Magnetic field in the core of a magnetic fluid seal taking magnetic structural elements into account

A V Radionov¹, A D Podoltsev², A A Radionova¹
¹LLC Ferrohydrodynamica, Mykolaiv, Ukraine
²NASU Institute of Electrodynamics, Kyiv, Ukraine

E-mail: ferrohydrodynamica@gmail.com

Abstract. According to the results of the finite element analysis of the magnetic field of the liquid metal seal designed to protect the bearing assembly from external aggressive influences, it is shown that its mounting directly on the bearing shield having magnetic properties leads to an increase in magnetic fluxes of scattering and to a decrease in the peak value of magnetic induction in the working gap from 1.6 T to 1.1 T, i.e. to a decrease of 31%. The use of a non-magnetic insert between the seal and the bearing assembly allows this induction to be increased. The dependence of this induction on the thickness of the insert is given, which makes it possible to choose its rational value when installing the seal. It is shown that the use of an additional permanent magnet located in the area of this insert allows one to increase the peak value of magnetic induction in the working gap from 1.3 T to 1.75 T and, as a result, improve the performance of the seal.

1. Introduction

Ensuring reliable and environmentally friendly operation of technological equipment containing rotating elements often requires guaranteeing the complete tightness of technical systems. By traditional methods, it is practically impossible to provide the required level of sealing, and they have well-known disadvantages [1-3]. So, contact seals (oil seals, cuffs, mechanical seals, etc.) have a high friction moment, wear out quickly and also allow a constant (so-called guaranteed) leakage of the medium being sealed [4]. Contactless seals (labyrinth, gap, etc.) can not work without leaks [5,6,7,8]. One of the possible solutions to this problem is the use of a new type of seals – magnetic fluid seals (MFS) [9,10,11].

An analysis of the latest research results shows that MFSs have found wide application in industry. This is facilitated by the combination in one material of the entire diversity of the properties of liquids and magnetic substances [12,13]. Two properties of magnetic fluid (MF) are primarily used in MFS: it is drawn into the region of an inhomogeneous magnetic field; a magnetized body immersed in the MF is acted upon by a buoyant force, which has a magnetic origin (magnetolevitational effect). The main advantages of MFG over traditional seals are almost zero leakages of the medium to be sealed, minimal wear due to purely liquid friction, low energy losses, high maintainability, ease of maintenance, operability in statics and dynamics, self-healing in case of accidental break of the sealing medium [13]. Maintenance of the MFS during operation is reduced to refueling the magnetic fluid once every 0.5 ... 2 years (depending on the design and operating conditions). This is especially important, since the two most common causes of the technological equipment emergency are two prerequisites: human error or equipment failure. The share of initial premises caused by erroneous and
unauthorized actions of a person is 50...80%, while technical premises - 15...25% [14]. When using MFS, the human factor is significantly minimized.

The main characteristics of MFS are determined by the parameters of the magnetic field in the working gap and the physical properties (primarily, sedimentation and aggregative stability) of the magnetic fluid (MF) in it. This article investigates the distribution of the magnetic field in the MFS design implemented in practice. It is practically impossible to measure the distribution of magnetic induction because of the small size of the working gap, since the Hall sensor has a larger size than the gap in the MFS. The only way to measure the induction in the gap is the use of Hall sensors from whiskers of indium antimonide [15], their thickness is up to 0.05...0.07 mm. However, it is also difficult to achieve a complete picture of the distribution of the magnetic field with their help, and it is practically impossible, given the fact that the magnetic field is sharply inhomogeneous in the working area of the MFS. Analytical methods also do not solve the problem due to the complex geometry in the gap due to the presence of magnetic flux concentrators, non-linear characteristics of permanent magnets, magnetic circuits and MF. For calculation and analysis of the magnetic field, methods based on a number of assumptions are used; accordingly, the results are obtained with a high error. Even the use of numerical methods did not give significant results until recently due to the great complexity of the calculations [16]. And only in recent years, the level of development of computer technology allows us to solve such problems.

In the proposed mathematical models [17-21], the authors determine magnetic induction for the classical MFS circuit, the magnetic circuit of which includes a magnetic field source, which are permanent magnets; magnetic circuit of high magnetic induction steel and magnetic fluid. In [22], the authors analyze the magnetic flux of the magnetic system, breaking it into two main components: the working magnetic flux and the scattering flux. However, a common consideration for all these models is the consideration of MFS without taking into account the fact that MFS is only a common element of a complex technical system containing structural magnetic elements. This can lead to serious errors in solving an important design problem - the choice of a rational scheme for connecting MFS to technological equipment.

The experience in introducing MFS, accumulated in LLC Ferrohydrodynamic, shows that most often seals are designed to protect against contamination of bearing assemblies.

