Magnetic bearings external magnetic field functional diagnostics and controlling systems synthesis

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Abstract: The paper presents the description of developed experimental installations for the axial and the radial controlled magnetic bearings studies; the method of controlled magnetic bearing external magnetic field (CMB EMF) experimental research; CMB experimental studies with the influence of external magnetic fields and environmental conditions; influence assessment of external magnetic field foreign sources, such as number of people, quantity of foreign magnetic fields sources (cell phones in particular were used), a temperature mode and relative air moisture on the accuracy of diagnosing by the presented method; numerical characteristics of the CMB diagnostic criterion with specific geometric dimensions obtained. Also the paper contains the expressions for the main types of electric machines such as induction motors, direct current (DC) machines and electric machines with a distributed secondary system external magnetic field coefficients were determined. The operational and technological factors influence was taken into account in determining the external magnetic field coefficients to improve the external magnetic field calculating accuracy for the electric machines technical condition diagnostics problems. The external magnetic field experimental dependences from different parameters for the induction motors, DC machines and electric machines with a distributed secondary system were obtained. Reynolds magnetic number essential influence on the electric machines with a distributed secondary system external field is established.
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Introduction.

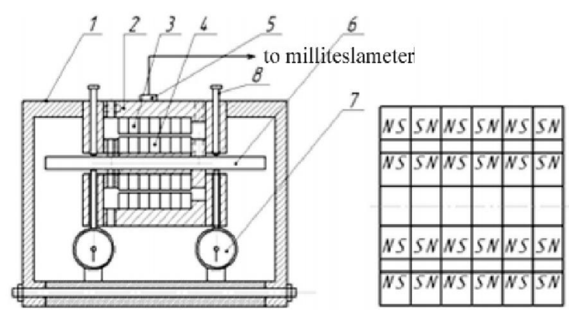
Controlled magnetic bearings (CMB) are becoming more widely used in modern industry [1–5]. The MB application in high-speed technical systems (HSTS), for example high-reversible motors and generators, allows to improve energy efficiency, to decrease friction losses, so it is having particular interest. However, jointly application of CMB and complementary system, such as automatically controlled systems leads to HSTS mass and dimensional parameters decrease.

Research problems.

The HSTS functional diagnostics and CMB automatically controlled systems synthesis in single system allows to solve such problem. The rotor attitude control method realizable with hybrid magnetic bearings by external magnetic field (EMF) parameters offered by authors [6], allows to control the CMB operation and technical condition, and also to increase the HSTS diagnostic efficiency.

Decision of research problems.

To prove such claim the installations for carrying out the EMF pilot studies as diagnostic criterion of radial controlled magnetic bearings (RCMB) (fig. 1) and axial controlled magnetic bearings (ACMB) (fig. 2) were developed.



a b

Figure 1 a –the experimental installation for EMF probes as diagnostic criterion of RCMB; 1 b – RCMB design: 1–engine support (bed); 2–controlled magnetic bearing; 3–external set of magnetic rings of NdFeBN33; 4–internal set of magnetic rings of NdFeB N33; 5–Hall sensor; 6–shaft; 7–indicator of the hour typ; 8–pusher

Installation (fig. 1 a) works as follows: the shaft with the studied CMB having a design given on figure 2 is arranged on an engine support 1. CMB consists of seven rings of magnets of NdFeB of the N33 brand magnetized in the axial direction, the air gap between an external and internal set of magnetic rings is equal to 1,5 mm. Geometrical parameters of external rings are: external diameter – 43 mm, internal diameter – 28 mm, axial length – 5 mm. Geometrical parameters of inner rings are: external diameter – 25 mm, internal diameter – 10 mm, axial length – 5 mm. Magnets rings are pressed in nonmagnetic bushings. The last are made nonmagnetic to avoid a magnetic flux short-circuit. The values of EMF induction are measured by the Hall sensor which is connected to milliteslameter. The concentric arrangement of internal set of magnetic rings relatively to external is accepted to MB working order, for faulty – eccentric. The eccentric arrangement of rings is reached by internal set of magnetic rings shaft misalignment relatively to external rings by pusher 8 (fig. 1 a) with a offset step equal 0,1 mm. The offset value and size are traced and fixed by indicators of the hour type. There are two indicators (right and left) for measurements error minimization. Measurements are carried out at various values of temperature and air moisture. The obtained data are exposed to mathematical interpolation in Matlab software, in the SplineTools module.

The received experimental data analysis showed that at misalignment of rings on 0,4 mm the RCMB EMF induction changes for 3 – 5 %. The thickness of the case in this experiment made 10 mm. Such changes of an induction are easily fixed by the Hall sensor that confirms possibility of use of the offered method in practice.

