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Review Article

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State-of-the-art and future trends in soft magnetic materials characterization with focus on electric machine design – Part 1

Stand der Technik und Trends im Bereich der Charakterisierung weichmagnetischer Materialien mit Fokus auf den Entwurf elektrischer Maschinen – Teil 1

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Abstract: The first of this two-part article illustrates the state-of-the-art in soft magnetic materials characterization starting with very early developments and giving a retrospective view of research carried out in this field. One famous measurement setup is the Epstein frame, named after Josef Epstein. Around 1900, he published a German article about "The magnetic testing of laminated steel". As it is highly likely interesting to researchers worldwide, the authors reconsidered his contributions in English language. Consequently, the most common measurement setups are introduced. Besides the Epstein frame, these are the single sheet tester and setups analyzing ring-shaped specimens. These setups allow for a 1-D characterization of the material, while it usually features anisotropic properties and cross-coupling of the magnetization axes. For this reason, 2-D and even 3-D setups are considered and presented here. This article provides a thorough introduction to the field of material characterization. It is the basis for modeling the material characteristics, which is presented in the second part, which also includes recent developments for considering manufacturing impact. It is of particular interest when dealing with mass-produced electric machines. Eventually, these articles shall constitute valuable references for both engineers new to this field as well as experienced researchers.

Keywords: Iron losses, soft magnetic materials, ferromagnetic materials, initial magnetization curve, eddy currents, hysteresis, degradation, manufacturing impact.

Zusammenfassung: Der erste Teil dieses zweiteiligen Artikels behandelt den Stand der Technik im Bereich der Vermessung weichmagnetischer Materialien. Ausgehend von den Anfängen in diesem Bereich wird ein Rückblick über die kontinuierliche Weiterentwicklung präsentiert. Eine sehr bekannte Messvorrichtung stellt der Epstein-Rahmen, benannt nach Josef Epstein, dar. Letztgenannter publizierte um 1900 einen deutschen Zeitschriftenartikel mit dem Titel "Die magnetische Prüfung von Eisenblech". Nachdem dieser Artikel für eine große Leserschaft von Interesse ist, wird er hier in englische Sprache übersetzt rekapituliert. Ausgehend davon werden die heute gängige Messvorrichtungen vorgestellt. Neben dem Epstein-Rahmen sind das noch der Einzelblechtester und die Messanordnung für toroidförmige Prüflinge. Alle diese Prüfverfahren ermöglichen die eindimensionale Vermessung des Prüflings. Allerdings hat das üblicherweise im Elektromaschinenbau eingesetzte Material ein anisotropes Verhalten und es gibt eine gegenseitige Beeinflussung der (orthogonalen) Magnetisierungsrichtungen. Aus diesem Grunde werden auch Anordnungen für die zwei- beziehungsweise dreidimensionale Vermessung in Betracht gezogen. In diesem Artikel werden alle Anordnungen vorgestellt und exemplarische Messergebnisse angeführt. Die erlangten Erkenntnisse stellen die Basis für den zweiten Teil des Artikels dar. Dieser behandelt anschließend die Modellierung des Materialverhaltens für den Einsatz im Bereich des Entwurfs elektrischer Maschinen. Ein spezielles Augenmerk wird dabei auf in hoher Stückzahl industriell gefertigte Maschinen gerichtet. In diesem Bereich ist die Berücksichtigung des Verarbeitungseinflusses auf das Mate-

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rialverhalten wesentlich und stellt einen Schwerpunkt der aktuellen Forschung in diesem Bereich dar. Zusammenfassend war es das Ziel, mit diesen beiden Artikeln eine wertvolle Grundlage sowohl für erfahrene AnwenderInnen als auch für NeueinsteigerInnen zu schaffen.

Schlagwörter: Eisenverluste, weichmagnetische Materialien, Neukurve, Wirbelströme, Hysterese, Materialschädigung, Herstellungseinflüsse.

1 Introduction

A moment of real inspiration due to extraordinary scientific work occurred when the original article of Josef Epstein [10] was read by the authors of this two-part article. Instantly, the idea was born to give to this work the honor it deserves and, at least in some part, to revive it after more than a century of appearance and to present it again to a broad scientific auditorium. Moreover, honor has been given to all scientists who significantly contributed to the research in the field of magnetism during 19th century and before, such as Oersted, Ampere, Biot and Savart, Faraday, Maxwell, Hertz and Heaviside, Stoletov, Rayleigh, Ewing, Rutherford, Madelung and Steinmetz [11, 12, 13, 28, 32, 33, 34, 35, 36, 37, 38]. It should be highlighted that the motivation for Epstein's work was an idea to "have a unique regulation for testing laminated steel" and it is quite remarkable that he managed to put this idea into action. Namely, Epstein frame has become a worldwide accepted standard in the testing of electrical steel sheets [19]. Among this standard method, other methods for testing of magnetic materials by 1-D magnetic field have been considered in this article [20, 21]. Additional attention has been given to the measurement methods for testing of magnetic materials in multi-axial magnetic field, especially in rotational field [3, 5, 7, 25, 31, 39, 44, 45, 47, 48]. These modern techniques are mostly devoted to the more comprehensive investigation of power loss that occur in the materials when rotational magnetization is present. Similar to Epstein's work, all these works have a motive to find "a unique regulation for testing" of soft magnetic materials.

This article is organized as follows: Section 2 is devoted to historical review of early soft magnetic material characterization and to the translation of Epstein's work. The authors of this paper decided not to put any comments in addition in order to give a reader a chance to create its own picture of the importance of this work. Section 3 gives the most important setups of classical measurement systems for magnetic material characterization that are part of international standards, such as Epstein frame, single sheet tester and ring specimen setups. Section 4 gives details on more modern systems for multi-dimensional testing of magnetic materials. Finally, Section 5 comes up with a summary and an outlook for the second part of this article.

