Chapter 4

Design Aspects of the Bearing Supports

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Abstract

This chapter examines different types of bearing supports. Technical parameters of different types of bearing supports are presented. The effectiveness of some types of bearings is determined. General approach for the calculation of bearing overall dimensions is considered.

Keywords: bearing supports, high-speed electrical machines, electromagnetic processes

1. Introduction

One of the main problems in the design of high-speed electrical machines (HS EM) is the task of selecting the bearing assemblies that forms design and determines its application area, allowable load, and efficiency.

The complexity of this task lies in the fact that the high-speed electromagnetic bearing assemblies must meet various criteria, which often contradict each other. So, bearing supports of HS EM should ensure minimum friction losses and maximum resource, wide operating temperature range (which is typical for non-contact bearings, and almost impossible to achieve on the mechanical bearings), but they must have a minimum ductility (maximum stiffness) for sub-critical rotor speeds and rotor dynamics requirements, providing significant mechanical stress and have a minimum weight and overall dimensions (it is ensured well enough mechanical bearing assemblies and is difficult to achieve on a contactless bearing supports).

Therefore, mechanical (ball and roller), hydrostatic and gas bearings, as well as various types of magnetic bearings applied in modern HS EM. The choice of bearings depends on the specific tasks and function of HS EM.

It is advisable to consider the selection criteria in more detail before analyzing the advantages and disadvantages of various types of bearings.

Bearing stiffness is a value that is characterized by an elastic deformation of the bearing under load. It is expressed as the ratio of the load to the elastic deformation, depending on the type, design and size of the bearing. In simplified form, the bearing stiffness can be defined as follows:

$$k_x = -\frac{F}{\delta}, \tag{1}$$

where F—load acting on the bearing; δ—change in the bearing gap under the load; k_x—bearing stiffness.

Typically, the stiffness is defined in the technical catalogs for the bearing supports.

The so-called stiffness background is used more often rather than bearing stiffness when calculating bearing supports in EM:

$$k_{x1} = \frac{k_x}{LD}, \tag{2}$$

where L—bearing length; D—bearing diameter.

Also used the damping coefficient attributable to the area of the bearing support:

$$c_{x1} = \frac{c_x}{LD}. \tag{3}$$

The static load is load acting on the bearing when the rotor is stationary and dynamic load is the load exerted on the bearing with a rotating rotor.

Bearing speed is a technical parameter that determines the maximum speed of the bearing. Bearing speed is measured in mm × rpm/min and defined as follows:

$$DN = D \cdot n, \tag{4}$$

where n—rotor rotational speed; D—bearing diameter.

The main producers of high-speed mechanical bearings are FAG, SKF, GMN and NTR companies.

High-speed bearings of SKF are made in accordance with ISO 683 ⟨⟨Heat-treated steels, alloy steel sand-free-cutting steels—Part 17: Ball and roller bearing steels⟩⟩ and presented in the N10 series. Under the conditions of the liquid lubrication of the bearings, rotation speed can be achieved 40,000 rpm and can be used at temperatures from −40 to + 150°C.

Rotor rotational speed of HS EM on the FAG bearings with oil lubrication can reach 170,000 rpm. In this mode, the bearings temperature is within the range from −40 to +150°C [1].

GMN Company produces mechanical bearings with speed limit of 75,000 rpm and its temperature limit corresponds to the analogues presented above [2].

Undoubtedly, mechanical bearings have reached significant technical heights. However, they have inherent weaknesses such as limited speed, considerable noise emission and low operating temperature.

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HS EM on the mechanical rolling bearings is characterized by thermal deformation; trajectory instability is caused by a change in the rotation angle of the separator with a set of rolling elements and a manufacturing error of the mechanical support rings, as well as limited service life determined by mechanical friction between the dynamic rotating parts. Therefore, for a more promising use in high-speed and high-temperature, EM have a contactless bearing supports: magnetic [active magnetic bearings (AMB), hybrid magnetic bearings (HMB)] or gas [aerodynamic bearings (ADB) or air bearings].

2. Bearings supports types

2.1. Air bearings (AB)

AB is a slide bearings (according to Standard ISO 4378-1-2001) in which the lubricating membrane pressure is created by the gas supply system. AB operating principle is based on the injection of air through a system of holes under pressure into the gap between the pin and the bearing. At the same time, the pin is separated by a layer of pressurized air from bearing. They are not used in HS EM due to the fact that the air bearings require additional pressurization system compressor.

