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IMPACT OF MAGNETIC PARTICLES CONCENTRATION IN FERRO-OIL ON ITS MAGNETIC SUSCEPTIBILITY COEFFICIENT χ

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Abstract

The purpose of this article is to determine the effect of the concentration of magnetic particles in ferro-oil on the value of its magnetic susceptibility coefficient χ.

Determination of the flow and operating parameters of slide journal bearings lubricated with ferro-oils requires, inter alia, designation the first magnetization N and the magnetic induction B vector components, dependent on the magnetic properties of the lubricant. These properties may be expressed by the ratio of the magnetic susceptibility χ of lubricant. The fundamental problem lies in the inability to make direct accurate measurement of magnetic induction in the lubricating gap of slide bearing and its solution is to determine it on the analytical and numerical way. A key issue for the accuracy of such solutions is to obtain reasonably accurate values of magnetic susceptibility χ. This article attempts to determine these values and estimate their relationship with the concentration of magnetic particles concentration in ferro-oil being potential lubricant above-mentioned bearings.

In this paper, the authors present the characteristic of experimental test benches to determine the coefficients of the magnetic susceptibility. They present method of determining this value from obtained measurement data and analyse the impact of the magnetic particles concentration in ferro-oil on its magnetic susceptibility values.

Tests were performed for selected concentrations of magnetic particles in ferro-oil ranging: 2%, 4%, 6% and 8% and the tested ferro-oil was product from Unterensingen FerroTec Company (Germany) which is a mixture of colloidal mineral engine oil LongLife Gold Penzzoil class SAE 15W-40 with addition of Fe_3O_4 magnetic particles and a surfactant.

Keywords: *ferro-oil, magnetic particles concentration, magnetic susceptibility coefficient*

1. Introduction

This paper refers to the wider research project, which concerns the analysis of hydrodynamic lubrication of slide journal bearings by ferro-oils with different concentrations of magnetic particles. The analytical determination of the values of the lubricant's flow parameters such as its hydrodynamic pressure or velocity, as well as operating parameters represented by the lift force, friction force or coefficient of friction, requires inter alia, previous obtaining the appropriate values of magnetization vector components **N,** vector components of the magnetic induction **B** and the vector components of the magnetic field strength **H** also. All of these vectors are directly related to the magnetic susceptibility coefficient χ of the ferro-oil. Due to the inability to the accurate direct measurement of magnetic induction in the lubricating gap of slide, bearing the solutions of the above-mentioned components of vectors must be searched through analytical and numerical way. The study results previously obtained by the authors [1-3] clearly show that the accuracy of the results depends directly among others on the accuracy of the substituted values of the equations. If the values are closer to the real ones then their utilitarian value and susceptibility to the possibility of experimental verification is greater. Taking into account the necessity of a final verification of the analytical and numerical results by comparing them with the results of the actual experiment on the test bench, it is necessary previous obtaining; possibly correct values of magnetic susceptibility coefficient χ of ferro-oil.

2. The theoretical foundations

The magnetic field we may define as the force field acting on the free, moving electrical charges of atoms, as well as on anyone single body having a magnetic moment, regardless of its movement in the field. Quantity that characterizes the field regardless of the magnetic properties of the environment, in which it is dealt with, is a magnetic field strength vector **H**. This quantity is related to another basic quantity, which characterizes the magnetic field, but relatively to the magnetic properties of the medium, i.e. to the magnetic induction vector **B** by commonly known dependence:

$$\mathbf{B} = \mu\, \mathbf{H}, \tag{1}$$

where:
B – magnetic induction vector [T=N/Am],
H – magnetic field strength vector [A/m],
μ – absolute magnetic permeability of medium [H/m].

In practice, μ is a characteristic magnetic property of a medium body, and the most common, to allow comparison of different materials it is used as the multiplication of the relative magnetic permeability and the vacuum magnetic permeability, as shown:

$$\mu = \mu_r\, \mu_o\,, \tag{2}$$

where:
μ_r – relative permeability of medium [-],
μ_o – vacuum magnetic permeability = $4\pi\ 10^{-7}$ [H/m].

