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Prediction of loss in non-oriented steel laminations

***Abstract**. Some problems related to loss prediction in hysteretic media are identified. The deficiencies of three term loss separation formulas are pointed out. A novel approach, based on loss separation into two terms, is presented and verified using experimental data concerning chosen grades of non-oriented steel.*

***Streszczenie.** Zidentyfikowano niektóre problemy związane z predykcją strat w medium wykazującym histerezę. Wskazano na ułomność formuł trójskładnikowych stosowanych do predykcji strat. Zaprezentowano nowe podejście, oparte na separacji strat na dwa składniki. Dokonano weryfikacji eksperymentalnej opisu wykorzystując dane dla wybranych gatunków stali o ziarnie niezorientowanym. (**Predykcja strat w arkuszach z blachy o ziarnie niezorientowanym**).*

Keywords: Loss separation, non-oriented steel, Steinmetz equation, eddy currents.
Słowa kluczowe: Separacja strat, stal o ziarnie niezorientowanym, równanie Steinmetza, prądy wirowe.

Introduction

Prediction of loss in laminations made of electrical steel is important for the designers of magnetic circuits in electric machines [1]. It is usually taken for granted in textbooks on magnetism, that loss can be decomposed into three components, related to the hysteresis phenomenon, eddy currents within the bulk material and eddy currents due to inhomogeneity of magnetic structure, cf. Fig. 1.

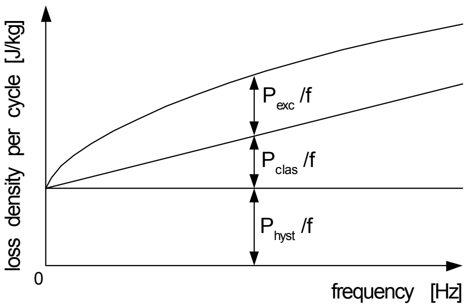

Fig.1. Conventional loss separation scheme

A number of theories has been developed in the past, aiming at a proper description of the mysterious third component of total loss, the so-called excess or anomalous loss. The studies on the issue in terms of the analysis of domain wall movement have been initiated already in the fifties of the last century with the papers by Williams *et al.* [2], Aspden [3] and Lee [4]. The landmark paper by Pry and Bean [5] has provided valuable insights into the role of magnetic domain structure, which have later been practically utilized in metallurgy (optimization of grain size through material processing, cf. e.g. [6-7]).

The Pry-Bean model has introduced the following formulas for the dynamic (classical+excess) loss component, in dependence on the geometry of the considered sheet:

$$P_{dyn}(t) = \begin{cases} P_{cl}(t) & \text{for } \; 2L/d << 1 \\ 1{,}63\dfrac{2L}{d}P_{cl}(t) & \text{for } \; 2L/d >> 1 \end{cases} \qquad (1)$$

where $P_{cl} = \dfrac{\sigma d^2}{12}\left(\dfrac{dB}{dt}\right)^2$ is the so-called classical loss, d is sheet thickness, whereas $2L$ is the average spacing between adjacent domain walls in the demagnetized state (the Pry-Bean description considers an infinite periodic structure of anti-parallel 180^o domains).

The unresolved problem with the Pry-Bean description is how to explain the abrupt increase of excess loss density for low excitation frequency. It has to be admitted though, that the curvature of the $P/f(f)$ dependence is vague in some grades of electrical steel [8].

Highly idealistic assumptions lying at the foundations of the Pry-Bean description have been criticized by Bertotti, who developed his statistical theory of excess loss in the eighties of the last century [9,10]. Bertotti has described the magnetization dynamics in terms of stochastic interactions between the so-called magnetic objects (MOs), identified as single domain walls for grain-oriented steels and as clusters of neighbouring domain walls in non-oriented steels. The dependence of total loss density per cycle versus excitation frequency has taken the approximate form

$$P/f = const + k_1 f + k_2\sqrt{f}. \qquad (2)$$

There are several problems with the Bertotti's description as well. These are related to the very existence of the classical loss term, which is derived under the assumptions of uniform magnetization, linearity and homogeneity of the sheet material. These assumptions are only approximately fulfilled in real-life materials [11-12], what results in a limited range of applicability of relationship (2). For example, Bertotti's formula may be applied for excitation frequencies lower than 225 Hz for sheet gauge 0,3 mm due to eddy current shielding [13]. On the other hand, it can be applied for excitation frequencies above several Hz, as pointed by the author himself [9].

