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THE INFLUENCE OF PERMANENT MAGNETIC RINGS ON THE LOSS POWER, VIBRATION AND STABILITY OF VERTICAL ROTORS

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Abstract: *Lifting the vertical rotors by permanent magnets is an advanced technological solution for reducing energy losses in the supports. The disadvantage of this design is the instable interaction between the magnetic rings, which may destabilize the rotor oscillations. The performed research was focused on the development of computational procedures for analysis of energy losses in the supports of magnetically lifted vertical rotors mounted in rolling element bearings and on analysis of stability of their vibration in a wide range of operating speeds. The computational simulations proved efficiency of the magnetic suspension.*

Keywords: lifting vertical rotors, magnetic rings, energy losses reduction, vibration stability evaluation, floquet theory

1. Introduction

The advanced technological solution for reducing energy losses in the supports of vertical rotors consists in lifting the rotors by permanent magnetic rings (Jiang et al., 2014). The basic study on efficiency and properties of this design arrangement is reported in (Zapomĕl et al., 2017).

As the equilibrium position of two permanent magnets repelling each other is always unstable, the mutual interaction between the magnetic rings attached to the rotor and its outer bearing structure together with material damping of the shaft can arrive at instable oscillation of rotating machines.

This paper deals with modelling the permanent magnets and their implementation in the computational procedures for dynamical analysis of vertical rotors, for determination of the loss power in the rotor supports, and for evaluation of stability of their lateral vibration in a vast range of operating speeds. The developed mathematical models, the set up computational procedures, and extended knowledge on behaviour of magnetically lifted vertical rotors are the main contributions of the carried out research.

2. The investigated vertical rotor

The investigated rotor is vertical. It consists of a flexible shaft and of one massive disc (Fig. 1). The rotor is mounted in rolling element bearings embedded in the cage springs of classical squeeze film dampers. The rotor turns at constant angular speed and is loaded by its weight and by the disc unbalance.

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The upper rolling element bearing is a ball bearing, which implies it transmits the force both in the radial and axial directions. The lower bearing is a cylindrical roller one, which transmits the force only in the radial direction.

Two permanent magnetic rings are coupled with the rotor disc and the outer bearing structure. They are used to reduce the loading of the upper ball bearing caused by the rotor weight. The force acting between the rings is repelling, which arrives at lifting the rotor.

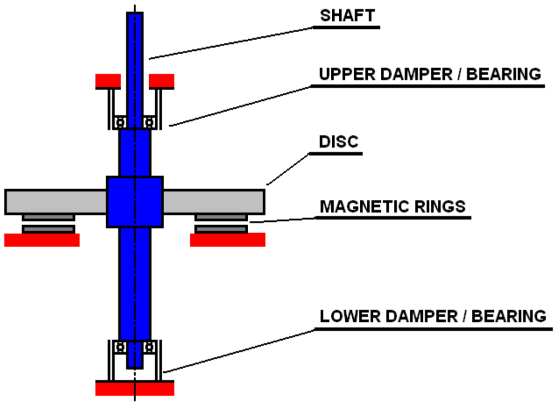

Fig. 1: The investigated vertical rotor.

3. Modelling the rotor and the magnetic rings

In the computational model the disc and the frame are represented by absolutely rigid bodies, the shaft by a beam body discretized into finite elements, and the squeeze film dampers with the bearings by springs and force couplings.

The equation of motion of the rotor expressed in the matrix form reads

$$\mathbf{M}\ddot{\mathbf{x}} + (\mathbf{B}_P + \mathbf{B}_M - \omega\mathbf{G})\dot{\mathbf{x}} + (\mathbf{K} + \omega\mathbf{K}_C)\mathbf{x} = \mathbf{f}_U + \mathbf{f}_H + \mathbf{f}_M\,, \tag{1}$$

$\mathbf{M}$, $\mathbf{G}$, $\mathbf{K}$, $\mathbf{K}_C$ are the mass, gyroscopic, stiffness, and circulation matrices, $\mathbf{B}_P$, $\mathbf{B}_M$ are the matrices of damping produced by the environment and the shaft material, $\mathbf{f}_U$, $\mathbf{f}_H$, $\mathbf{f}_M$ are the vectors of the unbalance, hydraulic, and magnetic forces, $\mathbf{x}$ is the vector of the system general displacements, ω is the angular speed of the rotor rotation, and $(\dot{})$, $(\ddot{})$ denote the first and second derivatives with respect to time.

