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Citation for published version (APA):

Bree, van, P. J., Lierop, van, C. M. M., & Bosch, van den, P. P. J. (2010). On hysteresis in magnetic lenses of electron microscopes. In *Proceedings of the IEEE International Symposium on Industrial Electronics (ISIE 2010), 4-7 July 2010, Bari, Italy* (pp. 268-273). Institute of Electrical and Electronics Engineers.
<https://doi.org/10.1109/ISIE.2010.5637564>

DOI:

[10.1109/ISIE.2010.5637564](https://doi.org/10.1109/ISIE.2010.5637564)

Document status and date:

Published: 01/01/2010

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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On Hysteresis in Magnetic Lenses of Electron Microscopes

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Abstract—This paper deals with an experimental procedure to illustrate the problems introduced by ferromagnetic hysteresis present in magnetic lenses of electron microscopes. The magnetic flux density is not available as a measurable quantity. Hysteresis expresses itself in the relation between the input current applied to the lens-coil and the level of sharpness (defocus) of the resulting images. The familiar hysteresis loops are not available, instead we measure hysteresis in the so-called butterfly representation. The input-profiles are non-periodic and illustrate the difficulties with reproducibility in microscopy applications. Image based feedback control is impossible since 99% of the input range yield unusable images. Analysis of the experiments is carried out using a qualitative model consisting of an interconnection of hysteresis representing the magnetic lens and a nonlinear function representing electron optics. Because this model introduces the intermediate magnetic field variable, it is possible to reconstruct and explain the results observed in the experiments.

I. INTRODUCTION

Automation of electron microscopy applications involves taking into account magnetization dynamics of the magnetic lenses and capturing the operators skills into control algorithms. Magnetic lenses suffer from hysteresis, which complicates reproducibility of the lens' focal distance.

The influence of a magnetic field on the trajectory of moving charged particles (electrons) forms the basis to obtain a similar behavior to light traveling through a lens made of glass. The focal distance of a magnetic lens can be varied changing the amplitude of the magnetic field distribution.

For decades most effort on charged particle optics was in improving the optical quality of such systems from micrometer down to sub-nanometer resolution. The major limiting factor for resolution is aberration (e.g. spherical or chromatic aberration [1]). During image formation the magnetic field has to be in steady state, which implies that aberrations are only of importance during image acquisition. As a result the design of the microscope is highly optimized for *static* use.

The result of microscopy applications is most of the time a high quality strongly magnified image of the specimen under study. However, new markets have evolved in which the image itself is no longer the main result. An example is feature extraction, e.g. detection of the number and size (nm) of particles within $1\mu m^2$ of the specimen, from a large series of images possibly obtained on different settings. The system's quality is now expressed in accuracy (number and size of

Fig. 1. Schematic view of a lens system of a scanning electron microscope

particles) and throughput. Image-resolution is only important for the feature extraction algorithms.

If the image is in focus (sharp), the sensitivity $\Delta S/\Delta I$ of the level of sharpness S to a change in the lens input current $I[A]$ is extremely high; A change in the input larger than approximately 1% of the total input range yields unusable images. Unusable images mean that no information about the specimen can be distinguished and the search procedures based on ΔS variation for small ΔI would fail.

The high sensitivity of defocus in a working point implies that 99% of the input range does not result in a usable image. The range in which an image is observed which has a sharpness level that is good enough (no further optimization required) can be as small as 0.01%. The reason for the input range to be so large is because the microscope has a lot of different working points (modes) (explained in section II). The high sensitivity itself is no problem, but hysteresis in the lenses makes that the optimal working point $S(I)$ is not uniquely defined. This complicates reproducibility: a set-point in terms of S cannot be reproduced by just applying the same input.

Measurement of the magnetic field, which controls the focal properties of the lens, is a possibility for analysis and feedback control. In the current implementation of the microscope no magnetic field sensors are available. However, information about the magnetic field is helpful as presented in section IV-B. Therefore, magnetic field measurement is considered as

an option, but it is studied separately, e.g. [2].

This paper shows the results of experiments that illustrate the open loop response when large but temporary changes in the input are applied. We take a phenomenological point of view in which the significance of hysteresis is extracted from the estimated level of sharpness obtained from image sequences. Analysis is complicated because of the limited range in which usable images are available. This is solved by a model based approach that deals with the main qualitative features of the experiments. The model consists of an interconnection of a hysteresis model representing the magnetization of the lens and a nonlinear static function describing the electron optics.