2 Early soft magnetic material characterization – Epstein's work revisited

The first observations on the magnetic nature of matter originated from the time before the new era, when Thales of Miletus noted that stone ore attracts iron [29]. Similar phenomena at that time were also recorded in ancient India and China, and already in the 12th century, the Chinese used a type of magnetic compass in navigation. At that time, similar inventions appeared in Europe as well.

The beginning of the new chapter in magnetism is usually attributed to Hans Christian Oersted who in 1819 discovered that the electric current affects the compass needle. In 1820, Andre-Marie Ampere identified that the existence of a magnetic field is related to the flow of electricity through a closed conductive contour, while the same year Jean-Baptiste Biot and Félix Savart arrived at an equation that determines the magnetic field strength in the vicinity of the conductor with current. These events were soon followed by a new one, such as Michael Faraday's discovery in 1831, showing that the time-varying magnetic field induces an electrical voltage (Faraday's law), illustrating the natural relationship between the electric field and the magnetic field. In 1865, James Clerk Maxwell consolidated and extended existing theories and laws into a unique theory – the fundamental postulates of the theory of electromagnetic field, later reformulated by Heinrich Rudolf Hertz and Oliver Heaviside to the four equations which are nowadays commonly known as "Maxwell's equations".

Among the first experimental investigations of ferromagnetism there is the distinguished work of Russian physicist Alexander Stoletov from 1872 [37, 38]. He noted that the magnetic permeability of iron (ferromagnetic material) changes with the change of the magnetic field strength. The curve that shows this change (Stoletov curve) is one of the first experimental results that relates to the characteristics of ferromagnetic materials in the presence of strong magnetic fields. On the other hand, work of Lord Rayleigh is devoted to the behavior of iron in weak fields [32]. This British physicist clearly showed that the initial permeability has a finite minimum value and that the magnetization depends quadratically on the applied magnetic field (Rayleigh's law). The idea of finite initial permeability was first introduced by Scottish physicist and engineer James Alfred Ewing et al. [13], but it was Rayleigh who proved it experimentally. Ewing is known for being the first to introduce the term "hysteresis" ("to lag behind") in 1881 [11]. Probably the most comprehensive work on magnetism of iron and magnetic hysteresis of that time was summarized in the third edition of his book [12]. A very significant experimental study of magnetic viscosity was published in 1895 by Ernest Rutherford [33], a physicist from New Zealand. From that time, the contribution of German physicist Erwin Madelung is also important [28], because his paper explained the basic rules of transient magnetizing curves and forming of small hysteresis loops within the major loop.

Further remarkable contributions to the development of electrical engineering in the field of magnetism were given by the German physicist Charles Proteus Steinmetz. At the end of the 19th century, he published a number of papers of utmost importance for future research in engineering, but also in physics, related to the law of energy losses that occur due to the magnetic hysteresis and eddy currents in ferromagnetic materials [34, 35, 36]. Steinmetz described in detail the measurement procedure and the used apparatus and gave a large number of new experimental results, such as measured hysteresis loops. According to the reported loops, he further calculated energy losses and proposed a simple law describing the variation of these losses with the frequency of the magnetizing field. This law became the basis for the calculation of magnetic circuits of the inductor with iron, transformers and various electrical machines and apparatus. Continuing Steinmetz's research (but also many others), in 1900, Josef Epstein[1] proposed a redesigned device for measurement of energy losses in steel sheets in order to improve the accuracy and repeatability of measurements, but also to simplify the construction and shorten the time required to prepare the experiment [10].

The proposed apparatus and the measurement method are the pioneers to the modern apparatus for measurement of the magnetic characteristics of steel sheets using the so-called Epstein frame. Considering it an interesting and important paper, the authors would like to bring the Epstein's paper in front of a wider audience by giving German to English language translation of the most important parts, including redrawn figures and numerical results converted to SI units.

"Die magnetische Prüfung von Eisenblech"
The magnetic testing of laminated steel

After giving a talk about how to have a unique regulation for testing laminated steel, which was done on behalf of the "Elektrotechnische Gesellschaft Frankfurt a. M.", representatives of the biggest German manufacturers of generators agreed to investigate one and the same specimen by the same method, but also by the method that they usually apply. The method which was the same for all participants was selected to be the one which is used for two years at the "Laboratorium der Elektrizitäts-A.-G.", formerly known as "W. Lahmeyer & Co.", Frankfurt a. M. That one performed very good in terms of agreement of the results when conducting multiple tests and when comparing them to the results that the "Physikalisch – Technische Reichsanstalt" found when conducting measurements for verification performed according to severe scientific criteria.

The following article is about the method applied by us and the details that need to be considered in order to allow others to organize such measurements in very short time. From this point of view, details that are useful for those that want to repeat the experiments were considered. Moreover, the experiments were done with higher accuracy and effort than they will be done afterwards if the method proves to be successful.

