

Control-Oriented Hysteresis Models for Magnetic Electron Lenses

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This paper deals with finding appropriate hysteresis models that predict the behavior of electro-magnetic lenses used with electron microscopy. The iterative selection procedure consists of experiment design and mathematical analysis of hysteresis models. We will show two examples of pitfalls when the suitability of models is assessed by means of curve-fitting to observations. The first example illustrates the inability of models with local memory to describe the magnetic hysteresis in our application. The second deals with accommodation. With both, the experiments carried out on an off-line setup of a magnetic lens are compared to hysteresis models.

Index Terms—Control systems, electron microscopy, hysteresis, limit cycles, magnetic field measurement, magnetic hysteresis, modeling, time domain measurements.

I. MODEL SELECTION AND EXPERIMENT DESIGN

SELECTION of the most appropriate hysteresis model for the application under study, is an iterative procedure consisting of experiment design and mathematical analysis. A common way to assess a model, is curve fitting of the model's behavior to experiments carried out on a real system. Although the fit to the experiment can be excellent, one has to know the mathematical properties of a nonlinear model before using it. As a first illustration, parameters of a model with local memory will be obtained by least squares fitting to measured data. Although the model has predictive capabilities, its usage for feed-forward controller design is inadmissible.

The second example deals with accommodation, a rate-independent drift of minor loops. The effect is implemented in several models during the last 20 years. Although the proposed definitions of the effect capture the observation, they are not sufficient to define it. Since a set of necessary and sufficient conditions is not available, it is very hard to evaluate the proposed models.

For both cases, experiments are carried out on an electromagnetic lens setup. Analysis of hysteresis properties is carried out for quasi-static experiments.

II. MAGNETIC ELECTRON LENSES

Magnetic electron lenses consist of a coil surrounded by a solid ferromagnetic lens-yoke (NiFe) (Fig. 1). The geometry of the yoke, in combination with the amplitude of the current running through the coil I [A], determines the magnetic flux density B [T] at the symmetry-axis. Charged particles (electrons) traveling at high speed, experience a force due to the cross product of magnetic field and velocity. This Lorentz force is used to obtain optical properties similar to light traveling through lenses made of glass. The focal distance of the lens is a function of the magnetic flux density at the optical axis and can be varied by changing the input current. The required operating point of the

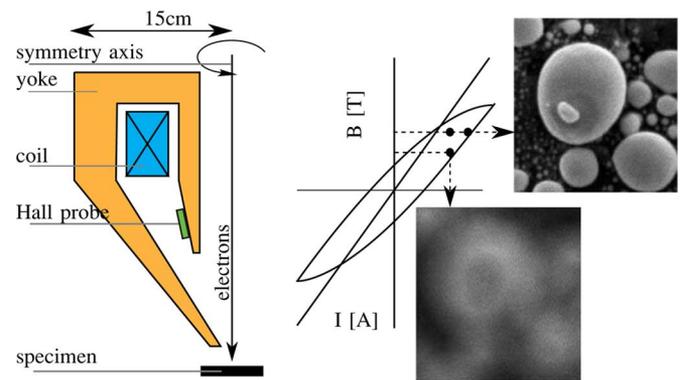


Fig. 1. Left: cross-section of a magnetic electron lens. As a first approximation the lens can be considered circle symmetric. Right: influence of hysteresis on image-quality; the same input current results in a completely different image.

lens varies with, e.g., the position of the specimen, the acceleration voltage of the electrons, and the required magnification.

The image formation is highly sensitive to changes in the magnetic field: only 0.01% of the input range yield acceptable images. Reproducibility of settings is complicated by hysteresis involved with the current-magnetic field relation. Image formation is a single-valued function of B and a multi-valued function of I . The history of the input $I[-\infty; t)$ determines which specific point $B(I)$ out of the set is used (Fig. 1).

Our aim is to characterize the hysteretic relation between current and magnetic field by means of experiments. For this purpose an off-line setup has been built which consists of a magnetic lens in air, a lens-current driver and a data-acquisition system to log the input current and the magnetic field (using a Hall probe). The influence of design properties, such as geometry and materials, is considered to be beyond the scope of our research. Properly designed experiments should help with the selection of the best available model and the phenomena it should take into account. Analysis of mathematical model properties, such as the memory organization and limit cycle behavior, form the basis for input trajectory/controller design.

III. RATE-INDEPENDENCE

Hysteresis phenomena are often denoted as *rate-independent*. For example, in [1, p. 13], a definition is provided which states that the output $w(t)$ at any instant t , depends

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completely on the input history $v[-\infty, t)$, but has no dependence on the rate $(dv)/(dt)$ it was applied. This means that input sequences applied at different rates show the same trajectory in the input-output plane. It is even stated that hysteresis = rate independent memory effect.