The installation for carrying out the pilot studies of ACMB EMF as diagnostic criterion is presented in figure 2. It contains an engine support 1, a calliper 2, the indicator of hour type 3, the rod 4, the axial magnetic bearing 5, the Hall sensor 6, the pusher 7, milliteslameter 8, connected to the Hall sensor. For ACMB serviceable conditions is accepted the equivalence of an operating air gap to nominal, to the faulty – a deviation of an operating air gap from nominal.

The installation (fig. 2) works as follows: the air gap in ACMB is changing by pushing on a rod. The value of air gap changing is fixed by the indicator of the hour type, and the value of EMF magnetic induction is measured by the Hall sensor and displayed on the milliteslameter screen. The obtained experimental data are given in figure 3 *a*. The HSTS thickness is measured by calliper.

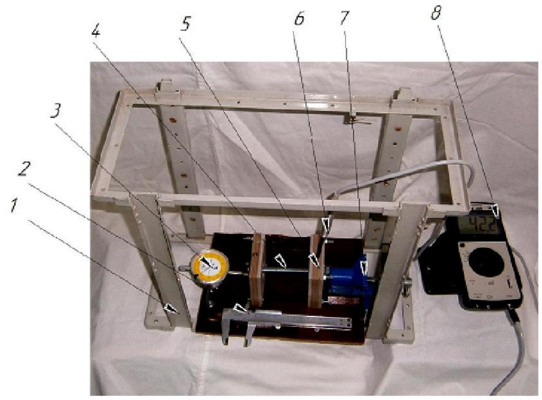


Figure 2 – The installation for carrying out the pilot studies of axial controlled magnetic bearing EMF as diagnostic criterion: 1 – the engine support; 2 – the calliper; 3 – the indicator of the hour type; 4 – the rod; 5 – the axial magnetic bearing; 6 – the Hall sensor; 7 – the pusher; 8 – the milliteslameter

The results analysis (fig. 4 *a*) showed that the air gap changing on 40 % the EMF induction changes for 4–5 %. These changes, as well as in the previous experiment with sufficient accuracy are fixed by the Hall sensor that confirms possibility of the offered CMB diagnostic method application in practice.

For the influence assessment of foreign sources EMF on the accuracy of diagnosing by the presented method, the following environment conditions changed: number of people, quantity of foreign magnetic fields sources (cell phones in particular were used), a temperature mode and relative air moisture. The obtained results are presented in figure 3 *b*.

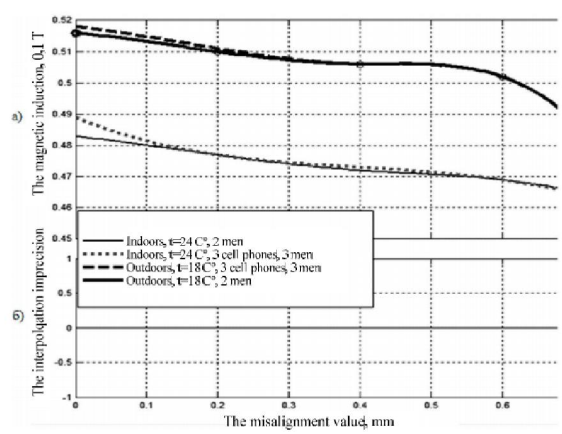


Figure 3 – The results of ACMB EMF measurements (the bowl thickness is 9 mm): *a* – the results of ACMB EMF as diagnostic criterion; *b* – the results of environment conditions influence on EMF parameters

The analysis of foreign magnetic fields and environment conditions influence on CMB EMF parameters showed that magnetic field additional sources incorporation in insignificant degree influences on the Hall sensor indications.

For the influence assessment of HSTS bowl thickness on diagnostic criterion numerical values, i.e. on EMF level, the bowl thickness was changed for 33 %, and serviceable and faulty ACMB EMF parameters were measured.

The obtained results analysis showed that the HSTS bowl thickness increases at 33 % causes the the EMF decreases in 1,8 times.

For functional diagnostics and CMB automatically control systems synthesis it is necessary also to review the HSTS technical condition diagnostic in detail. The most acceptable from the synthesis and measuring elements minimization point of view is HSTS diagnostics by the external magnetic field, because it is not required additional elements for signal processing.

The offered method technical realization is considered in famous works [7–11] and therefore it isn't considered here. However, to increase the diagnosing by the external magnetic field parameters accuracy of no salient pole electric machines by EMF parameters, and also for uniform synthesized system fail-safe functioning it is necessary to develop the settlement expressions for external magnetic field coefficients determination taking into account technology and operational factors influence.