2.2. Aerodynamic bearings (ADB)

Aerodynamic bearings (ADB) is the sliding bearings (according to ISO 4378-1-2001), in which the lubricant membrane pressure, and hence load bearing capacity is created by the surface movement. The operating principle of the ADB is that in the absence of rotation of the pin rests on the inner surface of the bearing, while rotating air or other gas is sucked from the environment, creating an air cushion with increased pressure, thus, lifting the pin and separating it from the bearing (**Figure 1**).

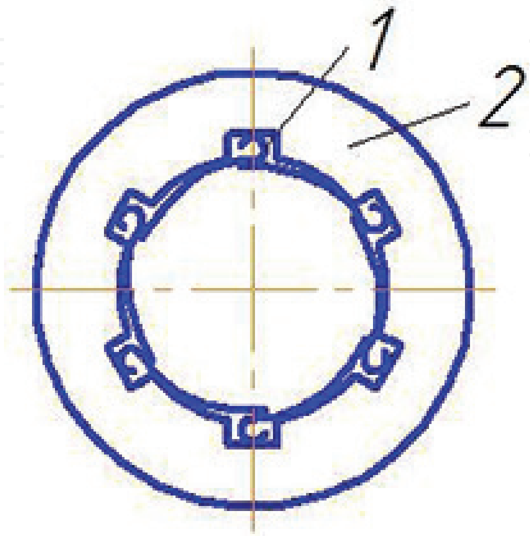

Figure 1. Aerodynamic bearing: 1—trunnion; 2—foil.

Table 1 shows the characteristics of radial ADP made by Russian production (produced by National Research University "Moscow Power Engineering Institute"). **Table 2** shows the axial ADB made by Russian production.

The advantages of ADB is the absence of necessity for a control system (as compared with the electromagnetic bearings), as well as their noncontact (compared to mechanical). The

Bearing type	The nominal diameter of the pin (mm)	The axial length (mm)	The recommended maximum speed (rpm)	The static load-bearing capacity (*N*)		The frequency of surfacing (rpm)
				Usual scheme	Enhanced scheme	
FGB11	10.5	13	364,000	2	–	19,000
FGB14	13.5	16	283,000	3	–	14,800
FGB16	15.5	18	247,000	4	–	13,000
FGB20	19.5	24	196,000	7	–	10,000
FGB30	30	34	127,000	15	–	6700
FGB35	35	31	109,000	16	27	5700
FGB40	39	44	98,000	25	42	5100
FGB61	61	70	63,000	63	105	3300
FGB67	67	70	57,000	69	115	3000
FGB74	74	70	52,000	76	127	2700
FGB80	80	70	48,000	82	137	2500
FGB84	84	85	46,000	105	175	2400
FGB103	103	70	37,000	–	177	1900
FGB103l	103	120	37,000	–	303	1900

Table 1. Radial ADB made by Russian production.

Type	The diameter of the heel (mm)	The outer diameter of the bearing (mm)	The inner diameter of the bearing (mm)	Rated speed (rpm)	Bearing capacity at rated speed (N)
TFGB37	37	43	19	207,000	95
TFGB44	44	49	22	174,000	137
TFGB64	64	74	34	119,000	277
TFGB72	72	82	42	106,000	322
TFGB85	85	95	52	90,000	426
TFGB105	95	116	93	75,000	702
TFGB120	120	132	70	64,000	895

Table 2. Axial ADB made by Russian production.

disadvantage is that ADB provides noncontact rotation of the rotor only with a certain speed (rate surfacing), and up to this frequency ADB acts as a mechanical bearing of a high friction (for example, from **Table 1** it is seen that the bearing frequency surfacing is 2400 rpm with a load capacity of 105 N). Furthermore, using ADB is an increased requirement for the surface treatment of the shaft. Also ADB cannot be operated in the absence of a gas environment, such as a vacuum, which limits their use in cosmic space.

2.3. Active magnetic bearings (AMB)

AMB (according to ISO 14839-1-2011) is a rotor maintenance device without mechanical contact by the magnetic attraction forces and uses feedback servo, in which the circuit typically contains sensors, solenoids, power amplifiers, power supplies and the controller (**Figure 2**).

AMBs are widely used in Russian and foreign industry [in Russia are engaged in the development of the ⟨⟨VNIIEM Corporation⟩⟩ JSC and ⟨⟨Pskov engineering company⟩⟩, among foreign manufacturers can mark SKF, CalnetixTechnologies (USA), the Synchrony (USA) and others.].

The advantages of the AMB are their features such as controllability, contactless operation, providing rotor levitation when power is supplied to the control electromagnets (unlike ADB), the ability to work at high temperatures and in corrosive environments, bearing stiffness control possibility (due to pulse changes the electromagnetic force) and the bearing damping ability and the ability to work in vacuum.

