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Angular and frequency behaviour of some properties of electrical steel sheets

***Abstract**. Electrical steel (ES) is one of the most widely used soft magnetic material. Hence, it is used to build magnetic cores of large electrical machines and transformers. At design of these cores it is necessary to take into account anisotropy and frequency influence on magnetic properties of ES. The paper presents angular and frequency behaviour of specific total loss, remanence and coercivity of ES. The carried out analysis allow to propose a frequency model of remanence and coercivity being consistent with the three component specific total loss model.*

Streszczenie.** Blachy elektrotechniczne (ES) są jednym z najczęściej używanych materiałów magnetycznie miękkich. Stąd wykorzystuje się je do budowy rdzeni magnetycznych dużych maszyn elektrycznych i transformatorów. Przy projektowaniu tych rdzeni należy wziąć pod uwagę wpływ zjawiska anizotropii magnetycznej i częstotliwości na własności magnetyczne ES. W artykule przedstawiono własności kierunkowe i częstotliwościowe całkowitych strat, remanencji i natężenia koercji ES. Przeprowadzona analiza pozwala zaproponować model częstotliwościowy indukcji remanentu i natężenia koercji, zgodny z trójskładnikowym modelem jednostkowych strat mocy. **Kątowe i częstotliwościowe właściwości niektórych parametrów blach elektrotechnicznych

Keywords: *specific total loss*, magnetic anisotropy, electrical steel, coercivity.
Słowa kluczowe: jednostkowe straty mocy, anizotropia magnetyczna, blachy elektrotechniczne, natężenie koercji.

Introduction

Electrical steel (ES) is the most widely used soft magnetic material in the electrical industry. Better understanding of the magnetisation processes including frequency and magnetic anisotropy influence can help in improvement of efficiency of electrical machines. Modelling of both anisotropy and frequency influence on magnetic properties of ES allows optimal design of electrical machines. Accurate modelling of ES means correct hysteresis modelling [1, 2] which is mandatory for an accurate design of circuits including magnetic cores. These models are implemented in electronic circuit simulators [3, 4, 1] and should include frequency and anisotropic behaviour of magnetic parameters. Particularly as frequency influence increases its significance as electronic inverters are more and more often used.

An investigation of frequency behaviour magnetic parameters of electrical steel sheets cut along different magnetising angles x was performed. There were proved simple frequency models of coercivity and remanence. The dependence between the specific total loss components, coercivity, remanence and magnetic anisotropy is shown.

Measurement setup

The measurements were carried out in a non-standard Single Sheet Tester (SST) with square sample shape of 100 mm width. The magnetizing and B-sensing coils are wound over sample cross sectional area. The magnetic flux from sample closes through two C-cores 25 mm thick. Air flux compensating coil was also used there. Determination of magnetic properties at different frequencies as the remanence B_R, coercivity H_C and the specific total loss P_S has been carried out in computerized system based on 16 bit NI PCI 6251M DAQ card [5] and based on LabVIEW^{TM} programming platform. The schematic diagram of the used computerized system is presented in Fig. 1.

The experiment was carried out on grain-oriented (GO) M140-30S grade and non-oriented (NO) M400-50A grade of electrical steel (ES) with Goss texture. The specific total loss P_S was measured for magnetisation directions 0°, 30°, 45°, 60° and 90° for GO ES and 0°, 27°, 54° and 90° for NO ES in respect to rolling direction (RD). The flux density range was varied in dependence on grade of ES and on magnetisation angle x. The peak flux density B_m range was varied from 0.1 T to 1.3T - 1.8 T in dependence on magnetization direction.

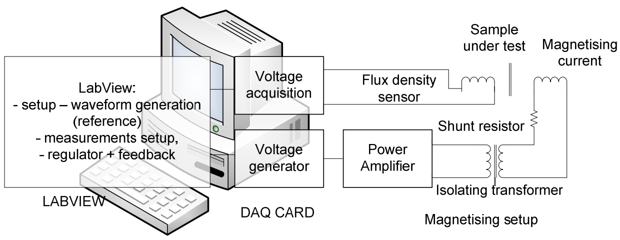


Fig.1. The block diagram of measuring system [6, 7].

