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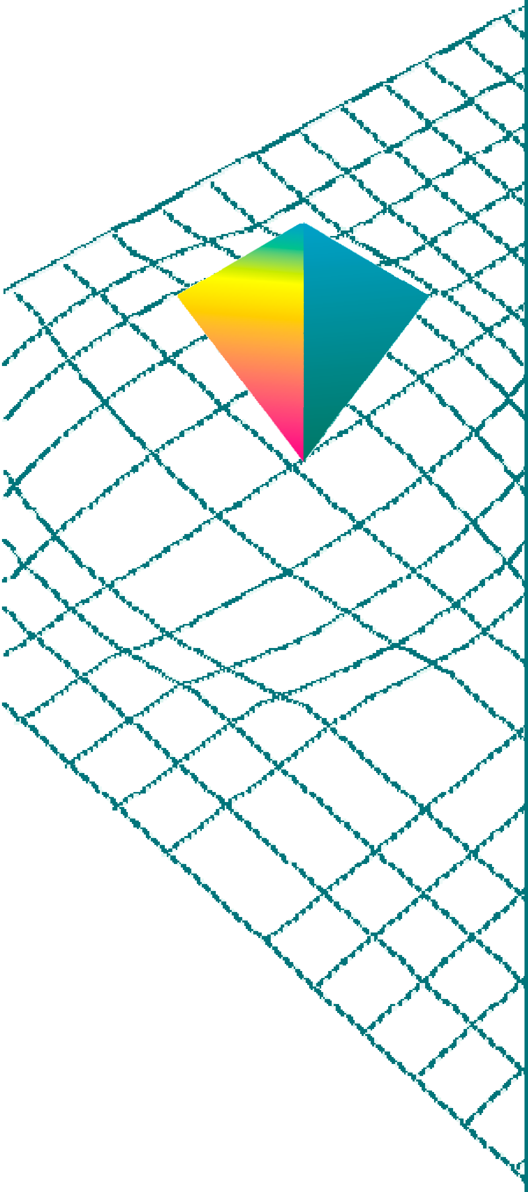

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50. Internationales Wissenschaftliches Kolloquium
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Measuring Device for Magnetic Characteristics of the Manufactured Parts Made from Soft-Magnetic Materials

ABSTRACT

Improvements in quality of electromagnets can be achieved through the creation of fast-acting devices that measure the magnetic characteristics of the soft-magnetic materials. Such devices provide critical information about the magnetic properties of the billets and parts of electromagnets at the various stages of an engineering process. This information is required for an efficient control of electromagnets' manufacturing method and assembly. The original calculation method of magnetic characteristics of ferromagnetic parts was developed and realized in the control device as a result of the cooperation between scientists of TU Ilmenau (Germany) and SRSTU Novocherkassk (Russia). The abovementioned device provides real-time data about the magnetic characteristics of the parts with complex shape with a margin of error no higher than ±5 %. This data is used in selection of optimal operation modes for the technological equipment, as well as application of selective assembly method to the technological electromagnets' assembly process.

1 Introduction

Electromagnets are widely used in practically all technological industries: in diesel engines; in road-, water- and other transportation vehicles; construction-, agricultural- and plastic-processing machinery; robots; production lines; scientific laboratories, etc. The electromagnet manufacturing is a complex technological process, each stage of which will affect the performance and the quality of the complete product [1].

The properties of an electromagnet depend on a large numbers of hard-to-control factors, which complicate the uniformity and performance of the electromagnet. Due to the miniaturization of the electromagnetic devices, the quality of the electromagnet as a wole depends on magnetic characteristics of all of its parts.

Creation of manufacturing and assembly control systems is an effective way to improve the quality of electromagnet. The manufacturing contol system can change technical equipment based on the results of the billets' magnetic properties measurement. Before the technological operation it is necessary to measure magnetic parmeters of the billet and simulate the changes of these parameters.

Such practice helps to select the optimumal operating modes for the process equipment – the modes that provide desired magnetic properties of the electromagnet parts. The method of selective assembly is possible due to the control of the magnetic properties of parts of the the electromagnet. In this case, the final performance of the electromagnet in achieved through the prior simulation of the electromagnet’s performance based on the magnetic characteristics of its parts. The most informative for such simulation are the static magnetic characteristics of materials used in the manufacturing of the billets or electromagnetic parts. The margin of error of these measurements significantly affect the efficiency of the contol systems of the electromagnets manufacturing / assembly, thus affecting the production of complete functioning product.