The nature of the relationship **B**=f(**H**) depends only on the magnetic properties of medium being under consideration. Substantially all of mediums subjected to an external magnetic field can be classified due to that relationship as materials with diamagnetic, paramagnetic or ferromagnetic properties. Tested and described in this paper ferro-oil ranks among the class of ferromagnetic materials. However, even here, is distinguished from other ferromagnetic materials due to its properties. These differences arise from the peculiar physico-chemical composition of the ferro-oils. In contrast to the classical solid ferromagnetic, ferro-oil is a colloidal mixture of the magnetic particles with a size of about 10 nm and base oil (mineral, in this case) in the presence of the addition of a surfactant, which prevent coagulation of the magnetically active particles. The composition of such has a significant importance in the context of consideration of its magnetic properties. Everyone single magnetic particle is isolated magnetic domain, which is oriented chaotically in oil. Now of the appearance of the external magnetic field the chaotic arrangement of each molecule is oriented in the direction and sense of the force lines of the field. Also, of course, these single domains are not "enlarged" as is the case in solid ferromagnetic, but only rotate to target under the action of a magnetic field. This is due to the fact that these particles do not directly contact each other and do not have to compete with each other in a confined volume of body material as it is in solids. Separated from each other, it can freely rotate in the direction of the force lines of the external magnetic field. Also in contrast to the solid ferromagnetic, ferro-oil can't be constant magnetized and at the disappearance of the impact of the external magnetic field returns to the magnetic neutrality which reveals by random orientation of the magnetic moments of individual molecules [7]. For this reason so characteristic phenomenon of ferromagnetism as hysteresis, has no place in the case of ferro-oils. It should also be noted that ferro-oils become relatively fast magnetic saturated compared to the solid ferromagnetic, as opposed to them don't need to overcome the forces due to the complicated structure of the domain. Initially, for low values of magnetic field strength, show clear anisotropic magnetic properties. For sufficiently large values of magnetic field strength of the external field, the magnetization vector **N**, which is the direction of the resultant magnetic moment of the substance, in the moment of magnetic saturation coincides completely with the direction of activities of external magnetic field strength.

It can be successfully assumed [6] that the magnetic susceptibility of ferro-oil resulting from the vector equation which binding magnetization vectors **N** with magnetic field strength vector H.

$$\chi = \mathbf{N}/\mathbf{H}, \tag{3}$$

where:
N – magnetization vector [A/m],
χ – magnetic susceptibility of medium [-],
in a situation of fully magnetic saturation can be treated as a scalar.

The values of the magnetic susceptibility χ depend mainly on the particular physicochemical properties of concerned ferro-oil, including the size and number (concentration) of magnetic particles, as well as the size of the magnetic moment, the type and direction of magnetic field and temperature, i.e., the values of which depend on coefficients in the Curie-Weiss equation:

$$\chi = C/T - T_C, \tag{4}$$

$$C = n\mu^2/3k_n. \tag{5}$$

where:
C – Curie constant [K],
T – temperature [K],
T_C –Curie temperature for ferromagnetic [K],
n – concentration of atoms.

It can be assumed as [8] that dependence of binding vectors of magnetic induction B, the intensity of the magnetic field H and the magnetization N for ferro-oils expressed by the following relationship:

$$\mathbf{B} = \mu_o (\mathbf{H} + \mathbf{N}),\ \mathbf{N} = \mathbf{H}\chi, \tag{6}$$

so,

$$\mathbf{B} = \mu_o \mathbf{H}(1 + \chi). \tag{7}$$

3. The test bench's and ferro-oil's characteristics

In the present study, has been measured the value of magnetic induction B in samples of ferro-oil mixture constituting colloidal mineral engine oil LongLife Gold of Penzzoil Company, which viscosity grade SAE 15W-40 with Fe_3O_4 magnetic particles and a surfactant. Studied ferro-oil is manufactured by FerroTec in Unterensingen (Germany). The percentage of the magnetic particles (by volume) in the tested samples of ferro-oil was 8%, 6%, 4% and 2%, and their average diameter was 10 nm. Surfactant content by volume accounted for approximately 15% Vol. Surfactant name has not been specified by the manufacturer, as this is his trade secret. For the purpose of offsetting 4% and 2% samples, which were made by diluting original 8% samples created by the manufacturer, was added 25% sodium hydroxide four-methylammoniumchloride $(CH_3)_4NOH$ as a surfactant replacement.

Research has been done on two independent measuring stations. The first of these measurement systems consist of an amplifier and the coils with a steel core. The distance between the arms of the core was 72 mm. Changes in the intensity of the magnetic field were carried out discreetly by changes on the power supply current with step 0.2 A. The advantage of the described arrangement was the possibility to obtain a stable, uniform distribution of magnetic field intensity in the area between the arms of the core. Drawback was the relatively small value of the current realizable in this collaborative arrangement of power supply and coil. AC current range was 5 A, which allowed for the achievement of the magnetic induction up to 120 mT. The construction of the measuring system is presenting in Fig. 1.