The bearing housing and the bearing shield are made of magnetic steel, which can significantly increase the magnetic fluxes of scattering in the MFS and weaken the magnitude of the magnetic induction in its working gap. The aim of this work is the numerical calculation by the finite element method of the magnetic field in the MFS core, taking into account the presence of structural ferromagnetic elements (bearing shield and bearing) taking into account their nonlinear magnetic properties, and studying the influence of these elements on the level of the magnetic field in its working gap.

2. A mathematical model for calculating the magnetic field in the active zone of MFS

The studied MFS, the design of which is shown in Fig. 1a, is intended to protect the bearing assembly from the effects of an external aggressive environment. Its design has axial symmetry; hence the field problem of calculating the magnetic field can be solved in a two-dimensional formulation in a cylindrical coordinate system in the plane . The calculated region for magnetic field analysis is shown in Fig. 1b and contains areas with different magnetic materials: a permanent magnet 1, magnetized in the axial direction, ferromagnetic material of the poles of the magnetic system 2 with the gear zone 3, the rotating shaft 4 and magnetic fluid 5, which is in the gap between the poles and the shaft and is held there by magnetic forces.

The field problem is considered as magnetostatic and is solved in an axisymmetric formulation in a cylindrical coordinate system in the plane having a unique -component, i.e. .

From the system of Maxwell differential equations for a stationary magnetic field:
**Figure 1.** General view of a typical MZHG design (a) the distribution of the magnetic field in the active zone of the seal (b) and the distribution of magnetic induction $|\mathbf{B}|$ on the shaft surface along straight line A-B (c) when it is located far from the bearing shield. The inset above shows the distribution of magnetic induction in the tooth zone on an enlarged scale.
\[ \nabla \times \mathbf{H} = 0, \quad \mathbf{B} = \nabla \times \mathbf{A}, \quad \nabla \cdot \mathbf{A} = 0 \quad (1) \]

Where \( \mathbf{H} \) is the magnetic field strength and \( \mathbf{B} \) is the magnetic induction, and the nonlinear equation of state of the magnetic material is \( \mathbf{H} = f(\mathbf{B}) \), we obtain the following nonlinear differential equation for the vector magnetic potential:

\[ \nabla \times (f(\nabla \times \mathbf{A})) = 0. \quad (2) \]

As equations of state of magnetic materials were used:
- for the MFS magnetic circuit, the dependence given in the form of a table \( \mathbf{H} = f_1(\mathbf{B}) \) given in [17] was used;
- ferromagnetic structural elements (rotating shaft and bearing shield) — dependence specified in the form of a table given in the library of materials of the COMSOL package [23];
- for the permanent magnet, the dependence \( \mathbf{B} = \mu_0 \mu_r \mathbf{H} + \mathbf{B}_r \) was used, where for the case of the NdFeB permanent magnet of the 38SH grade, \( B_r = 1.26 \) T was assumed and \( \mu_r = 1.06 \), which corresponds to the coercive force \( H_c = 950 \) kA/m;
- for the BM-3 magnetic fluid, the dependence \( \mathbf{M}(\mathbf{H}) \) given in [17] and characterized by a saturation magnetization of \( M_s = 30 \) kA/m was used.
- as the boundary conditions were used - the condition of symmetry on the axis of rotation of the shaft and the condition of magnetic insulation - \( \mathbf{B} \cdot \mathbf{n} = 0 \) on all external surfaces. To numerically solve the partial differential equation (2) with the indicated boundary conditions, we used the finite element method implemented in the Comsol software package [23].

3. Analysis of the calculation results

The distribution of the magnetic field lines (isolines \( A_\theta r \)) and magnetic induction (in the color gamut) in the core of the MFS in the absence of a bearing assembly is shown in Fig. 1b. The absence of this node in the calculation corresponds to the case when the MFS is located at a considerable distance from it. This version of the calculation of the solitary MFS corresponds to the limit idealized case given for a comparative analysis of the influence of this structural element on the magnetic field in the MFS gap. In the upper inset in Fig. 1b shows the field directly in the gap on an enlarged scale, from which it can be seen that the presence of a tooth structure on the surface of the poles creates a strongly inhomogeneous field in the gap with a maximum (peak) value \( B = 2.25 \) T in the tooth region. Figure 1C shows the distribution of the magnetic induction vector module on the shaft surface along straight line AB. From this figure it is seen that the field distribution corresponds to the tooth structure, approximately the same under both poles and is characterized by a peak value of \( 1.6 \div 1.68 \) T achieved under the extreme teeth.