Currently there are several developed techniques and devices that allow measuring of static characteristics of magnetic materials, which, however do not provide the level of productivity required for the factory setting. Low productivity of existing devices is caused by the inffective process of magnetic reversal of the tested sample and by imperfections of the measurement devices used to determine the field intensity on the sample surface. This confirms the need in measuring device for magnetic characteristics of the manufactured parts made from soft-magnetic materials with required accuracy and productivity. Following original solutions have been implemented:

– “Actual Simulation”experiment for definition of magnetic characteristics;
– adaptive method of magnetic reversal;
– principle for magnetic field intensity measurement on a surface of a part.

2 Measuring Device for Magnetic Characteristics of the Manufactured Parts Made from Soft-Magnetic Materials

The structure of the device for the “Actual Simulation” experiment [2] is shown in the fig 1. The generator of stimulating signals influences with the produced vector S on the object of testing. The measuring unit gets a vector of the physical characteristics F – the result of the influence, and transforms them to a vector

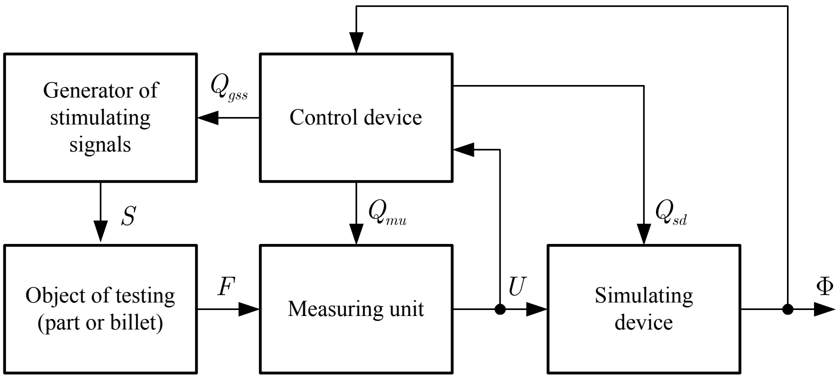

Fig. 1: Generalized structural diagram of the device for Implementation of the “Actual Simulation” experiment

of measuring information U. The measuring information, received from the simulating device, will be transformed to a vector of the physical characteristics Φ, shown by the tested object in simulated conditions.

"Actual Simulation" experiment is described by system of following equations:

$$\begin{cases} F = W_{\mathrm{ot}}\left(S\right) \\ S = W_{\mathrm{gss}}\left(Q_{\mathrm{gss}}\right) \\ Q_{\mathrm{gss}} = W_{\mathrm{cd}_1}\left(U, \Phi\right) \\ Q_{\mathrm{sd}} = W_{\mathrm{cd}_2}\left(U, \Phi\right) \\ Q_{\mathrm{mu}} = W_{\mathrm{cd}_3}\left(U, \Phi\right) \\ U = W_{\mathrm{mu}}\left(Q_{\mathrm{mu}}, F\right) \\ \Phi = W_{\mathrm{cd}}\left(Q_{\mathrm{cd}}, U\right) \end{cases}$$

where W_{ot}, W_{gss}, W_{sd}, W_{mu} – are transfer functions of tested object, generator of stimulating signals, simulation device and measuring unit ; W_{cd_1}, W_{cd_2}, W_{cd_3} – are transfer functions of the control device on the first, second and third outputs. The entire test process occurs under the control device, which develops control vectors for signals Q_{gss}, Q_{mu}, Q_{sd} as a result of the analysis of the measuring information and results of simulation by the program recorded in the control device.

Fig. 2 shows the detailed block diagram of the device used to implement the offered method. In this circuit controlled source of current and magnetizer form the generator of stimulating signals are guided by the control device. It provides given mode for change in intensity of external magnetic field H_{ext}.

$$H_{ext} = W_{mag}\left(W_{\mathrm{csc}}\left(U_{ctrl}\right)\right)$$

where U_{ctrl} – command to the controlled source of a current; W_{mag}, W_{csc} – transformation functions of the magnetizer and controlled source of current. Sensors of a magnetic induction and intensity of a magnetic field, provide transformation in change of a magnetic condition for tested sample $B(H)$ to electric signals or the codes $\widehat{B}(t)$ and $\widehat{H}_{\mathrm{ext}}(t)$ proportional to changes in time of an induction and intensity of magnetic field:

$$\widehat{B}(t) = W_{B-s}\left(B(H), t\right)$$

$$\widehat{H}_{ext}(t) = W_{H-s}\left(B(H), t\right)$$

where W_{B-s}, W_{H-s} – transformation functions of the induction sensor and the sensor of intensity. Parts of an electromagnet are complex, therefore their test is being executed in half-closed and open magnetizers.

