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Analysis of the influence of radial clearance in a bearing on its operating modes, taking into account mass and magnetic imbalance of the induction motor rotor

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Abstract

The article studies the problem of the journal motion of a three-phase induction motor rotor in a bearing. A simplified model of the journal motion is studied at the moment of journal separation and transition from the pendulum mode of journal motion to the impact mode. In this case, the elastic-damping properties of the bearing and the final rigidity of the rotor are ignored. The model takes into account the eccentricity of the rotor mass and the radial internal clearance of the bearing. In addition, the forces of unbalanced magnetic pull (UMP) caused by the magnetic eccentricity of the induction motor rotor, which is caused by the radial clearance of the bearing, are taken into account. It is analytically shown that the forces of UMP cannot be ignored, since even the rated clearance of bearings of low- and medium-power motors causes an unbalanced force commensurate with the force caused by the eccentricity of the mass. Using numerical modeling and simulation for a three-phase induction motor with a squirrel-cage rotor with a power of 11 kW and a speed of 3000 rpm, the dependences of the critical frequency of the journal separation from the bearing for different values of the mass eccentricity and radial clearance are presented. It is shown that without taking into account the UMP, an increase in the radial clearance leads to a decrease in the critical separation speed. In this case, a bearing with a passport radial clearance is able to switch to the mode of periodic impacts of the journal at a speed lower than the nominal speed of rotation of the rotor with an acceptable eccentricity. Taking into account the UMP, on the contrary, it significantly increases the value of the critical separation speed. At the same time, it is necessary to take into account that with an increase in UMP, the radial load on the bearing also increases, which in turn leads to increased wear of the bearing.

Keywords: Bearing internal clearance, Induction motor, Unbalanced magnetic pull, Mass eccentricity, Bearing vibration

Introduction and review of publications

When the rotor of an induction motor rotates, dynamic forces caused by rotor imbalance act on its pins. In general, unbalance can be caused by mass eccentricity, rotor deflection, and magnetic eccentricity. Unbalanced dynamic forces act on the bearings, causing increased bearing wear [1, 2].

According to researchers, more than 40% of induction motor failures are related to bearings [1]. During operation of rotor machines, radial clearances in rolling bearings increase, which leads to reduction of design values of critical shaft speeds [2, 3]. Excessive clearance can cause vibration at the fundamental train frequency (FTF) as the rolling elements accelerate and decelerate through the load zone which can result in large impact forces between the rolling elements and cage pockets. Also outer race defects and roller defects can be modulated with the FTF fundamental frequency [4]. Several researchers have studied the increase of bearing loads due to Unbalanced Magnetic Pull (UMP) [5-7]. It has been shown that the additional bearing loads are affected by curved eccentricity and the axial variation of eccentricity, and this can shorten the lifetime of the bearing.

It is known that, depending on the dynamics, bearings can operate in three modes: the mode of pendulum oscillations, the mode of periodic journal impacts on the bearing, and the mode of journal movement around the bearing circumference, in which the journal rolls with slippage [8-10]. The most dangerous is the second mode, the impact mode of bearing operation, which occurs as a result of the journal separation from the bearing. This causes rapid bearing failure. The journal separation from the bearing occurs at a certain frequency, the value of which depends on the geometric and mass parameters of the bearing and rotor. Therefore, the criterion for smooth, reliable operation of the rotor of an induction motor is a rotor speed that is less than the critical speed that occurs when the journal separates from the bearing.

The issue of the stability of operating modes of bearings with radial clearance is well studied [11, 12, 13]. Researchers use the Hertz theory, models with elastic and elastic-plastic contact [14, 15]. The issue of modeling the dynamics of bearings with defects has also been well studied [16-19]. However, most studies on bearing failures do not take into account the peculiarities of electric motors, such as unbalanced magnetic pull (UMP) on the rotor of a three-phase induction motor.

Aims of the paper

This paper analyzes the effect of internal radial clearance in a bearing of a three-phase induction motor on the occurrence of unbalanced forces and the conditions for the emergence of an undesirable shock mode of bearing operation.

