INVESTIGATION OF THE CHARACTERISTICS OF FRICTION PAIRS IN THE OSCILLATION REGIME: THE METHOD AND IMPLEMENTATION OF THE MECHATRONIC OSCILLATORY SYSTEM

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Abstract: An oscillatory method for identifying the characteristics of friction pairs of drive systems is considered. It is based on the use of mechatronic systems with a controlled "electric spring" and allows us to investigate dissipative characteristics in the regime of forced steady oscillations in the operating frequency range, with low laboriousness and high accuracy. The mechatronic oscillatory system is realized on the basis of a synchronous electric machine with permanent magnets on the rotor and a control system for the oscillation regime. The peculiarity of the method and the technical means realized on its basis is that the determination of the moment of frictional forces occurs not in the static state of the system, but under conditions close to the operational ones, i.e. with continuous motion by changing the direction of motion.

Keywords: friction, oscillations, bearing, engine, mechatronic, measuring, model, system

1. INTRODUCTION

Provision of reliable and safe functioning of industrial machinery mainly depends on quality of functioning of bearings and moving couples [1, 2]. Characteristics of this component determines an dissipative, vibration, vibro-acoustic, noise, thermaus and other effects, appearing on the contact surface of moving mechanical couples [3, 4]. Experience of exploitation of electric drives reveals that main part of malfunctions are caused by failures of the bearings [5]. For example, more than 25% of emergency cut off of pumps and compressors are caused by bearing failure in electric motors. Taking this into account, extensive testing and checking of bearings in electric motors in assembled device are very important. Technology of testing without dismantle the device corresponds to modern strategy of technical systems reliability management. Its provides for choosing and implementation of control actions, depending on real technical condition of the system, climatic and other outer conditions, i.e. by factors, presents at the time of taking decision about condition of the system.

Results of the theoretical and experimental researches testifies about the fact that most reliable method of diagnostics of the machinery and drive systems are testing of its bearing assemblies by mean of characteristics of resistance to torque. Particular interest represented not only by static value of torque resistance, but also by instantaneous values of this dynamic variable in various exploitational modes [6, 7].

In this paper an oscillating method of testing of friction pairs of machinery discussed. This method relies on using an electromechanical systems with controlled “electrical spring”, and allows to probe the characteristics of friction in dynamic modes of operation, and lets to obtain a dissipative characteristics for given working conditions [8, 9]. Testing with periodical object move allows to identify bearings failure of any kind faster than traditional static methods.

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2. CONTROLLED ELECTROMECHANICAL OSCILLATING SYSTEM

Functional diagram of electromechanical system are shown at figure 1. It serves as a basis for technical implementation of the different measuring oscillating systems and contain an AC drive M with stator windings, active rotor and mechanical load. Control system consists of an adjustable DC reference source, adjustable DC source, two DC and AC amplifiers, voltage, current and speed sensors and a controller. One of the windings (A) of the stator of electric drive M, which is a standard two-phase or three-phase motor or special electric motor, is connected to the output of the DC amplifier. Another winding (B) of a two-phase motor (or another two windings of a three-phase motor in serial connection) has a spatial shift relative to the first by an angle of \( \frac{\pi}{2} \), connected to the output of a harmonical oscillations amplifier.

With such connection of windings of an AC motor in the gap between the stator and the rotor appears an oscillating magnetic field. Active rotor induces an constant magnetic field. Interaction between an oscillating and constant magnetic fields leads to an alternating moment that causes the rotor to oscillate. In this case, the parameters of electrical and mechanical oscillations are functions of the characteristics of the mechanical part of the system: the moment of inertia, the friction characteristics, and rigidity [10]. The nonlinear and non-stationary dependence of the friction torque on velocity is of primary interest in evaluating the tribological properties of friction pairs.

The stator winding connected to a direct current source performs the function of an "electric spring", which places the active rotor in its initial position in the absence of an alternating current in the other stator winding. The "stiffness" of the electric spring is determined by the magnitude of the DC current in the winding, which creates a proportional synchronizing moment, returning the rotor to its initial position.

![Functional diagram of an electromechanical oscillatory system with CAN BUS.](image)

Thus, the parameters of the oscillatory motion of the rotor are determined by the amplitude and frequency of the master oscillator and the value of the direct current in winding A (the rigidity of the electric spring). The regulation of the direct current makes it possible in a simple way to control the rigidity of the electric spring and, consequently, the parameters of the oscillations.

