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THE INFLUENCE OF SELECTED FACTORS ON AXIAL FORCE AND FRICTION TORQUE IN A THRUST BEARING LUBRICATED WITH MAGNETORHEOLOGICAL FLUID

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Key words:

magnetorheological fluid, thrust bearing, axial force, friction torque

Słowa kluczowe:

ciecz magnetoreologiczna, łożysko wzdłużne, siła normalna, moment tarcia

Abstract

Magnetic fluids belong to the class of materials in which rheological properties can be controlled by magnetic fields. Magnetic fluids are suspensions of ferromagnetic particles in a carrier fluid, and the magnetic field can change their internal structure. This phenomenon is fully reversible, almost instantaneously.

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Of the two basic types of magnetic fluids, i.e. ferrofluids and magnetorheological fluids in the field of applications in systems with controlled operating parameters, magnetorheological fluids have mainly been applied. They are characterized by the ability to change their rheological characteristics in a wider range compared with ferrofluids.

This paper is focused on presenting the results of experimental studies conducted on a laboratory stand designed to study thrust bearings lubricated by magnetic fluids.

The influence of selected factors is analysed using the values of axial force and friction torque in the friction zone lubricated by magnetorheological fluids. Factors, such as the type of magnetic fluid, the rotational speed of the bearing, the height of the working gap, and the value of magnetic induction, are taken into account.

Application of magnetic fluids in bearing engineering

The most preferable operating condition of bearings, from the viewpoint of minimizing the friction losses and maximizing durability, is to achieve fluid friction. In typical applications, the lift force that tends to separate the elements of a bearing is formed by a hydrostatic or hydrodynamic pressure. In the case of hydrodynamic bearings, the main problems connected with ensuring optimal working conditions are the suitable shape of the sliding surface, the method to bring grease in the friction zone, material selection, dynamic viscosity change as temperature changes, and the control of bearing operation parameters at variable loads. Maintaining relatively constant lubricating film thickness, which provides the high stiffness of the bearing, is possible through the use of suitable flow regulators, for example **[L. 6]**. Controlling the operation of conventional hydrostatic bearings by changing the flow rate of the lubricant is a concern while building complex systems that often break down.

Application as a lubricant fluid with controlled rheological properties provides the opportunity to develop new constructions of friction pairs **[L. 13]**. Magnetic fluids may allow the construction of some types of bearings to be simplified and enable effective, fast, and precise control of the system with a significantly shorter response time and higher stiffness than is the case in conventional solutions. Another argument is the ability to shape the geometry of the bearing in more configurations than conventional bearings, keep the magnetic fluid in a fixed position, and control the direction and flow rate through the magnetic field.

An important aspect is the ability of the magnetic fluid to generate a normal force in the direction of the magnetic field intensity vector, which can be another source of load in the bearing system, in addition to the hydrodynamic and hydrostatic force. In this article, only this component of the lift force will be analysed.

The test results of a hydrostatic bearing lubricated by magnetic fluid are shown in the publication **[L. 7]**. It has been shown that the use of MR fluids as a lubricant allows high stiffness of the bearing to be obtained regardless of the height of the bearing gap. The publication **[L. 8]** presents the results of a thrust bearing lubricated by magnetic fluid with no external feed pump. The load capacity of the bearing was achieved by a self-sealing effect. This effect is associated with the ability to hold a magnetic fluid in a predetermined position through the magnetic field. This is caused by the appropriate geometry of the bearing surface. This effect retains the flow of the magnetic fluid out of the bearing gap as a result of the occurrence of a magnetic barrier, which counteracts the movement of the magnetic fluid. This barrier is a result of a local increase or decrease in magnetic induction similar to magnetic fluid seals. Another phenomenon highlighted in **[L. 9, 10, 11]** is the generation in the magnetic fluid of additional pressure due to the interaction of the magnetic field gradient. The result is an additional buoyancy force.

When selecting a magnetic fluid for application in the thrust bearing, a number of factors should be taken into account. In addition to the parameters describing the typical lubricant, such as lubricity, corrosion properties, and work at high temperatures, the magnetic fluid used in the friction zone should allow a wide range of the rheological properties to be obtained due to changes in the magnetic field intensity. It is also important that the magnetic fluids have the ability to generate the appropriate value of the normal force due to the magnetic field.

The test stand

The research experiments of the thrust bearings lubricated with magnetic fluids were performed at the Department of Machine Design and Technology on a test stand specially adapted for this purpose **[L. 12]**.

The scheme of the research stand is presented in **Fig. 1b**. On the support frame is an axial drive system, consisting of a linear servomotor (1). An essential part of the measurement system is the torque and axial force transducer (2) on which the rotating plate bearing is mounted (4).