However, in many systems that show hysteresis, the system's output heavily depends on the rate at which the input was applied. In these systems, dynamic effects and hysteresis are coupled [2]. Here the definition of hysteresis is not based on rate-independence, but on the fact that a closed input-output trajectory still exists when the frequency content of the input approaches dc. By this definition hysteresis effects are still present for quasi-static excitation, whereas dynamics are not.

In this paper we will use rate-independent models, but we are aware of the fact that the presented measurements can not be considered rate-independent [3]. The input $v(t)$ represents the normalized coil-current $I[A]$ and the output $w(t)$ the normalized measured magnetic flux density $B[T]$ at the position of the Hall probe (Fig. 1). Symbols without physical meaning are used since all measured quantities are normalized to be $\in [-1, 1]$. Next to that, due to the geometry of the lens $H [A/m]$ cannot be measured.

IV. USING A MODEL WITH LOCAL MEMORY

The difference between hysteretic systems with local memory (or history independence [4]) and nonlocal memory (history dependence) comes forward in the limit cycle behavior. For systems with local memory the response to an oscillating input will always converge to be positioned around the anhysteretic curve. The position does only depend on the offset of the oscillation. The amount of repetitions it takes before the closed trajectory is reached is only dependent on the starting point $w(v)$ and the applied trajectory. Fig. 2 illustrates this behavior for oscillations with a different amplitude. In [1, p. 148], it is illustrated that for systems having local memory, two increasing curves in the input-output plane can never cross each other. In [5, p. XVI], it is illustrated that $(dw(v))/(dv)$ in a point $w(v)$ can have only two possible values, one for increasing and one for decreasing input.

The counterpart is nonlocal memory. Instead of two values, $(dw(v))/(dv)$ consists of two bounded sets (one for increasing and one for decreasing inputs). Next to the current output $w(v)$ and the direction of input $(dv)/(dt)$, the derivative is determined by the history $v[-\infty; t)$.

We will discuss the results of least squares parameter fitting of a model with local memory to measured data. As an example we take the Coleman-Hodgdon model [6], [7]. This model is described by the following differential equation:

$$\frac{dw(t)}{dv(t)} = \alpha \cdot \text{sgn}(\dot{v}(t)) [f(v(t)) - w(t)] + g(v(t)). \quad (1)$$

The function $f(v)$ is an odd, monotonically increasing, real-valued function that represents the anhysteretic curve and $g(v) \leq (df(v))/(dv) = f'(v)$ are even, real-valued functions. For the analysis, the simplest implementation is considered. The function $f(v) = bv$ is a line (dashed line in Fig. 2) and $g(v) = u$ is a constant. To ensure a counter-clockwise

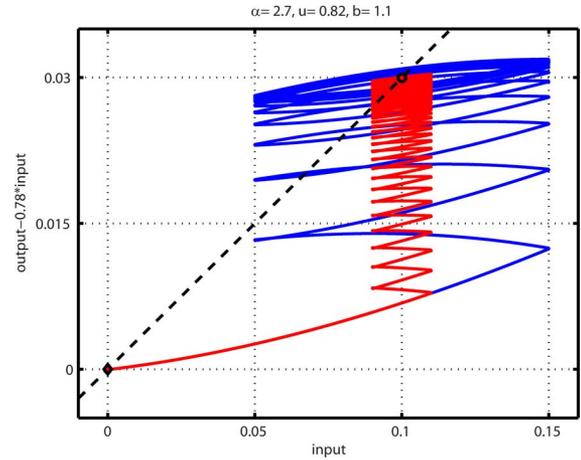


Fig. 2. The output will always converge to the anhysteretic curve when an oscillation is applied at the input. The simulation is carried out for 2 amplitudes (0.01 and 0.05). The dashed line represents the anhysteretic curve. By removing a linear part from the output (output-0.78*input), the illustration becomes more clear: It shows that we are still dealing with a loop, otherwise a line is observed after a few periods.