II. SCANNING ELECTRON MICROSCOPY

The name scanning electron microscope comes from the fact that an electron beam is scanned over a surface (Fig. 1). The incoming (primary) electrons generate a stream of secondary electrons which are collected by the electron-detector, e.g. [1], [3]. The number of secondary electrons varies with the material-type and the composition of the sample. For example, at edges more secondary electrons can escape from the sample and, therefore, the electron-intensity corresponding to an edge will appear white in the image.

A magnetic electron lens consists of a cylinder shaped coil surrounded by a ferromagnetic (e.g. NiFe) pole-piece (yoke). The magnetic field observed by the electrons is a function of the geometry and material of the pole piece and the input current applied to the coil $I[A]$. The trajectory of an electron can be derived from the Lorentz force which relates the velocity of a charged particle to the magnetic field it is traveling through. First the electrons are accelerated (by a voltage e.g. $\in (0.5, 30kV)$) to about a fraction of the speed of light [4]. The incoming beam is considered parallel and has a diameter of $\approx 1\mu m$. The electron lens focuses the diameter to within $1 - 100nm$ (demagnification 10, 1000 times). The required diameter of the beam on the surface of the specimen (spot-size) depends on the scan pattern. If the pattern is a rectangular grid, the spot-size should be equal to one cell of the grid. An image is constructed by mapping the measured intensity of secondary electrons to the corresponding position of the electron beam on the sample.

As Fig. 1 illustrates, a set of deflectors is able to drive the beam through a virtual pivot point, such that any xy -movement is possible. The magnification is therefore a property of the deflection system instead of a property of the lens which only controls the spot-size. As an example the width of the sample is $30\mu m$ which is divided into a grid of 512^2 . The required spot-size is then $30\mu m/512 = 58.6nm$. If the resulting (computer) image has a horizontal width of $15cm$, the magnification is 5000 times. In the presented experiments, the acquisition-time of a single image (for this particular setting) is about $70ms$ which results in $14 images/s$.

The focal distance of the magnetic lens cannot be measured directly, but if the sample is positioned in the focal plane the resulting images will show maximum sharpness. Fig. 2 provides a schematic overview of the relation between the

Fig. 2. Schematic overview of the focal distance f , the working distance wd and the position of the sample z in a scanning electron microscope

focal distance f and the distance of the specimen to the bottom of the lens z . A reference distance related to the focal distance is called working distance wd in microscopy. If $wd = z$ the radius of the electron beam projected at the sample (spot-size) is as small as possible, and high resolution (sharp) images can be recorded. If the spot-size is too large the images will look blurred. So if z is unknown but constant, it is possible to access variation of f by studying the level of sharpness/defocus/blurredness.

In the presented experiments in section IV the following settings are used: acceleration voltage $1kV$, scan width $\approx 10\mu m$ (visible specimen size, Fig.1), electron beam current $0.7pA$, $z \approx 5mm$.

III. SHARPNESS

The sharpness evaluation techniques considered here are based on pre-knowledge on the variation of intensity along with variation of the focal distance. An image which is in (or near) focus will show a lot of (almost) black and (almost) white, whereas blurred images will appear more gray. More gray, also indicates that on average there is a smaller deviation from the average gray intensity over all pixels $\bar{p}$ than for images that contain both black and white. This measure is defined as variance S :

$$S = \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m (p(i, j) - \bar{p})^2 \quad (1)$$

$$\bar{p} = \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m p(i, j) \quad (2)$$

Sharpness has a correction for the number of pixels ($n \cdot m$), but not for the image content. Therefore, the maximum sharpness is only known if the original intensity distribution is known. This is not the case in this application, but for a particular combination of settings (e.g. electron beam intensity, sample orientation and position) it can be obtained experimentally. The lower bound on sharpness is zero, since it takes into account squared differences. Zero sharpness would imply a uniform intensity. In a practical situation this is highly dependent on the electron detector characteristics (Fig. 1) for low signal to noise ratios.

Variance belongs to the class of functions that does only take into account the average pixel variation, e.g. [5]. These

Fig. 3. Block diagram of the setup.

functions do not take into account any information about image contents (the relation between neighboring pixels). The level to which the assumption about black and white variation is satisfied will highly depend on the specimen under study. The method does not hold for all possible samples. However, this research aims at a test to illustrate the variation of focus as a function of input variation. The sample is free to choose and the sharpness measure can be tuned such that it works optimally for this testing purpose.