The investigations are based on the "Wattmetermethode" and the "Laboratorium der Elektrizitäts-A.-G." used a device composed of a magnetic circuit that comprises two bunches of the material to investigate and two yokes to connect these two bunches. The winding was placed to the final yoke and the device was similar to the one which was presented by Dobrowolsky and Kapp. Besides the material to investigate, the magnetic circuit comprised also other iron component. Hence, the hysteresis loss of the specimen, which the measurement is based on, is only half of the measured loss. Moreover, as the specimen is not wound, leakage appears, which causes the loss in the yoke to be different with regard to measurements with and without specimen. Thus, the device was redesigned such that it did not comprise any external iron component and, secondly, the magnetomotive force was distributed as uniformly as possible. Considering these aspects, the most suitable specimen is a ring. However, the specimen components should be easy to manufacture and it should be easy to assemble and disassemble the device. These requirements can most simply be met by designing a mag-

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[1] Strangely, Josef Epstein's initial was misspelled in his original paper, which appeared in print as "I. Epstein" [10]. There is no doubt however that the author of this paper was in fact Josef Epstein [46].

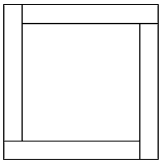

Figure 1: Typical arrangement of the lamination stripes in the measurement setup, top view.

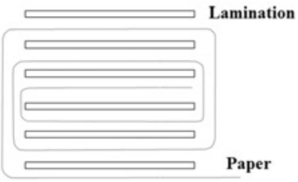

Figure 2: Sketch about insulating the lamination stripes by using paper – cross section, flux direction in picture plane.

netic circuit based on four bunches of laminated steel, which can be assembled as it is presented in Fig. 1. A uniformly wound coil is fit to each bunch. Hence, the entire bunch, except at the intersections[2] of two bunches, is completely covered. To avoid vibration of the device, the laminated steel is fixed by wooden components on a wooden base. There was emphasis put on not using any metallic components in which currents could develop.

When investigating ferromagnetic materials, the big differences among a batch of material should not be neglected. Depending on whether the specimen is extracted from the edge area or the middle of a sheet (metal), depending on if the sheet is taken from the inner or outer area of a box used for annealing and also depending on other reasons there will be differences present even if most care is taken during production. Moreover, very often the parts of one delivery are taken from different batches of the production. Thus, it is essential to take such an amount of material for the specimen(s) that is representative for the delivery. Thus, we are using approximately 19 kg coming from six different sheets, which are taken from arbitrary parts of a delivery. The sheets were cut in strips of 500 mm in length and 40 mm in width. Consequently, the material will be distributed to four portions using a weighing balance, where approximately 65 to 70 stripes belong to a single portion. The stripes are separately wound with a tissue paper, as illustrated in Fig. 2, and it proven to be useful.

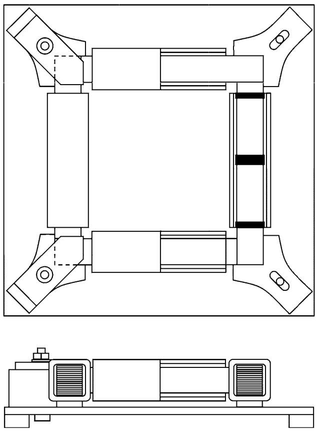

Figure 3: Detailed illustration of the mechanical construction of the early Epstein frame.

In order that the paper part does not get too thick along the sides, each bundle comprises approximately 20 stripes. Using a sheet thickness of 0.5 mm, this follows three separations per bundle. Each package is put into the vise jaws and pressed and then three rings hold the paper used for insulation. The four packages now should be arranged to a magnetic circuit according to Fig. 3. At the intersections of two packages, the paper is removed. The "touching" of two consequent packages is prevented by pressboard of 0.15 mm in thickness. A pressboard spool slides on each package, which comprises 100 evenly distributed turns of 2.8 mm diameter copper wire. The coils have a clear square cross-section of 48 mm by 48 mm and a length of 420 mm, so they preferably cover the core material as evenly as possible. Neglecting the corners, the whole ferromagnetic structure is facing the same magnetomotive force. Hence, the leakage is reduced to the minimum possible. Considering this aspect, the length of the core material was selected that long compared to the cross-section, even though other aspects would have led to other ratios.

Care has to be taken for mounting the arrangement such that the parts are pressed to each other. The arrangement is placed on a wooden board (Fig. 3), the corners of the core material are placed on wooden strips and the four core material parts are pressed through the four jaws in diagonal direction and against each other, while the plate, which is held through the screw, is used for holding the sheets down as well as fixing the position of the jaws. If this arrangement is mounted correctly by further using hammer strokes, the ampere meter is showing a minimum for the magnetizing current. With some practical experience, the worker achieves this also by listening, as the buzzing noise vanishes if everything is correctly assembled. The

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[2] It should be noted that in the original paper (Fig. 1) the corners of laminations are not double overlapped, as it is the case in the current version of the Epstein frame standards.

Table 1: Measured results.

0. w Ω	1. $B_{\max}$ T	2. p Hz	3. E V	4. J A	5. P W	6. J^2w W	7. p_{fe} W	8. p_{fe} per 100 kg W/kg	9. $\frac{p_{\mathrm{fe}}}{p}$ per 100 kg J/kg
0.641	0.6	50	67.05	1.49	34.00	1.42	32.58	168.53	3.37
		40	53.64	1.47	25.00	1.39	23.61	122.17	3.05
		35	46.94	1.47	21.00	1.39	19.61	101.47	2.90
		30	40.23	1.42	17.00	1.29	15.71	81.26	2.71
		25	33.53	1.41	13.60	1.27	12.33	63.76	2.55
		20	26.82	1.39	10.51	1.24	9.27	47.96	2.40
0.264	1.0	50	111.75	2.61	82.80	1.80	81.00	419.05	8.38
		40	89.40	2.58	60.70	1.76	58.94	304.93	7.62
		35	78.23	2.58	50.75	1.76	48.99	253.45	7.24
		30	67.05	2.52	41.35	1.68	39.67	205.24	6.84
		25	55.88	2.50	32.50	1.65	30.85	159.60	6.38
		20	44.70	2.42	24.60	1.55	23.05	119.26	5.96
0.246	1.5	50	167.63	6.19	177.20	9.43	167.77	867.95	17.36
		40	134.10	6.17	132.00	9.36	122.64	634.43	15.86
		35	117.34	6.20	112.20	9.46	102.74	531.52	15.19
		30	100.58	5.98	91.20	8.80	82.40	426.30	14.21
		25	83.81	6.06	73.20	9.03	64.17	331.95	13.28
		20	67.05	5.85	56.26	8.42	47.84	247.50	12.37

preparation and mounting of the core take up to 1.5 h for a trained worker.