Bishop has proven that due to eddy current interactions between different MOs, a correction to P_{clas} of the order of 30 % might be expected [14, 15]. This uncertainty could destroy any sophisticated attempt to describe the excess loss.

Whereas Bertotti attributes the excess loss to domain wall processes, Mayergoyz and Serpico claim that this component might be in fact related to the intrinsic dynamics of switching between metastable states in elementary hysteresis operators [16]. Thus the excess loss could be called frequency-dependent hysteresis loss. The existence of frequency-dependent hysteresis loss has been envisaged already by Graham [17], as well as by Seagle and Charap [18]. The idea has been further developed and interpreted by Pfützner et al. [19].

Some authors have reported rather puzzling results about negative excess loss values obtained from calculations [20, 21]. Those may also be attributed to the consideration of classical loss term, which neglects skin effect and is derived for a linear medium. Numerical results concerning nonlinear diffusion in hysteretic media clearly indicate that due to eddy current shielding the instantaneous flux density distribution is non-uniform across the lamination, thus the three-term model assumptions are violated [22-24]. Some attempts to take into account skin effect in the formula for the classical loss have been reported in the literature [11, 25, 26].

Yet another distinct approach to the issue is to reject the idea of loss separation at all. Already in 1963 Becker has written: "… the concept that hysteresis loss is something that can be added to eddy-current loss implies that it has a different independent mechanism, operating at all times and independent of frequency. However, as we have been trying to emphasize so far, there is only one mechanism of losses in these materials, namely resistive losses due to eddy currents associated with moving walls. Since the number of moving walls changes with frequency, it is difficult to see what meaning should be attached to the separation of a "hysteresis" loss involving few moving boundaries from another loss involving more, or even, if the collapsing wall region is reached, an entirely different configuration" [27].

The concept to consider together all dissipation phenomena occurring at different time and spatial scale has been advanced in [28].

Recently, a two term formula for total loss density per cycle has been proposed, where the component related to eddy currents is envisaged as a power law with a fractional exponent [29, 30],

$$P/f = W_{hyst} + A \cdot f^{\alpha}, \quad (3)$$

where A is a parameter and α comprises all dynamic effects. Its value is dependent on flux density amplitude.

The line of reasoning beyond the introduced formula is based on an analogy with the Poynting theorem, which considers just two terms related to distinct physical phenomena for the industrial frequency range of interest, i.e. when the displacement currents could be neglected.

The aim of the present paper is to extend the proposed formula to take into account the effect of flux density amplitude and to present an experimental verification of the description on chosen grades of non-oriented steel used in electrical engineering.

Modelling

Measurements of loss density were carried out using a computer-aided measurement system [31] and a Single Sheet Tester device in rolling and transverse directions for four grades of non-oriented steel, differing in magnetic properties and thickness. The Single Sheet Tester was chosen, because magnetic measurements using the Epstein frame require a tedious sample preparation; at this stage, during sample cutting, some inevitable stresses are introduced into the material [32-35]. Moreover there are some unresolved problems with interpretation of measurements carried out with the latter method (the problems with frame corners and determination of the effective magnetic path length) [36-38].

The dimensions of examined sheets were 500 x 500 mm. The catalogue data concerning the examined steel grades is comprised in Table 1. The fundamental parameter concerning their quality is maximum loss density at B_m = 1,5 T, as well as minimum values of induction for field strengths H_m = 2500 A/m and 5000 A/m. The values given in Table I refer to Epstein frame measurements at f = 50 Hz on samples subjected to 24-h thermal aging at 220 °C.

All measurements were carried out under condition of sine dB/dt-wave in the examined samples. The admissible deviation of form factor from 1,11 (characteristic for sine wave) did not exceed 0,1 %. The accuracy of material characterization in the normalized region conformed to IEC and DIN requirements. The expanded B-type uncertainty of loss density measurements was below 1,5 % (for 0,95 confidence level). The accuracy of frequency setting in the system was equal to 0,2 % of the preset value.