Problem analysis and model justification

Let's estimate the actual radial internal clearance of a radial single row bearing of an 11 kW induction motor with a rated speed of 3000 rpm. According to ISO 5753, the internal clearance of a 6208 ZZ-C3 deep groove ball bearing is 15...33 μm. It is known that average bearing wear can lead to a 100% increase in the nameplate clearance. The actual clearance consists of the nameplate clearance and the clearance caused by elastic deformation. For stiffness $5{,}52 \cdot 10^7$ N/m, under the influence of rotor gravity and imbalance from the permissible mass eccentricity of 20 μm at the nominal speed ω=304 rad/s, the gap will additionally increase by 26,4 μm [20]. Thus, the total gap of the worn bearing during operation of the motor under consideration is about 2Δ=56…92 μm and can lead to a significant unevenness of the air gap δ between the rotor and stator of the induction motor (Fig. 1). In particular, for the engine under study, the average air gap is δ_0=450 μm. The variable unevenness of the air gap, called dynamic eccentricity, causes a change in the bearing's restoring force, which leads to wear. The permissible magnetic eccentricity of the rotor in question is 10%. In the event of improper motor assembly, thermal deformation of the rotor, severe wear of the bearing during operation, and an increase in its clearance, the magnetic eccentricity may increase, increasing dynamic unbalanced forces that further accelerate bearing failure.

Research methodology

Mathematical modeling of the problem of journal movement in a bearing

To create a simplified mathematical model of the journal dynamics in a bearing with an internal radial clearance 2Δ we neglect the elastic-damping properties of the bearing and rotor. We assume that the rigid rotor rotates in rigid supports, and the centrifugal forces acting on it are caused only by mass and magnetic eccentricity. This assumption is valid for a significant number of low- and medium-power induction motors. Let's also assume that the unbalanced magnetic pulling forces are applied in the geometric center of the rotor and result from a reduction of the air gap between the stator and rotor by the value $\Delta/2$, which is equal to half the radial displacement of the journal in the bearing of the gap in the bearing Δ. Then the minimum air gap formed is equal to $\delta_{\min} = \delta_0 - \Delta/2$, the maximum is equal to $\delta_{\min} = \delta_0 + \Delta/2$. In the following, we will assume that the angular position of the minimum air gap between the stator and rotor δ_{min} and the angular position of the journal are the same and equal to the angle ψ. The resulting magnetic eccentricity of the rotor is equal to $\left(\delta_{\max} - \delta_{\min}\right)/2 = \Delta/2$.

Let a rotor with mass eccentricity e rotate with angular speed ω. At a certain moment of the pendulum mode, the journal occupies the position in the bearing shown in Fig. 2. Due to the clearance Δ the movement of the journal relative to the bearing consists of a rotational movement with a speed ω and angular oscillations determined by the angle ψ. The speed of the journal movement along the bearing is equal to $\Omega = \dfrac{d\psi}{dt}$.

Forces act on the journal: gravity mg, centrifugal force of the trunnion movement $m\Omega^2\Delta$, tangential force of inertia $m\dot{\Omega}\Delta$, centrifugal force due to rotor unbalance $m\omega^2 e\cos\left(\omega t - \psi\right)$, friction force F, interaction force between the journal and bearing R, projections of the unbalanced magnetic pull force F_{UMP}.

The equilibrium condition implies that

$$mg\cos\psi + m\Omega^2\Delta + m\omega^2 e\cos\left(\omega t - \psi\right) + F_{UMPx} - R = 0\,, \tag{1}$$

$$-m\dot{\Omega}\Delta - mg\sin\psi + m\omega^2 e\sin\left(\omega t - \psi\right) + F + F_{UMPy} = 0\,, \tag{2}$$

where g is the acceleration of free gravity; m is the reduced mass of the rotor; ψ is the angular displacement of the journal from the vertical equilibrium position; Ω is the journal movement speed along the bearing; Δ is half the bearing clearance; F is the friction force; R is the bearing reaction force; F_{UMPx}, F_{UMPy} are projections of the unbalanced magnetic pulling forces on the axes Ox, Oy, respectively.

