dobra tačnost. Ovaj rad razmatra model Jiles-Atherton-a kao jedan od načina za modeliranje efekata histerezisa i njegovu inverziju za kompenzaciju histerezisa. Prikazana je implementacija na 16-bitnom digitalnom signalnom kontroleru. Ovaj rad je urađen u okviru projekta Saveznog ministarstva za obrazovanje i istraživanje Republike Nemačke BMBF (broj projekta TRI 03I2916B).

Ključne reči: *elektromagnet, histerezisna kompenzacija, model Jiles-Atherton-a.*