In a real design, the MFS is mounted on the bearing shield using an additional insert made of non-magnetic material. The thickness of this insert can take various values \( \delta = 2 \div 10 \) mm and the magnitude of the magnetic flux scattering MFS, which is closed through the bearing shield, depends on its thickness. To quantify the effect of the \( \delta \) on the level of these flows, calculations were performed at various values of \( \delta \). The calculation results are shown in Fig. 2 - 4, respectively, for values \( \delta = 4 \) mm, 2 mm and 0 mm. From the results shown in these figures, it can be seen that part of the magnetic field lines of the upper pole of the MFS are closed through the bearing shield and the bearing, and the thinner this insert, the greater the magnitude of this scattering flux. The presence of this flux leads to a weakening of the magnetic field in the gap of the upper pole of the magnetic system mounted on this insert, which, as a result, leads to deterioration in the performance of the seal.

From the magnetic field distributions along the shaft shown in fig. 2 - 4b, it follows that when installing the MFS using an insert with a thickness of 4 mm, the peak value of the magnetic induction in the working gap under the upper pole decreases compared with a single MFS from \( 1.6 \) T to \( 1.3 \) T - seen from a comparison of Fig. 1s and Fig. 2c.
Figure 2. The distribution of the magnetic field in the active zone of the seal (a) and the distribution of magnetic induction $|B|$ on the surface of the shaft along the straight line A-B (b) with the gap value $\delta = 4$ mm.
Figure 3. The distribution of the magnetic field in the active zone of the seal a) and the distribution of magnetic induction $|\mathbf{B}|$ on the surface of the shaft along straight line A-B b) with a gap of $\delta=2$ mm.
Figure 4. The distribution of the magnetic field in the active zone of the seal (a) and the distribution of magnetic induction $|\mathbf{B}|$ on the surface of the shaft along the straight line A-B (b) with the gap value $\delta = 0$ mm.
With a further decrease in the thickness of the insert, the value of this field decreases monotonously to 1.1 T (the case of the absence of an insert, when the MFS is attached directly to the bearing assembly. Note that in this case, there is a slight increase in the peak value of magnetic induction under the other lower pole, from 1.68 T (see Fig. 1c) to 1.78 (see Fig. 4b). This is due to the fact that the presence of a bearing assembly made of magnetic material leads to a decrease in the total magnetic resistance in the path of the magnetic flux created by the permanent magnet. And from here to a certain increase in this flux, which leads to an increase in the peak value of magnetic induction in the gap under the lower pole.

The dependence of the peak value of magnetic induction in the gap of the upper pole on the thickness of the nonmagnetic insert \( \delta \), constructed from the results of a numerical calculation of the magnetic field, is shown in Fig. 5. It can be seen that the insert with a thickness of 15 mm leads to a small decrease in the field from 1.6 T to 1.56 T, i.e. by 2.5%. The dependence in Fig. 5 allows for the installation of MFS to choose a rational value for the thickness of the insert, taking into account a number of factors - reliability, simplicity of design, required performance, etc.

One of the possible ways to increase the magnetic field under the upper pole of the MZHG at a small insert thickness is, along with the main magnet PM, the use of an additional permanent magnet PM1 located in the insert region as shown in Fig. 6a and having a relatively small volume. This magnet must have axial magnetization directed counter to the magnetization of the main magnet so that the magnetic fields created in the gap under the upper pole by both magnets have the same direction. The calculation results of this option with an insert thickness \( \delta = 4 \) mm are shown in Fig. 6. It is seen that when using an additional magnet, the peak value of the magnetic induction under the upper pole can be increased to 1.75 T.

![Graph of B1_max vs \( \delta \)](image)

**Figure 5.** The dependence of the peak value of magnetic induction in the working gap MFS from the thickness of the non-magnetic \( \delta \).
Figure 6. The distribution of the magnetic field in the active zone of the sealant a) and the distribution of magnetic induction $|B|$ on the shaft surface along the straight line A-B b) with a gap value of $\delta = 4$ mm and in the presence of an additional permanent magnet PM with axial magnetization in this gap.
4. Conclusion

- According to the results of finite element analysis of the magnetic field of a liquid metal seal designed to protect the bearing assembly from external aggressive influences, it is shown that its mounting directly on the bearing shield having magnetic properties leads to an increase in magnetic fluxes of scattering and, as a result, to a decrease peak value of magnetic induction in the working gap from 1.6 T to 1.1 T, i.e. to a decrease of 31%.
- The use of a non-magnetic insert between the seal and the bearing assembly allows this induction to be increased. The dependence of this induction on the thickness of the insert is given, which makes it possible to choose its rational value when installing the seal.
- It is shown that the use of a small additional volume cylindrical permanent magnet located in the insertion region allows increasing the peak value of magnetic induction in the working gap from 1.3 T to 1.75 T and, as a result, improving working seal characteristics.

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