IV. EXPERIMENTS

All measurements are carried out on an extended version of a commercial scanning electron microscope (FEI Helios). Using the normal microscope interface, magnification, pixel grid, acceleration voltage, detector settings and the specimen position can be controlled (Fig 3). A rapid prototyping and data acquisition system (dSPACE) is connected in order to add transient currents $I_{ref}[A]$ to the working point I_{dc} . The transients are designed offline in matlab. All images (about 14/s) are stored on the experiment PC. The sharpness of each image is evaluated afterwards by a matlab implementation of the sharpness measure (1). All settings except the lens current $I[A]$ are constant during the presented experiments. Since the analysis is carried out offline, the image sequence can be synchronized to the measured transient current trajectory by detection of characteristic changes in both signals.

A. Sensitivity

This first experiment shows the response of a low frequent sine-wave which provides insight into the sensitivity $\Delta S/\Delta I$ around a working point. The intention is to have a quasi-static approach, which does not involve dynamic magnetization effects like eddy currents. Moreover, the variation of sharpness within one image should be insignificant; $\Delta S/\Delta t$ should be so small that S can be considered constant within a single image.

Variation in the input current (Fig. 4), the amplitude of the sine $\approx 15mA$ on a full scale of $\pm 2.2A$, is about $\approx 0.3\%$ of the total range. The graph of current vs. sharpness is given in Fig. 5. Hysteresis does not significantly express itself on this scale: From the presented results it cannot be concluded that there is a multivalued map. Variation of the measured curve can be due to measurement noise in both I and the electron intensity, a possible synchronization error between S and I

Fig. 4. Sharpness variation as response to a sine wave. The sine's amplitude is about 0.3% of the total range. Images corresponding to (a), (b), (c), (d) are shown in Fig. 6.

Fig. 5. Measured current vs. sharpness ($I-S$ map). The dashed lines indicate the estimated sharpness levels of the images shown in Fig. 6

(delay) and hysteresis. Fig. 6 shows the images corresponding to the dashed lines indicating the sharpness variation.

The results provide an indication of the sensitivity $\Delta S/\Delta I$ around a working point. Since the amplitude of the sine wave ΔI is limited, the behavior of the obtained sharpness for images that are defined as unusable in the introduction (section I) is not shown. Extrapolation of the $I-S$ curve of Fig. 5 may seem to result in negative sharpness, which is not possible by definition of the implemented measure (1). The lower bound on S is equal to zero (section III). Due to sensor noise it will always be slightly larger than zero. The variation ΔI in this experiment is too small to illustrate this.

Fig. 6. Images corresponding to the sharpness levels indicated in Fig. 4 and 5

Fig. 7. Sharpness and applied lens current. At the start of the measurement the image is focused by hand.

B. Hysteresis

The following experiments show that hysteresis is significant when switching from one working point to another and back. I.e. the reproducibility/sharpness deviation for large but temporary changes in the input. Large is here defined as a variation during which sharpness cannot be evaluated since it is too low. The quasi-static experiments already showed a drastic decrease in sharpness for changes of $\Delta I \leq 0.3\%$, now the input is varied up to 10%.

A temporary change implies that the input is set back to the original constant value after a certain amount of time. Since all other settings are kept constant, any change in defocus is a result of a magnetic lens effect (reference experiments, in which all settings affecting the magnetic lens were kept constant, have been carried out, but are not provided in this paper). Experiments prove that a different sharpness value can be obtained with the same constant input; a multivalued quasi-static relation (hysteresis) exists.

As shown in Fig. 7, the experiment starts with the quasi-static sine wave. The images (e,f,g,h) in Fig. 8 are snapshots of the recorded sequence at $t = 50, 60, 70, 149s$. From both the images and the estimated sharpness it appears that the large pulse in negative direction $n1$ has no influence; the sharpness values and images look the same before and after the pulse (compare images (e) and (f)). However, the pulses in positive direction $p1 \dots p8$ result in a significant decreased sharpness (compare images (f) and (g)). When the negative pulse is applied again ($n2$) it results in the original sharpness (image (h)). This is not a temporal effect; If the $n2$ was not applied, the images would have stayed out of focus. The observed phenomena are explained in the next section using a model based approach.

V. INTERCONNECTED HYSTERESIS MODEL

In this section, a model is introduced which can explain the results of the presented experiments by introducing the

Fig. 8. Images corresponding to the sharpness at 50, 60, 70, 149s in Fig. 7.