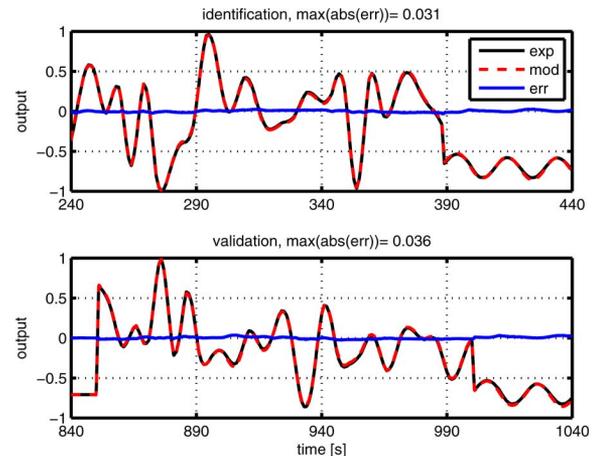


Fig. 3. Upper. Identification result of least squares parameter optimization of the Coleman-Hodgdon model on 200 s of measured data. Lower. Validation by comparison of model prediction and measurement. The maximum absolute error is less than 4% for both identification and validation.

orientation and $(dw)/(dv) \geq 0$, the three model parameters are defined as $\alpha > 0$, $0 < u < b < 2u$. This represents hysteresis considered in a working range; the input $v(t)$ is only a fraction of the total possible input range. As a consequence there is no major loop, but the input-output space is bounded in between two asymptotes $u_{lim} = bv + (b - u)/(\alpha)$ and $l_{lim} = bv - (b - u)/(\alpha)$.

Fig. 3 shows the identification and validation results of least squares parameter optimization ($\alpha = 2.7, b = 1.1, u = 0.82$). The parameters were optimized using 200 s of measured data. Validation takes place by comparing 200 s of measured data to the output predicted by the model. At first glance the results look promising: The largest absolute prediction error is less than 4% with data that covers the complete operating range of the lens.

The magnetic lens application requires reproducibility of a magnetic state. The Coleman-Hodgdon model fits the data well and the model's limit cycle behavior is highly suitable to design

a control strategy for reproducibility: e.g., apply an oscillation and the output will always converge to the anhysteretic curve. However, real systems with magnetic hysteresis have nonlocal memory, e.g., [5]. The response of magnetic systems to periodic inputs can show a rate-independent initial drift, but the limit cycle will not necessarily be positioned around the anhysteretic curve. This effect is called accommodation or reptation and will be dealt with in the next section. The good results of curve fitting for local memory models can be explained by the characteristics of the used data. In this case (Fig. 3) the response to oscillations was underexposed in the data sets.

V. ACCOMMODATION

The phenomenon accommodation is often observed as a drift of minor loops when varying the input between two fixed values. In [8] accommodation is defined as: *A rate-independent drift of successive minor loops towards a limit cycle.* In the input-output plane it is observed that a trajectory will converge to a closed trajectory. Time-dependent effects (e.g., viscosity, aftereffect, creep) can show the exact same trajectory, since the input-output plane does not contain any information about time. To be sure we are dealing with accommodation, we have to test if the effect is still present with quasi-static variations.

Models that describe/predict accommodation models are still under development. As stated in the previous section, models with local memory show accommodation that always converges to the anhysteretic curve. Models with nonlocal memory that show the deletion property [9] show no accommodation at all. In [4] these two models are combined to capture accommodation. An extension to Preisach models is developed in [8], [10], [11], and [12].

Measured data illustrating accommodation is published in [13]. Here accommodation is observed as the drift of minor loops as a response to oscillations. The minor loops are attached to the descending branch of the major loop. Model validation on this data is carried out in [4], [12], and [14]. The presented results show that models with a different basis are capable of describing the presented measurements. That is, a curve-fit of the presented models to the data looks promising. However, validation data containing more complex trajectories seems not available in literature. Analysis of the mechanisms behind the models can provide the experiments that reveal the differences.

In [4] a similar request for experimental data is made by showing a simulation of an uninterrupted trajectory with 5 accommodation cycles. A similar experiment is carried out on the electromagnetic lens setup. The input sequence is shown in Fig. 4, the experiment takes about 35 min. The input consists of low-pass filtered steps ($f_{\text{cut-off}} = 1$ Hz) with a period of 10 s (0.1 Hz). To be sure that accommodation is not mixed up with time dependent effects, constant inputs were applied in front of the accommodation cycles. The drift observed with the accommodation-cycles is about 4 times larger than the time-dependent drift with constant input (Fig. 7).

