PROBLEMS WITH MAGNETIC MEASUREMENT OF 41CRMO4 STEEL

Tomáš Bulín

Doctoral Degree Programme (2), FEEC BUT

E-mail: xbulin01@stud.feec.vutbr.cz

Supervised by: Čestmír Ondrůšek

E-mail: ondrusek@feec.vutbr.cz

Abstract: This article deals with a problem of measuring a soft magnetic material with different geometrical dimensions. Steel 41CrMo4 was chosen as tested solid material. Two geometrical dimensions of this material were measured from the view of magnetic properties and compared each other. It is very difficult to determine proper commutation and hysteresis curve because eddy currents occur in every solid material.

Keywords: Magnetic measurement, losses, solid material, eddy currents.

1. INTRODUCTION

Magnetic measurement is not an easy task as it seems. Every difference of geometry dimensions gives various results. Similar results can be obtained on the samples composed of sheets with the same measuring method. But when it is desirable to measure solid material there are differences because of eddy currents. These currents are generally undesirable. Electric machines have worse efficiency due to the greater value of losses. Eddy currents can be restrained using sheets instead of solid material but sometimes it is necessary to use the solid material for example in high-speed induction motors with a solid rotor. It is desired to determine the correct magnetic parameters for the proper analytical design and subsequent simulation.

2. MAGNETIC MEASUREMENTS

2.1. TYPE OF MAGNETIC MEASUREMENTS

It is very important to know the magnetic properties of selected material because this knowledge is a prerequisite for the correct design of the electrical machine. The most suitable method for measuring of solid material is the inductive method, which is based on the principle of Faraday law of electromagnetic induction. Other measuring methods [1] are not so much suitable. For example some methods can be based on a change of material properties in presence of magnetic field. There are very small specimen and not enough volume to closure eddy-currents of the material. Induction law represents the following equation:

$$v_i = -N \frac{d\phi}{dt}, \qquad (1)$$

where v_i is induced voltage, Φ is magnetic flux and N is number of turns. Measurement of magnetic flux through the coil is based on formula $\phi = B \cdot S$, so it is necessary to know the size of the cross sectional area S. Then induced voltage can be easily measured. The growth of the vector magnetic flux density $\boldsymbol{B}$ causes the growth of the induced voltage v_i.

The calculation of magnetic field strength H_z from magnetizing current can be calculated according to equation:

$$H_z = \frac{N_1 \cdot I_1}{l_s}, \quad (2)$$

where N_1 is a number of turns of magnetizing windings, I_1 is magnetizing current and l_s is mean magnetic path length. Manufacturer of measuring instruments is using equation (1) and (2) as introduction to problem of magnetic measurement. Generally the secondary winding is wound closely on the test specimen so the air flux is insignificant over the range of magnetic field strength 0 to 4 kA/m. At higher values of magnetic field strength, an air flux correction should be applied. The amount of total core losses P_S in the specimen depends on hysteresis losses, eddy current core losses and the excess losses. Hysteresis and eddy current core losses are applied at low magnetic flux densities B approximately until 1.0 T. It is necessary to calculate with excess losses for higher saturation which is in the teeth of stator and rotor in electric machine. The equation for calculation of magnetic total core loss is:

$$P_S = P_h + P_c + P_e = k_h f B_m^2 + k_c f^2 B_m^2 + k_e (f B_m)^{1,5}, \quad (3)$$

where B_m is amplitude of AC flux component, f is frequency, k_h is hysteresis core loss coefficient, k_c is eddy-current core loss coefficient and k_e is excess core loss coefficient. The loss coefficients $k_{h,}$, k_c, k_e are constants for the conventional model and they are dependent on the material property. Amount of losses is changing with frequency f and/or flux density B_m. This equation is valid for materials under sinusoidal flux conditions.

2.2. MEASURED DATA

All measurements were carried out at the measuring station made by Magnet-physik Dr.Steingroever GmbH. The station consists of two devices called RemaCOMP and RemaGRAPH C-710. These devices are able to measure static hysteresis curve (for DC excitation) and dynamic hysteresis curves (for AC excitations). There is a signal generator connected to a power amplifier, which supplies current to the primary winding of the specimen. The field strength H can be calculated from the current and the magnetic path length l_m. The secondary induced voltage u_{i2} is proportional to the time change of the magnetic flux $d\phi/dt$. It is numerically integrated and then calculated flux density B. Difference between AC and DC measurement is only in use of another device but the specimen and winding is the same for both types of measurements. DC measurement is using a very small change of supply current so there must be special integrator like fluxmeter, which is a precision integrator for slowly variable signals because it calculates the flux density B [2].