Table 1. Catalogue data concerning the examined steels

Grade according to PN-EN 10106	Nominal thickness, [mm]	Maximum loss density [W/kg] at f = 50 [Hz]		Minimum induction [T]	
		@ B_m = 1,0 T	@ B_m = 1,5 T	@ H_m = 2500 A/m	@ H_m = 5000 A/m
M330-35A	0,35	1,30	3,30	1,49	1,60
M330-50A	0,50	1,35	3,30	1,49	1,60
M530-50A	0,50	2,30	5,30	1,56	1,65
M530-65A	0,65	2,30	5,30	1,54	1,64

From the form of the $P/f = P/f\ (f)$ dependence (2) it follows, that there should exist two terms in the formula for loss density, related to hysteresis and eddy currents, respectively. For the description of quasi-static hysteresis term the Steinmetz formula was applied. Measurement datasets for lowest obtainable excitation frequency (5 Hz or in some cases 10 Hz) were used to determine the Steinmetz exponent.

It can be stated that in all cases the Steinmetz formula gave very good fitting results, despite some inevitable distortion introduced by eddy currents. The formula remained correct for the whole examined induction region, not just for the range 0,3-1,2 [T], as suggested by some authors [39-40]. An exemplary fitting is depicted in Fig. 2.

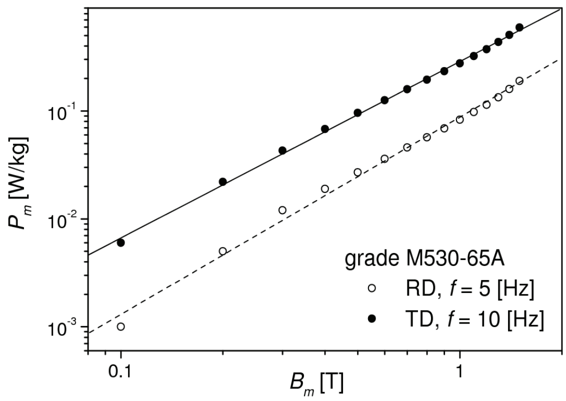

Fig. 2. An exemplary fitting to the Steinmetz law; RD- rolling direction, TD- transverse direction

Table 2 comprises the Steinmetz law fitting results for all examined grades of steel. Parameters I and J appear in the straight line equation $y = I + Jx$ obtained after expression of $Physt = Physt(f)$ dependence in the log-log scale. R is the correlation coefficient, SD is standard deviation, N denotes the number of data points used, whereas P is the probability to reject the correlation hypothesis. The values of Steinmetz exponent obtained from fitting for all examined steel grades are given in Fig. 3.

It can be noticed, that the Steinmetz exponent values for rolling direction are higher than for transverse direction for all examined steel grades. The presented values correspond to some extent to the value 1,6 reported in the literature.

Table 2. Steinmetz law fitting results for all examined steel grades

	M330-35A		M330-50A		M530-50A		M530-65A	
	RD	TD	RD	TD	RD	TD	RD	TD
I	-1,0658	-0,89642	-0,80429	-0,9543	-0,90403	-0,76512	-1,05664	-0,54108
uncertainty in I	0,01305	0,01542	0,0054	0,00411	0,00674	0,00713	0,01491	0,00675
J	1,83543	1,68573	1,72577	1,55208	1,63311	1,5832	1,82805	1,63587
uncertainty in J	0,03431	0,03947	0,01421	0,01052	0,01812	0,01876	0,03922	0,01775
R	0,99774	0,99673	0,99956	0,99972	0,99914	0,99909	0,99702	0,99924
SD	0,0436	0,04784	0,01805	0,01276	0,02405	0,02383	0,04983	0,02255
N	15	14	15	14	16	15	15	15
P	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001

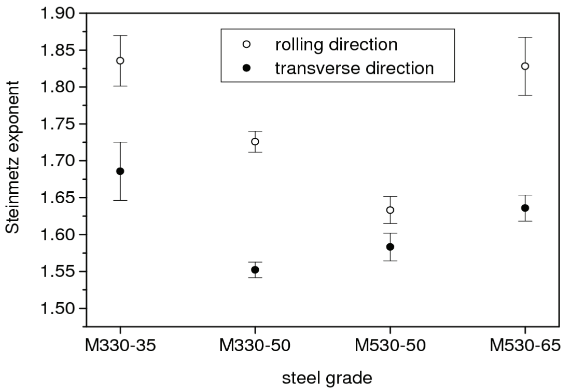

Fig. 3. Steinmetz exponent values

In order to determine how the loss term related to eddy current flow in different time- and space scales depends on maximum flux density, the appropriate loss values from measurements were subtracted $P_{dyn} = P_{total} - P_{quasi\text{-}static}$, where $P_{quasi\text{-}static}$ denotes loss values for lowest admissible excitation frequency. As there was no reason to get stick to the rigorous exponent value equal to 2, as envisaged in the formula for "classical" eddy current loss, the possibility whether the data might fit a power law was checked by expressing the values of P_{dyn} versus B_m in log-log scale.