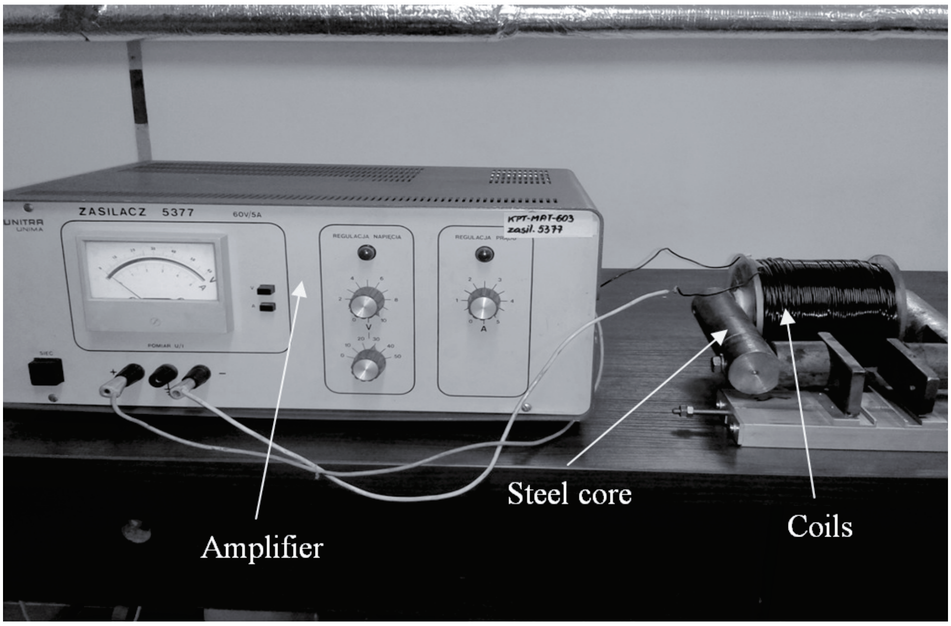

Fig. 1. Construction of the 1-st testing bench

The construction of the second measuring system presents the following Fig. 2.