The steady state solution of the motion equation was calculated by the trigonometric collocation method. Its stability was evaluated by employing the Floquet theorem. The procedure leads to setting up the transition matrix over the span of time of one period. The rotor vibration is stable if magnitudes of all its eigenvalues are less than 1.

The pressure distribution in the full oil film in the squeeze film dampers is governed by the Reynolds equation (Zapoměl, 2007 and Szeri, 1980). In areas where the pressure drops to a critical level, a cavitation takes place. The pressure of the medium is assumed to be constant there and equal to the pressure in the ambient space.

The magnetic rings are discretized into small volumes and each volume is considered to be a point magnetic dipole. The magnetic field produced by magnetic dipoles of the ring fixed to the stationary frame acts on the i-th magnetic dipole of the ring coupled with the disc by the force $\vec{F}_{MGi}$ and the force moment $\vec{M}_{MGi}$ (Knoepfel, 2000)

$$\vec{M}_{MGi} = \vec{m}_{MGi} \times \vec{B}_i\,, \tag{2}$$

$$\vec{F}_{MGi} = \left(\vec{m}_{MGi}\vec{\nabla}\right)\vec{B}_i\,. \tag{3}$$

$\vec{m}_{MGi}$ is the magnetic moment of the point dipole i and $\vec{B}_i$ is the magnetic induction of the magnetic field produced by the magnetic ring fixed to the rotor frame at location of the point dipole i.

The loss power in the bearings is given by product of the angular speed on the rotor rotation and the rolling resistance moment M_R (Bolek et al., 1989)

$$M_R = \left(X\, F_R + Y\, F_A\right) f_B \frac{d_H}{2} \,. \tag{4}$$

d_H is the diameter of the shaft journal, f_B is the rolling resistance coefficient, F_R, F_A are the radial and axial components of the force transmitted through the bearing and X, Y are the loading coefficients, the value of which depends on the bearing type (Bolek et al., 1989).

4. The results of the computational simulations

The main technological parameters of the studied vertical rotor system are: the rotor mass is 139 kg, the speed range of the rotor rotation is between 0 and 2000 rad/s, the outer/inner diameter/thickness of the magnetic rings are 320/200/20 mm and the magnets polarization is 0.9 T.

The dependence of the axial component of the magnetic force, by which the magnetic ring fixed to the stationary part acts on the rotor disc, on the width of the gap between the magnets is drawn in Fig. 2. The results show that to compensate the rotor weight by the magnetic force the distance between the magnetic rings must be 18 mm.

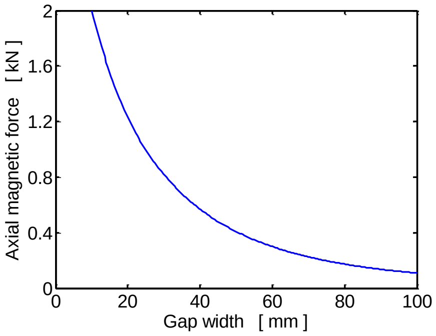

Fig. 2: Dependence of the axial magnetic force on the gap between the permanent magnets.

The frequency responses of rotor (the vibration amplitude of the disc centre) for the design variants without and with the permanent magnets are drawn in Fig. 3. The results show that the critical speed of the rotor is 542 rad/s and that the magnetic rings have almost no influence on the vibration amplitude. It implies magnetic stiffness of the permanet magnets is low relative to that of squeeze film dampers.