The simulation device transforms the signals, received on its inputs $\widehat{B}(t)$ and $\widehat{H}_{\text{ext}}(t)$ to magnetic characteristics $\widehat{B}_i\left(\widehat{H}\right)$

$$\widehat{B}_i\left(\widehat{H}\right)=W_{\text{sd}}\left(B(t),H_{\text{ext}}(t),Q_{\text{T}_i}\right),$$

where W_{sd} – transformation functions of the simulation device; Q_{T_i} – vector of simulation parameters. Information processing device performs analysis of the result of measurements and makes changes in commands to transport unit.

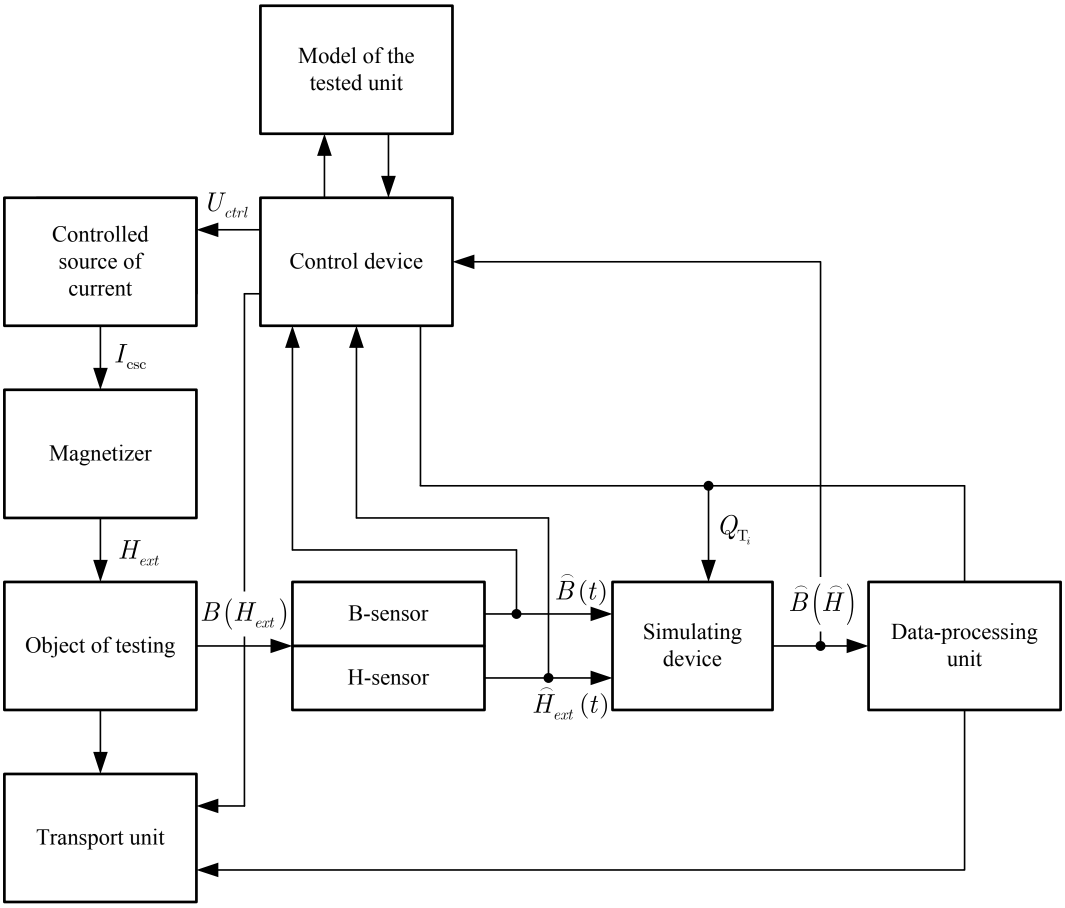

Fig. 2: The Block diagram of the device in "Actual Simulation" experiment

The unit is then moving the article after final tests in the corresponding tray of the selective assembly system. The information about modeling process is being supplied to the inputs of the control unit. It is necessary to ensure the required characteristic $\widehat{B}_i\left(\widehat{H}\right)$ for the control of the magnetic reversal.

