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# MEASUREMENTS OF MAGNETIC PROPERTIES OF ELECTRICAL STEEL SHEETS FOR THE AIM OF LOSS SEPARATION

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Magnetic loss separation is an excellent tool for loss mechanism evaluation thogether with ferromagnetic material and electrical machines optimisation and modelling. Therefore, it is very important to perform loss separation so precisiely as possible. Samples of non-oriented and grain-oriented electrical steel have been tested in non standard Single Sheet Tester at ten different frequencies. Specific total loss was measured and than separated into hysteresis, classical eddy current and additional eddy current loss components. The aim of this paper is to provide a contribution to the better understanding of magnetic losses phenomena in soft magnetic materials.

Keywords: loss separation, hysteresis loss, eddy current loss, additional loss

## 1 INTRODUCTION

Ferromagnetic materials development and electrical machines optimisation are still in progress due to better and better magnetic loss mechanism understanding. Magnetic loss separation is an excellent tool for this progress and it enables for example the optimisation of grain size and thickness of electrical steel sheets [1]. It allows also analysis of electrical machines performance in the time domain [2] and shows good loss prediction even in case of PWM (PulseWidth-Modulated) power supply [3]. Statistical loss model proposed by G. Bertotti [4] meets majority of the needed requirements. As it is well known this model comprises three components: hysteresis $P_h$, classical eddy current $P_e$ and additional eddy current $P_a$ loss. The classical eddy current loss $P_e$ can be calculated, (1) and two others have to be obtained from measurements.

Hysteresis $P_h$ and additional $P_a$ loss components can be obtain even by means of two loss values measured for two frequencies $f_1$ and $f_2$ but in this case the loss separation will not necessary be proper (differences between Fig. 1 and Fig. 2). For modern electrical steel sheets with well developed domain structure, even for the Bertotti loss model, such procedure of loss separation do not ensures good accuracy of loss separation. The “form factor” of sinusoidal flux defined by a standard [5] also can be related to an inaccurate loss separation. More, because many and different measurement data have to be considered (Fig. 2) – not only accuracy – but the value of the form factor of sinusoidal wave [5] becomes very important at proper loss separation. It is proven the shrinking waveform shape factor from 1.11 ±1% (according to standard [5] to 1,11 ±0.5% will help to increase loss separation methodology.

The paper presents behaviour of statistical loss model components (1) investigated in flux density range 0.4 T - 1.7 T and frequencies between 2 Hz and 100 Hz. The investigation was preformed for grain-oriented (GO) and non-oriented (NO) electrical steel sheets. There was found that the model [4] can be use for analysing of magnetic properties of electrical steel sheet as it is kept in assumed ranges of flux density, permeability and frequency [6]. Because of this fact, quantitative differences in additional loss factors calculated from the model based on 2 and 10 measurements, have been proved as dependence on frequency $f$ and flux density $B$ (Fig. 5).

## 2 LOSS SEPARATION

As mentioned - from historical point of view - loss separation procedure requires two experimental points measured at two different frequencies (Fig. 1). This procedure can be recognised as a proper one for electrical steel sheets manufactured 40-50 years ago [7].

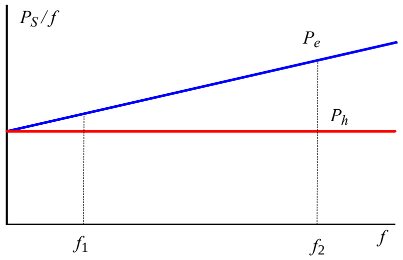

**Fig. 1**. Model of loss separation in electrical steel sheet based on two measurement data ($P_a$ = 0, from (1)).

The two component model $P_h$ and $P_e$ (Fig. 1) and procedure of loss separation is applicable for electrical steel sheets only with weakly developed domain structure. In currently manufactured electrical steel sheets their domain structure outcomes as reason of the additional eddy current loss $P_a$, (1). The model which includes the additional component $P_a$ of the specific total power loss $P_S$ is the statistical loss model, described by Bertotti [4], and it consists of three components: $P_h$ – hysteresis, $P_e$ – classical eddy current and $P_a$ – additional eddy current loss, as shown by formula

$$P_s = \underbrace{C_0 B_m^2 f}_{P_h} + \underbrace{\frac{\pi^2 d^2 B_m^2}{6\rho\gamma} f^2}_{P_e} + \underbrace{C_1 B_m^{3/2} f^{3/2}}_{P_a}, \qquad (1)$$