Measurement, recording and processing of oscillations in the electrical and mechanical subsystems of the drives is carried out using a computer measuring system. Data from the outputs of the digital current, voltage and speed sensors via the CAN bus is transmitted to the controller and the computer. The digital system allows you to measure the amplitudes of current and voltage with an error of not more than 0.5%. The angle of rotation is measured with a digital encoder. The error does not exceed 0.1 deg, until the amplitude of the rotor oscillations not more than 360°. The error in measuring the phase shift and the frequency for all signals does not exceed 0.5%. The decomposition of signals into a harmonic series is carried out by the Levenberg-Marquardt algorithm. The computer system allows...
you to register the processes of changing voltage, current, angular velocity and rotational angle of the rotor, and data processing, including spectral analysis, calculations of the phase shifts, angular acceleration, energy characteristics, etc.

Equations, describing an oscillating system [10]:

\[
\begin{align*}
J \frac{d^2 \theta}{dt^2} - k_A \psi_A \cos \theta + k_B \psi_B \sin \theta &= F(M, M_f, \Omega); \\
L_A \frac{d i_A}{dt} + R_A i_A + k_A \psi A \cos \theta &= U_A(t); \\
L_B \frac{d i_B}{dt} + R_B i_B - k_B \psi B \sin \theta &= U_B(t).
\end{align*}
\]

In this equations, \( J \) – moment of inertia of the drive at the motor shaft; \( \theta \) – turn angle of the rotor; \( \psi \) – angular speed of the rotor, \( \psi = \dot{\Omega} \); \( M \) – electromagnetic moment; \( M_f = M_f(\Omega) \) – moment of friction force; \( \psi \) – the flux coupling of the stator phase with the field of the inductor (rotor) with the coincidence of their axes; \( k_A \) and \( k_B \) – coefficients of the construction; \( L_A, L_B \) – inductance of the corresponding phases of the stator of the motor; \( R_A, R_B \) – active resistances of the windings of the motor; \( U_A(t) \) and \( U_B(t) \) – voltages on the windings of phases A and B respectively; \( F(M, M_f, \Omega) \) – non-linear dependence representing the mechanical motion of the control object caused by the action of the electromagnetic moment of the motor, the torque of the electric spring and the moment of load resistance, taking into account the static friction force.

Non-linear dependence of friction force from angular speed approximated by the equation:

\[
M_f(\Omega) = M_{f0} e^{-|\frac{\Omega}{\beta}|} \frac{\text{sgn} \Omega + \chi \Omega}{2}.
\]

In this equation, \( \beta \) – coefficient, representing semi-liquid friction; \( \chi \) – coefficient of viscous friction; \( M_{f0} \) – moment of static friction force.

Function \( F(M, M_f, \Omega) \) has the form of

\[
F(M, M_f, \Omega) = \begin{cases} 
M - M_f & \text{at } \Omega \neq 0; \\
0 & \text{at } |M| < |M_{f0}| \text{ and } \Omega = 0.
\end{cases}
\]

Structural diagram of the oscillating system for the case of \( i_B = I_0 = \text{const} \), are shown at the figure 2.

Denoted on this diagram: \( H_a(s) \) – amplifier transmission function; \( H_c(s) \) – corrector device transmission function. As the correcting device, a first-order inertial unit is used.

At Figure 3 are shown the process diagrams obtained as a result of simulation of the oscillation system using Simulink at the following parameters values: \( \psi k_A = \psi k_B = 0.45 \text{Nm/A} \); \( I_0 = 1 \text{ A} \); \( R_A = R_B = 1 \text{ Ohm} \); \( L_A = L_B = 0.05 \text{ H} \); \( J = 0.1 \text{ kgm}^2 \); \( M_{f0} = 0.2 \text{ Nm} \); \( \beta = 1.5 \text{ s/rad} \); \( \chi = 0.01 \text{ Nms/rad} \); \( H_a(s) = 1 \). Initial conditions are: \( \theta(0) = 0.5 \text{ rad} \). Transmission function of the corrector device has the form of \( H_c(s) = \frac{2}{2s + 1} \).

3. ENERGY PROCESSES IN THE OSCILLATORY SYSTEM

Summary momentum of the friction forces in the system are calculated by the equation:

\[
M_f = J_0 \omega_0^2 \cos \Omega t - M_a(t) + M_c(t).
\]
Here \( J \) – momentum of inertia of the moving part of the measuring system; 
\( \theta_m \) – amplitude of the mechanical oscillations of the rotor; 
\( \Omega \) – frequency of the mechanical oscillations of the rotor; 
\( M_a(t) \) – additional momentum of the electrical motor, caused by the polyharmonic current of the stator winding; 
\( M_e(t) \) – electromagnetic momentum of the electric motor.