The control unit creates continuous information exchange with the simulation unit. This helps in optimizing the process of magnetic reversal for tested object.

3 Method of Experimental-simulation

The method of experimental-simulation [3] of definition of the magnetic characteristics is based on association of two approaches: an experimental research and mathematical modelling of a magnetic field. It is fullfilled in the simulating device for definition of material magnetic characteristics. At the same time the results of an experiment provide input data for the solution of an opposite problem. The problem of calculation of a magnetic field for magnetic system with the test sample. It is also used as a validity criterion for the solution of this given problem. The method of "experimental-simulation" is implemented as follows. Tested sample is placed into the magnetizer. The magnetic reversal is being performed by the program corresponding to the required magnetic characteristic. (corresponding to the normal magnetization curve – fig.3) As a result of the experiment is a magnetic characteristic of the tested sample $B(H)_\mathrm{e}$ in the given magnetizer. The induction is being defined as $B = {}^{\Phi}\!/_{S}$, where Φ – is a magnetic flux in the central section of the test sample, S – is the area of this section. Field intensity is measured from some distance away from the surface of a sample. $B(H)_\mathrm{e}$ characteristic is determined as a result of the joint processing of the received data. Resulting $B(H)_\mathrm{e}$ characteristic is accepted as an initial approximation for the B-H curve of tested sample. Then using one of the known methods the calculation of B-H characteristic in the area of sensors by the changing value of the field intensity, i.e. the coordinates for points of the characteristic $B(H)^{(1)}$ are calculated. Then characteristics $B(H)_\mathrm{e}$ and $B(H)^{(1)}$ are compared. For the specified values of B_i, the difference is $H^{(1)} - H_e = \Delta H_e^{(1)}$ defined. If the value $\Delta H_e^{(1)} > \varepsilon$, where ε is one order lower, than the value of the precision error of field intensity measurement, than characteristic $B(H)_m^1$ is drown – the first approximation to the $B(H)$ characteristic of the magnetic medium of tested sample. For the fixed values of B_{mj}^1, the value of field intensityintensity is $H_{mj}^1 = H_{ej} - \Delta H_{ej}^{(1)}$. And then, using curve $B(H)_m^1$ as a characteristic of the magnetic medium of the tested sample, once again the coordinates of the required curve have to be calculated. The curve $B(H)^{(2)}$ has been defined. It

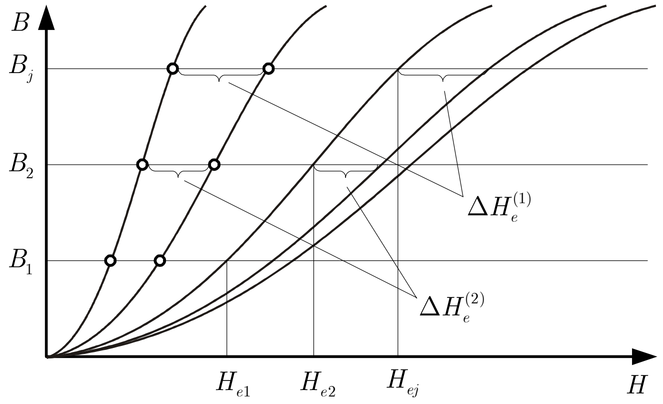

Fig.3: Explonation of method of "experimental-simulation" by the measuring of the normal magnetization curve.

is compared with experimental characteristic $B(H)_e$ and for each of B_j the values $\Delta H_e^{(2)} = H^{(2)} - H_e$ received. The correction $\Delta H_e^{(2)}$ in to the coordinates of the curve $B(H)_m^1$ is inserted. The curve $B(H)_m^2$ has been defined. And so on, until the curve of a charecteristic $B(H)_m^i$ of the magnetic medium of the tested sample $B(H)^{(i+1)}$ will alligh closely with the experimental characteristic $B(H)_e$ with the desired error. In this case, $B(H)_m^i$ curve is a sought characteristic of of the magnetic medium of the tested unit. Another experimental findings of the parameters and characteristics shows the data accuracy. The calculation of values of magnetic induction and field intensity in the area of the sensors with prescribed accuracy can be done in a real-time mode by the use of the small scale mathematical models. A space integration equation model will comply with this demands. Integral equation is being composed relative to the magnetization $\vec{M}$, with the application of scalar magnetic potentials for single and double layers. The last one is used for taking into account a small gaps in the magnet systems. Integral equation looks like:

$$\vec{H}_m\left[\vec{M}(Q)\right] = \frac{1}{4\pi}\iint_S \frac{M_n(P)\vec{e}_{PQ}}{r_{PQ}^2}\,dS_P + \sum_{i=1}^{m}\frac{1}{4\pi}\iint_{S_{mg}^{(i)}}\left[\frac{3\left(\vec{n}_{mg},\vec{e}_{PQ}\right)}{r_{PQ}^3}\vec{e}_{PQ} - \frac{\vec{e}_{PQ}}{r_{PQ}^3}\right]\frac{\left(M_{mg1n}+M_{mg2n}\right)_i}{2}\,\delta_i dS_P$$

where M_n – normal projection $\vec{M}$ to the surface S of the ferro magnet in point P; M_{mg1n}, M_{mg2n} – projections to the normal of magnetization of the ferromagnetic parts border to the surface S_{mg} of the gap δ; r_{PQ} – the distance between points Q and P; $\vec{e}_{PQ}$ – single vector, directed from point P to point Q; $\vec{n}_{mg}$ – normal to the middle of the gap δ surface S_{mg} in point P; m – number of a small gaps. Numerical analysis of a field with this model is being executed via algebraization of the integral equation.

4 Field intensity measurement at a surface of a part

The essence of this problem is to measure the tangential component of the field intensity intensity in fixed points of the space (x_1, x_2, x_3) in some distance from the part along the axes x and to calculate the field intensityintensity on the surface. In order to use this methodology it is necessary to solve two main problems: algorithm for measurement of field intensity on the surface of a part in several points of a space and optimization of the distances between these points (x_1, x_2, x_3) [4]. To solve this problem a dependence between field intensity, the current of the magnetizer and the distance to the part have been analyzed. From the analysis of the received characteristics it is possible to draw a conclusion, the magnetic intensity change from

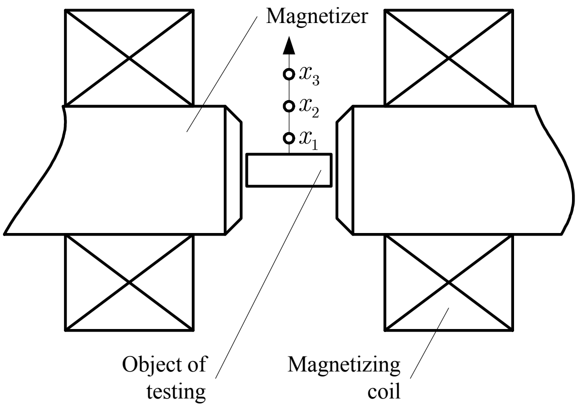

Fig.4: Schema of field intensity measurement on the surface of a part

distance x can be described in following expression:

$$H = b_0 + b_1 x + b_2 x^2 + \ldots + b_n x^n$$

where b_i – coupling coefficient, [(a/m)·m^{-n}]; b_0 – free coefficient, which characterizes the value of the field intensity H at $x = 0$, [a/m]; $(n+1)$ – number of points for the measurement of the field intensity H_i at a distance x_i from the part. Thus, the free coefficient b_0 is a sought value of the field intensity H_0 on the surface of the part. The value of this coefficient can be found by the solving the following set of combined equations:

$$\begin{cases} H_1 = b_0 + b_1 x_1 + b_2 {x_1}^2 + \ldots + b_n {x_1}^n \\ H_2 = b_0 + b_1 x_2 + b_2 {x_2}^2 + \ldots + b_n {x_2}^n \\ \ldots \\ H_{n-1} = b_0 + b_1 x_{n-1} + b_2 {x_{n-1}}^2 + \ldots + b_n {x_{n-1}}^n \end{cases} .$$

The calculations of the coefficient b_0 was made in character expression for the values $n = 2$ and $n = 3$, i.e. for three and four measurement points H_i