For direction 60° to RD used flux density range was from 0.1 T to 1.3 T and for rolling direction flux density range was from 0.1 T to 1.8 T. The form factor of magnetic flux FF was kept well under 0.5% and the THD < 2% [8, 9]. There were chosen 10 to 12 measurement frequencies from the range of 2 Hz to 80 Hz or 100 Hz for NO or GO ES respectively. The upper frequency was determined by induced voltage in secondary coil is limited to 10 V as used testing system allows.

Experimental results

Using measurement system (Fig. 1) were measured waveforms for $b(t)$ and $h(t)$ at different values of maximum flux density B_m, at different frequencies *f* and at different magnetization angles x. From these waveforms the related magnetic parameters of hysteresis loops, i.e. coercivity H_C and remanence B_R were then calculated. Experimental data of both coercivity H_C^x and remanence B_r^x for different angles x in dependence on square root of frequency for GO ES are presented as in Fig. 2.

The frequency behaviour of coercivity for different magnetic materials is presented in voluminous literature as for example [10, 11, 12, 13]. The literature concerning frequency dependencies of remanence flux density is very limited. Most often the frequency behaviour of coercivity is analyzed as dependent on frequency as $f^{1/2}$. Experimental dependences of coercivity and remanence for both ES and different magnetization angles x follow well the model described by (1) and (2) for coercivity and remanence respectively.

(1) $$H_C^x = a_{H_C}^x + b_{H_C}^x f^{0.5}$$

(2) $$B_R^x = a_{B_R}^x + b_{B_R}^x f^{0.5}$$

where:- $a_{H_C}^x$ and $b_{H_C}^x$ are coefficients of coercivity frequency model, $a_{B_R}^x$ and $b_{B_R}^x$ are coefficients of remanence frequency model

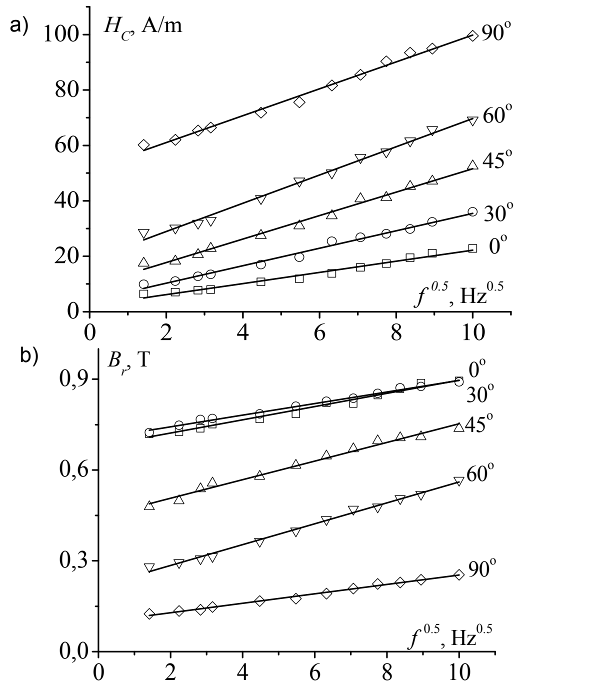


Fig. 2. Coercivity H_C^x (a) and remanence B_r^x (b) versus frequency $\sqrt{f}$ for GO grade M140-30N at B_m = 1.0 T

Coefficients $a_{H_C}^x$ and $a_{B_R}^x$ correspond to coercivity or remanence value at close to zero magnetization frequency and coefficient $b_{H_C}^x$ and $b_{B_R}^x$ are associated with dynamic magnetization condition which, according to three components model of specific total loss [16], with impact of classical and additional eddy current specific total loss components. The above models ((1) and (2)) well describe frequency behaviour of coercivity and remanence and the fitting of experimental points (as in Fig. 2) is performed with correlation factor R^2 equal or better than 0.99.

As can be seen in Fig. 2 dependence of coercivity H_C^x (a) and remanence B_R^x on $f^{1/2}$ exhibits nearly linear increase for all considered magnetization angles which means they follows the $f^{1/2}$ law [14]. The slope of the curves $H_C^x = f(f^{1/2})$ for different magnetization angles x can be related to increasing number of active domain walls with frequency [15, 16]. Also the slopes are related to angular dependences of hysteresis loss components. In the case of dependences $B_R^x = f(f^{1/2})$ (Fig. 2 b) the largest slope can be observed for x = 60° and x = 45°. The rest curves slopes are nearly parallel to each other. This can be directly related to low additional eddy current loss as the additional eddy current loss factor η [6] is higher for "magnetically hard" directions as presented in Fig. 3.