The scheme of the test chamber (3) for the tested bearing is shown in **Fig. 1c**. The magnetic fluid (5) is between the flat rotary plate (4) and the core of the electromagnet (7). The value of the magnetic field inside the fluid is controlled by the current value in the coil of the electromagnet (8). A magnetic circuit is closed by the lower and upper part of the test chamber (6). Elements (6 and 7) are made of a ferromagnetic material. The rotating plate is made of a material with paramagnetic properties. Its diameter is d_k = 58.5 mm, while the electromagnet coil is d_r = 45 mm. The height z = 9 mm. The height of the bearing gap h is adjustable, and its value depends on the type of tests. This height is determined with an accuracy of ± 1 μm. The number of coil turns is

N = 1175. The current value in the coil of about 5A can generate magnetic induction of about 0.7 T in the MR fluid. In the core of the electromagnet and in the lower and upper parts of the test chamber, there are coolant orifices through which the coolant fluid flows. This provides the temperature stabilization of the test chamber.

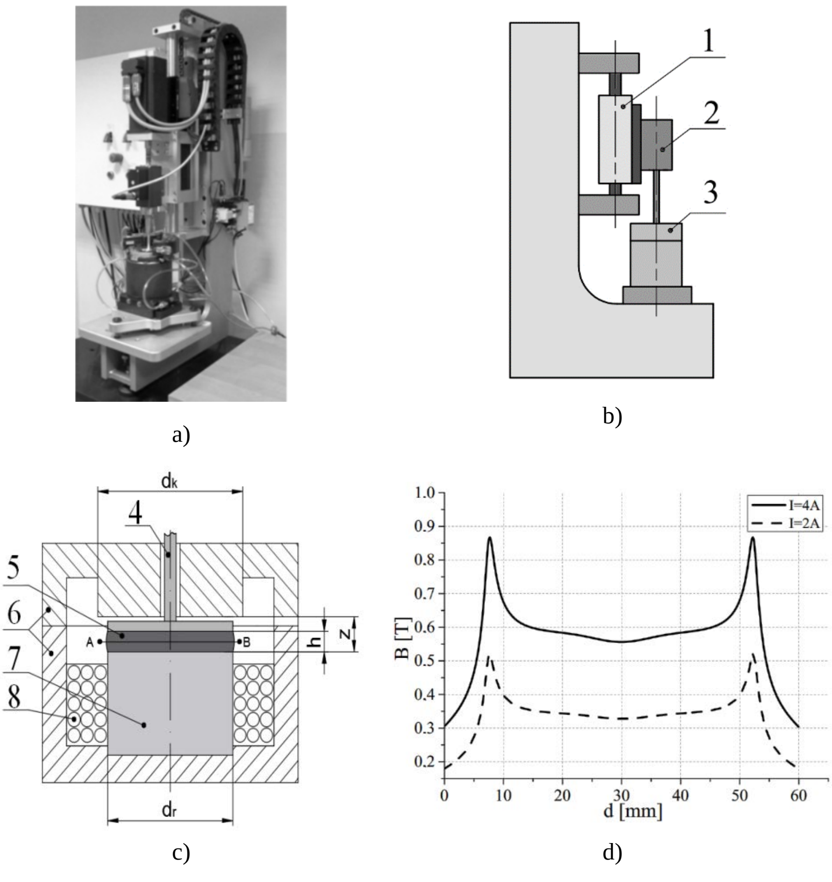


Fig. 1. (a) General view of the test stand, (b) scheme of the test stand, (c) scheme of the test chamber, and (d) distribution of the magnetic induction in the gap of the bearing

Rys. 1. a) widok ogólny stanowiska, b) schemat stanowiska, c) schemat komory badawczej, d) rozkład indukcji magnetycznej w szczelinie roboczej łożyska

Figure 1d shows the distribution of magnetic induction in the bearing for the lines between Points A and B. Magnetic induction is not a constant value. On the edge of the core, there is a local increase in the value. This provides the effect of self-sealing. In turn, in the axis of the electromagnet core, there are local decreases in magnetic induction due to the orifice present in the upper part of the test chamber.

Test method

The study was conducted for four magnetorheological fluids. Due to the fact that there are no MR fluids dedicated for work in thrust bearings, two fluids (Basonetic 2040 Basonetic 5030) manufactured by the BASF Corporation **[L. 15]** and two (MRF-122EG MRF-122EG) manufactured by the LORD Corporation **[L. 16]** were selected. Their physical properties are shown in **Tab. 1**.