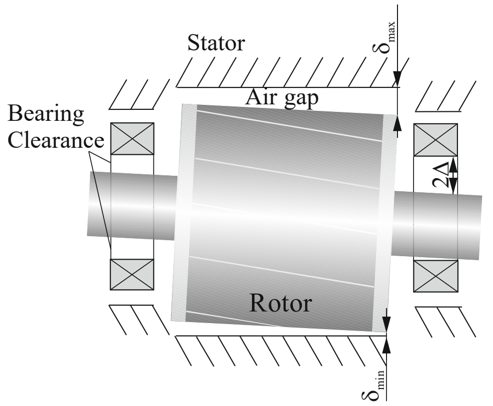

Fig. 1. Formation of an uneven air gap between the stator and rotor

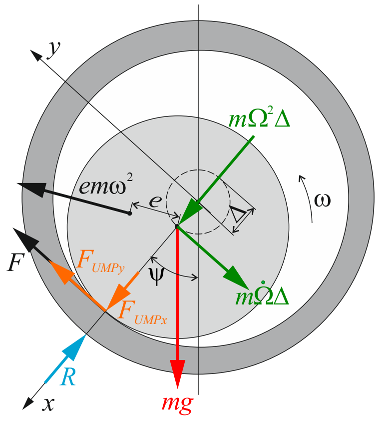

Fig. 2. Diagram of the forces acting on the journal in the bearing

Assuming a constant rotational speed ω=const we use the theoretical expressions proposed in [21, 22] to estimate the UMP force (Fig. 4). UMP is highly nonlinear. Without loss of generality, let us consider the UMP of a bipolar motor. The projections of the unbalanced magnetic pulling forces on the given coordinate axes for the number of pole pairs p=1 are approximately defined as

$$\begin{array}{ll} F_{UMPx} = f_1 + f_2\cos 2\omega_e t, & f_1 = 0.25Rl\pi\mu_0^{-1}F_j^2\left(2\Lambda_0\Lambda_1 + \Lambda_1\Lambda_2 + \Lambda_2\Lambda_3\right), \\ F_{UMPy} = f_2 \sin 2\omega_e t, \quad \text{де} & f_2 = 0.125Rl\pi\mu_0^{-1}F_j^2\left(2\Lambda_0\Lambda_1 + \Lambda_1\Lambda_2 + \Lambda_2\Lambda_3\right), \end{array} \qquad (3)$$

where ω_e is the angular frequency of the power supply of the motor stator windings, $\omega_e = \omega(1-s)^{-1}$, s is the slip of the motor; f_1, f_2 are the amplitudes of the UMP components, R is the rotor radius; l is the rotor length; F_j is the amplitude of the fundamental harmonic of the rotor magnetomotive force (MMF) excitation; μ_0 is the absolute magnetic permeability of air; Λ_i Fourier coefficients in the record of the magnetic permeability of the air gap, which can be calculated as

$$\Lambda_i = \frac{\mu_0}{\delta_0}\frac{1+(1-\delta_{i0})}{\sqrt{1-\varepsilon^2}}\left(\frac{1}{1+\sqrt{1-\varepsilon^2}}\right)^i, \; i \geq 0. \qquad (4)$$

where $\varepsilon = \Delta/2\delta_0$ is the relative eccentricity, δ_0 is the average value of the air gap when the rotor is centered; δ_{i0} is Kronecker symbol.

The condition for journal separation from the bearing is R=0. Having differentiated (2) according to ψ and adding the result from (1), we have

$$\frac{d}{d\psi}\left(m\dot{\Omega}\Delta\right) = m\Omega^2\Delta + F_{UMPx}. \qquad (5)$$

Multiplying both parts of equation (5) by $\frac{d\Omega}{dt}$ and taking into account (3) and $\Omega = \frac{d\psi}{dt}$ after simplifications we have

$$d\left(\frac{d\Omega}{dt}\right)^2 = \frac{1}{2}d\left(\Omega^4\right) + \frac{f_1 + f_2\cos 2\omega_e t}{m\Delta}\cdot d\left(\Omega^2\right), \qquad (6)$$

After integrating both parts, we have

$$\left(\frac{d\Omega}{dt}\right)^2 = \frac{1}{2}(\Omega)^4 + \frac{f_1 + f_2\cos 2\omega_e t}{m\Delta}\cdot \Omega^2 + \frac{f_2}{m\Delta}\int \Omega^2 d\left(\cos 2\omega_e t\right) + C. \qquad (7)$$