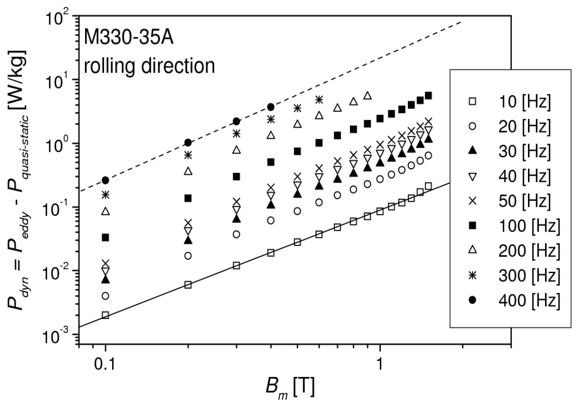

Fig. 4. Dependence of P_{dyn} term on Bm for M330-35A steel grade, rolling direction

It turned out that the transformed dependence $P_{dyn} = P_{dyn}(B_m)$ in all cases stayed close to straight line. Moreover for a given steel grade, the slopes of straight lines from fitting the transformed dependence $P_{dyn} = P_{dyn}(B_m)$ for different excitation frequencies were similar, cf. Figs. 4-5.

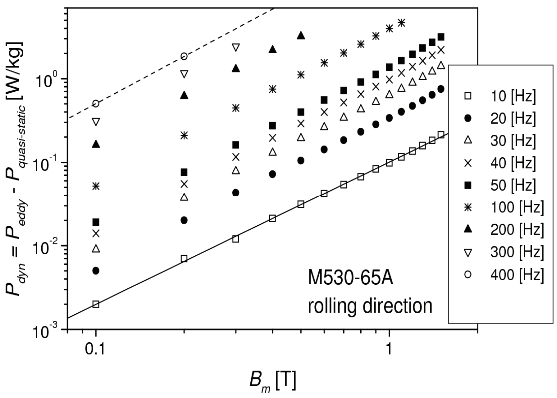

Fig. 5. Dependence of P_{dyn} term on B_m for M530-65A steel grade, rolling direction

The values of correlation coefficient in most cases exceeded 0,998, cf. Table II, whereas the probability values to reject the correlation hypothesis in most cases were lower than 0,001 (in individual cases the latter values were slightly larger, due mainly to insufficient number of data points). It allowed us to conjecture, that the examined dependence could be indeed be given as a power law. Notation used in Table II: K - the exponent in the examined power law $Pdyn = Pdyn\ (Bm)$; *n.a.* - not available, n.d. - no data, *unc.* - uncertainty. *N, SD* and *P* - meaning the same as discussed earlier.

It should be remembered, though, that for validation of the formula $P(B_m, f) = k_{hyst} B_m^J + k_{eddy} B_m^K f^{\alpha}$,measurement data referring to conditions only approaching the quasi-static ones were used, due to the limitations of measurement setup.

Conclusions

In the paper an approach to loss prediction in non-oriented steels sheets has been presented. The loss dissipated in conductive ferromagnetic material has been separated into two terms. For the description of the term related to quasi-static hysteresis phenomenon, the Steinmetz formula has been applied. The dependence of dynamic term related to eddy currents on flux density has been described as a power law. It is shown, that for the four steel grades under tests, differing in thickness and basic magnetic properties and examined both in rolling and transverse directions, the proposed description might be useful. Further research shall focus on model verification for other classes of magnetic materials.

Table 3. The results of fitting the dependence $P_{dyn} = P_{dyn}(B_m)$ as power law