The corresponding input-output trajectory is shown in Fig. 5. The minor loops of all 5 cycles are given in Fig. 6. In combination with Fig. 7, exponential convergence of the minor loops to a stable limit cycle is illustrated. Note that the largest loop shown is not the major loop. In fact the major loop can not be

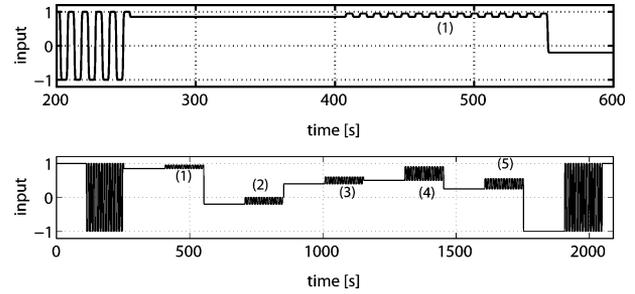


Fig. 4. Input sequence used to illustrate the accommodation effect. Lower: complete sequence. Upper: zoomed in.

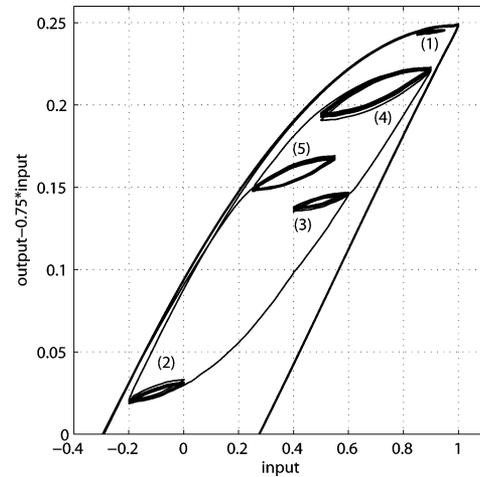


Fig. 5. Input-output plane corresponding to the experiment.

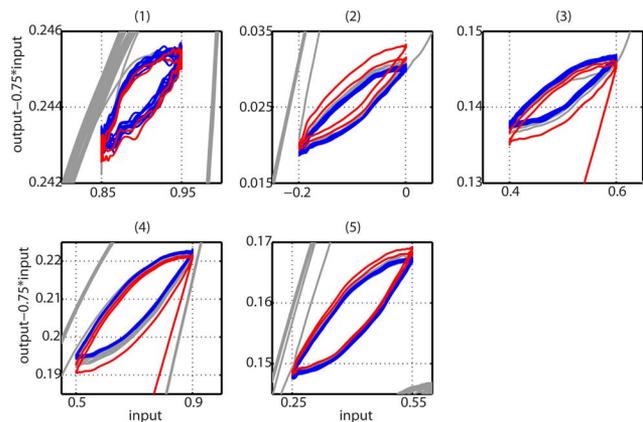


Fig. 6. Zoomed version of separate minor loops.

reached due to the combination of geometry (a large solid piece of iron and lens coil) and the limited input current. The lens is not designed to be magnetically saturated.

The experiment shows a remarkable similarity with the presented simulation (compare Fig. 11 in [4] and Fig. 5 in this paper). The major difference is found in the 5th loop which shows accommodation in the experiment that is not present in the simulation. The cause of this is the memory implementation in the model. However, the key-point is not the memory implementation of the model but the fact that if the 5th loop (indicated as (5) in Fig. 5) was not included in the simulation, the difference between model and experiment would not be revealed.

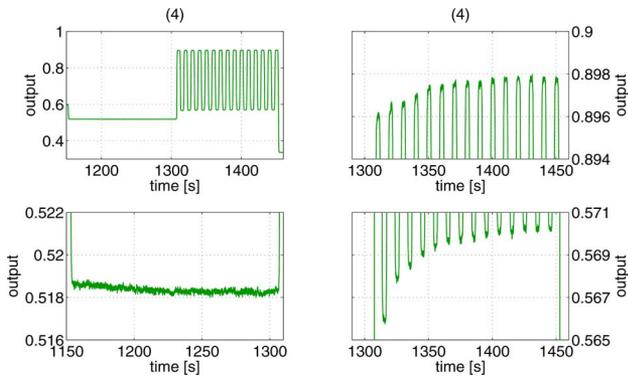


Fig. 7. Upper left. Observed accommodation in time of minor loop (4). As expected an exponential convergence to a stable situation is observed. Upper right. zoomed version (top) of accommodation cycles. Lower left. response to constant input. Lower right. zoomed in to lower part of accommodation cycles. Note that the output varies a factor 4 more with accommodation compared to the time response for a constant input.

The presented definition of accommodation contains necessary conditions for accommodation. If observed trajectories as a response to periodic and quasi-static excitation are not closed after a single period, but converge to a closed trajectory, accommodation is likely to be present. However, a single accommodating loop does not reveal all properties of the effect. The presented definition is therefore not sufficient. The presented measurement is also not sufficient to base a model on. We should at least repeat the measurement several times and report on the deviations. Identification and validation of the model-parameters should take place on different data (same conditions, material, but a different applied input sequence). A rule which is often ignored.