The alternating current is taken by using slip rings of a four pole AC machine which features a separately-excited field. The machine is connected with a DC machine by direct coupling. Errors in the determination of the turnover number led to mistakes in the results in the beginning. To avoid any further mistakes, the axis of the tachometer was directly mounted to the motor shaft. The tachometer, a construction of Horn, features a measuring range of 500–2000 rpm.

The setting for the considered magnetic flux density requires the exact determination of the cross-section area. We computed it by considering the absolute and the specific mass. The latter one is determined most easily by identifying the volume of a small number of strips, for example 12 pieces of 1 cm by 12 cm, which were weighed in advance by using a measuring cylinder. For sureness, the pieces are taken from different parts of the delivery. The therewith observed specific weights vary from 7500 kg m^{-3} to 8100 kg m^{-3}.

To account for a potential dependence of the Steinmetz coefficient on the magnetic flux density, we worked with three different levels of magnetic flux density, i. e. 0.6 T, 1.0 T, 1.5 T, which also allowed verifying the results. In the following, we would like to present the investigation step-by-step:

- net mass of the total specimen is $M = 19.33\,\mathrm{kg}$,
- density is $\rho = 7610\,\mathrm{kg\,m^{-3}}$ and
- specimen cross-section area is $q = \frac{19.33\,\mathrm{kg}}{7610\,\mathrm{kg\,m^{-3}} \cdot 4 \cdot 0.5\,\mathrm{m}} = 12.7\,\mathrm{cm}^2$.

At the beginning, the work should be started with magnetic flux density of 0.6 T. This gives the magnetic flux maximum as follows:

- $\Phi_{\max} = 0.6\,\mathrm{T} \cdot 12.7\,\mathrm{cm}^2 = 0.762\,\mathrm{mWb}$.

Considering the number of turns (400), the averaged back EMF for a particular number of periods p is equal to $E_{\max} = 4p \cdot 400 \cdot \Phi_{\max} = 1600p \cdot 0.762\,\mathrm{V}$. Defining α as the ratio of the rms value of the back EMF over the averaged back EMF, this follows: $E = 1600\,\alpha\,p\,\Phi_{\max}\,\mathrm{V}$.

The characteristics of the applied AC machine for the considered circumstances are: $\alpha = 1.11$, with $E/p = 1.341\,\mathrm{V\,s}$. The tests will be conducted for p equal to 20 Hz, 25 Hz, 30 Hz, 35 Hz, 40 Hz and 50 Hz. For the present example and the considered flux density of 0.6 T, taking the equation from above the following values can be defined: $E_{20} = 26.8\,\mathrm{V}$, $E_{25} = 33.5\,\mathrm{V}$, $E_{30} = 40.2\,\mathrm{V}$, $E_{35} = 46.9\,\mathrm{V}$, $E_{40} = 53.6\,\mathrm{V}$ and $E_{50} = 67.1\,\mathrm{V}$.

In this way, the computation is also done for the magnetic flux densities $B_{\max} = 1.0\,\mathrm{T}$ and $B_{\max} = 1.5\,\mathrm{T}$ and we obtain the value of the voltage of the iron apparatus, with which we have to work for each particular measurement and which are given in the third column of Table 1. First of all, the control of the excitation current of the DC machine

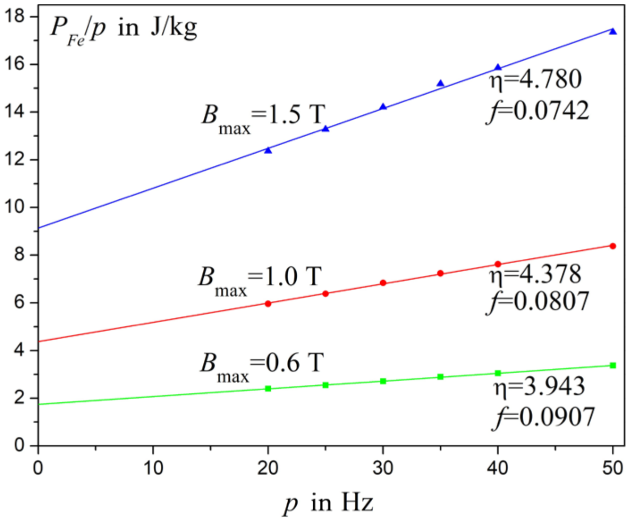

Figure 4: Loss data obtained by Josef Epstein.