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with: $C_0$ – hysteresis loss coefficient, (Am$^4$/Vskg), $C_1$ – additional eddy current loss coefficient, (Am$^3$/kgV$^{1/2}$), $\rho$ - resistivity, ($\Omega$m), $B_m$ - peak magnetic flux density, (T), $d$ - sheet thickness, (m), $\gamma$ - mass density, (kg/m$^3$).

As it is well known only the classical eddy current component $P_e$ of (1) can be calculated. Two remaining components have to be determined in experimental way, usually by dividing (1) by frequency $f$ and then fitting $P_S/f$ to experimental points. Performing the measurements of $P_S$ at many different frequencies $f$ is obviously time-consuming. Therefore it is easier to use (1) in the form as given below, to perform the measurements only at two frequencies $f_1$ and $f_2$ and at the end to solve system

$$\begin{aligned}\frac{P_S^0}{f_1} &= C_0 B_m^2 + \frac{\pi^2 d^2 B_m^2}{6\rho\gamma} f_1 + C_1 B_m^{3/2} f_1^{1/2} \\ \frac{P_S^0}{f_2} &= C_0 B_m^2 + \frac{\pi^2 d^2 B_m^2}{6\rho\gamma} f_2 + C_1 B_m^{3/2} f_2^{1/2}\end{aligned} \quad . \tag{2}$$

This procedure leads to an improper loss separation and is only applicable to electrical steel sheets with weakly developed domain structure. The function $P_S/f$ depends on proper coefficients value $C_0$ and $C_1$ what obviously depends on proper number of experimental data. This is especially important in low frequency range, see Fig. 2(a) and Fig. 2(b), and it was assumed [8] that fitting as much as 10 measurement points can be considered as proper.

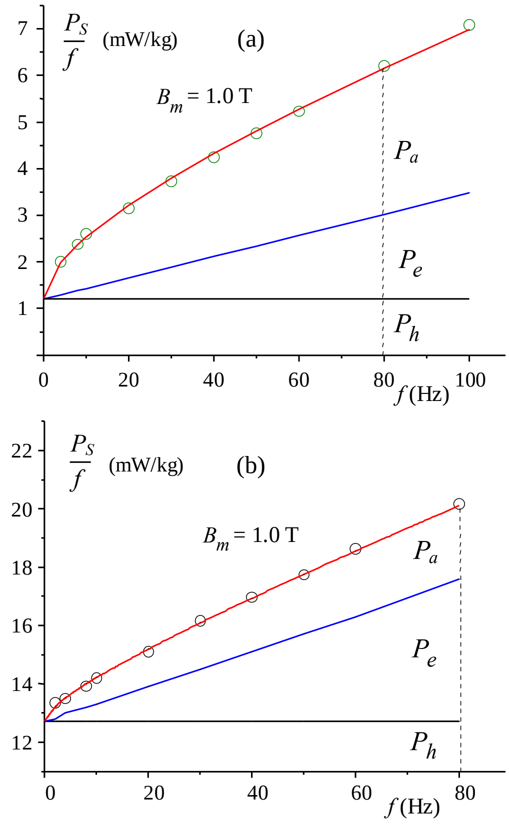


**Fig. 2.** Energy loss per unit mass versus frequency obtained for sample (a) grain-oriented 23ZDKH90 and (b) on-oriented M330-35A

As can be seen in Fig. 2, the dependence of $P_s/f$ for an electrical steel grade 23ZDKH90 shows larger non-linearity than for NO electrical steel, especially at low frequency range. The repeatability and measurement accuracy become very important (first of all keeping the wave shape form factor (*FF*) as low as possible).