The AMB disadvantages include the complexity of their design, the complexity of their control systems, significant product price and their high weight and overall dimensions. The stiffness of the AMB under normal operating conditions is comparable or slightly higher than the stiffness of the ADB.

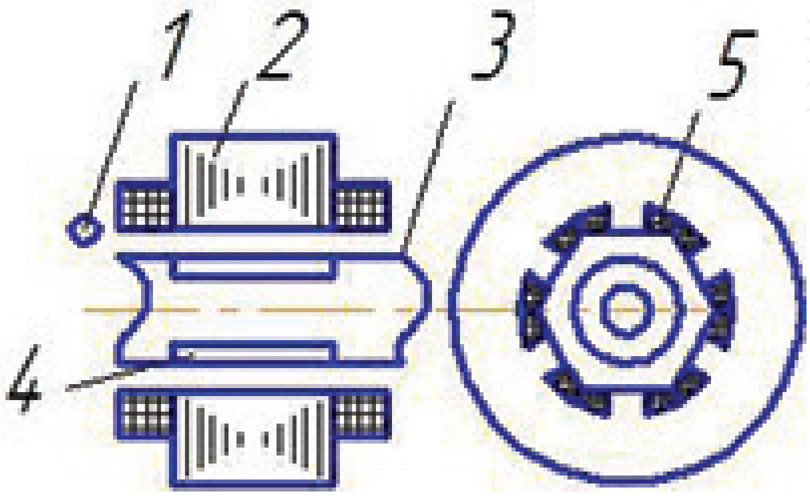

Figure 2. AMB: 1—rotor position sensor; 2—AMB magnetic core; 3—shaft; 4—ferromagnetic sleeve; 5—AMB winding.

Despite these disadvantages, the AMB are widely used in HS EM. Moreover, the use of AMB in the Russian Federation is rationed by the technical documentation (ISO 14839-1-2011, ISO 14839-2-2011, ISO 14839-3-2013, ISO 14839-4-2014).

Importantly, the AMB are not only electromagnets, in which the shaft is concentrically located but an intellectual complex system consisting of microscopic sensors, signal amplifiers, etc. A more complete design of AMB control systems, as well as their control algorithms is described in Refs. [3, 4].

Table 3 shows the geometric dimensions of the AMB, produced by ⟨⟨Pskov Engineering Company⟩⟩.

To evaluate the effectiveness of the AMB and ADB energy characteristics, it is advisable to make a comparison on the specific speed and static load, which is accepted in the form:

$$F_{sp} = \frac{F}{DL} \tag{5}$$

ADB and AMB of Russian production are considered when comparing.

From **Table 3**, it is seen that when the static load-bearing capacity is 180 N, the specific speed of AMB is 3,750,000 rpm and the specific static load is 100,000 N/m^2. At the same time at the static load of 175 N, specific speed is 3,864,400 rpm and the specific static load is 24,509 N/m^2. That is, the AMB of Russian production exceeds ADB by the specific static load, and the specific speed of both variants is about the same (AMB's specific speed at 2.4% less than ADB).

d (mm)	*D* (mm)	*L* (mm)	*n* (10^3 rpm)	*F* (N)	*m* (kg)
15	44	14	252	20	0.07
20	52	16	190	30	0.12
25	58	20	150	50	0.18
30	66	24	125	70	0.3
35	72	27	110	90	0.4
40	80	30	95	120	0.52
50	94	36	75	180	0.84
60	110	42	63	250	1.32
70	130	46	54	360	2
80	148	50	47	450	2.7

Notes: d—diameter of the shaft; D—external diameter; m—mass of the AMB; L—active length; F—static load-bearing capacity; n—permissible speed.

Table 3. Standards of ⟨⟨Pskov engineering company⟩⟩ for radial AMB.

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To eliminate the AMB and ADB disadvantages, hybrid magnetic bearings (HMB) are applied in HS EM. HMB is the bearing that combines AMB design and magnetic bearing at permanent magnets (MB PM) in accordance with ISO 14839-1-2011.

At the same time, as shown in Ref. [5], the concept of the HMB goes far beyond the definition of an ISO and represents a combination of different bearing types in a single product that allows them to combine their design merits and ADB, and AMB, reaching thus the minimum weight and overall dimensions, controllability and stability of the entire HS EM.

There are three main types of structural HMB: gas-magnetic bearing, magnetomechanical and various combinations of MB PM with AMB.