If $n = 2$, the solution is as follows:

$$H_0 = A_1 H_1 + A_2 H_2 + A_3 H_3 ,$$

$$A_1 = \frac{M_1}{\sum_{j=1}^{n} M_j}, \; A_2 = \frac{M_2}{\sum_{j=1}^{n} M_j}, A_3 = \frac{M_3}{\sum_{j=1}^{n} M_j},$$

$$M_1 = x_2 x_3 \left(x_2 - x_3\right); \; M_2 = x_1 x_3 \left(x_3 - x_1\right); \; M_3 = x_1 x_2 \left(x_1 - x_2\right).$$

If $n = 3$, the solution is as follows:

$$H_0 = \sum_{i=1}^{n} A_i H_i , \; A_i = \frac{M_i}{\sum_{j=1}^{n} M_j}$$

$$M_1 = x_2 x_3 x_4 \left(-x_2^2 x_3 + x_2^2 x_4 + x_2 x_3^2 - x_2 x_4^2 - x_3^2 x_4 + x_3 x_4^2\right)$$
$$M_2 = x_1 x_3 x_4 \left(-x_3^2 x_1 + x_3^2 x_4 + x_3 x_1^2 - x_3 x_4^2 - x_1^2 x_4 + x_1 x_4^2\right)$$
$$M_3 = x_1 x_2 x_4 \left(x_2^2 x_1 - x_2^2 x_4 - x_2 x_1^2 + x_2 x_4^2 + x_1^2 x_4 - x_1 x_4^2\right)$$
$$M_4 = x_1 x_2 x_3 \left(x_2^2 x_3 - x_2^2 x_1 - x_2 x_3^2 + x_2 x_1^2 + x_3^2 x_1 - x_3 x_1^2\right).$$

Found coefficients A are the constants, which depend only on the distances x_i where the measurement of the field intensity H_i takes part. Thus, the field intensity H_0 on the surface of the part by the testing in half-open magnetizers can be calculated from

$$H_0 = \sum_{i=1}^{n+1} A_i H_i \,. \tag{1}$$

For the purpose of optimization of the distance between the measuring points on the parts surface The analysis was performed on the expression (1) for different distances h between the field intensity measuring points H_{1i}^j, H_{2i}^j, H_{3i}^j. The measurement results for $h = 1$ ($x_1 = 1$, $x_2 = 2$, $x_3 = 3$) mm, $h = 2$ ($x_1 = 1$, $x_2 = 3$, $x_3 = 5$) mm, $h = 3$ ($x_1 = 1$, $x_2 = 4$, $x_3 = 7$) mm, $h = 4$ ($x_1 = 1$, $x_2 = 5$, $x_3 = 9$) mm, $h = 5$ ($x_1 = 1$, $x_2 = 6$, $x_3 = 11$) mm was analyzed. The output of the regression equation coefficients A_i for the different combination of the distances is shown in the table

	H				
Parameters	1	2	3	4	5
A_1	0,647	1,128	0,451	1,415	1,3
A_2	2,801	0,795	2,134	- 0,382	- 0,145
A_3	- 2,443	- 0,935	- 1,584	- 0,041	- 0,152
$\delta_{\max}$, %	1,9	1,6	2,0	2,0	5,0

Table – The computation results

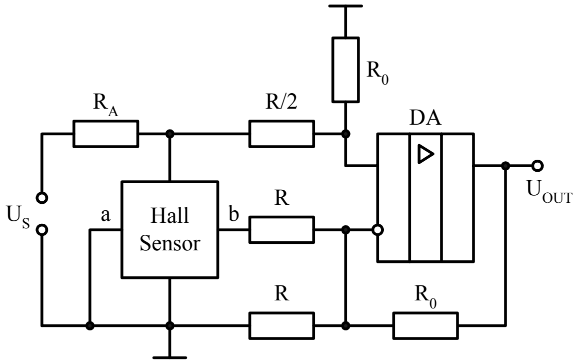

Fig.5: Field gradient measurement with one Hall-sensor

The quality check on received models was made by the calculation of the maximal precision discrepancy $\delta_{\max}$. Based on the data in this table it is possible to make a conclusion, that this model is appropriate for calculation of the field intensity on the surface of the part. Minimal error $\delta_{\max}$ corresponds to the optimal distance $h = 2$ mm between the measuring points. Required model for the field intensity measurement on the surface of a part looks like