## 2 MEASUREMENT PROCEDURE

The experiment was carried out on grain-oriented and non-oriented electrical steel sheets. Because of industrial character of this work, non-standard Single Sheet Tester with square samples with side length 100 mm were used. 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. The magnetizing conditions were controlled by computerized system presented in Fig. 3.

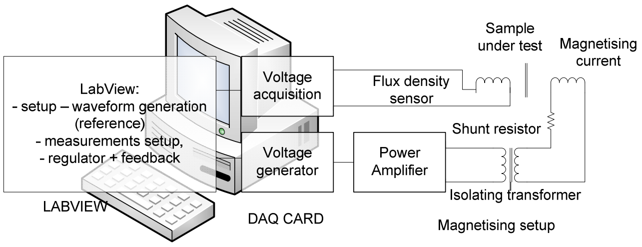
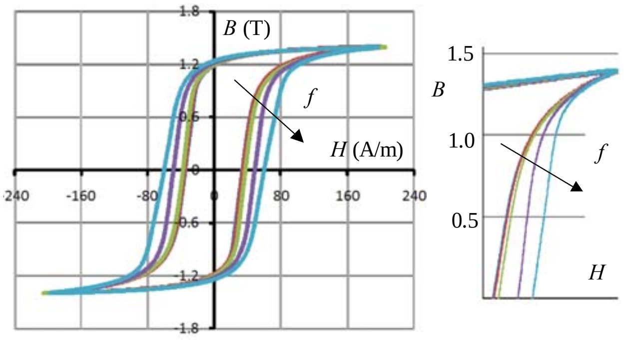


**Fig**. 3. The block diagram of measuring system [6]

The measuring system was based on 16 bit NI PCI 6251M DAQ card [9] and LabView™ programming platform. The LabView™ program uses similar feedback algorithm to that presented in [10] and maximum acquisition speed in order to control a time shift between channel responsible for measurement of flux density and magnetic field strength. The specific total loss $P_s$ was measured under controlled sinusoidal magnetic flux waveform. The measurements were performed at ten frequencies in the range from 2 Hz or 4 Hz to 80 Hz or 100 Hz. Example of measurements is presented in Fig. 4.



$f$ = 2, 4, 10, 50, 100 Hz

**Fig. 4.** Hysteresis loops measured at 1.4 T and 2, 4, 10, 50 and 100 Hz for NO electrical steel sheet M330-35A

Due to the fact that the measurement system is operated in LabView™, there exists the possibility of easy change of measurement conditions. The measurements can be performed under controlled value of form factor (*FF*) [5], total harmonic distortion (*THD*) of magnetic flux density (5). Determination of the specific total loss $P_S$ for loss separation of electrical steel sheets was performed along rolling direction in the range of magnetic flux density from 0.4 T to 1.7 T for GO steel sheets and from 0.4 T to 1.6 T for NO steel.

## 3 EXPERIMENTAL DATA

### Frequency selection

In Fig. 2 it is visible that experimental points do not lie ideally on fitted curve. Higher discrepancy is observed in low frequency range and for NO steel sheets. This discrepancy, and non-linearity cause that the accuracy of loss separation depends on number of measurements points (frequency) and chosen values of frequencies. Additional loss factor $\eta$ is a function of maximum flux density and frequency and it is defined by formula

$$\eta(B_m, f) = \frac{P_s(B_m, f) - P_h(B_m, f)}{P_e(B_m, f)} \qquad (3)$$

In Fig. 5 there are presented the percentage differences in additional loss factor $\Delta\eta$, as calculated form the following

$$\Delta\eta(B_m, f) = \frac{\eta^{(10)}(B_m, f) - \eta^{(2)}(B_m, f)}{\eta^{(10)}(B_m, f)} 100\% \, , \qquad (4)$$

where: number in superscrip means that the factor $\eta$ was calculated from experiment based on 10 or 2 experimental points.