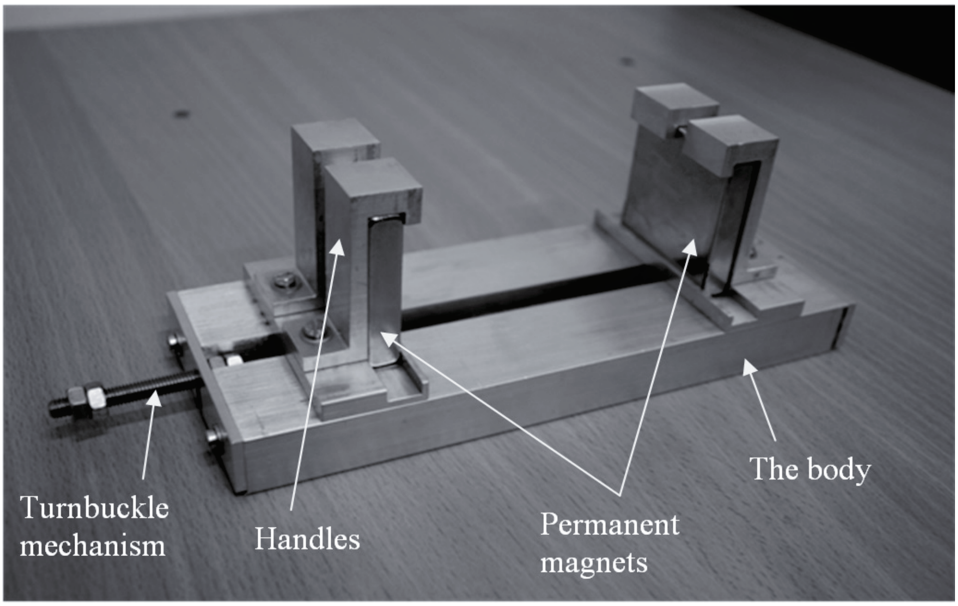

Fig. 2. Construction of the 2-nd testing bench

The second measurement systems accounted own designed and constructed structure consisting of the two permanent neodymium magnets with dimensions of 50x50x10 mm, placed in a moving jaws. Magnetic spacing change was implemented by means of a mechanism of “turnbuckle”. The accuracy of spacing changes was 0.1 mm, and the range of possible changes was 20-100 mm. All elements of the test bench have been done with non-magnetic materials - aluminum and brass. The advantage of this system was the possibility of obtaining a much higher value of magnetic induction, however, a homogeneous distribution of the field was limited to a small area in the geometrical middle of the arrangement of permanent magnets. Moreover, a small space measuring prevented measurements at some of orientations of the sensor probe. In practice, this meant that valuable results of the measurements were limited to the range of values where obtained were full magnetic saturation of ferro-oil samples.

The samples tested ferro-oil were placed in a container of plastic material, whose structure preventing "pulling" the oil through the ferro-magnetic field and enable stable, repeatable fixing of the probe. Induction measurements have been made using the magnetic field meter Magnetic Sensor Smart SMS 102 using the Hall effect. The ongoing measurement accuracy was 0.1 mT. Placed below Fig. 3 presents the described instrument with the measuring probe attached to it.

Fig. 3. Hall Effect Meter SMS102, together with the measuring probe

4. Experimental researches

Experimental studies on both test benches have been carried out in two steps. In the first one there were determined characteristic H=f(l) of the magnetic field strength H in the geometrical centre of the measuring system depending on the separation of permanent magnets (test bench 2), or changes the current value (test bench 1). There have been adopted some crucial assumptions, namely assume that the magnetic field in the area under consideration is fixed, uniform and unidirectional, oriented perpendicular to the face of the magnet or face of the arms of cores. Furthermore, the simplification was adopted - assumed that the vectors of magnetic induction B and the magnetic field strength H in the air are parallel to each other and have the same sense. In fact, the air is paramagnetic, but the weakest of the encountered in nature, with the relative permeability of μ_r=1.00000037. In the second step was carried out analogous measuring the magnetic induction B at the same point in space and for the same value of spacing magnets or values of current, but in the presence of oil samples with ferro-magnetic particles with the chosen concentrations. The following Fig. 4 and 5 present the obtained results.

Results obtained in the first of the described test benches allowed identifying the value of the magnetic field strength at which the complete magnetic saturation of the ferro-oil samples has been obtained. This area fell on the value of the field strength H approximately 80,000 A/m. Slightly lower values related to the probes with smaller concentration of magnetic particles, bigger - greater concentration. It has been accepted that only above those values the intensity of magnetization vector field **N** of ferro-oil has the same direction and sense as the vector of magnetic field strength **H**. These results became the starting point for the measurement at the second test bench. Credibility and accuracy of the results required the attainment of full magnetic saturation of the sample. With a greater distance between the magnets, impact of anisotropy of ferro-oil falsifies the obtained results, on account of the method of calculation. The obtained maximum values of ferro-magnetic susceptibility χ oil ranging from 0.0928 for a sample of 2% to 0.165 for a sample of 8% correspond well with the results for which the authors encountered in the literature include in [4, 5, 8] and which were by the Langevin curve method. Also the same shape of characteristics χ=f(H) in this area are compatible with the assumed ones.