41CrMo4 steel was chosen for measurement because this material is used for construction of solid rotors of high-speed motors. It is a very strong material with good mechanical properties. There is a lot of stresses due to extreme centrifugal forces in high-speed machines, which material has to withstand and it must have a good magnetic conductivity in the same time. Unfortunately, these parameters are difficult to find and then it does not have to be accurate. Two specimens in the shape of toroid were used for measurement. Geometrical dimensions are in Table 1:

	Larger	Smaller	
Outer diameter	120	44.3	mm
Inner diameter	100	38.1	mm
Height	10	3	mm
Primary winding	220	101	
Secondary winding	200	20	
Mass	267	9.07	g

Table 1: Geometrical dimensions of specimens

Magnetic measurement can be affected in different directions. For example the dimensions of the specimen has to be square. The magnetic measurement can be affected by temperature change and mechanical stress of specimen.

On the Figure 1 there can be seen comparison of hysteresis curves for a smaller sample for different frequencies. The area of hysteresis curves is increasing with higher frequencies too, due to eddy currents in the sample.

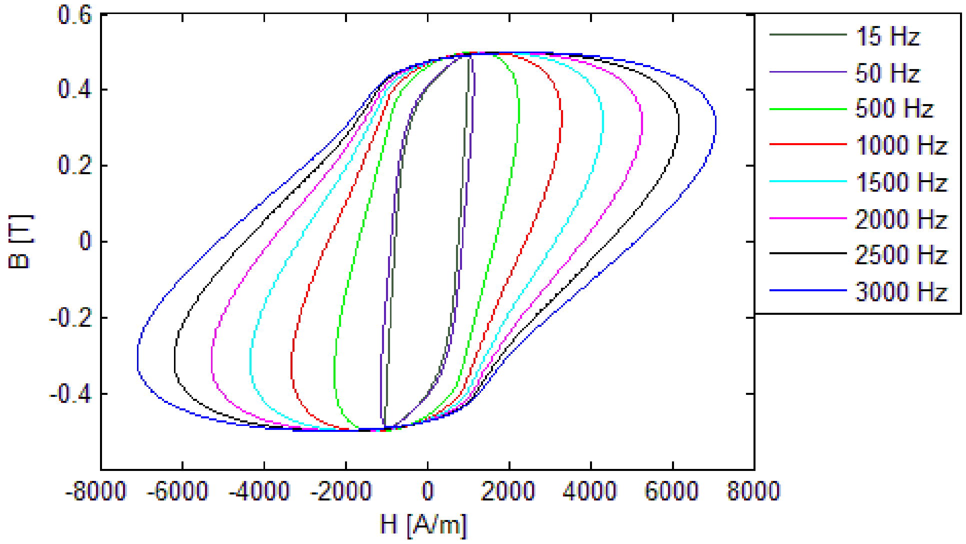


Figure 1: Comparison of hysteresis curves (smaller sample) for different frequencies

In the following graphs there can be seen how the value of magnetic losses *Ps* (Figure 2 and Figure 3) or permeability (Figure 4 and Figure 5) is changing in dependence on magnetic flux density.

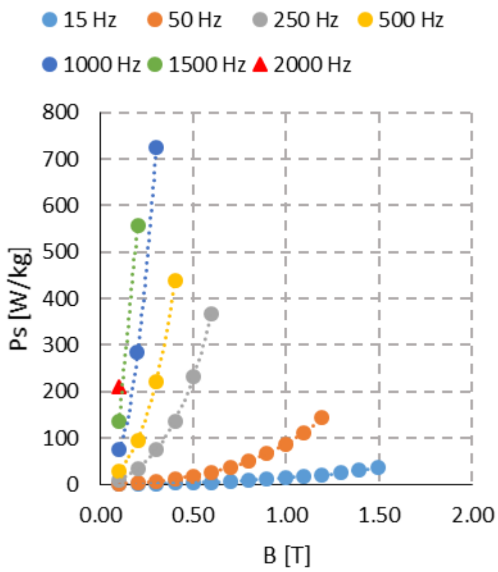


Figure 2: Dependency amount of magnetic losses on magnetic flux density Larger sample