The selected MR fluids can be divided into two groups. The first concerns the different dynamic viscosity values measured for the value of magnetic induction equal to zero (B = 0 T) at a shear rate of 100 1/s. The MRF-122EG and Basonetic 5030 fluids have a significantly lower value of this parameter compared with the MRF-140CG and Basonetic 2040 fluids. A low dynamic viscosity value primarily indicates the low dynamic viscosity of the carrier fluid, which, in the absence of the magnetic field, has a crucial impact on the rheological properties of the fluid.

The second group concerns different values of saturation magnetization. Two of the selected fluids (MRF-122EG and Basonetic 2040) have approximately half the saturation magnetization values compared with the remaining two MR fluids (MRF-140CG and Basonetic 5030).

Table 1. Selected properties of the studied magnetorheological fluids
Tabela 1. Wybrane właściwości badanych cieczy magnetycznych

No.	MR fluid	Density	Saturation magnetization	Zero field viscosity
		g/cm^3	kA/m	mPa·s (B = 0 T, t = 25°C, = 100 s^{-1})
1	MRF-122EG	2.38	361	203.4
2	MRF-140CG	3.54	698	1569.1
3	Basonetic 2040	2.47	424	1075.7
4	Basonetic 5030	4.12	791	582.9

The study was conducted for linearly increasing rotation speed from 0 to 150 rpm with angular acceleration $\varepsilon = 0.349$ rad/s^2. Due to the lack of constant magnetic induction in the MR fluids, the comparison value for the test was the average value of the magnetic induction occurring between the length 15 and 45 mm (**Fig. 1b**). All the tests were carried out at 25°C. The temperature stability was ensured by the cooling system mentioned in Section 2.

The aims of the studies were to analyse the impact of such factors as working gap height “h”, the type of MR fluid, the value of the magnetic induction on the value of the normal force (along the axis of the rotating plate), and the friction torque in bearings lubricated with MR fluids.

RESULTS

Comparison of fluids

Experiments were performed for four MR fluids with the linear ramp of rotational speed n = 0-150 rpm, in the constant magnetic induction B = 0.3 T, and constant gap height h = 0.5 mm. The volume of the sample was 0.8 ml. The results are shown in **Fig. 2**.

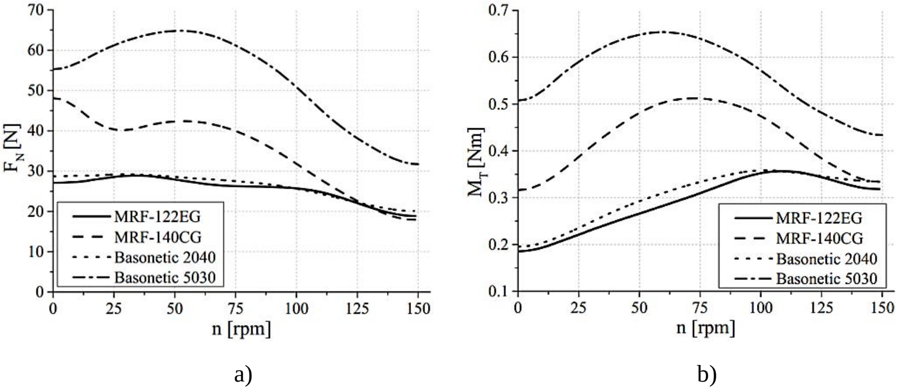


Fig. 2. Measurement results for different MR fluids: a) normal force, b) friction torque
Rys. 2. Wyniki badań wybranych cieczy MR: a) siła normalną w funkcji prędkości obrotowej łożyska, b) moment tarcia w funkcji prędkości obrotowej łożyska

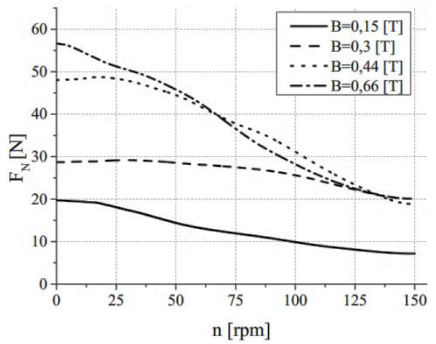
The variation of both measured parameters, in all analysed cases, has a similar course. In the first phase, the increase in the parameter occurs, and after reaching the maximum, the value decreases. The rotational speed at which the maximum occurs is lower when the density of the tested fluid is higher (**Tab. 1**). This is probably due to an inertial force of fluid being thrown out of the area of the bearing's working gap.