In the case of NO ES curves of additional eddy current loss factor η^x (Fig. 3 b) for different angles x are situated near each other showing, not surprisingly, weak texture influence for NO ES. This is in opposite to GO ES which shows significantly larger texture degree [17]. The presented in Fig. 3 angular dependence of additional eddy current loss factor η^x are correlated with to angular dependencies of additional eddy current loss component $P_{a,y}^x$ presented in Fig. 4.

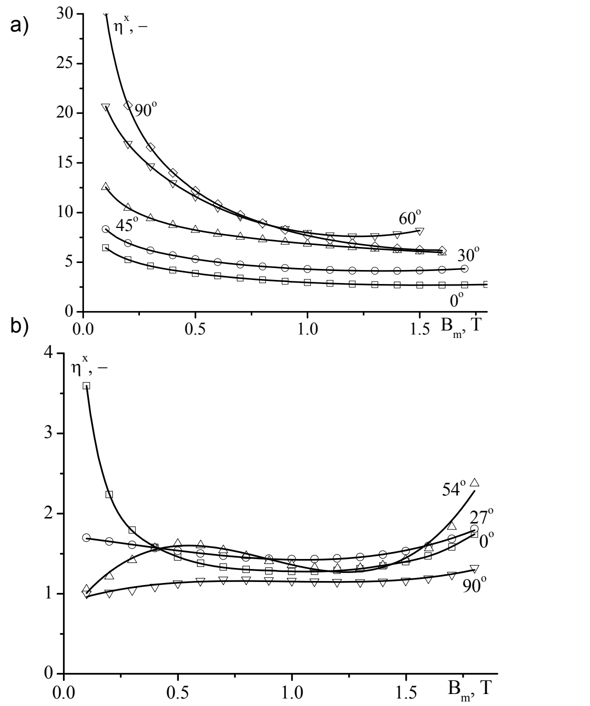


Fig. 3. Angular dependence of additional eddy current loss factor η^x versus maximum flux density B_m in a) GO ES grade M140-30N and b) NO ES grade M400-35S

The models describing the frequency dependence of coercivity and remanence are substantiated by the three component specific total loss model (3) [18, 16]. One can find that multiplying the model for coercivity (1) the model for remanence (2) takes form appropriate for the three component specific total loss model.

Calculation of specific total energy loss by multiplying of (1) and (2) is limited to particular cases of materials with rectangular hysteresis loops [19]. Hence, it cannot be used in a case of magnetization along different angles than rolling direction. However, it shows agreement of the models of coercivity (1) and remanence (2) with three components loss specific total loss model.

Specific total loss

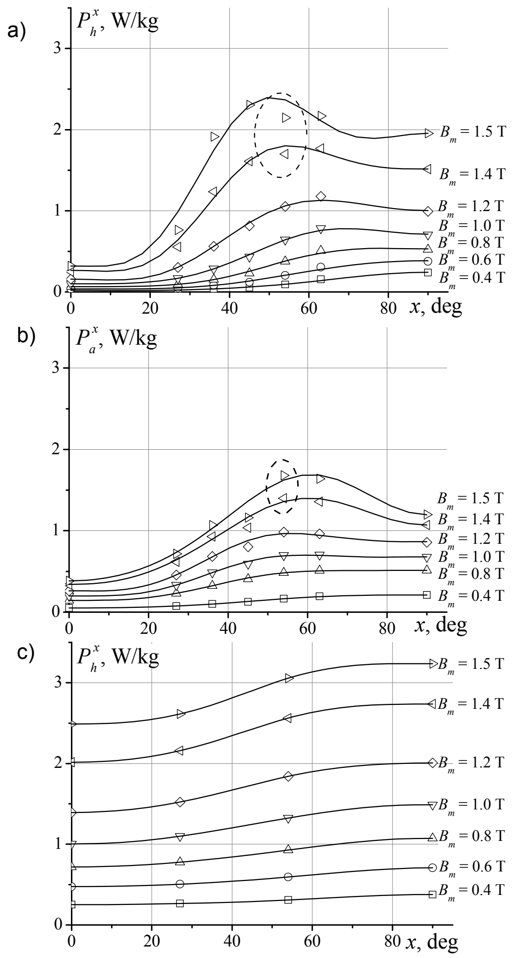
The three component model (3) was developed for many years [20, 21, 22, 23] contribute to formulate a statistical loss model proposed by G. Bertotti [18, 16]. Simplified form of his model is described by following equation:

(3) $$P_S / f = \underbrace{C_0(B_m)B_m^{\alpha}}_{P_h / f} + \underbrace{C_1 B_m^2 f}_{P_{ce} / f} + \underbrace{C_2(B_m)B_m^{3/2} f^{1/2}}_{P_a / f}$$

where: C_0 is the hysteresis loss coefficient, $C_1 = \pi^2 d^2 / (6\rho\ \gamma)$ is the classical eddy current loss coefficient, C_2 is the additional loss coefficient, ρ is the resistivity, d is the sheet thickness, γ - mass density.

In (3) the classical eddy current P_{ce} component was calculated under assumption that ferromagnetic material is homogenous and isotropic. Lack of fine and complicated domain structure in hot-rolled ES was a reason for quite accurate dynamic loss prediction in early years [20]. Together with introduction of Goss texture larger discrepancy between measured and calculated loss values using hysteresis P_h and classical eddy current P_{ce} appeared. This caused introduction of third component named anomalous or additional eddy current loss P_a. Explanation of the additional loss component is given by the statistical loss model. This model describes the additional eddy current loss component P_a as equal to $P_a = 2B_m f(8\sqrt{n_0^2 V_0^2 + 16\sigma GSV_o B_m f} - n_0 V_0)$ [18, 16]. Because, in NO ES the value of n_o is in the order of few then n_o can be set to be equal to zero and the equation for P_a simplifies to $8\sqrt{\sigma GSV_o}$. This simplification cannot be used in a case of GO ES as n_o reaches large value and more explanation of additional eddy current loss P_a cannot be used for modelling of anisotropy influence on specific total loss P_s. This is due to the fact that n_0 reaches negative values [24]. However, the three component model in its simplified form (3) can be used for specific total loss P_S^x analysis for different magnetization angles x [7].

The angular dependences of both hysteresis and additional eddy current specific total loss components are very complex. The hysteresis loss component is more significant for magnetically hard magnetization directions and for NO ES, as in Fig. 4



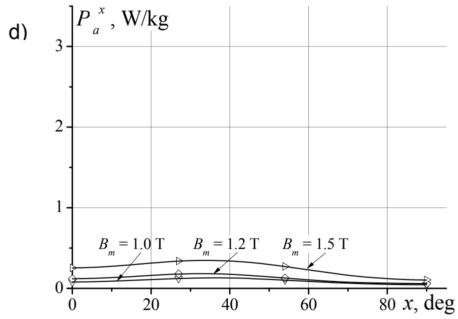


Fig. 4. Angular dependencies of hysteresis $P_{h,y}^x$ a), c) and additional eddy current $P_{a,y}^x$ b), d) specific total loss components at 50 Hz and at flux densities B_m = 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, and 1.5 T for a), b) grade M140-30S at angles x = 0°, 27°, 36°, 45°, 54°, 63° and 90° and c),d) grade M400-50A at angles x = 0°, 27°, 54° and 90°, (circle made by a dotted line mark the extrapolated points) [7]

As can be seen in Fig.4 the influence of magnetic anisotropy can be separated into two regions of flux density which differ by loss mechanisms that occurs in both regions [17]. At "lower" flux density region, up to about 1.1 T, both hysteresis P_h (Fig. 4a) and additional P_a specific total loss components continuously increase with increasing angle x. At "upper" flux density region, above about 1.1 T, both components increase with increasing angles x up to 45° and then both components decrease up to angle x = 90° and faster as flux density increases. This shows that also loss models should be separated into "lower" and "upper" flux density region.