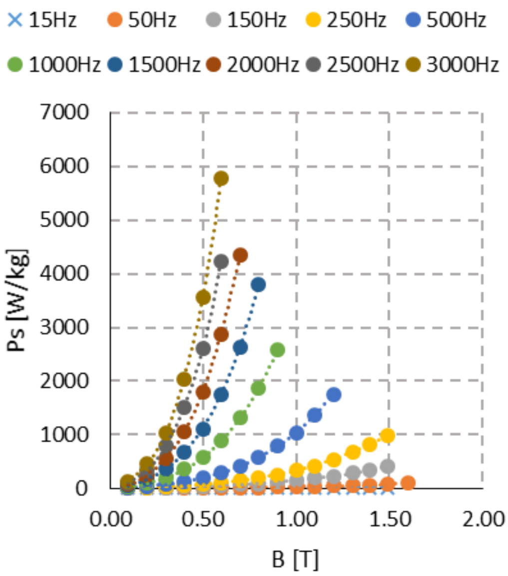
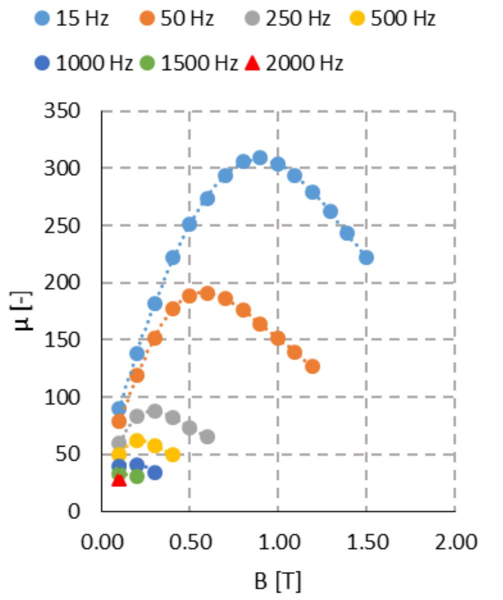


Figure 3: Dependency amount of magnetic losses on magnetic flux density Smaller sample



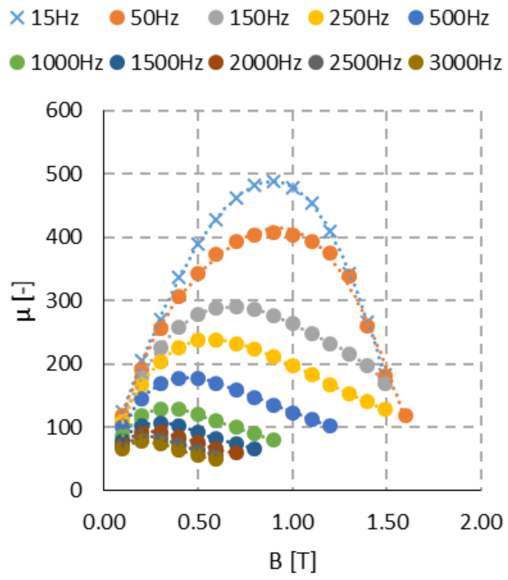
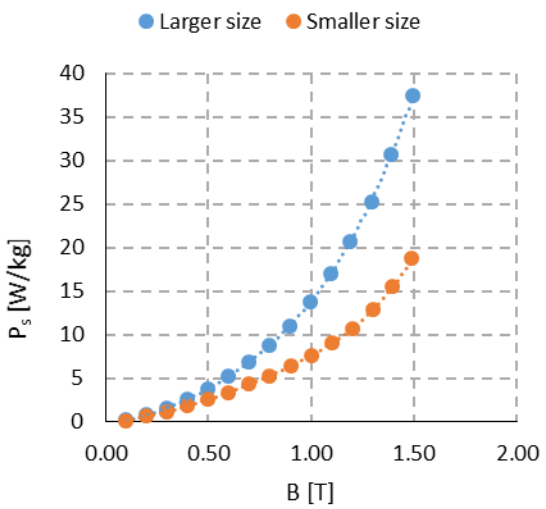


Figure 4: Dependency size of permeability on magnetic flux density Larger sample

Figure 5: Dependency size of permeability on magnetic flux density Smaller sample

Comparison of larger and smaller sample for magnetic losses (Figure 6 and Figure 7) shows that in the larger sample there is a greater amount of eddy current and due to this fact there are higher total magnetic losses.