The highest values of force and torque were obtained for the fluid with the highest value of saturation magnetization and the largest volume fraction of particles (Basonetic 5030). In addition, high values of torque were also observed for MRF-140CG. Due to the high movement resistance, these two fluids were omitted from further analysis. The most advantageous conditions, due to the low friction torque and low variability of the normal force, were registered for the MRF-122EG and Basonetic 2040 fluids.

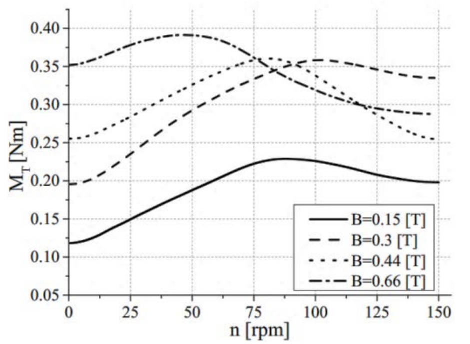
Analysis of the effect of magnetic induction

Figure 3 shows the variation of the force and torque as a function of rotational speed for Basonetic 2040 (**Figs. 3a, b**) and MRF-122EG (**Figs. 3c, d**) obtained at different values of magnetic induction.

In the area of lower speeds, higher friction torque and normal force are observed for higher values of magnetic induction. However, no significant differences between the examined fluids were found in the course of the variation of friction torque.



a)



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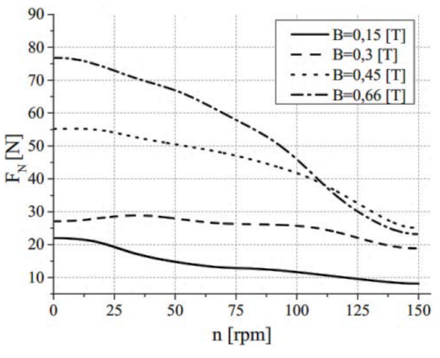

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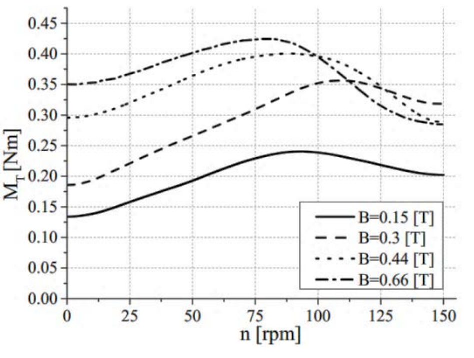


d)

Fig. 3. Measurement results for different magnetic induction: a) normal force for Basonetic 2040, b) friction torque for Basonetic 2040, c) normal force for MRF-122EG, d) friction torque for MRF-122EG

Rys. 3. Wyniki badania wpływu indukcji magnetycznej na: a) siłę normalną (Basonetic 2040), b) moment tarcia (Basonetic 2040), c) siłę normalną (MRF-122EG), d) moment tarcia (MRF-122EG)

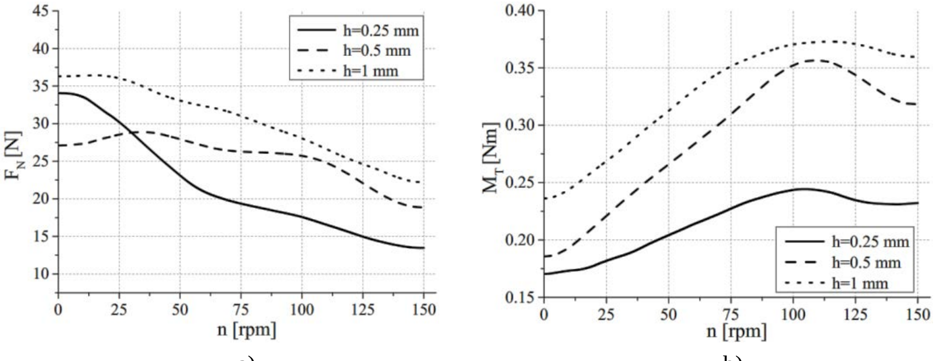
With the increase in speed, a decrease in the normal force is observed. In the case of magnetic induction of 0.15 T and 0.3 T, the values of the force for both fluids are similar, while there are significant differences between the fluids for

0.44 and 0.66 T. Changes in magnetic induction in this range for Basonetic 2040 results in an increase in normal force no more than 5 N. In turn, for MRF-122EG, the same increase in magnetic induction causing an increase in force was recorded up to 20 N. Attention should be paid to the fact that higher force values were obtained for MRF-122EG, although Basonetic 2040 has a higher saturation magnetization value. This is probably because Basonetic 2040 was prepared based on oil with a higher viscosity, where:by the particles contained in the fluid have a greater resistance to movement, which significantly affects the dynamics of forming their chain-like structures. Due to the higher normal force, further analyses were carried out with the MRF-122EG fluid.

