Development Prospects of High-Vacuum Mechanical Pumps Using Magnetic Bearing Support

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**Abstract.** The analysis of existing high-vacuum mechanical pumps with magnetic suspensions is carried out. The schemes and algorithms used for calculations for permanent magnetic suspensions (PMS) and active magnetic suspensions (AMS) are presented. Based on the results of the analysis, the relevance of the use of magnetic suspensions in high-vacuum mechanical pumps was evaluated, the development prospects of high-vacuum mechanical pumps with magnetic suspensions were noted.

**INTRODUCTION**

Nowadays, mechanical vacuum pumps are increasingly being used, the operating principle of which is based on the movement of gas from the pumped volume due to the mechanical movement of pump parts. [1–5] High-vacuum pumps of this type include: molecular, turbomolecular (hereinafter TMP), and molecular-viscous vacuum pumps.

For most mechanical vacuum pumps, a rotating rotor is an important part of the pumping process. To ensure the rotation of the rotor, supports are needed that will take the load arising in this process. Rolling bearings or plain bearings are usually used as such supports, but often they cannot cope with the extreme requirements, for example, work under vacuum conditions or durability at high speeds. Such arising problems can be solved by using an active magnetic suspension (hereinafter AMS) or a permanent magnetic suspension (hereinafter PMS) as bearing support.

**OPERATING PRINCIPLE OF AMS**

The operating principle of AMS is based on the creation of the necessary effect of magnetic forces from the support site on the suspended body (Fig.1). A displacement sensor measures the displacement of a suspended body from a given equilibrium position. The measurement signal is processed by the regulator. A power amplifier, powered by an external power source, converts this signal into a control current in the electromagnet winding, which induces magnetic adhesion in such a way that the disturbed equilibrium is restored. The stability of such a magnetic suspension depends on the selected control law.

Thus, we get that structurally AMS consists of two main parts (Fig. 2):
- electromechanical part;
- electronic control system.
The electromechanical part includes a rotor suspended in a magnetic field, electromagnets fixed to the stator, and rotor position sensors. The rotor and stator do not interact mechanically. In case the suspension is disconnected, or in case of an emergency failure in the control system, the rotor rests.
on auxiliary bearings. These bearings are often rolling bearings, they are installed with a gap, which excludes their rotation when the AMS is connected.

The electronic control system consists of a regulator and a power amplifier. Its main functions are to ensure a stable position of the rotor and its axial alignment in the gap. This is done by processing signals from the rotor position sensors. Structurally, the electronic control system is an electronic unit connected by cables with magnetic bearings and a power supply.

**OPERATING PRINCIPLE OF PMS**

In magnetic suspensions of this type, permanent magnets or DC electromagnets are used to maintain the rotor in a suspended state, i.e. there is no function of regulating the magnetic field in the suspension. It is customary to make the suspended body partially or completely from a ferromagnetic material; it can also carry permanent magnets. The suspension of the body is carried out using magnetic forces of repulsion and adhesion.

Here is the scheme of radial magnetic bearing on permanent magnets with possible rotor shifts from the equilibrium position (Fig. 3).

![FIGURE. 3. Radial magnetic bearing circuit with possible rotor shifts from equilibrium position: a) no deviation; b) z-axis deviation; c) x-axis deviation.](image)

In this design, the axial stability of the rotor is ensured by a plate that is put on the shaft. The rotor magnets interact with the stator magnets to create magnetic forces that hold the rotor in suspension.

**ANALYSIS OF EXISTING CALCULATION ALGORITHMS TO DETERMINE THE MAIN CHARACTERISTICS OF MAGNETIC BEARINGS**

In works [6–18], algorithms for calculating the main parameters of a radial magnetic bearing in AMS are considered. The presented algorithms are similar to each other; in general, their content can be shown in the block diagram (Fig. 4).
The first step is to calculate the tractive effort. This is such a force that can be developed for a long time without overheating the coil. To do this, it is necessary to determine the magnetic force of adhesion acting on the element of the area of the ferromagnetic body in a uniform magnetic field with induction $B$ in the gap:

$$dF = \frac{B^2}{2 \cdot \mu_0} \cdot dA, \quad (0.1)$$

where $\mu_0 = 4\pi \times 10^{-7} \frac{H}{m}$ — is the magnetic constant.