Presented in Fig. 4 angular dependences as well as other physical properties can be represent by a periodic function but most often a trigonometric function is used [25, 26, 27]. Such function allows modelling of magnetic properties related to magnetic anisotropy which is directly attached to crystallographic texture. Angular dependences of hysteresis $P_h^x = \mathrm{f}(x)$ and additional $P_a^x = \mathrm{f}(x)$ specific total loss components are similar to each other [28, 29] can be represent by series of trigonometric functions as in [25, 26, 7]. Experimental points presented in Fig. 4 were fitted with trigonometric function as below, [26, 7]:

$$F(x) = A_0 + A_1\cos(2x) + A_2\cos(4x) + \ldots \\ \ldots + A_3\cos(6x) + A_4\cos(8x) \quad (4)$$

where: A_0, A_1, A_2, A_3, A_4 are coefficients that vary with flux density.

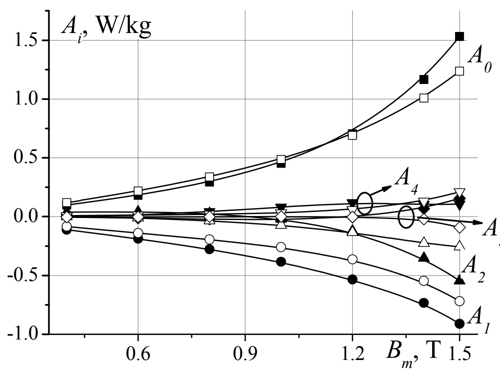


Fig. 5. Variation of coefficients A_i of (5) versus flux density B_m at 50 Hz for sample M140-30S, filled symbols hysteresis $P_{h,y}^x$ and empty symbols additional eddy current $P_{a,y}^x$ specific loss components [7].

In a case of NO ES may be used fife coefficients [26] but three first coefficients of (4) were used with success [27]. However, in a case of GO ES three first coefficients can be used only up to about B_m < 1.0 T, that is in "lower" flux density region, Fig. 4. For flux density above 1.0 T magnetic anisotropy influence manifest itself and to fit experimental data it is was necessary to use all components of (4). Variation of coefficients A_i with flux density for sample M140-30S are presented in Fig. 5.

In Fig. 5 are visible similarities between corresponding coefficients of (4) used for approximation of dependences of hysteresis P_h and additional P_a loss components on flux density. This similarity can be explained by fact that both specific total loss components are associated with domain structure and micro eddy currents which are generated at quasi static magnetisation conditions as well as at higher magnetisation frequency. The main reason to separate these two components is the different frequency behaviour.

Summary

The loss phenomenon in electrical steel sheets is very complex and complicated. The transformation of Poynting vector allow to get loss equation in a form which consists of only two components, but it must be underlined that the transformation involve many simplifications leading to large inaccuracy in the calculation of eddy current loss [30, 31]. The inaccuracy is higher in GO than in NO ES, as the additional eddy current loss factor η reaches values near 1 and in GO ES the factor η is much larger, Fig. 3. It is believed the main source of such inaccuracies are micro eddy currents generated around moving magnetic domains. The micro eddy currents are relatively small in a case of small domains as in NO ES and much larger in GO ES where the domain structure is expanded. Magnetic domains also contribute to magnetic anisotropy and the classical eddy current loss equation normally does not take into account anisotropy, particularly in its simplified form, as apart from resistivity ρ no anisotropic parameter is included. As a results calculation of the eddy current loss for different magnetisation directions gives the same results. Hence, discrepancy between calculated and experimentally achieved values exists. Therefore often the three component specific total loss P_S^x model if used.

In this paper there was proposed experimental model describing frequency dependence of remanence (2) and it can be used for different magnetization angles x. There was also proved the model for dynamic coercivity for different magnetization angles x and both models exponential equation with exponent equal to 0.5. It was shown that the models of remanence and coercivity justify the specific total loss separation into the three components. The influence of magnetic anisotropy on both hysteresis and additional eddy current loss components as presented in Fig. 4 and 5 as well as in presented in another way in [24] allow to propose specific total loss P_S^x as follows:

$$P_S^x = F(x) \cdot (P_h^0 + P_a^0) + P_e \tag{5}$$

The function $F(x)$ can be any function describing angular dependence of hysteresis and additional eddy current specific total loss components as for example (4) and P_h^0 and P_a^0 are values of these components at magnetisation angle x = 0°. Closure of the two loss components in one bracket is caused by similarity in $F(x)$ function describing their angular behaviour. This similarity of can be explained by the fact that both components are dependent on domains. This fact was taken into account in specific total loss model that takes into account anisotropy phenomenon. However, due to the fact that the loss phenomenon is very complex and complicated the model needs still more research.

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