Let us find the integration constant C from the initial conditions. Suppose that at the initial moment t=0 the journal has an angular displacement from the vertical position ψ_0. This can only be accomplished when the journal speed is very high. Hence, we have the initial condition: at t=0 ψ=$\propto$. Analyzing (10), it is clear that the term on the right-hand side $\frac{1}{2}(\Omega)^4$ is asymptotically increasing much faster than the other terms and the latter can be neglected. With sufficient accuracy, equation (7) can be simplified to the form

$$\left(\frac{d\Omega}{dt}\right)^2 = \frac{1}{2}(\Omega)^4. \tag{8}$$

By integrating, we have

$$\Omega = \frac{\sqrt{2}}{t} \tag{9}$$

Since $\psi(t)$ has a break at t=0, integrating expression (11) using the Dirac delta function, we obtain the value of the journal separation angle from the bearing [8]

$$\psi_{cr} = \sqrt{2}\int_0^{t_{cr}} \delta t dt = \sqrt{2}\,. \tag{10}$$

According to (10) the trunnion separation angle is equal to ≅81° and does not depend on the unbalance forces caused by the mass and magnetic eccentricity.

Analysis of (1) shows that the condition for journal separation is R=0, which is possible only when the condition

$$m\omega^2 e\cos(\omega t-\psi)+F_{UMPx} < 0\,. \tag{11}$$

Considering what $f_1 \geq 0$ is an integral part of the zero frequency, we have

$$\cos(\omega t-\psi)+\frac{f_2}{m\omega^2 e}\cos\left(\frac{2}{1-s}\omega t\right) < 0\,. \tag{12}$$

Special cases of dependence (12).

1. The component force of the UMP of a double electric frequency is small compared to the unbalanced force from the mass imbalance $f_2 \ll m\omega^2 e$:

$$\cos(\omega t-\psi) < 0 \Rightarrow \frac{\pi}{2} < \omega t-\psi \leq \frac{3\pi}{2}\,. \tag{13}$$

The smallest value of the unbalanced force corresponds to the condition $\omega t-\psi = \pi$, hence the critical rotor speed is equal to

$$\omega_{cr} = \frac{\pi+\sqrt{2}}{t_{cr}}\,. \tag{14}$$

After substituting expression (14) into (1), we have the value of the separation time t_{cr} . Using t_{cr} , the critical rotor speed can be found from the expression:

$$\omega_{cr} = \frac{\left(\frac{\pi}{\sqrt{2}}+1\right)\sqrt{\cos\sqrt{2}+\frac{f_1}{mg}}}{\sqrt{\frac{\left(\pi+\sqrt{2}\right)^2 e}{2\Delta}-1}}\cdot\ \omega_p\,, \tag{15}$$

where $\omega_p = \sqrt{\frac{g}{\Delta}}$ is frequency of pendulum oscillations of the journal.

Under this condition $\Delta = 0.5\left(\pi+\sqrt{2}\right)^2 e$ we have $\omega_{cr} \to \infty$ and the pendulum mode is ensured at any speed without journal separation.

Consequently, the component of the unbalanced magnetic pulling force of the zero electric frequency increases the value of the critical frequency of rotor journal separation from the bearing.

The analysis of the magnitude of the UMP forces for the considered induction motor shows that the condition is fulfilled only for very small values of Δ<1 μm, which are not encountered in practice, so dependence

(15) has no practical significance. This confirms the need to take into account the UMP when analyzing the dynamics of induction motor bearing supports.

2. The UMP force component of the double electric frequency is significantly higher than the unbalanced force from the mass imbalance, we have $f_2 \gg m\omega^2 e$:

$$\cos\frac{2}{1-s}\omega t < 0 \Rightarrow \frac{\pi}{2} < \frac{2}{1-s}\omega t \le \frac{3\pi}{2} . \tag{16}$$

Assuming that the separation occurs at the lowest value of f_2, we have $2(1-s)^{-1}\omega t = \pi$, hence the critical rotor speed is equal to

$$\omega_{cr} = \frac{\pi}{2t_{cr}}(1-s) . \tag{17}$$

Substituting the value of (17) into (1), we have the value of the separation time t_{cr} . Using t_{cr} , the critical rotor speed can be found from the expression:

$$\omega_{cr} = \frac{\pi(1-s)}{2\sqrt{2}}\sqrt{\frac{f_2-f_1}{mg} - \cos\sqrt{2}} \cdot \omega_p . \tag{18}$$

The analysis of the components of the UMP force in (3) in the case of the condition $f_2 \gg m\omega^2 e$ shows that it is always $f_2 - f_1 \le 0$, and therefore dependence (18) cannot be fulfilled, i.e., the pendulum mode of bearing operation never goes into the shock mode.