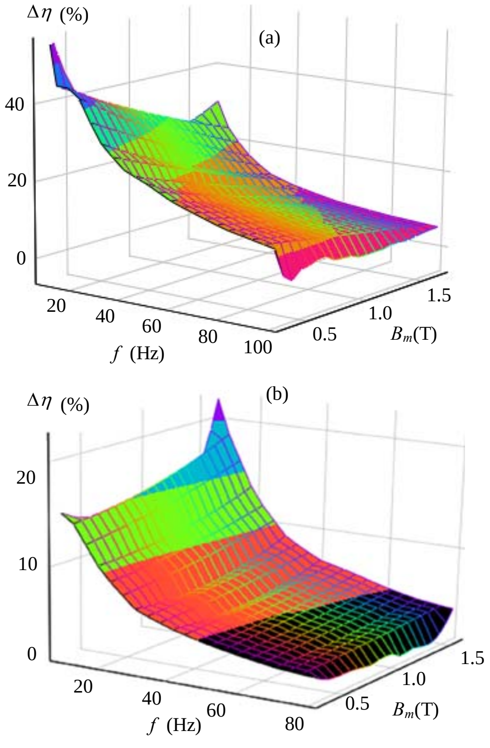


**Fig. 5.** Percentage difference $\Delta\eta$ between additional loss factor $\eta$ measured for ten frequencies and two frequencies versus frequency and flux density obtained for (a) - GO steel 23ZDKH90 and, (b) -NO steel M530-50A

Dependencies as in Fig. 5 were calculated from measurements performed at ten frequencies in the range from 2 Hz to 80 Hz for NO sheet or from 4 Hz to 100 Hz for GO steel and for two frequencies 20 Hz and 80 Hz for NO steel or 20 Hz and 100 Hz for GO steel. The differences in frequency ranges resulted from the fact that there was higher induced voltage for NO steel (larger cross sectional area of a sample).

The difference in factor $\Delta\eta$ (Fig. 5) shows decrease if the loss separation measurement for frequency significantly below 20 Hz will be done. It is visible in Fig. 5 that the difference $\Delta\eta$ is smaller for NO steel, Fig. 5(b) and larger for GO steel, Fig. 5(a). This is due to non-linearity of function of energy loss versus frequency, Fig. 2(a) and Fig. 2(b) respectively. For example in the case of NO steel like M530-50A measurements at two frequencies 8 Hz and 80 Hz cause difference between 10 frequencies and 2 frequencies approximately 7% while for GO 23ZDKH90 steel such difference (7%) occurs when are taken measurements at 6 frequencies.

### Influence of form factor

The significance of the form factor increases, as increases the importance of both, classical and additional eddy current loss components. This is because the form factor has no relation to the hysteresis loss, as discussed in [2]. Standardized magnetic measurements require that the value of FF differ from ideal value (1.11072) not more than 1% [5].

The form factor (*FF*) was defined as the ratio between RMS (root mean square) value and average (average of rectified values) value of magnetic flux. For the same waveforms Total Harmonic Distortion of flux density *THD*(*B*) was calculated

$$THD(B) = \frac{\sqrt{\sum_n B_n^2}}{B_1} 100\% \, . \qquad (5)$$

where: $n$ – number of harmonics taken into account.

The form factor (*FF*) relates to difference in value of measured specific total power loss value and hence, to the accuracy of loss separation. In Fig. 6 and Fig. 7 the dependences of measured values of specific total power loss $P_S$ on form factor (*FF*) and on Total Harmonic Distortion of flux density,*THD*(*B*) for 0.8 and 1.2 T are presented, respectively.

In all measurements presented in Fig. 6 and Fig. 7 amplitude of magnetic flux density differ less than 0.05%. This limits error in loss separation caused by measurements performed at different amplitude of flux density. The presented in Fig. 7(a) measurements results show that even if *FF* changes from its ideal value 1.11072 ± 1% the power loss can differ about 14% from average about 1.85 W/kg in result group marked in Fig.7.