The induction motor external magnetic field coefficient is defined by a ratio [12]:

(1)

where $\rho_{\tilde{n}} = \frac{1}{l_1}\int_0^{l_1} |f_i - g_i| dz$ – the external magnetic conductor internal surface ovality average value; $f_i = a(z)$; $g_i = b(z)$; *a* – boring elliptic profile half axis of internal or external magnetic conductor on the axis *x*; b – boring elliptic profile half axis of external magnetic conductor or internal magnetic conductor external surface on the axle *y*; *z* – the axis coinciding with induction motor rotation axis; l_1 – induction motor active length; $\rho_{\tilde{n}} \le R_{ext}$; R_{ext} – external magnetic conductor external radius;

$$\dot{\psi}_{\acute{\imath}} = \frac{\dot{\xi}_{\text{礅}}}{\varsigma_{\text{礅}}\mu_r};\ \dot{\psi}_k = \frac{\dot{\xi}}{\varsigma\ \mu_r};$$

$$\lambda_r = \frac{\pi(2n-1)}{l_1}\quad ; \quad n=1,2,3\ldots;$$

$\dot{\xi}_{\text{ext眈}} = j\sqrt{j\omega p_{\nu i}\mu\gamma\ R^2\ + \varsigma^2}$; j – imaginary unit; $\varsigma_{\acute{\imath}} = \sqrt{(\lambda_r R_{ext})^2 + p_{\nu i}^2}$; f – power line frequency; $\omega = 2\pi f$;

$\dot{\xi}_{\text{ext怦}} = j\sqrt{j\omega p_{\nu i}\mu\gamma\ R^2\ + \varsigma^2}$;

$\varsigma_{\text{忖}} = \sqrt{(\lambda_r R\ )^2 - p_{\nu i}^2}$; $p_{\nu i}$ – pole couples number of any external magnetic conductor electromotive force harmonica; for the main harmonica $p_{\nu i} = p$; μ , $\gamma_{\tilde{n}}$ – external magnetic conductor material magnetic permeability and specific conductance.

The experimental dependences for the induction motor, with a rotor diameter equal to $D_2 = 71,5^{+0,02}_{-0,05}$ mm and a stator with diameter internal boring equal to $D_1 = 72^{+0,03}_{-0,06}$ mm are given in figure 4. The induction motor rotor static eccentricity was taken as an operational and technology factor.

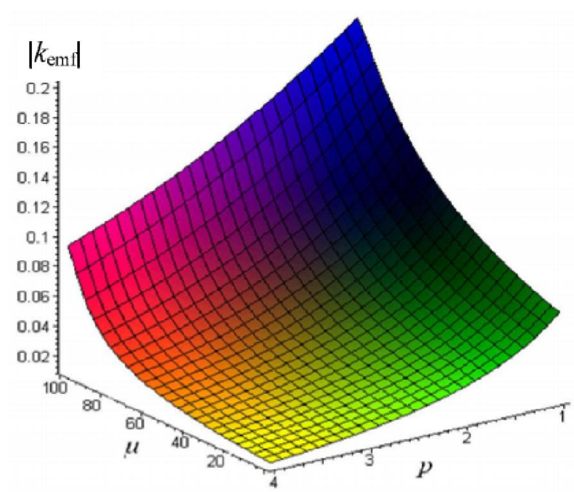


Figure 4 – Induction motor EMF coefficient dependence from number of pole couples

The direct current electric machine external magnetic field coefficient is defined by taking into account (1) provided that $\omega = 0$:

$$k_{emf} = \frac{\left[\begin{array}{l}\exp\left(8\pi\left(\sqrt{\left(\lambda_{\text{肥}} R_{\text{ext}}\right)^2 + p_{\nu}^2} - \sqrt{\left(\lambda_r R_?\right)^2 - p_{\nu i}^2}\right)\right)\times \\ \times\left(R_{\text{ext}} + 0{,}5\rho_c\right)\end{array}\right]}{\left[\begin{array}{l}2\rho_c \,\text{jchj}\left(\sqrt{\left(\lambda_{\text{肥}} R_{\text{ext}}\right)^2 + p_{\nu}^2} - \sqrt{\left(\lambda_r R_?\right)^2 - p_{\nu i}^2}\right) + \\ +(1-1/\mu^2)\text{shj}\left(\sqrt{\left(\lambda_{\text{肥}} R_{\text{ext}}\right)^2 + p_{\nu}^2} - \sqrt{\left(\lambda_r R_?\right)^2 - p_{\nu i}^2}\right)\end{array}\right]}.$$