will allow modifying the periods p. Consequently, the computed voltage is adjusted. Thereby, the ohmic losses in the conductors and in the current coil of wattmeter (in the sense of phase shift) can be totally neglected. When the correct periods p and voltages are set through the excitation and the voltage of the DC and AC motor, the readings of the amperemeter are recorded, provided in the fourth column, and also for the wattmeter, given in the fifth column. By subtracting the losses in the conductors and in the wattmeter (sixth column), the total iron losses can be derived based on the wattmeter numbers (seventh column). Finally, eighth column gives the losses per 100 kg and ninth column gives the losses per 100 kg and period p. The latter computation is essential in order to separate hysteresis and eddy current losses. The separation is done based on the well-known relations $P_{\mathrm{fe}} = \eta B^{1.6} p + f B^2 p^2$ and $P_{\mathrm{fe}}/p = \eta B^{1.6} + f B^2 p$, respectively. In Fig. 4 the iron losses per 100 kg and per period are illustrated as function of the periods. This relation should be linear according to the previous equation. Even though some measurement errors would follow some points being off this linear curve, the six points definitely give confidence about this relation. It was justified that a relation of the change of eddy current losses with the change of the specific resistance can be derived. However, no satisfying result could be observed so far. The constant for these currents should be, from theoretical point of view, defined by the thickness of the sheets and the specific resistance of iron. Thus, to get a rough check for the observed constants, different sheet thicknesses were investigated. An exact match with theory of textbooks, which are specifying that the eddy current coefficient is proportional to the sheet thickness, could not be expected, as the sheets have not been identical and cannot be identical due to the steps of manufacturing. The investigations thus gave just one remarkable result, that the losses due to the eddy currents were much higher than they can be computed using the above equation. Thereby, we have to take into account that, based on our knowledge Mr. Dettmar pointed out the first time, the derivation based on Fleming has a computational error and the theoretically computed losses are just of half size compared to what is defined by the equation. Thus, based on our experiments it turned out that it is somehow invalid to derive the hysteresis losses by just subtracting the computed eddy current losses from the total losses.

– End of translation –

3 Classical measurement systems for material characterization

Since the early beginnings of the magnetic measurements by Epstein et al., both the measurement methods as well as the interpretation of the measurement results have become more sophisticated. A broad overview is offered by [14, 23, 42]. Nowadays the magnetic characteristics of ferromagnetic materials under alternating magnetisation are determined by using standardized methods of measurement [19, 20, 21]. They precisely define the conditions of measuring, form and dimensions of sample, as well as the measuring characteristics of the required instruments. Three methods are approved by IEC, which are: Epstein frame, single sheet tester and toroidal core. Mainly, these methods differ in the part that concerns the shape and dimension of the sample, while other requirements are the same or very similar. The electrical diagram of connections, customised to measurement by the computer, is given in Fig. 5 [21]. The alternating voltage source is connected in series with the magnetic (primary) winding of the sample and a non-inductive resistor. Secondary circuit contains only secondary winding. Voltages from the

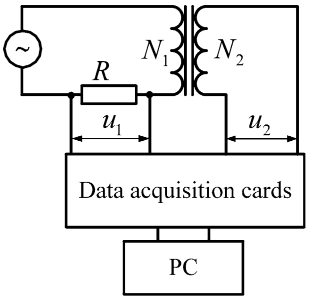

Figure 5: Simplified scheme of the measurement setup.

resistor and the secondary winding are connected to two analogue inputs of a data acquisition system. Computer program collects all the data, processes them, and performs calculations of interest. According to the standards, voltage induced at the secondary winding should be sinusoidal during the measurements with a form factor of 1.111 ± 1 % [19, 20, 21]. Air flux compensation should be applied, following recommendations given in the standards. Also, test samples should be demagnetized before the measurement starting from a field strength of not less than ten times the coercivity by slowly reducing the magnetizing current to zero. It should be carried out at the same or lower frequency as for further measurements.

According to the measured voltage, magnetic field strength H, magnetic flux density B, and specific power loss p_s in the sample can be calculated using the following expressions [21]:

$$H = \frac{N_1}{R\,l_{\text{eff}}} u_1(t), \tag{1}$$

$$B = \frac{1}{N_2 A} \int_0^t u_2(\tau)\,\mathrm{d}\tau, \tag{2}$$

$$p_s = \frac{f N_1}{N_2 m R} \int_0^T u_1(t)\, u_2(t)\,\mathrm{d}t, \tag{3}$$

where N_1 is the number of the primary turns, N_2 is the number of turns of the secondary winding, m is the mass of the sample, l_{eff} is the effective length of the magnetic circuit, A is the cross-section area of the sample, R is the resistance of the non-inductive resistor, f is the frequency and $T = 1/f$ is the period.

A geometry and photographs of a typical Epstein frame (EF) [19], single sheet tester (SST) [20] and toroidal samples (TS) [21], are presented in Figs. 6–8. Currently, regardless the setup type significant research activities can be observed. For instance, selected examples are given here for the EF [40, 1, 6], the SST [15, 9, 30], and the TS [27, 49, 26, 2, 8].

While all these setups provide integral information about the devices, sometimes magnetooptical sensors are applied to measure local quantities [4, 24]. A drawback of the latter technique is that usually no absolute values can be observed. Consequently, some authors normalize the data with regard to, e. g., the saturation magnetization [18, 43]. Others even consider non-magnetic quantities, for instance the 'degrees of rotation' of the light beam [41] or 'grey levels' [22].

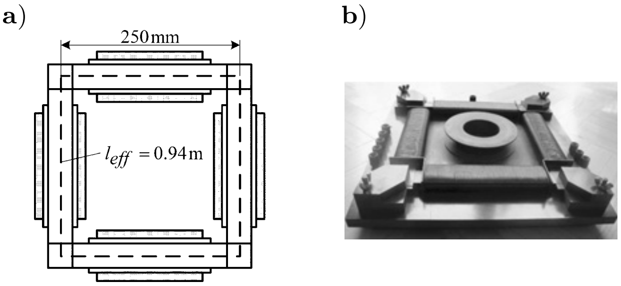

Figure 6: a) Typical geometry of an Epstein frame with its dimensions. b) Photograph of an Epstein frame.