$$\widehat{H}_0^j = 1{,}128H_1^j + 0{,}795H_2^j - 0{,}935H_3^j \,. \tag{2}$$

Additional researches have been conducted about the possibility of the H measurement in two points according to the equation:

$$H_0 = A_1 H_1 + A_2 H_2 + A_3 \frac{dH}{dx} \,, \tag{3}$$

where $\frac{dH}{dx}$ – derivative, which characterizes the tilting of the curve $H(x)$; $A_1 \div A_3$ – coefficients calculated with least-squares method. The derivate can be found with the help of the Hall-effect sensor, which is included as shown an in the figure 5. The analysis allows us to conclude, that the error in measuring of derivate and field intensity in two points is not more than an error in the measuring in three points. In addition to that, the error is smaller if the derivative is calculated from the nearest point away from the part.

5 Adaptive method of remagnetisation

The control device combined with the simulation unit used together to implement the adaptive method of magnetization [5]. The method of measurements used for determination of normal magnetization curve of Ferro magnet part contains two stages:

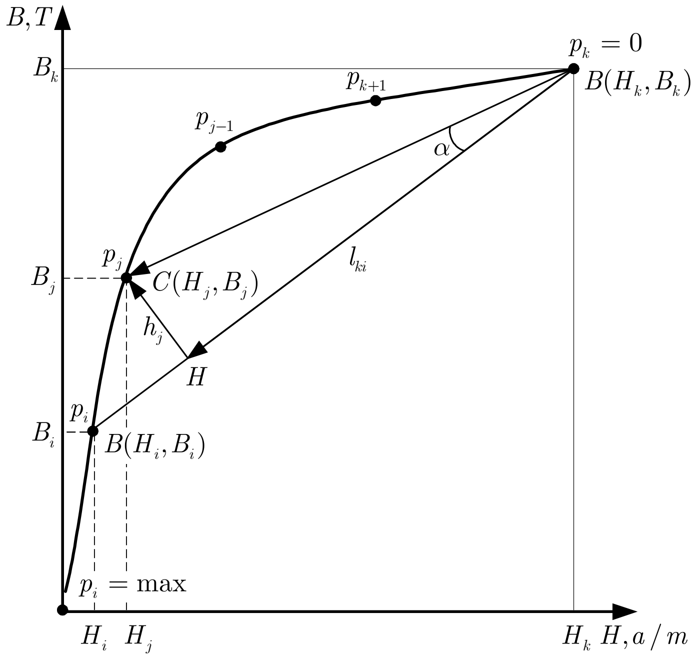

Fig. 6: Explanation of the algorithm

Stage 1. It is necessary to demagnetize the source unit by the remagnetization in a variable-polarity field with evenly dumping amplitude decreasing from maximum to minimum value before taking the measurements of the normal magnetization curve.

Stage 2. Normal magnetization curve is measured starting from the minimum value of field intensity gradually to the maximum value. A return from the bigger values to the smaller is not allowed. Algorithm is explained on the fig. 6. A priori information about a form of the B-H curve can be collected if the amplitude of the demagnetizing impulses during the first stage remains fixed. It can be taken by the semi static measurements of the test unit. In both solutions the B-H curve consists of large number of points – hundreds and thousands. Based on the analysis of the received data it is possible to determine the minimal number of the measuring points for the normal magnetization curve with a required accuracy. p_k, p_i – first and last points of the approximating segment ($k \in [o, i]$, $i \in [\max, k+1]$); $\max$ – number of the steps by demagnetization; p_j – point on the B-H curve, which has to be checked for relation to the approximating segment l_{ki}, ($k < j < i$). Specifying the initial conditions $k = 0$, $i = \max$.

1. Drawing the approximating segment l_{ki}.

2. Continuously checking the relations of points p_i to approximating segment l_{ki} (beginning from $j = i - 1$) till $j < k$.