Analysis of the effect of the gap height

In the next step of the studies, the effect of gap height on the bearing working conditions was examined. For testing, due to the previously obtained results, the MRF-122EG fluid was selected. Tests were carried out for three different gap heights, h = 0.25, 0.5 and 1 mm. For each of the analysed cases, the corresponding volumes of fluid are given as, respectively, v = 0.4, 0.8, and 1.6 ml. Tests were performed on a constant value of the magnetic induction B = 0.3 T.

In **Fig. 4**, the results of normal force and bearing torque measured for different gap heights are presented. As in the earlier stages of research, a decrease in force was observed with increasing rotational speed. Generally, higher forces were obtained for larger gap height. Only in the case of the speed range 0 to 30 rpm, for the gap of 0.25 mm, was force greater than for the gap of 0.5 mm. This may be due to inaccuracies connected with applying a small volume of the sample for a narrower gap.



a) b)

Fig. 4. Measurement results for different gap heights: a) normal force, b) friction torque

Rys. 4. Wyniki badań wpływu wysokości szczeliny łożyska „h" na: a) zależność siły normalnej od prędkości obrotowej łożyska, b) zależność momentu tarcia od prędkości obrotowej łożyska

The registered course of friction torque is similar to those obtained in previous studies. The reduction in gap height results in reduced resistance to motion in the bearing.

Conclusions

Influencing an oriented magnetic field onto MF fluid causes the formation of normal force, which may increase the capacity of the bearing. The value of this force depends significantly on fluid properties and rotational speed. Basonetic 5030 and MRF-140CG fluids demonstrate high values of saturation magnetization, but are unsuitable for use in bearing engineering due to the significant values of friction torque.

The value of magnetic induction significantly affects the normal force and friction torque.

Increased speed causes a decrease in the normal force and generally increases friction torque.

The possibility of obtaining a relatively large gap height, as well as the limited impact of its value at the normal force, can provide previously unseen possibilities for the design of bearings lubricated with MR fluids.

Due to the relatively high density of MR fluids, attention should be paid to the need to consider the phenomena associated with the presence of mass forces during design. The phenomenon of MR fluid ejection from the working gap of the bearing was observed. In addition, impacts associated with the centrifugal forces causes of such phenomena can be traced back to the uneven distribution of the magnetic field in the bearing gap.

Bearings lubricated with magnetic fluids can exhibit increased movement resistance in relation to the operation of conventional bearings. In the case of no magnetic field, the value of viscosity (in the range 0.2 to 1.5 Pa·s, see **Tab. 1**) allows the examined MR fluids to be classified as typical lubricants. However, in the case of higher values of magnetic field, friction in the bearing may reach significant values. In the performed experiments, the observed coefficient of friction is at levels of 0.2 to 0.8.

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Streszczenie

Ciecze magnetyczne należą do klasy materiałów sterowalnych. Fizykalnie stanowią one zawiesinę cząstek o właściwościach ferromagnetycznych w cieczy nośnej. Oddziaływanie polem magnetycznym na tego typu substancje skutkuje zmianą ich struktury wewnętrznej, a w efekcie makroskopowym w pełni odwracalną, niemal natychmiastową zmianą właściwości reologicznych.

Spośród dwóch podstawowych typów cieczy magnetycznych, tj. cieczy ferromagnetycznych i magnetoreologicznych, w obszarze zastosowań w układach o sterowanych parametrach pracy znalazły zastosowanie przede wszystkim ciecze magnetoreologiczne. Charakteryzuje je możliwość zmiany ich charakterystyk reologicznych w bardzo szerokim zakresie, co w połączeniu z łatwością generowania i sterowania polem magnetycznym stwarza znaczne możliwości zastosowania tego typu substancji w układach o kontrolowanych parametrach pracy.

W artykule przedstawiono wyniki badań eksperymentalnych przeprowadzonych na stanowisku laboratoryjnym przeznaczonym do badania wzdłużnych łożysk ślizgowych smarowanych cieczami magnetycznymi. Analizie poddano wpływ wybranych czynników na wartość siły osiowej oraz momentu oporu ślizgowego węzła tarcia smarowanego cieczą magnetoreologiczną. Wzięto po uwagę wpływ takich czynników jak rodzaj cieczy magnetycznej, prędkość obrotowa łożyska, wysokość szczeliny roboczej i wartość indukcji pola magnetycznego.