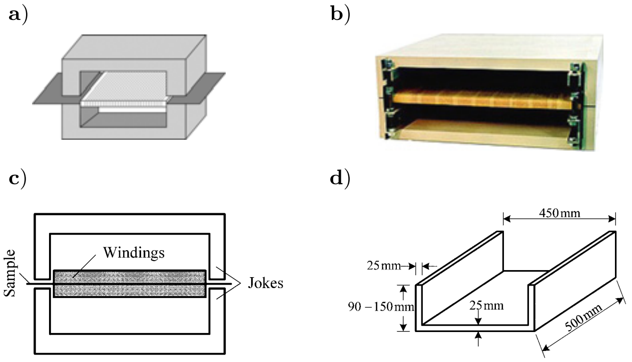

Figure 7: Single sheet tester a) graphical representation b) photograph c) cross section d) typical geometry of the back iron with its dimensions.

The Epstein frame consists of primary and secondary winding, as well as of the sample to be examined (steel sheets). The sample made of a number of strips (always a multiple of 4) is arranged in a square, by double overlapping of the strips at the corners. Thus, all four sides of the frame have the same length and cross-sectional area of the sample under test. Individual sheets are cut from a larger piece (e. g., the final product). They can be cut in different directions with respect to the rolling direction if necessary, for example for anisotropy measurement. The dimensions of the strips are 30 mm by 280 mm (minimum), and they overlap at the corners and form a square of 250 mm side length (see Fig. 6). The strips can be longer (e. g., 300 mm) and, therefore, their ends extend beyond the frame during the measurement. The minimum weight of the sample should be 0.24 kg, which for a typical 0.5 mm thick electrical steel requires at least 12 strips, or 16 strips for a steel of 0.3 mm thickness. The total thickness of the stacked sample is limited by the inner dimension of the coil formers and it is recommended not to exceed 10 mm. The four primary windings (one on each side of the square, with length of around 190 mm), are connected in series to form a single winding. In the same way, under the primary winding, the secondary winding is wound. The recommended total number of turns is 700 or 1000, for both windings. The effective length of the magnetic circuit l_{eff} is arbitrarily assumed to be 0.94 m, and the area of the cross-section should be calculated according to the following expression:

$$A = \frac{m}{4\,l\rho}\,. \tag{4}$$

where l is the length of a single sheet (e. g., 280 mm), and ρ is the density of the material. Quantities of interest can be calculated using expressions (1)–(3).

In the case of a single sheet tester (SST), the sample is just one sheet of steel with size 500 mm × 300 mm (minimum, but not more than 500 mm), and the magnetic circuit is completed by two halves of low-loss steel yokes, made from grain-oriented electrical steel or nickel-iron alloy, with power loss lower than $1\,\mathrm{W\,kg^{-1}}$ at frequency of 50 Hz, and magnetic flux density of 1.5 T. The primary winding is placed over the whole sample, Fig. 7a–c, it features at least 400 turns. Dimensions of the yokes are given in Fig. 7d. The number of turns of the secondary winding is not defined but depends on the measuring equipment. The effective length of the magnetic core l_{eff} is 0.45 m and the area of the cross-section should be calculated by

$$A = \frac{m}{l_{\mathrm{eff}}\,\rho}\,. \tag{5}$$

Again, quantities of interest can be calculated using expressions (1)–(3). These two measurement samples (Epstein frame and single sheet) are used by the manufacturers of ferromagnetic material worldwide. A relation between the results obtained using the Epstein frame and the results obtained using the single sheet tester, for magnetic flux density between 1.0 T and 1.8 T, is given in the international standard [20] by

$$p_{\mathrm{s,SST}} = p_{\mathrm{s,EPS}}\,\left(1 + \tfrac{\delta p}{100}\right)\,. \tag{6}$$

$p_{\mathrm{s,SST}}$ is the result obtained with single sheet tester and $p_{\mathrm{s,EPS}}$ is the result obtained using the Epstein frame, and $\delta p = 1.46 + 0.242\,J^5$, where J is the magnetic polarization.

Magnetic properties of ferromagnetic materials are commonly measured on toroidal samples. However, according to the IEC standards only the Epstein frame and the SST methods should be used for testing electrical steels. Following the IEC standard [21], the toroidal sample method should be used for other materials: special alloys, amorphous and nanocrystalline materials, pressed and sintered materials, injected and cast parts and soft magnetic composite materials. For these purposes, three forms of toroidal sample can be used: wound tape (Fig. 8a), rings punched from a larger piece of sheet (Fig. 8b) and pressed powder materials or cores cut from larger pieces of material (Fig. 8c).

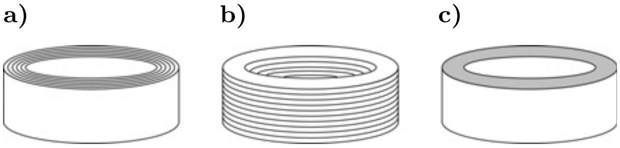

Figure 8: Three different shapes of toroidal samples a) wound tape b) separated rings punched from a larger piece of sheet c) pressed powder materials or cores cut from a larger piece of material.