Fig. 9. Interconnected model structure, hysteresis operator H and positive nonlinear static curve F

magnetic field $B[T]$ as intermediate variable. The model incorporates an interconnection of hysteresis $I-B$ and a static nonlinearity, Fig. 9. The static positive nonlinear function F represents the relation between magnetic field B and the level of sharpness S . The goal is to show that it is possible with just these building blocks to reconstruct the scenario obtained with the experiments: Temporary changes of the set-point in one direction should have minor influence, while changes in the other direction result in a significantly decreased sharpness level.

Quasi-static periodic excitation of hysteresis observed in the input-output plane shows a loop structure known from magnetics $H[A/m]$ or $I[A]$ vs. $B[T]$. If another quantity is observed, in this case S instead of B , and the relation between B and S is an positive nonlinear static function (unimodal function), the hysteresis $I-S$ is transformed into a so-called 2-to-1 map [6]. Depending on the specific function, this map can look like a butterfly. Therefore, if the relation between I and S is studied it will be called butterfly hysteresis. This to emphasize the distinction with respect to the more conventional $I-B$ hysteresis.

The hysteresis model used is a differential equation implementation of the Coleman-Hodgdon model [7] (Duhem class, [8]). The specific implementation is explained in more detail in [2]. The time derivative of dw/dt is denoted as $\dot{w}$. The parameters are bounded by $h_3 > 0, h_1 < h_2 < 2h_1$. The parameters (constants) of the model used in simulations are denoted above the different graphs in Fig. 10.

$$\dot{w} = \dot{v} \{ \text{sign}(\dot{v}) h_3 [h_2 v - w] + h_1 \} \quad (3)$$

The positive nonlinear static function is represented by a bell-shaped function (4). Tuning of the constants a_1, a_2, a_3 results in similar curves as observed in Fig. 5. An example is the implemented function as shown in Fig. 11 b).

$$y = F(w) = a_1 \left(1 + \left(\frac{w - a_2}{a_3} \right)^2 \right)^{-1} \quad (4)$$

Fig. 10. Simulation of the interconnected model in the time domain

A. Simulation

To explain the essence of the experiment, just the 2 negative pulses ($N1, N2$) and in between one positive pulse $P1$ with smaller amplitude are applied as an input to the model. Fig. 10 shows all signals of the interconnected model. Besides the pulse, four time instances (I), (II), (III), (IV) are indicated at which all signals (v, w, y) are constant. In order to get the same behavior as in the experiment, the initial value of the hysteresis model w_0 and the offset a_2 of the nonlinear static curve are the most important parameters to tune. In this case, they are equal resulting in maximum sharpness $y(0) = 1$.

The output of the hysteresis model $w = H(v)$ converges to values close to the initial value w_0 after applying $N1$ and $N2$, Fig. 11. After applying $P1$ a significant higher value w is obtained.

By studying the various input-output plots (Fig. 11), insight is gained into the construction of this scenario. The hysteresis plot a.) and its zoomed version c.), show that the trajectory from (I) to (II) as a result of applying $N1$ is almost closed (if it had been closed it would have been called a minor loop). Whether the trajectory is closed depends on the initial condition of the hysteresis model w_0 and the amplitude of $N1$. $P1$ results in an increased output w at time instance (III). An increased hysteresis output w can result in a decreased butterfly hysteresis output y (compare subplot c.) and d.)). By the combination of the amplitudes of $N1, P1$ and $N2$, the parameters w_0, h_1, h_2, h_3 and the memory organization of the hysteresis model, the output level (IV) is again similar to the initial value. Note that the change of any of these parameters result in a different trajectory that is not likely to show the recovery of y after $N1$ and $N2$.

The time plot of the output y (Fig. 10) shows two peaks $Q1, Q2$ which need some explanation. Actually $Q1$ is almost invisible since (II) is close to the maximum. However, $Q2$ shows a small steep peak introduced by $N2$. What happens is that during the transition from (III) to (IV) the nonlinear

Fig. 11. Input-output plots of the simulation. a.) hysteresis $v - w$, b.) positive nonlinear static function, c.) zoomed version hysteresis, d.) butterfly hysteresis $v - y$

function F passes through its maximum. The overall model $v - y$ in Fig. 11 d) also shows hysteresis, but not in the familiar $I - B$ input-output map known from magnetics but in the so-called butterfly representation [6]. From this plot, it is more clear what happens.

The combination of presented plots, time-domain, hysteresis, and butterfly hysteresis makes the analysis feasible, since each plot highlights a different view on the problem. Only taking into account the butterfly hysteresis which represents the actual situation $I - S$ may sometimes seem to provide counterintuitive results. This is mainly due to the fact that an increase in input can result in a decrease in output, depending on the initial conditions.