2.4. HMB, as a combination of MB PM and AMB

This type of HMB is the most common and used in practice. Moreover, it is considered the most promising design of HMB. This area has two main ways of development: the permanent magnets are installed in the magnetic AMB (**Figure 3**) to increase the magnetic flux. Separation of the AMB and MB PM, for example, two radial MB PM placed on one shaft, and the rotor axial fixation is provided by axial AMB (**Figure 4**).

A significant pulling force of the electromagnet is required when using the second option, so the first design most widely used in industry. At the same time some technical branches of second design has broad application prospects.

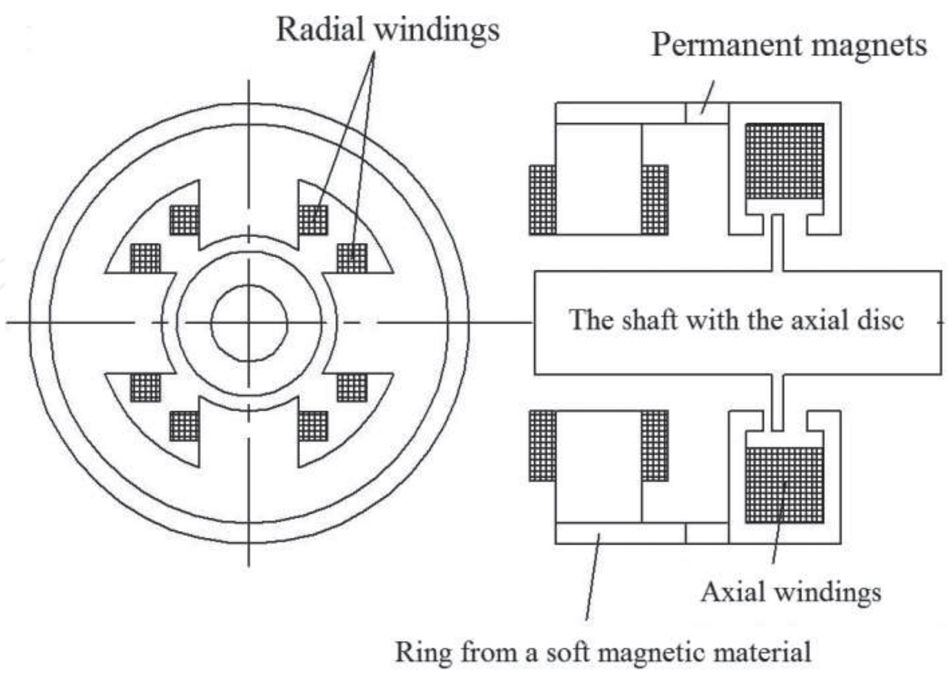

Figure 3. Radial-axial HMB, in which PM are used to amplify the magnetic flux.

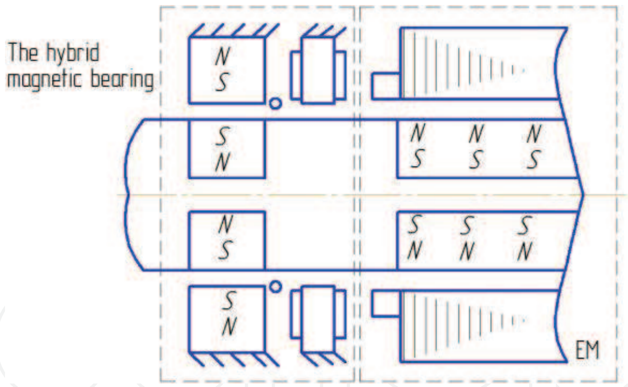

Figure 4. HMB where AMB and MB PM used separately.

2.5. Magnetomechanical HMB

This HMB class is a combination of mechanical bearings, which serve as the main shaft support and MB PM, which are intended for unloading mechanical bearings. The advantages of this HMB type is the lack of a control system and simplicity of design and the disadvantages is the presence of mechanical bearings friction, and consequently also their low reliability.

For example, it is known that magnetomechanical bearing (MMB) design [6] for the electromechanical battery consists of flywheel and a high-speed electric generator with a vertical shaft. A feature of this design is the use of a ball in HMB made of sapphire, which provides the axial support system. **Table 4** shows the effectiveness of different ball materials and plate in the MMB.

To improve the efficiency of MMB in rotary system of the HS EM the passive vibration damper also entered besides mechanical bearings and MB PM, which is needed for damping vibration energy. A passive vibration damper is an electrically conductive plate installed with a gap relative to the PM. Eddy currents are induced in the copper sleeve with displacements of the PM, which provide damping of vibration energy.