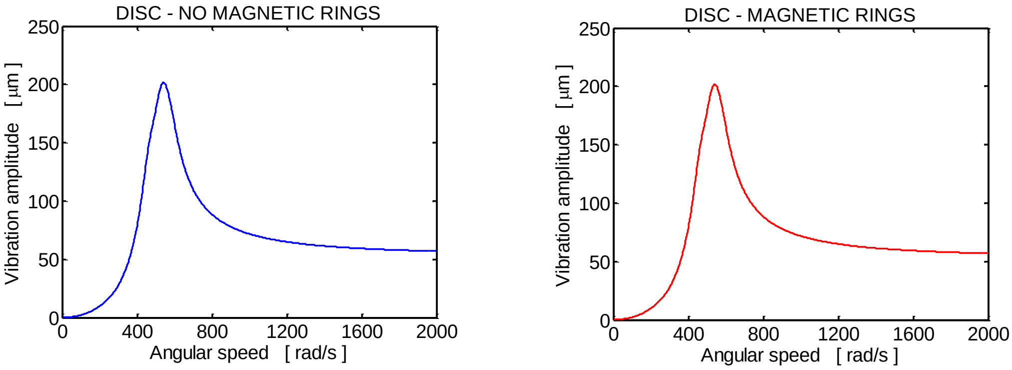

Fig. 3: Frequency response of the disc centre (left - without magnetic rings, right - with magnetic rings).

The dependence of the loss power in the top bearing (ball bearing) is depicted in Fig. 4. Lifting the rotor reduces the axial loading of the bearing, which evidently arrives at significant reduction of the loss power especially, in the ranges of higher angular velocity.

Fig. 5 shows the dependence of the stability factor, which is defined here as 1 - λ, where λ is the maximum eigenvalue of the transition matrix set up over the span of time of one period. The results of the simulations yield that the stability factor takes only positive values and goes down with raising velocity even if the decrease is not monotonous. The results give evidence that the magnetic rings do not destabilize the rotor vibration, which can be explained by large damping in the squeeze film dampers.

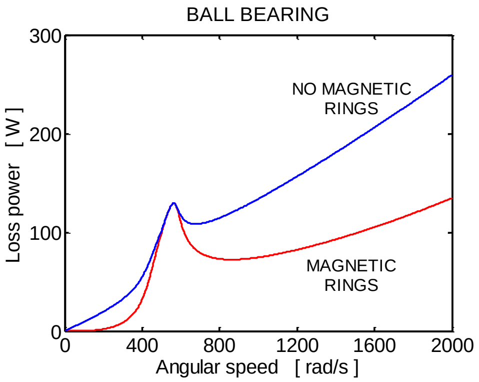

Fig. 4: Dependence of the loss power on the angular speed.

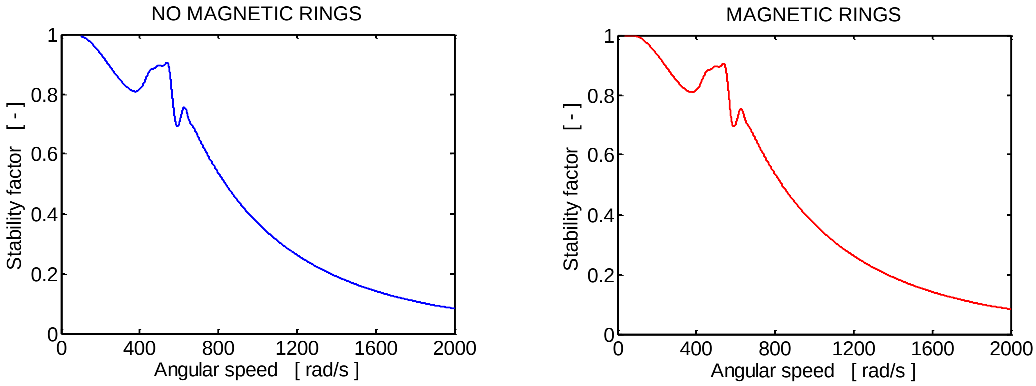

Fig. 5: Dependence of the stability factor on angular speed of the rotor rotation.

5. Conclusions

Lifting the vertical rotors by permanent magnets represents a simple design solution leading to reducing energy losses in the rotor supports. The mutual interaction between the magnetic rings and material damping of the shaft are the main sources, which may destabilize lateral oscillation of the vertical rotors. The performed analysis confirmed efficiency of application of the magnetic rings for reducing energy losses. It proved that in spite of the destabilization effects sufficient amount of damping in the rotor supports keeps the rotor vibration stable. The carried out computational simulations contributed to extending knowledge on operation of vertical rotors lifted by permanent magnets in a wide range of running speeds.

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