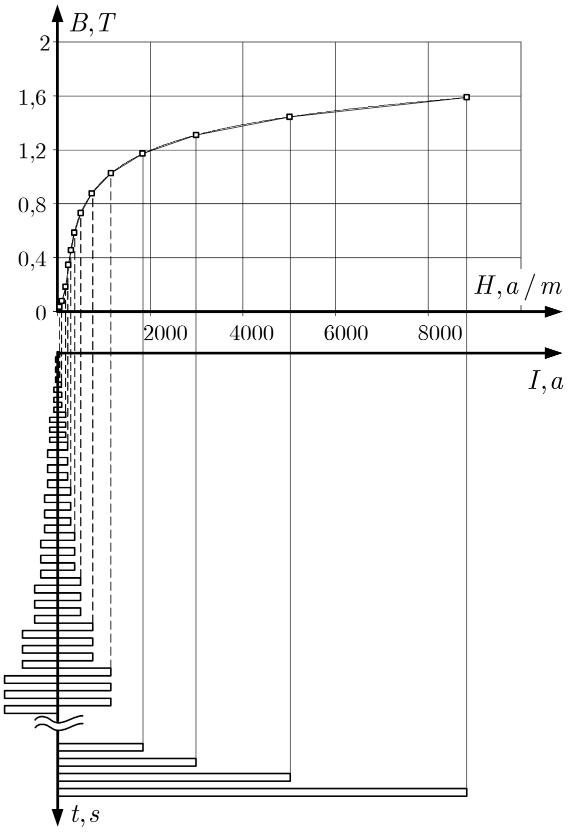

Fig. 8: Result of the approximation

3. If all points of the section of the B-H curve belong to the approximating segment l_{ki}, then this section can be replaced by the segment l_{ki}. Point transfers p_k in to the point p_i and algorithm starts from the beginning.

If even only one point from this section does not belong to the approximating segment l_{ki}, than a new approximating segment l_{ki-1} has to be drown and the checking between points p_k and p_{i-1} repeats itself. The test for belonging of the point p_j to the approximating section l_{ki} described by following conditions H. Examine the right triangle AHC, formed with vectors AH, AC, CH. Geometrical interpretation of the approximation absolute error constitutes a perpendicular h_j to the approximating segment l_{ki} from point p_j. The length of the segment h_j is calculated by following equation

$$h_j = \sqrt{\left|\overline{AC}\right|^2 - \left|\overline{AH}\right|^2}\,.$$

In it's own turn $\left|\overline{AH}\right| = \left|\overline{AC}\right| \cdot \cos\alpha$, and $\cos\alpha = \dfrac{\overline{AC} \cdot \overline{AB}}{\left|\overline{AC}\right| \cdot \left|\overline{AB}\right|}$. Consequently

$$\overline{AC} \cdot \overline{AB} = (H_j - H_k)(H_i - H_k) + (B_j - B_k)(B_i - B_k).$$

By Pythagorean Theorem

$$\left|\overline{AC}\right| = \sqrt{(H_j - H_k)^2 + (B_j - B_k)^2}\,,$$

$$\left|\overline{AB}\right| = \sqrt{(H_i - H_k)^2 + (B_i - B_k)^2}\,.$$

After the calculation of h_j, the condition $h_j < H$ is being checked. In execution of this condition, we assume, that point p_j belongs to the approximated segment with precision error H. Fig. 6 illustrates the points received after the demagnetizing of the tested unit and their approximation. The application of this method in the measuring device for magnetic characteristics of the manufactured parts allow to optimize the prozess of the measurement. Collection of a prior information can be accomplished by demagnetising or by quazistatische measurments. The measured curves in bouth cases have a truncation error. From this curves it is possible to detect the minumum number of the points for further messurements with the stepped changes in external magnetic field.

6 Results

The described medodolody can be applied in control of magnetic properties of soft-magnetic materials. It represents a coordinated process, which combines the results of the measurements and simulation. The calculation of the magnetic fiels is made with help of a space integral equation model. This model provides real-time calculation of paremeters of the magnetic field . It also delivers prescribed accuracy in the space where sensors are dislocated. We have developed the principles and the algorithms used for automatic measuring devices. Such devices used in the laboratory and production environment to measure the magnetic characteristics of parts used in electromagnets. It was established, that main elements of such devices are: magnetizer with half-closed magnetic system, controlled source of current, which combines the impact and quazistatische magnetizing of the tested unit, the measuring channel of magnetic induction and magnetic field intensity, simulation and control units. A new adaptive method of magnetizing has been developed. It allows us to approximate minimal number of information points dependent on B-H curve. New thechnology of field intensity measurements at a surface of a part has been developed. It based on a continuity of the tangential component of a field intensity on the boundary of two envoromments. It allows us to calculate the value of the field intensity on the surface based on the measurements in two or three points at a fixed distance from the tested unit. Thus it is possibleto measure the magnetic characteristics of the material by the testing in half-opened magnetizers.

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