MMB are actively developing due to their simple application design. The major trends in the development of this type of HMB are reduction of friction in the mechanical bearings by the use of coatings and materials, as well as by the maximum discharge of mechanical bearings

Ball material	Material plate	Friction coefficient	Friction losses at 50,000 rpm (MW)
Sapphire	Sapphire	0.1	152
Steel	Steel	0.42	628
Cast iron	Cast iron	0.15	230
Teflon	Steel	0.04	63

Table 4. The effectiveness of different ball materials and plate in the MMB.

and levitating shaft vibration reduction. It is obvious that in a number of industries, especially in high-speed systems with short life cycles, the HMB type have broad prospects.

2.6. Gas-magnetic HMB

This HMB is a combination of ADB and AMB. **Figure 5** shows a design of this HMB type [7].

The advantages of this type of HMB include high stiffness and handling, but they have considerable design complexity of execution, so they are not widely used in the industry. Gas-magnetic HMB are considered in Refs. [8–10] in more detail.

2.7. Electrostatic bearings

At low mass of the rotor, as well as to the possibility of providing vacuum in the cavity of the EM, it seems appropriate to use electrostatic poles. Electrostatic support is a noncontact bearing assembly, in which efforts are created by attractive forces between two surfaces having different potentials (**Figure 6**). The created ascensional power in electrostatic supports is insignificant and is accepted in the form:

$$f = \frac{\varepsilon E^2}{2} \tag{6}$$

where ε—the dielectric constant of the suspended body; E—the electric field strength.

The advantage of the electrostatic poles relates primarily to no energy losses due to eddy currents. The electrostatic bearings application allows creating ultra-high-speed, contactless, vacumed, miniature EM with low noise and heat generation. Electrostatic supports are controlled.

In the Russian Federation industry, the electrostatic support is most widely used as gyro bearings. Basic electrostatic bearing theory is presented in Refs. [11–16].

Additionally, certain industrial application perspectives have bearings, which are based on the Lorentz force, which are defined as follows:

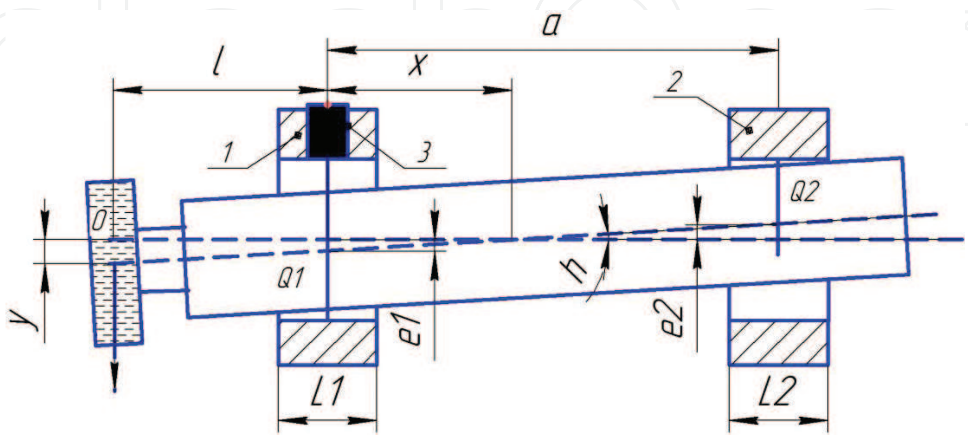

Figure 5. Hybrid gas-magnetic shaft suspension of high-speed spindle: 1—front gas-magnetic bearing; 2—rear gas-static bearing; 3—electromagnet.

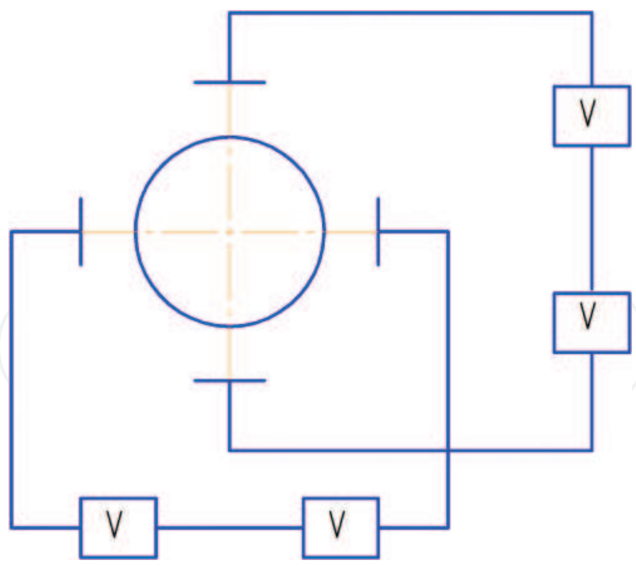

Figure 6. The electrostatic support.

$$f = q(E + [v \times B]). \tag{7}$$

This type of bearings has broad prospects for use in HS EM. For example, the Swiss company Seleroton has developed ultra-high-speed vacuumed motor CM-AMB-400 using this type of bearings (power of 250 W, the rotor speed of 400 000 rpm).