The general formula for the tractive effort is

$$F = \frac{B^2}{2 \cdot \mu_0} \cdot \frac{p \cdot a \cdot l \cdot d}{4} \cdot \sin\left(\frac{\Delta \alpha}{2}\right), \quad (0.2)$$

where $a$ — is the coefficient of pole number, $p$ — is the polenumber, $\Delta \alpha$ — is the pole angle.
Then the geometric characteristics of the bearing are calculated. This point is necessary to obtain the smallest required volume occupied by the bearing, in which the maximum tractive effort is realized. The value of the bearing capacity $F_{\text{max}}$ (tractive effort in this case) must be greater than the static load of the bearings $Q$, which is often known precisely or approximately. In calculating, one should take into account the influence of dynamic loads; for this, under standard operating conditions, a safety factor is introduced, varying in the range from 1.5 to 2:

$$\frac{F_{\text{max}}}{Q} = 1.5...2. \quad (0.3)$$

The initial problem in calculating the bearing geometry is as follows: let the outer diameter $D$ and the pack length $l$ be given. Let the gap $\delta$ and the permissible current density $j_{\text{max}}$ be also given. It is required to find the trunnion diameter $d$ and the pole width $t$ at which the tractive effort and induction in the gap will be maximum.

The solution to this problem begins with determining the magnetic induction in the gap. It is determined from Ampere's law for a magnetic circuit. To simplify the task, we neglect the magnetic resistance of steel:

$$\mu_0 \cdot B = \frac{k_{\text{Cu}} \cdot A}{2 \cdot \delta} \cdot j_{\text{max}}, \quad (0.4)$$

where $k_{\text{Cu}}$ — is the filling area of groove $A$ with copper, $A$ — is the area occupied by the winding in the groove:

$$A = \left(\frac{D}{2} - \frac{d}{2} - t\right) \cdot \left(\frac{\pi d}{p} - t\right), \quad (0.5)$$

where $p$ — is the pole number.

Hence follows the expression for the induction in the gap:

$$B(d,t) = C_B \cdot \left(\frac{D}{2} - \frac{d}{2} - t\right) \cdot \left(\frac{\pi d}{p} - t\right), \quad (0.6)$$

And also, the expression for the tractive effort:

$$F(d,t) = C_F \cdot C_B^2 \cdot \left(\frac{D}{2} - \frac{d}{2} - t\right)^2 \cdot \left(\frac{\pi d}{p} - t\right)^2 \cdot t, \quad (0.7)$$

where $C_F$ and $C_B$ — constants, are defined by ratios:

$$C_F = \frac{p \cdot a \cdot l}{8 \cdot \mu_0}; \quad (0.8)$$
$$C_B = \frac{\mu_0 \cdot k_{\text{Cu}} \cdot j_{\text{max}}}{2 \cdot \delta}. \quad (0.9)$$

The problem of calculating the geometry of a radial active magnetic bearing is mathematically reduced to a problem for a conditional extremum: it is necessary to find the maximum of the function $F(d,t)$ with the additional condition $B = B_{\text{max}}$, which can be written as an equation:

$$\varphi(d,t) = \left(\frac{D}{2} - \frac{d}{2} - t\right) \cdot \left(\frac{\pi d}{p} - t\right) - \frac{B_{\text{max}}}{C_B}, \quad (0.10)$$

The method for solving such a problem is known. The function $\Phi(d,t)=F(d,t)+\lambda \varphi(d,t)$, where $\lambda$ is the Lagrange multiplier, is formed. Three unknowns $d$, $t$ and $\lambda$ are found from the joint solution of equation (1.10) and two equations:
\[
\frac{\partial \Phi(d,t)}{\partial d} = 0, \quad \frac{\partial \Phi(d,t)}{\partial t} = 0. \quad (0.11)
\]

In a radial active magnetic bearing, calculated by this method, the inner diameter \( d \) must be more than half of the outer diameter \( D \). The pole width \( t \), depending on the ratio between the selected values of the parameters \( B_{\text{max}}, j_{\text{max}}, \text{and} \delta \) can vary within certain limits [1].

After determining the geometric parameters of the bearing, it is necessary to calculate the winding. Each electrical circuit contains \( p/4 \) pole coils. The number of circuits is equal to the number of electromagnets. The calculation is carried out under the condition that the maximum current \( i_{\text{max}} \) causes the maximum tractive effort \( F_{\text{max}} \) and the maximum magnetomotive force:

\[
2 \cdot n \cdot i_{\text{max}} = j_{\text{max}} \cdot k_{Cu} \cdot A, \quad (0.12)
\]

where \( n \) — is the number of windings per pole. At known \( i_{\text{max}} \), we find this number of turns. Next comes the following sequence for determining the required values.