B. Discussion hysteresis

A qualitative (behavioral) comparison between the model and the experiment is presented. No quantitative comparison, the error between model and experiment in time, is carried out. A quantitative comparison would require a fitting (e.g. least squares) procedure in which the measured current I serves as u in the model and the output w should coincide with the obtained sharpness S . In this stadium that is not possible. In the first place since the presented (Duhem class) hysteresis model does not capture the magnetization phenomena as observed between I and B in the real system (offline experiments with an $I - B$ setup were carried out in [2]). It is possible to carry out a similar analysis with other models like the Preisach model. However, the second reason that modeling is problematic is the extremely high sensitivity of the sharpness. Other phenomenological models will also have their limits and disadvantages. The presented hysteresis model is used since it

is relatively easy to implement and has few parameters and a single initial condition.

VI. CONCLUSION AND FUTURE WORKS

The significance of the problem introduced by ferromagnetic hysteresis in magnetic lenses was illustrated by experiments carried out on a scanning electron microscope. The presented procedures provide an objective test for performance of the lens system. Performance is expressed in reproducibility of a set-point and the time to converge to the set-point.

Hysteresis expresses itself in a multivalued relation between the lens' input current I and the resulting sharpness S (level of defocus) of the obtained images. This implies that a single set-point of the lens current can result in a large range of image-sharpness. It can even result in completely unusable images.

In order to actually measure the influence of hysteresis, the lens-system of a commercial scanning electron microscope (FEI Helios) was extended with a rapid prototyping and data acquisition system. In this way transient inputs could be added to the working point and all resulting images (about 14/s) were stored. The sharpness of each image was analyzed offline.

The defined sharpness measure is based on the intensity differences between pixels and the average intensity. The specimen is chosen such that this difference is large when the specimen is in focus and small when out of focus. The measure does not take into account information about the geometric properties.

The sensitivity of the change in sharpness as a function of the change of input current $\Delta S/\Delta I$ is so high that a change of input larger than $\approx 1\%$ of the total range will result in unusable images. This implies that an automated procedure (e.g. for finding optimal focus) cannot be based on images since they do not always provide enough information. Sensitivity around a working point was obtained by a quasi-static periodic excitation. The exact sensitivity depends on the combination of settings, like electron acceleration voltage, specimen type, etc.

At a small scale, for instance the range that results in usable images around a working point, hysteresis is not dominant. However, it becomes significant for changes in the input larger than a few percent. These changes are required whenever one of the other quantities, determining the required focal distance is changed. In the presented experiments all settings are kept constant except the lens current. The obtained difference in sharpness before and after a temporary change in the input current is a result of hysteresis.

The sharpness is, among others, related to the magnetic field B within the lens. The actual hysteretic behavior is present in the current-magnetic field relation. However, currently the magnetic field cannot be measured directly in the microscope. Therefore, the current sharpness relation is taken into account.

The familiar counter-clockwise hysteresis map in the input-output plane observed for the $I - B$ relation, is now transformed in a so-called butterfly hysteresis map $I - S$. This representation is difficult to interpret for non-periodic excitations. This difficulty is illustrated by a comparing experiments that show convergence of image-sharpness after large changes.

An interconnected model of dynamics and ferromagnetic hysteresis $I - B$ and a static nonlinearity representing electron optics $B - S$ is introduced. Since the intermediate signal B is available in the model, both the $I - B$ and butterfly $I - S$ map are available. By a combination of time-domain and hysteresis plots and tuning of the model and input parameters, a qualitative analysis of the hysteresis behavior during the experiments is carried out.

In the near future we will focus on the magnetization behavior of the lens itself. With the help of magnetic field measurements in a setup containing the lens, without the rest of the microscope, hysteresis-problems can be studied in the more convenient $I - B$ -plane. The accuracy and sensitivity of the microscopy application are obtained from the tests presented in this paper. In this way further tests that fit the applications' requirements can be developed without the trouble of running out the admissible range in which images can be used.

ACKNOWLEDGMENT

This work is carried out as part of the Condor project, a project under the supervision of the Embedded Systems Institute (ESI) and with FEI company as the industrial partner. This project is partially supported by the Dutch Ministry of Economic Affairs under the BSIK program. The authors would like to thank M. Bierhoff (FEI), A.A.S. Sluyterman (FEI), N. Venema (Technolution), W.H.A. Hendrix (TU/e), M. Rudnaya (TU/e) and various others for their help with the experimental microscope setup and processing of the results.

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