Using the suspension based on the Lorentz forces in the electric motor in conjunction with vacuum allowed to almost completely solve the problems of the rotor friction of the air and the friction in the bearing supports. Overall efficiency of the EM reaches 91–92%.

3. A generalized approach to the calculation of the basic AMB and HMB overall dimensions

In view of prospects for using of AMB and HMB, it is useful to consider the approach for the calculation of their overall dimensions in more detail.

In view of the design similarity of AMB and HMB (HMB, in which PM are used to create an additional magnetic flux), the development of a generalized approach for the AMB and HMB calculation is proposed.

To solve this problem, consider HMB design with radial or axial magnetic inserts. The fundamental difference of these designs is the arrangement of the PM for reinforcing the magnetic flux in the way of the magnetic field line. Thus, these design differences have no significant influence on the mathematical description of the HMB. Moreover, one can get AMB, equating the energy characteristics of a PM to zero that allow making a conclusion about the generalization of considered designs for AMB and HMB.

The following assumptions are used in solving the problems:

1. Permeability of air is equal to the magnetic permeability of vacuum;
2. Temperature and HMB electromagnetic mode are established;
3. AMB active materials are isotropic.

Based on the terms of the problem, the developed generalized approach should take into account both the thermal and electromagnetic processes in HMB. Therefore, the equivalent circuit method (equivalent circuits) has been selected for HMB research that is widely used in the electromagnetic and thermal processes calculations. **Figure 5** shows the equivalent circuit of the magnetic (a) and thermal circuit (b) of HMB.

The strength of the HMB determined as:

$$F = \frac{pl\tau B_\delta^2}{8\mu_0}, \tag{8}$$

where p—number of poles; l—active length of HMB; $\tau = \frac{\pi D}{2p}$—pole pitch; B_δ—flux density in the HMB air gap.

According to the equivalent circuit from the total current law, it should be:

$$F_m + 2Iw = 2F_\delta + 2F_z + F_j + 2F_{zr} + F_{jr}, \tag{9}$$

where F_m—m.m.f of the PM; F_δ—m.m.f of the air gap; F_z—m.m.f. of the stator magnetic core teeth; F_j—m.m.f. of the stator magnetic core back; F_{zr}—m.m.f. in the radial length of the rotor; F_{jr}—m.m.f. in the axial length of the rotor.

Taking into account that $F_\delta = \frac{1}{\mu_0} B_\delta \delta$, then:

$$\frac{1}{\mu_0} B_\delta \delta = \frac{F_m + 2Iw - 2F_z - F_j - 2F_{zr} - F_{jr}}{2}, \tag{10}$$

M.m.f. of the PM is defined as follows:

$$F_m = H_{cB}\, l_m \tag{11}$$

Taking into account the temperature dependence of the energy characteristics of PM:

$$F_m = H_{cB}\, l_m \left(1 - \frac{k_{Hc}(\Theta_{\mathrm{PM}} - 20)}{100}\right), \tag{12}$$

where $H_{cB}(\Theta)$—RMS values of the coercive force of the PM; Θ_{PM}—the temperature of the PM; k_{Hc}—tension temperature coefficient.

It should be noted that the tension temperature coefficient can be assumed to be constant only when the temperature of the PM is 60–80°C (for intermetallic alloys *NdFeB* and *SmCo*). At temperatures outside this range, this ratio has a nonlinear dependence.

The PM temperature in the steady state operation of the HMB is determined on the basis of the thermal equivalent circuit, **Figure 7**b.