We analyze the general case of dependence (12) using numerical methods.

Numerical experiment and simulation results

To change from the pendulum mode to the impact mode, the eccentricity e of the rotor mass must be sufficient to make the unbalanced force $m\omega^2 e$ caused by it exceed the vector sum of the forces F_{UMP} and mg . This condition can be investigated using the example of a specific induction motor. An 11 kW motor was chosen for modeling The main characteristics of the motor are shown in Table 1. The simulation was carried out in the *Simulink* environment of the *MATLAB* mathematical package.

Table 1

Parameters of the three-phase motor

Notation	Description	Value
	Motor data	
n	Synchronous speed (rpm)	3000
s	Rated slip	0,033
R	Radius of the rotor (mm)	63,5
l	Length of the rotor (mm)	130
m_r	Mass of the rotor (kg)	14,22
δ_0	Mean air-gap length (mm)	0,45
μ_0	Air permeance (H/m)	$4\pi\cdot10^{-7}$
F_j	Fundamental MMF amplitude of the rotor excitation current (A)	358
p	Number of pole pairs	1
e	Permissible eccentricity (μm)	20

The radial force of pressing the journal against the bearing is found from (1):

$$R = mg\cos\psi + m\Omega^2\Delta + m\omega^2 e\cos(\omega t - \psi) + F_{UMPx} . \tag{19}$$

At the moment of journal separation from the bearing, we have: R=0, $\psi = \sqrt{2}$, $\Omega = \sqrt{2}t^{-1}$ and the following relationship is fulfilled

$$g\cos\sqrt{2} + \Delta\frac{2}{t^2} + \omega^2 e\cos(\omega t - \psi) + \frac{f_1}{m} + \frac{f_2}{m}\cos\left(\frac{2}{1-s}\omega t\right) = 0 . \tag{20}$$

Comparative dependences of the critical separation velocity on the mass eccentricity at different values of the radial air clearance in the bearing without and with consideration of UMP forces are shown in Figs. 3, 4.

An increase in the radial clearance in the bearing leads to an increase in the critical journal separation rate. But at the same time, the radial force increases significantly.

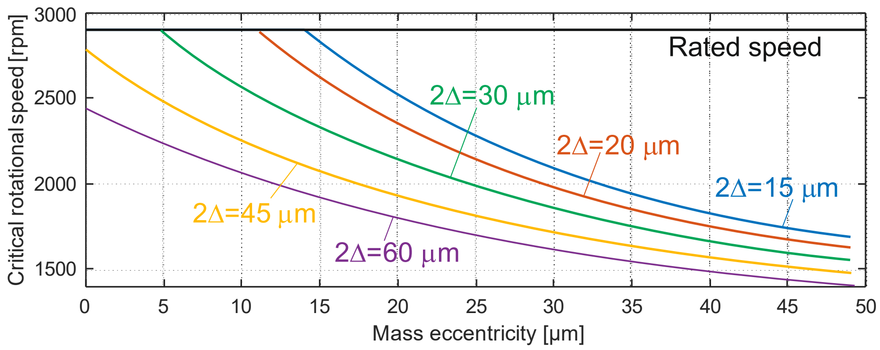

Fig. 3. Dependence of the critical separation speed on the mass eccentricity at different values of the radial air gap in the bearing without taking into account the UMP forces