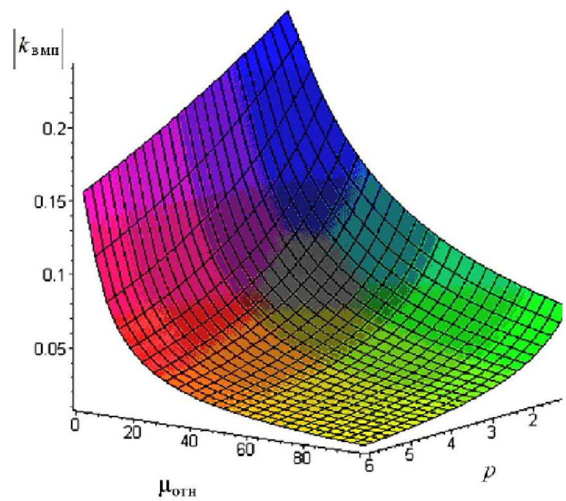


Figure 5 – Direct current electric machine external magnetic field coefficient module dependence from external magnetic conductor magnetic permeability and pole couples number

$$\dot{k}_{emf} = \sum_{1}^{n} \frac{6\pi^2 \sqrt{k\varpi_{\text{礅}} \varpi} \times e^{\delta_1 \times \sqrt{\left[\frac{\pi(2n-1)}{2l_1}\right]^2 + \alpha_\tau^2}}}{\left[\begin{array}{l}(r_1\varpi_{\text{礅}} + \varpi_{\text{胹}})ch(\varpi - \varpi_{\text{忭}}) + \\ +\mu\chi_{\text{忭}}\left(1 - \frac{? k\varpi_{\text{礅}} \varpi}{\mu_r^2 \chi_{\text{忭}}^2}\right) sh(\varpi_{\text{礅}} - \varpi_?)\end{array}\right]},$$

where

$$\dot{\varpi}_? = j\sqrt{jp_{\nu i}\,\mu\varepsilon + \left(R + h_{\text{ï}}\right)^2\left(\frac{\pi(2n-1)^2}{4l_1^2} + \alpha_\iota^2\right)} \quad ;$$

$$h_{\text{ï}} = R_{ext1} - (R_1 + \frac{\delta_1}{2}) \quad ; \quad \alpha_\tau = \frac{\pi}{\tau} \quad ;$$

$$\chi_{\text{忭}} = \left(R_1 + \frac{\delta_1}{2}\right)\sqrt{\frac{\pi\left(2n-1\right)}{2l_1} + \alpha_\tau^2} \quad ;$$

$$\chi_? = \left(R + h_{\text{ï}}\right)\sqrt{\left(\frac{\pi(2n-1)}{2l_1}\right) + \alpha_\tau^2}$$

$$r_1 = \frac{\chi_{\text{忭}}}{\chi_{\text{i}}} \quad ;$$

$$\dot{\varpi}_{\text{忭}} = j\sqrt{jp_{\nu i}\,\mu\varepsilon + \left(R_1 + \frac{\delta_1}{2}\right)^2\left(\frac{\pi(2n-1)^2}{4l_1^2} + \alpha_\tau^2\right)} \quad ;$$

$p_{\nu ì}$ – pole couples number of any internal magnetic conductor electromotive force harmonica;

$\varepsilon = \frac{\mu_0\gamma\omega_1}{\alpha_\iota^2}k_d$ – Reynolds magnetic number;

$k = \frac{k_q}{k_d}$; k_d, k_q – reduction coefficients on longitudinal axis and transverse axis.

For electric machines with a distributed secondary system with electromagnetic excitement (electromagnetic damper) and hollow nonmagnetic rotor, with pole number $p = 1$; $k = 1$ with geometrical ratios: the relation of a nominal air gap to electric machine polar division $\frac{\delta}{\tau}$ =0,025÷0,05 and $\frac{a}{\tau}$ =0,25÷0,5; $\varepsilon = 0{,}2 \div 3$. The dependences presented in fig. 6.

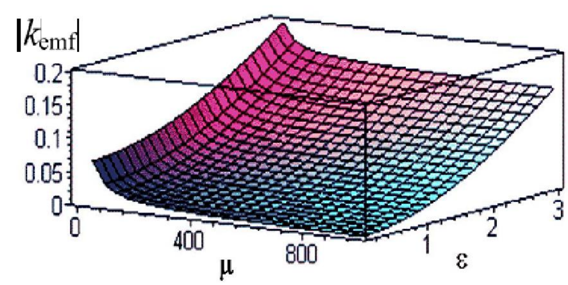


Figure 6 – The electric machines with the distributed secondary system external magnetic field coefficient module dependence from Reynolds magnetic number and from external magnetic conductor magnetic permeability

The technological and operational factors influence on EMF change at the pole number value $p = 2$, much more, than at pole number value $p = 1$. If EMF intensity amplitude change at value $p = 2$ makes 52%, at $p = 1$ it makes 35% (for induction motors and direct current electric machines nominal mode).

Conclusions.

Thus, it was developed mathematical apparatus confirmed by experimental data, which allows to synthesize MB controlling systems, MB diagnostics systems and HSTS diagnostics systems in uniform system.

The received results can be used in practice at the high-speed electrotechnical complexes on magnetic bearings engineering.

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