International standards do not strictly define the dimensions of the sample, as in the case of the Epstein frame and the single sheet tester. Standards only give certain recommendations related to the dimensions of the toroid. If measurement is made by a time-changing magnetic field at frequencies between 20 Hz and 200 kHz, the standard specifies that the ratio of outer to inner diameter should not exceed 1.4, and it is recommended to be less than 1.25 [21]. The ribbon width (Fig. 8a) or the height of the core (Fig. 8b,c) are not specified in [21]. However, studies show that a larger width of the tape, i. e. more than 30 mm, should be used in measurements with wound toroidal samples [17]. Standard recommendations for primary and secondary winding are to distribute them uniformly over the whole perimeter of the sample.

For toroidal cores made of tape of ferromagnetic material the standard recommends that the effective length of the magnetic core l_{eff} is calculated as the mean magnetic path length of the test specimen [21]

$$l_{\mathrm{eff}} = \frac{\pi(D+d)}{2}\,. \tag{7}$$

where D and d are the outer and inner diameters of the toroid, respectively. Also, it is recommended that the area of the cross-section is calculated using

$$A = \frac{2m}{\pi\,\rho(D+d)}\,. \tag{8}$$

All quantities of interest can again be calculated using expressions (1)–(3).

4 Measurement apparatus for multi-dimensional testing

Industrially-pertinent measurement standards define such methods as the Epstein frame [19], single-sheet tester (SST) [20] and toroidal sample methods [21]. These measurements are carried out under alternating magnetization. It is possible to test strips cut at different directions (e. g. 0° and 90° with respect to the rolling direction) during the same test in an Epstein frame, as it is sometimes

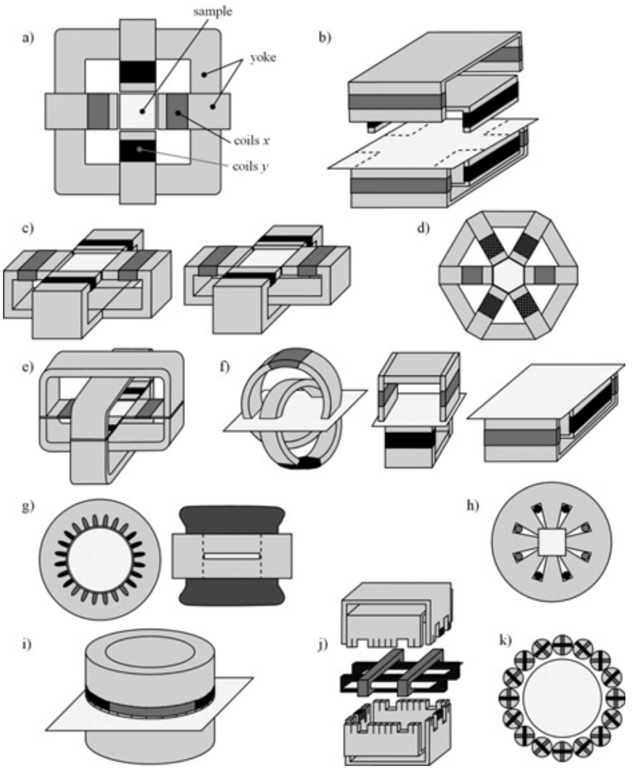

Figure 9: Various types of magnetising yokes used with the fieldmetric method [47].

done for non-oriented electrical steels in order to obtain "average" properties. However, for each strip the excitation is still applied along the same direction during one cycle of magnetization.

Magnetic cores of rotating machines are magnetized simultaneously at different directions in different points of the core. Stator teeth necks are subjected to magnetization which approximately resembles alternating conditions, but each tooth is positioned at a slightly different angle, and hence the direction of excitation is varied accordingly. A big part of the stator core is magnetized in a rotational way, with elliptical field whose values of aspect ratio and direction of the major axis also vary accordingly. Rotating magnetization also occurs in T-joints of three-limb transformer cores made out of grain-oriented electrical steel.

Magnetic loss under rotating (i. e. two-dimensional) magnetization differs from that under the alternating excitation, with the unusual behaviour that the loss reduces when the amplitude of excitation is increased towards saturation. However, at medium amplitudes the rotational power loss can be many times greater than the alternating power loss. These phenomena were demonstrated for the first time experimentally by F. Baily in 1897 [5].

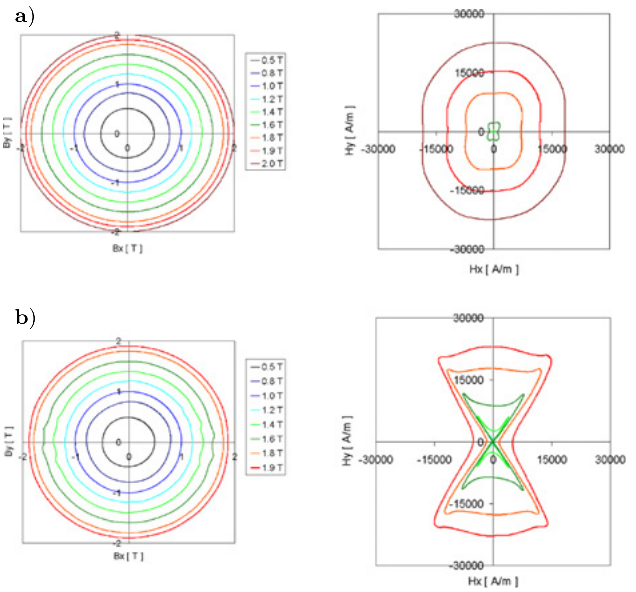

Figure 10: Loci of *B* (left) and *H* (right) vectors at 50 Hz and controlled circular *B*, for a typical electrical steel: a) non-oriented, b) grain-oriented.

Multi-dimensional testing involves purposely magnetizing the sample under test at different directions. This can be achieved by rotating the sample, the magnetizing yoke, or the magnetic field.