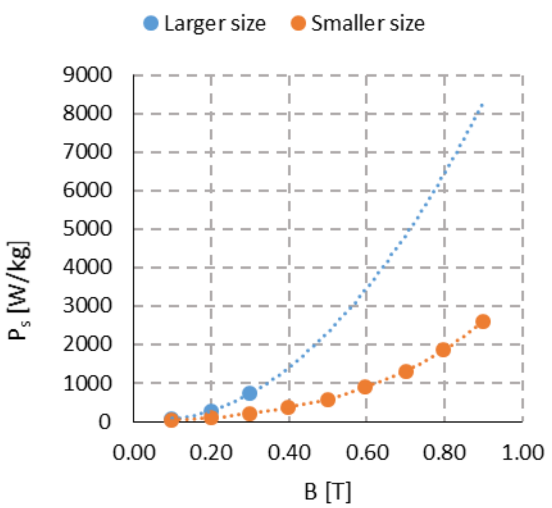


Figure 6: Comparison of magnetic losses at frequency 15 Hz

Figure 7: Comparison of magnetic losses at frequency 1000 Hz

Total magnetic core losses are rapidly exponentially increasing with magnetic flux density and frequency. The Larger sample could not be measured for the same excitation as a smaller sample because of measuring device limitation. But even for measured values excitation, there are significant differences between both samples. The curve of the total magnetic loss (Figure 7) depending on magnetic flux density was interpose at larger sample by the polynomial and estimated for higher excitation because of the better display.

After measuring the magnetic properties at frequency samples were measured with the quasi-static device too. This device has the advantage that measuring frequency is near to 0 Hz so there are no additional losses, which come from eddy currents. Comparison of quasi-static and AC measurement can be seen in Table 2. higher value of coercivity H_c represents larger area of hysteresis curve and consequently higher total magnetic core losses. Parameter H_c is dramatically increasing with the growth of supply frequency. Device which serves for magnetic measurement at 0 Hz is not able to measure total magnetic losses, so coercivity H_c is a better parameter to compare.

	Larger		Smaller	
	f = 0 Hz	f = 50 Hz	f = 0 Hz	f = 50 Hz
	H_c [A/m]	H_c [A/m]	H_c [A/m]	H_c [A/m]
B = 0.5 T	865	1668	664	875
B = 1.0 T	1097	3792	783	1340
B = 1.5 T	1275	-	881	2196

Table 2: Comparison quasi-static and AC measurement

In Table 3, there can be seen magnetic total loss *Ps* for different excitation and frequencies. The deviation between Smaller and Larger sample is significant and is increasing with both changing parameters. Even if the higher frequency (250 Hz) is only five times greater than fundamental frequency (50 Hz) deviation is larger by 138 % for investigated samples at 0.6 T.

	f = 50 Hz			f = 250 Hz	
	B = 0.2 T	B = 0.6 T	B = 1.2 T	B = 0.2 T	B = 0.6 T
	P_s [W/kg]	P_s [W/kg]	P_s [W/kg]	P_s [W/kg]	P_s [W/kg]
Larger	3.83	27	143	35	367.4
Smaller	2.27	13.4	47.5	15,7	108.3
Deviation	68.7 %	101.5 %	201.1 %	122.9 %	239.2 %

Table 3: Comparison of values of magnetic measurements

3. CONCLUSION

The magnetic measurement was performed on toroidal shape samples. The properties of the material were measured for different frequencies from 0 Hz to 2000 Hz. Unfortunately, it was not possible to measure high magnetic flux density at higher frequencies because of measuring device limitation. The differences are caused by different geometrical dimensions of samples and consequently generation of larger amount of eddy currents. The same results were expected at zero frequency, but coercivity *Hc* differs too and area of hysteresis curve is also greater for the large sample. Appropriate geometrical dimensions with respect to more precise results, which can be used as right input parameters of simulation, should be the subject of further investigation

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