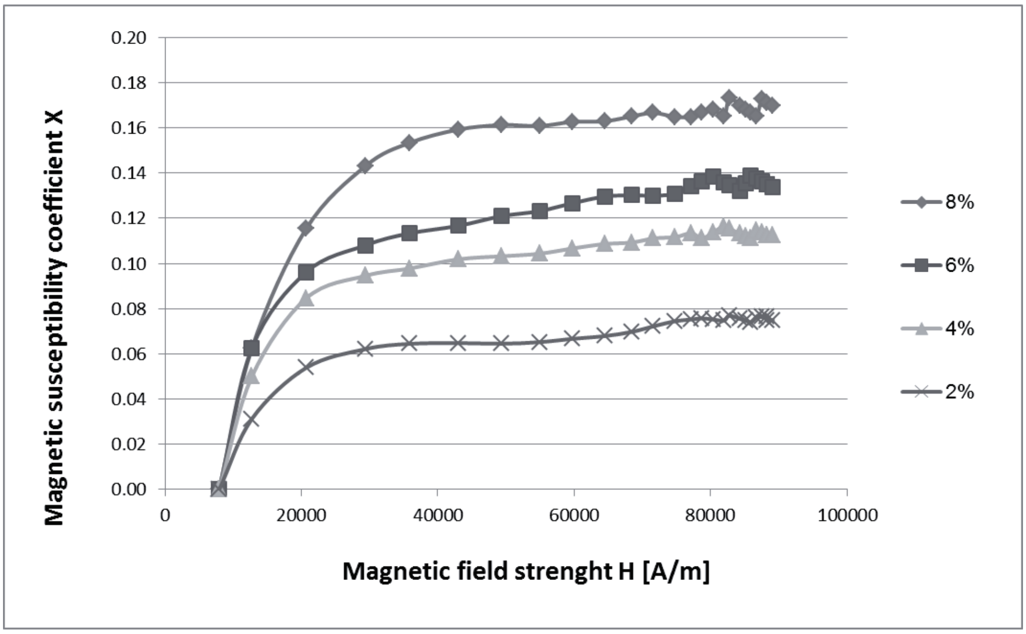

Fig. 4. Characteristic χ=f(H) for the studied ferro-oils obtained at test bench 1

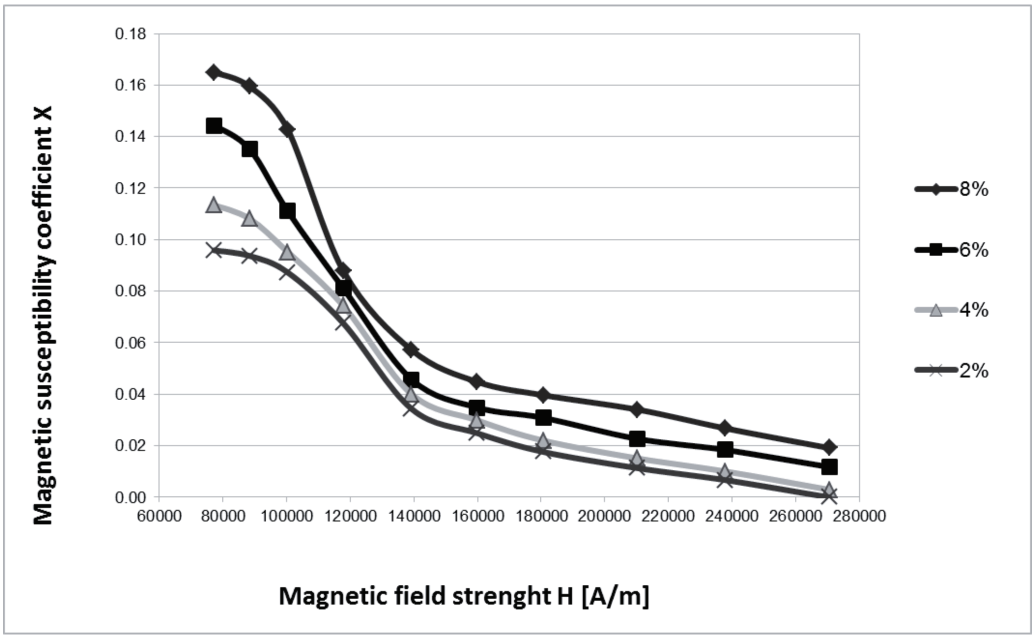

Fig. 5. Characteristic χ=f(H) for the studied ferro-oils obtained at test bench 2

3. Observations and conclusions

The purpose of this study was to determine the characteristics of changes in the magnetic susceptibility χ of the value of the magnetic field strength for ferro-oils samples with different concentrations of magnetic particles. Used a simplified measurement method allowed to obtain satisfactory results in terms of both full magnetic saturation of the samples and when the saturation was partial.

On the basis of results, it can be concluded that there is a correlation between the concentration of magnetic particles in the tested ferro-oil and the value of its magnetic susceptibility. With the increase in the concentration also increasing susceptibility value. Each additional 2% of the concentration of magnetic particles revealed approximately 15% increase in the magnetic susceptibility values of ferro-oil.

In addition, we also pay attention to the fact that in the whole range of the study there was an increase the induction of the magnetic field B in samples of ferro-oil, compared to measurements carried out for the reference conditions - without the sample. The size of the observed growth of ΔB ranged from 1% even up to 13%. The largest relative increases related to values in terms of the ferro-oil's samples reached a state of complete saturation. Also, in this case, the relationship between the growth of induction and the concentration of magnetic particles has been observed. If the higher particle concentration was, the increments Δ B induction also increased.

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