The method with rotating magnetizing yoke was used by Baily. "Mechanical" methods were also applied by other researchers and for all of them the power loss was measured on the basis of proportionality of the torque developed on the sample to the energy loss [3, 7, 44].

Also, the thermometric method could be used in which the measurement utilizes the temperature rise of the sample caused by the dissipated energy [31, 39]. However, in practice the method is difficult to apply due to calorimetric requirements [47].

Modern approaches for two-dimensional and rotational testing tends to concentrate on the fieldmetric method [47]. Various types of magnetizing yokes were used for this purpose by many researchers (Fig. 9). The yokes differ greatly in shape and size, but the common feature is two-phase (or three-phase) windings which allow for generating rotating magnetic field without any mechanical movement.

Very high controlled flux density values can be obtained with a compact yoke (as, e. g., shown in Fig. 9g). With an appropriate power amplifier and control algorithm [47] it is possible to perform measurements exceeding 1.9 T for all electrical steels (grain-oriented or non-oriented), as well as other soft magnetic materials. Typical results of measured *B* and *H* loci are shown in Fig. 10.

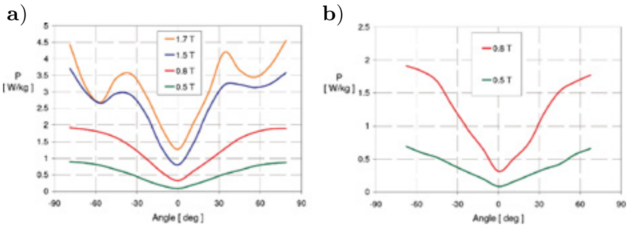

Figure 11: Anisotropy of power loss for typical electrical steels: a) conventional grain-oriented, b) high-permeability grain-oriented as measured in a rotational yoke [48].

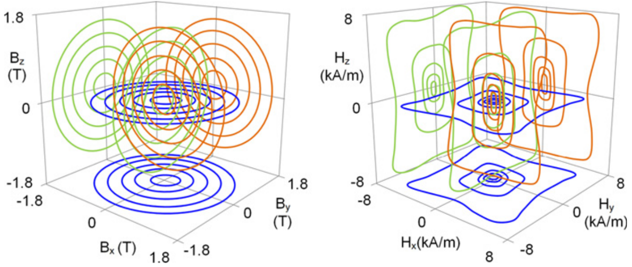

Figure 13: Loci of *B* (left) and *H* (right) vectors for a typical non-oriented electrical steel; after [25].

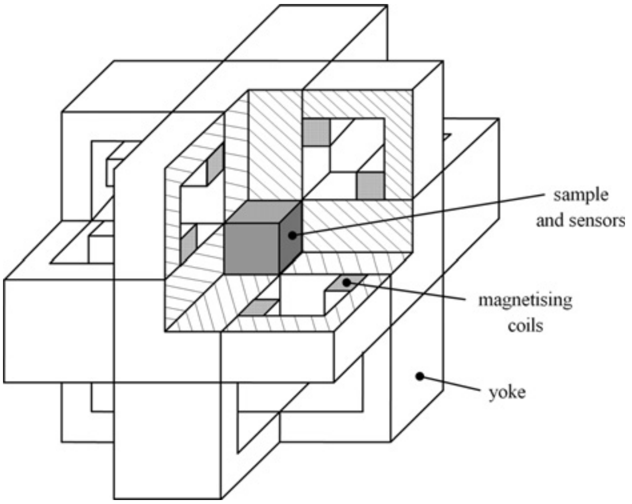

Figure 12: Magnetizing yoke for three-dimensional magnetization [45].

Using the same setup, the excitation can be also applied such that it can emulate alternating magnetization positioned at an arbitrary direction within the plane of the sample, Fig. 11 [16, 48]. It is therefore possible to measure directional properties without the need for cutting multiple samples at various directions.

In the fieldmetric method, the power loss p is calculated from the orthogonal components of the magnetic field. For two dimensions, the equation takes the following form:

$$p = \frac{f}{\rho} \int_{0}^{T} \left(H_x(t) \frac{dB_x(t)}{dt} + H_y(t) \frac{dB_y(t)}{dt} \right) dt \qquad (9)$$

where f is the frequency, ρ the sample density, $T = 1/f$ in seconds, H the magnetic field strength, B the magnetic flux density, x, y – indices denoting orthogonal directions, and t the time.

Similar approaches can be applied for three-dimensional magnetization. The magnetizing yoke is then equipped with three windings, one for each orthogonal direction (x, y, z), as shown in Fig. 12, and the excitation trajectories can be applied in an arbitrary way in the 3-D space (Fig. 13). The equation for calculation of power loss is similar to (9) but contains components for all three orthogonal directions.

5 Conclusions and outlook

This article is devoted to the extraordinary work of Josef Epstein published in the year 1900. The original article is published in German language and therefore not available for reading to a wide scientific audience all over the world. Besides this, Epstein did not publish many scientific papers after this paper and he, as a person and as a scientist, and his work is not well known in a modern scientific society. Therefore, the authors' idea was to give a translation of his work such that this bright event from the past gains attention. Moreover, the article gives an overview of the most important methods for characterization of soft magnetic materials from the angle of modern science, which is intended to attract the readers' attention. Besides, a comprehensive list of state-of-the-art references is given, as well as a proper discussion of relevant topics in magnetic material characterization. This part can be considered as a separate entity for itself, but it is also an excellent introduction for the second part of the two-part article. The latter one focuses on the modeling of material characteristics with particular emphasis on electric machine design.

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