Conductor cross-section area

\[
\alpha_0 = \frac{i_{\text{max}}}{j_{\text{max}}}. \quad (0.13)
\]

The Ohmic resistance of the coil

\[
R = \frac{\rho \cdot n \cdot l_m}{\alpha_0}. \quad (0.14)
\]

Heat loss power of one electromagnet

\[
P_i = \frac{i^2 \cdot R \cdot p}{4}. \quad (0.15)
\]

The task of thermal calculation is to determine the maximum temperature of the coil conductor and compare it with the allowable temperature for the used insulation class. The calculation is based on Ohm's law for a steady heat flux:

\[
\Delta T = P \cdot R_T, \quad (0.16)
\]

where \( \Delta T \) — is the temperature difference on thermal conductor; \( P \) — is the dissipation power; \( R_T \) — is the thermal resistance.

The last step in the algorithm is to determine the inductance of the bearing. At this stage, we derive the expressions for self-inductances and mutual inductance as functions of the rotor displacement \( x \) and \( y \). They (expressions) will help in describing electromagnetic processes in AMS.

The improved calculation method is essentially similar to the previously analyzed one, however, the stage of calculating the bearing geometry includes determining the geometric parameters of the bearing along the pack length (Fig. 5). Such an additional point of calculation helps us to avoid those cases in which the values of the pack length obtained by the general method may exceed the required ones.

In this technique, at the beginning of the calculation algorithm, the pack length \( l \) is set equal to zero and is increased step by step with a step equal to the error of the equipment on which the magnetic bearing will be manufactured. The pack length increases according to the law:

\[
l = l + l_{pr}, \quad (0.17)
\]

where \( l \) — is the pack length, \( l_{pr} \) — is the error of the device on which the magnetic bearing will be manufactured, as long as the condition is wrong:

\[
F_{\text{wag}} \geq F_{\text{max}}. \quad (0.18)
\]
where $F_{tuag}$ is the bearing tractive force. Once this condition is met, the calculation moves on to the next step — the "winding calculation" step.

In works [9–11], an algorithm for calculating forces in a radial permanent magnetic bearing is presented. The calculation is carried out using the Monte-Carlo method, which assumes a constant sample density at each iteration. This algorithm can be reduced to the following block diagram (Fig. 6):
Algorithm:
1. Setting the maximum number of iterations, introducing boundary conditions (d), setting the number of random points, and the number of divisions on the integration domain.
2. The input of known parameters.
3. Evaluation of standard integration errors by the domain of integration.

FIGURE 6. Block diagram of an algorithm for determining PMS parameters using the Monte-Carlo method.
4. Find the domain in which the standard error of integration is maximum. Divide this domain into two.
5. Conduct the next iteration.
6. Repeat steps 2–5 until the number of iterations exceeds the specified one.

This technique allows one to determine the required magnetic forces in the supports to hold the rotor in the required position.

CONCLUSION

Magnetic bearings are widely used in technology due to many advantages over rolling and plain bearings:

- no mechanical contact between the rotor and the support;
- no probability of the lubricant penetration into external environments;
- no sealing required;
- almost unlimited resource of work;
- ability to reach rotor speeds, which are limited only by the strength properties of the material.

It should be noted that the use of AMS in vacuum technology has great prospects than PMS. This is justified by the following disadvantages of the PMS:

- there is no possibility to regulate the magnetic field;
- impossibility of implementation of a complete stable non-contact suspension using only permanent magnets;
- low specific carrying capacity;
- special dampers are required to dissipate energy from vibrations of the suspended body.

All these disadvantages make the use of PMS in mechanical vacuum pumps not only difficult to implement, but also undesirable.

In turn, the advantages of AMS make it highly demanded use in turbomolecular pumps. The main ones are:

- the ability to achieve extremely high rotor speeds;
- the almost complete absence of vibrations of the suspended body;
- elimination of noise;
- absence of hydrocarbons in TMP.

However, at the moment no algorithm allows calculating AMS for TMP in compliance with all the features of its operation, which makes this direction extremely promising.

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