The magnetic lens will be studied in a feedback-controlled configuration. The magnetic field will be controlled to repetitively switch between a set of values. Also here, accommodation is expected. Only this time the loops will not only drift up or down, but also left or right.

VI. CONCLUSIONS AND FUTURE WORK

We have shown the experiment-design and model-analysis procedure in progress for a magnetic lens application. The focus was on accommodation. By means of two examples it is shown that model development and selection can be misleading if only based on observations and curve fitting. It is shown that mathematical definition of the experiments and mathematical analysis of the model is an absolute requirement for the design of model-based input-trajectories for magnetic systems suffering from hysteresis.

In the case of the Coleman-Hodgdon model it is shown that the local-memory is the problem. The parameters of the model are optimized on measured data. The model fits well and has predictive power for similar data. However, limit cycle analysis shows that the output will always converge to the anhysteretic curve if oscillations are applied. This is not the case for magnetic hysteresis. Therefore, this model is not suitable for designing feed-forward control strategies.

Within electron microscopy, magnetic lenses have to switch between different settings. Due to the high sensitivity of the image formation on the magnetic field, accommodation becomes a significant effect. To find a suitable model for designing control strategies for the magnetic lens application, we found that only limited experimental accommodation data is available. Several available models suit the presented data well, but the mathematical basis of the models is different. By comparison of published model simulations and magnetic lens experiments our conclusion is that the available data is not rich enough to capture all aspects of the physics involved with accommodation. I.e., the data reveals that accommodation is present, but is not sufficient to assess the suitability of the available models.

As future work we would like to design a necessary and sufficient set of experiments and corresponding mathematical definitions describing the behavior of our application including accommodation. Our aim is to study reproducibility of magnetic states without the possibility to completely saturate the material and the implications for model identification. Models will be used to design transient inputs and control strategies in order to deal with hysteresis in magnetic lens applications.

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REFERENCES

- [1] A. Visintin, *Differential Models of Hysteresis*. New York: Springer, 1994.
- [2] J. Oh and D. Bernstein, "Semilinear Duhem model for rate-independent and rate-dependent hysteresis," *IEEE Trans. Autom. Control*, vol. 50, no. 5, pp. 631–645, May 2005.
- [3] G. Bertotti, *Hysteresis in Magnetism*. New York: Academic, 1998.
- [4] S. Zirka, Y. Moroz, and E. Della Torre, "Combination hysteresis model for accommodation magnetization," *IEEE Trans. Magn.*, vol. 41, no. 9, pp. 2426–2431, Sep. 2005.
- [5] I. Mayergoyz, *Mathematical Models of Hysteresis*. New York: Springer-Verlag, 1991.
- [6] B. Coleman and M. Hodgdon, "A constitutive relation for rate-independent hysteresis in ferromagnetically soft materials," *Int. J. Eng. Sci.*, vol. 24, no. 6, pp. 897–919, 1986.
- [7] B. Coleman and M. Hodgdon, "On a class of constitutive relations for ferromagnetic hysteresis," *Archive for Rational Mechanics and Analysis*, vol. 99, no. 4, pp. 375–396, 1987.
- [8] E. Della Torre and Y. Jin, "Comparison of the DEMAM and DEAM accommodation models," *IEEE Trans. Magn.*, vol. 45, no. 3, pp. 1198–1201, Mar. 2009.
- [9] E. Della Torre, *Magnetic Hysteresis*. Piscataway, NJ: IEEE Press, 1999.
- [10] E. Della Torre, "A Preisach model for accommodation," *IEEE Trans. Magn.*, vol. 30, no. 5, pp. 2701–2707, Sep. 1994.
- [11] E. Della Torre, L. Yanik, A. E. Yarimbiyik, and M. J. Donahue, "Differential equation model for accommodation magnetization," *IEEE Trans. Magn.*, vol. 40, no. 3, pp. 1499–1505, May 2004.
- [12] L. Yanik, A. E. Yarimbiyik, and E. Della Torre, "Comparison of the differential equation accommodation model with experiment," *J. Appl. Phys.*, vol. 99, no. 8, 2006.
- [13] L. Bennett, F. Vajda, U. Atzmony, and L. Swartzendruber, "Accommodation study of a nanograin iron powder," *IEEE Trans. Magn.*, vol. 32, no. 5, pp. 4493–4495, Sep. 1996.
- [14] J. Takacs, "Analytical way to model magnetic transients and accommodation," *Phys. B: Condens. Matter*, vol. 387, no. 1–2, pp. 217–221, 2007.