Functions approximating the actual magnetization curve of soft magnetic material from which the HMB magnetic core and shaft are made is used when taking into account the HMB magnetic core saturation:

$$H_z = \alpha_1 \mathrm{sh}\, \beta_1 B_z \tag{13}$$

$$H_j = \alpha_1 \mathrm{sh}\, \beta_1 B_j \tag{14}$$

$$H_{zr} = \alpha_2 \mathrm{sh}\, \beta_2 B_{zr} \tag{15}$$

$$H_{jr} = \alpha_2 \mathrm{sh}\, \beta_2 B_{jr} \tag{16}$$

where α_1, β_1—approximation coefficients for the soft magnetic material of the HMB magnetic core; α_2, β_2—approximation coefficients for the soft magnetic material of the shaft; B_z—flux density in the magnetic core teeth; B_j—flux density in the magnetic core back; B_{zr}—flux density on the shaft in the radial direction and B_{jr}—flux density on the shaft in the axial direction.

Then, using the obtained expression and real magnetization curve of the HMB magnetic core material, it is possible to create HMB characteristic taking into account the saturation (the dependence of the force of gravity from the current).

In **Figure 8**, as an example, dependence of the force from a current is made based on the saturation and for various ambient temperatures. All dependencies are built in static mode, transient thermal and electromagnetic processes when making the dependencies were not considered.

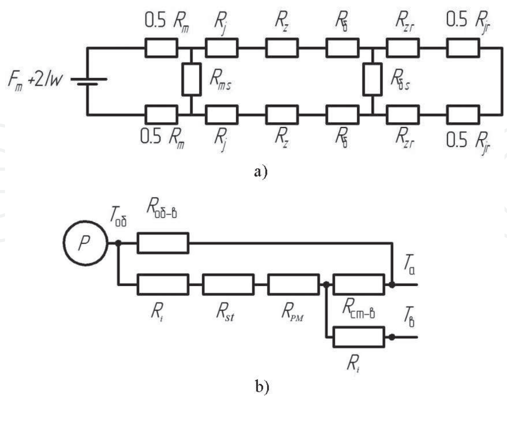

Figure 7. Equivalent circuit of the magnetic circuit HMB: (a) equivalent circuit of the magnetic circuit; (b) equivalent circuit of the thermal circuit. Here, F_m—m.m.f. of the PM; I—current in the AMB winding; w—AMB winding number turns; R_m—the magnetic resistance of the PM; R_j—the magnetic resistance of the AMB magnetic core back; R_z—the magnetic resistance of the AMB magnetic core teeth; R_δ—the magnetic resistance of the HMB air gap; R_{zr}—the magnetic resistance of the rotor radial length; R_{jr}—the magnetic resistance of the rotor axial length; $R_{\delta s}$—the magnetic resistance of the air gap scattering; R_{ms}—the magnetic resistance of the PM scattering; R_i—thermal resistance of the winding insulation; R_{st}—thermal resistance of the stator; R_{PM}—thermal resistance of the PM insertion.

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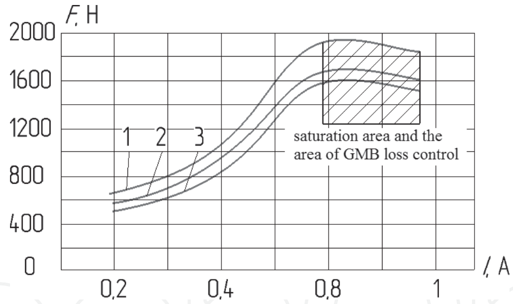

Figure 8. Dependence of the HMB tractive force from a current value (taking into account changes in ambient temperature and magnetic core saturability). Here, 1—at a temperature of 20°C; 2—at a temperature of 60°C; 3—at a temperature of 90°C.

From these curves, it is seen that the HMB is losing its control in the magnetic core saturation area and at high temperatures. This is due to a significant nonlinearity dependence of HMB forces from the current and the magnetic flux of the PM. AMB and HMB control system is usually built on the linearization of these dependencies. Loss controllability area occurs at 0.8 A. In this area, HMB tractive force remains practically unchanged as current increases, since the magnetic core reaches saturation. At a significant saturation, HMB tractive force is slightly reduced, which causes a significant increase in stator back and teeth m.m.f. Steel 2421 was used for making dependence.

4. Computer modeling of dynamic electromagnetic processes in HMB

The developed mathematical apparatus can be used to study the general physical processes in HMB, as well as for engineering calculation of basic geometric dimensions of HMB and AMB considering nonlinear electromagnetic and thermal processes. At the same time, developed mathematical apparatus does not allow making selection of the most rational radial HMB design with magnetic inserts. To solve these problems, the computer simulation methods of the magnetic field of various HMB and AMB designs are more appropriate to use.

Software complex Ansoft Maxwell was used to solve this problem, where two main radial HMB designs with magnetic inserts considered, **Figure 1**, and AMB design present for comparing.

Overall dimensions and constructive parameters of the researched designs are presented in **Table 5**.