If the changes of the specific total loss $P_S$ exceed 1% from average in result group marked in Fig. 7(b) then the *THD*(*B*) can take values above 11%. However, there is no clear dependence between change of $P_S$ and *THD*(*B*) as well as between $P_S$ and *FF* factor. The conclusion that can be draw here is that if the *THD*(*B*) is lower than 2% the sparse in measured $P_S$ do not exceed about 1%. Similar conclusion applies to *FF*. If the *FF* differs less than 0.5% from its ideal value than the specific total loss spread also does not exceed 1%. From measurements results presented in Fig. 6 and Fig. 7 it seems that *THD*(*B*) of flux density is less pertinent parameter than *FF*.

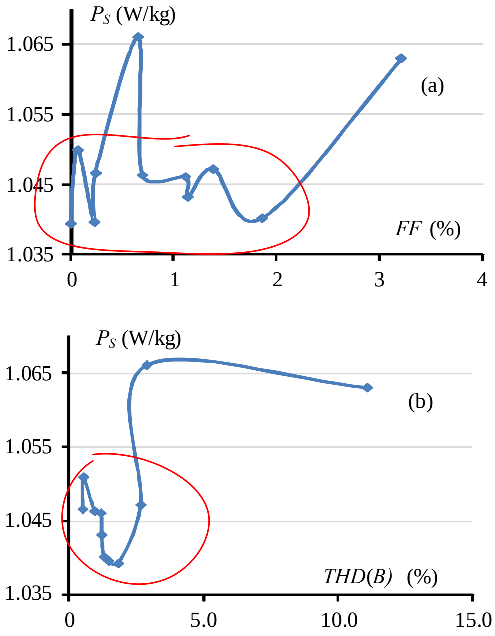


**Fig. 6.** Dependence of measured values of specific total power loss $P_S$ on factor FF and on THD(B) for flux density of $B_m$ = 0.8 T

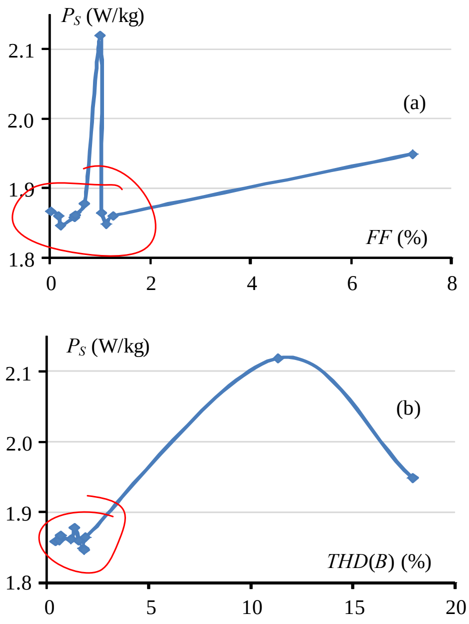


**Fig. 7.** Dependence of measured values of specific total power loss $P_S$ on factor FF (a) and on THD(B) (b) for flux density of $B_m$ = 1.2 T

On the other hand, discrepancy of $P_S$ is satisfactorily small if measurements are taken at FF difference from its ideal value less than 0.5%. Such condition is more strict than in standardised measurements [5]. This condition can be relatively easy satisfied in up-to -date magnetic measurement systems.

## 4 SUMMARY

The accuracy of loss separation is significantly influenced by the condition of specific total loss measurement. The most important factors influencing loss separation were found to be:

- choose of frequency, values and number of measurements with taking into account electrical steel sheets grade,
- value of form factor (FF) should differ less than 0.5% from its ideal value,
- difference in value of the flux density at which measurements for different frequencies are taken should be as low as possible.

Optimised number of measurements which has to be taken for proper loss separation is important task as the measurements are time consuming.

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