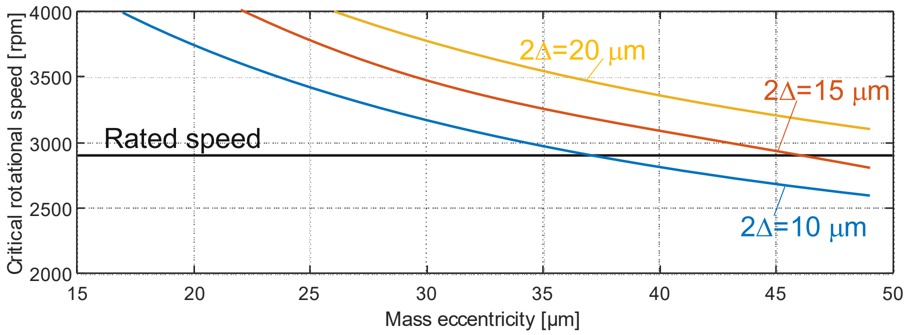

Fig. 4. Dependence of the critical separation speed on the mass eccentricity at different values of the radial air gap in the bearing, taking into account the UMP forces

Research conclusions and recommendations for further research in this area

In addition to mechanical forces, electromagnetic forces, in particular, UMP forces, affect the magnitude of the rotor journal pressing force against the bearing in a three-phase induction motor. Since the UMP are applied at the point of the smallest air gap between the stator and rotor and increase with the magnetic eccentricity, they have a significant impact on the critical rotor speed at which the journal separation from the bearing occurs.

Neglecting the UMP phenomenon, it can be concluded that an increase in the radial clearance in the bearing leads to a decrease in the critical journal separation speed and a faster transition from the pendulum to the dangerous shock mode of bearing operation. This shock mode is more dangerous because it leads to faster wear.

The presence of radial bearing clearances indicates that it is unlawful to neglect the UMP phenomenon when analyzing a three-phase induction motor. The UMP phenomenon creates additional forces of double electrical frequency that press the journal against the bearing. An increase in the radial clearance in the bearing leads to an increase in the critical journal separation speed. But at the same time, the radial force acting on the bearing increases significantly. The pendulum mode of operation is preserved, but the load on the bearing increases significantly, which in turn leads to accelerated one-sided wear.

Despite the fact that the developed model is approximate and does not take into account the elastic-damping properties of the bearing and the flexibility of the rotor, important results have been obtained. The analysis of the bearing assembly in accordance with the Hertzian contact stress theory will make it possible to refine the results obtained here.

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Горошко А.В., Зембицька М.В. Аналіз впливу радіального зазору у підшипнику на режими його роботи з врахуванням масового і магнітного дисбалансу ротора асинхронного двигуна

У статті досліджується проблема руху цапфи ротора трифазного асинхронного двигуна в підшипнику. Досліджується спрощена модель руху цапфи в момент відриву цапфи та переходу від маятникового режиму руху цапфи до ударного режиму. Модель враховує ексцентриситет маси ротора та радіальний внутрішній зазор підшипника. У моделі не враховуються пружно-демпфувальні властивості підшипника та кінцева жорсткість ротора. Крім того, враховуються сили незбалансованого магнітного тяжіння, викликані магнітним ексцентриситетом ротора асинхронного двигуна, який зумовлений радіальним зазором підшипника. Аналітично показано, що силами незбалансованого магнітного тяжіння не можна нехтувати, оскільки навіть номінальний зазор підшипників двигунів малої та середньої потужності викликає незбалансовану магнітну силу, порівнювану з силою, викликаною ексцентриситетом маси. За допомогою чисельного моделювання та симуляції для трифазного асинхронного двигуна з короткозамкненим ротором потужністю 11 кВт та синхронною швидкістю 3000 об/хв отримано залежності критичної частоти відриву шийки від підшипника для різних значень ексцентриситету маси та радіального зазору. Показано, що без урахування магнітного ексцентриситету ротора збільшення радіального зазору призводить до зменшення критичної швидкості відриву. У цьому випадку підшипник з паспортним радіальним зазором здатний переходити в режим періодичних ударів шийки на швидкості, нижчій за номінальну швидкість обертання ротора з допустимим ексцентриситетом. З урахуванням магнітного дисбалансу, навпаки, зростання радіального зазору викликає підвищення критичної швидкості відриву. Водночас необхідно враховувати, що зі збільшенням радіальної магнітної сили збільшується і радіальне навантаження на підшипник, що, в свою чергу, призводить до збільшення зносу підшипника.

Ключові слова: радіальний зазор підшипника, асинхронний двигун, незбалансоване магнітне тяжіння, ексцентриситет маси, вібрація підшипників