Comparison of the considered HMB designs was made under the same weight and overall dimensions, output power and materials properties on the following criteria: the magnitude of the force in the air gap of the HMB (main energy characteristic), stiffness when the rotor is displaced by 60% of the air gap. The forces in the air gap were also compared in the absence of current in the windings. Comparison results are presented in **Figure 9**.

Comparison of HMB and AMB characteristics produced in relative units, the characteristics ascribed to the AMB. The AMB strength and stiffness were taken as 1, and the HMB characteristics are already determined from this base value.

Design	Parameter					
	Number of poles	**Air gap (mm)**	**Active length (mm)**	**Bore diameter**	**The outer diameter of the stator**	**Weight (kg)**
HMB with a radially magnetized PM inserts	8	0.5	60	30	60	0.7
HMB with a tangentially magnetized PM inserts	8	0.5	60	30	60	0.7
AMB	8	0.5	60	30	60	0.7

Table 5. HMB and AMB researched designs.

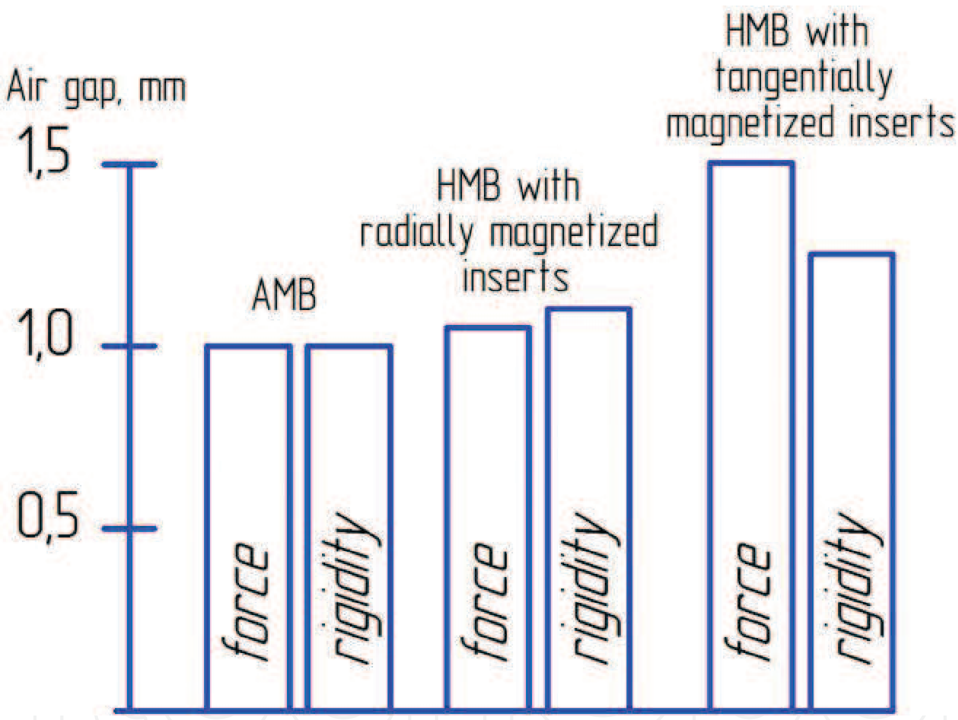

Figure 9. Comparison of the AMB parameters and various HMB designs.

5. Results and conclusions

From the obtained data analysis, it is seen that the maximum stiffness and force value in the air gap has HMB with tangentially magnetized inserts (50 and 40%, respectively, more than AMB indicators for the same weight and overall dimensions). Achieving these characteristics due to the PM inserts will reduce the AMB power consumption at almost two times. The use of a radially magnetized inserts gives little effect: increasing the strength of AMB characteristics by 5–8% and stiffness by 10–12%. In this case, the AMB consumption can be reduced by 8–10%.

HMB with tangential insert provides strength about 130 N in the absence of current in the windings, while the impact strength falls uniformly on the whole rotor. The presence of this force value (25% of the AMB power at maximum current) allows more “gently put” rotor on the bearing harnesses and minimizes the consequences of super heavy transients at AMB failure. HMB with radial inserts provides power of 125–130 N in the absence of power supply, but this force is applied to a small rotor section, and this may lead to a complication of the transition process in case of AMB failure, as it will cause additional “build up” of the rotor.

This chapter also shows that at high temperatures and magnetic core saturation HMB loses control. Thus, generalized approach to the design of AMB and HMB considering nonlinear electromagnetic and thermal dependencies has been developed in this paper.

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