grade	*f*	10 Hz	20 Hz	30 Hz	40 Hz	50 Hz	100 Hz	200 Hz	300 Hz	400 Hz
M330-35A RD	*K*	1,67751	1,79389	1,80453	1,81011	1,82322	1,83579	1,88271	1,9161	1,91614
	unc. K	0,02243	0,02411	0,02191	0,02301	0,0221	0,01806	0,0269	0,03513	0,02442
	R	0,99884	0,99883	0,99904	0,99895	0,99905	0,99937	0,99929	0,99933	0,99984
	SD	0,02851	0,03063	0,02784	0,02924	0,02808	0,02295	0,02377	0,02261	0,01104
	N	15	15	15	15	15	15	9	6	4
	P	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	1,62E-04
M330-35A TD	*K*	1,61014	1,64941	1,67356	1,67803	1,68339	1,71767	1,77803	1,82933	n.d.
	unc. K	0,0236	0,02098	0,02284	0,02062	0,01959	0,02138	0,03223	0,0309	n.d.
	R	0,99871	0,99903	0,99888	0,9991	0,99919	0,99907	0,99885	0,99943	n.d.
	SD	0,02861	0,02543	0,02768	0,02499	0,02374	0,02591	0,02848	0,01989	n.d.
	N	14	14	14	14	14	14	9	6	n.d.
	P	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	n.d.
M330-50A RD	*K*	n.d.	1,79338	1,8065	1,8057	1,82677	1,83976	1,86062	1,87295	1,86736
	unc. K	n.d.	0,01466	0,01762	0,01342	0,01753	0,00964	0,01728	0,01387	0,01151
	R	n.d.	0,99957	0,99938	0,99964	0,9994	0,99984	0,99978	0,99995	0,99998
	SD	n.d.	0,01863	0,02239	0,01705	0,02227	0,01168	0,01259	0,00627	0,00393
	N	n.d.	15	15	15	15	14	7	4	3
	P	n.d.	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	0,00392
M330-50A TD	*K*	1,67156	1,62896	1,62555	1,64589	1,64675	1,68782	1,77929	1,79449	1,8069
	unc. K	0,04148	0,02259	0,01683	0,01833	0,01528	0,01603	0,03025	0,02072	0,02123
	R	0,99633	0,99885	0,99936	0,99926	0,99948	0,99946	0,99942	0,99987	0,99993
	SD	0,05028	0,02738	0,02039	0,02222	0,01852	0,01943	0,01946	0,00937	0,00724
	N	14	14	14	14	14	14	6	4	3
	P	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	1,33E-04	0,00748
M530-50A RD	*K*	1,75933	1,72432	1,73572	1,75605	1,77069	1,78068	1,78383	1,77799	1,77113
	unc. K	0,02902	0,01834	0,01552	0,01551	0,01629	0,01241	0,01396	0,01819	0,02167
	R	0,9981	0,99921	0,99944	0,99945	0,99941	0,99976	0,99988	0,9999	0,99993
	SD	0,03852	0,02435	0,0206	0,02059	0,02163	0,01351	0,00898	0,00823	0,00739
	N	16	16	16	16	16	12	6	4	3
	P	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	1,05E-04	0,00779
M530-50A TD	*K*	1,61956	1,6072	1,6371	1,65437	1,66762	1,71062	1,756	1,77555	n.d.
	unc. K	0,0189	0,01267	0,01373	0,01343	0,01257	0,01232	0,01427	0,01609	n.d.
	R	0,99912	0,9996	0,99954	0,99957	0,99963	0,99974	0,99987	0,99992	n.d.
	SD	0,02402	0,0161	0,01745	0,01706	0,01597	0,01341	0,00918	0,00728	n.d.
	N	15	15	15	15	15	12	6	4	n.d.
M530-65A RD	*K*	1,70346	1,80045	1,81919	1,8329	1,84681	1,8567	1,85949	1,86717	1,88021
	unc. K	0,01292	0,01612	0,0153	0,0116	0,01303	0,01441	0,02528	0,02605	n.a.
	R	0,99963	0,99948	0,99954	0,99974	0,99968	0,99973	0,99972	0,9999	1
	SD	0,01641	0,02049	0,01945	0,01474	0,01655	0,01475	0,01396	0,00889	0
	N	15	15	15	15	15	11	5	3	2
	P	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	0,00888	<0,0001
M530-65A TD	*K*	n.d.	1,69856	1,71029	1,73091	1,74191	1,79299	1,85331	1,88429	1,91222
	unc. K	n.d.	0,02118	0,01889	0,01771	0,01669	0,0206	0,02155	0,02473	n.a.
	R	n.d.	0,99899	0,99921	0,99932	0,9994	0,99947	0,9998	0,99991	1
	SD	n.d.	0,02691	0,024	0,0225	0,02121	0,01967	0,0119	0,00844	0
	N	n.d.	15	15	15	15	10	5	3	2
	P	n.d.	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	0,00835	<0,0001

Acknowledgements
The work has been supported by the research grant N N510 702540 from the National Centre of Science. Stalprodukt S.A. is thanked for supplying the samples. The author acknowledges continuous support from the Management of the Electrotechnical Institute, Warsaw.

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