To calculate the momentum of the static friction force \( M_{f0} \), i.e. when the speed passes through zero, for the case of the harmonic law of the distribution of the magnetic field in the gap between the rotor and the stator, are used following equation:

\[
M_{f0} = J\theta_m\Omega^2 - M_{am}\sin\theta_m + M_e(t),
\]

(5)

Here \( M_{am} \) – maximum value of an additional momentum.

Additional momentum \( M_a(t) \) in the case of a sinusoidal induction distribution in the air gap of the considered design of the magnetic system, is calculated from the known relationship:

\[
M_a(t) = M_{am}\sin\theta.
\]

(6)

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**Figure 2.** Structural diagram of the electromechanical oscillatory system.

**Figure 3.** Processes in the electromechanical oscillatory system.

Equation (4) makes it possible to perform a full calculation of the friction characteristics with the
harmonic law of motion of the mechanical part of the system. All parameters and dynamic variables are measured in a steady dynamic mode, the results can be repeated many times. Therefore, the oscillating method provides increased accuracy of measurement of the \( M_f (\Omega_m) \). In addition, it is possible to determine the friction characteristics over a wide range of frequencies by varying the amplitude of the oscillations \( \theta_m \) and the stiffness of the electrical spring by variations in the electrical parameters of the control system.

An amplitude \( \theta_m \) of rotor oscillations in equation (4) may be measured experimentally or calculated by amplitude-frequency characteristic of the drive:

\[
a_0 \alpha^4 + a_3 \alpha^3 + a_2 \alpha^2 + a_1 \alpha - M_e^2 = 0, \tag{7}
\]

Here \( a_0 = -\frac{1}{24} M_m^2 \); \( \alpha = \theta^2 \); \( a_1 = \frac{1}{3} M_m \left( M_m - \frac{1}{4} J_\omega^2 \right) \); \( a_2 = -M_m \left( M_m - J_\omega^2 \right) \); \( a_3 = \left( M_m - J_\omega^2 \right)^2 + 4h^2 J^2 \omega^2 \).

In given equations (7) values \( M_m \) and \( J \) characterize at maximum synchronizing momentum of the motor and its momentum of inertia, respectively. They are preliminarily calculated from the experimental data obtained by the developed oscillatory methods.

In accordance with the above procedure, the dissipative characteristics of the bearing assemblies of the synchronous motor I6615 with permanent magnets were experimentally investigated and calculated for the following values of the dynamic variables:

a) \( U_A = 15 \text{ V}; \ I_A = 150 \text{ mA}; \ I_B = 0.5 \text{ A}; \ \theta_m = 90^\circ; \ f = 8.6 \text{ Hz}; \)

b) \( U_A = 12.3 \text{ V}; \ I_A = 103 \text{ mA}; \ I_B = 0.5 \text{ A}; \ \theta_m = 88^\circ; \ f = 9.05 \text{ Hz}. \)

Dynamic friction characteristics calculated on the basis of the obtained data are presented in Figure 4 a and Figure 4 b.

**Figure 4.** Examples of dynamic friction characteristics of the bearings of the motor I6615 with different variables values: a) \( U_A = 15 \text{ V}; \ I_A = 150 \text{ mA}; \ I_B = 0.5 \text{ A}; \ \theta_m = 90^\circ; \ f = 8.6 \text{ Hz}; \)

b) \( U_A = 12.3 \text{ V}; \ I_A = 103 \text{ mA}; \ I_B = 0.5 \text{ A}; \ \theta_m = 88^\circ; \ f = 9.05 \text{ Hz}. \)

**4. CONCLUSION**

The oscillatory method for studying the characteristics of friction pairs provides experimental determination of nonlinear and non-stationary drag forces in a dynamic mode and, as a result, an increase in the reliability of tribological models. An important advantage of the method considered is the possibility of diagnosing friction nodes without disassembling the device. The obtained theoretical and experimental data confirm the wide possibilities of the developed method for identification of
The obtained experimental quasi-static friction characteristics are in good agreement with the well-known Stribeck curve, and the presented dissipative dynamic characteristics clearly demonstrate the essential difference between these dependences and the known static ones, contribute to refinement of the analytical approximation of the nonlinear frictional characteristics for various devices, nodes, drives in corresponding modes of operation.

REFERENCES