Journal of Sound and Vibration 370 (2016) 230–258

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Unstable force analysis for induction motor eccentricity

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ARTICLE INFO

Article history:
Received 14 May 2015
Received in revised form
21 January 2016
Accepted 22 January 2016
Handling Editor: H. Ouyang
Available online 8 February 2016

ABSTRACT

The increasing popularity of motors in machinery trains has led to an intensified interest in the forces they produce that may influence machinery vibration. Motor design typically assumes a uniform air gap, however in practice all motors operate with the rotor slightly displaced from the motor centerline in what is referred to as an eccentric position. Rotor center eccentricity can cause a radially unbalanced magnetic field when the motor is operating. This will results in both a radial force pulling the motor further away from the center, and a tangential force which can induce a vibration stability problem. In this paper, a magnetic equivalent circuit MEC modeling method is proposed to calculate both the radial and tangential motor eccentric force. The treatment of tangential force determination is rarely addressed, but it is very important for rotordynamic vibration stability evaluation. The proposed model is also coupled with the motor electric circuit model to provide capability for transient vibration simulations. FEM is used to verify the MEC model. A parametric study is performed on the motor radial and tangential eccentric forces. Also a Jeffcott rotor model is used to study the influence of the motor eccentric force on mechanical vibration stability and nonlinear behavior. Furthermore, a stability criteria for the bearing damping is provided. The motor radial and tangential eccentric forces are both curved fitted to include their nonlinearity in time domain transient simulation for both a Jeffcott rotor model and a geared machinery train with coupled torsional-lateral motion. Nonlinear motions are observed, including limit cycles and bifurcation induced vibration amplitude jumps.

1. Introduction and literature review

Motors are becoming increasingly popular in rotating machinery application. They have several advantages compared to traditional gas turbines, such as high efficiency and low cost. Motors are well known for mechanical torque generation from electrical energy, based on the theory of electromagnetic interaction. However, in reality, radial forces are produced along with the drive torque since no motor operates perfectly centered with a uniform air gap all around the circumferential direction. There are many reasons causing a non-uniform air gap, such as rotor center eccentricity due to shaft misalignment, which always happen in practice. A rotor center eccentricity can cause unbalance magnetic field when the motor is operating. This will results in both a radial force pulling the motor further away from the center, and a tangential force which can induce stability problem in a mechanical system. Both of these forces produce negative stiffness effects.

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http://dx.doi.org/10.1016/j.jsv.2016.01.045

The motor eccentricity problem has been studied in many research efforts. As early as in 1987, Belmans et al. [1] calculated the radial eccentric force for two pole induction machines and investigated the homopolar flux. In their calculation, the stator and rotor iron core were assumed to have infinite permeability, which resulted in magnetomotive force (MMF) drop only in the air gap. Also, the MMF along the air gap was assumed to be sinusoidally distributed, which meant only the fundamental component was considered. They wrote the nonlinear air gap permeance in Fourier series expansion. Then the energy method was used to calculate the radial eccentric force. Similar assumptions and motor modeling method was used in [2–6]. In [2], Guo et al. derived an analytical solution for the radial eccentric force using Maxwell stress tensor and concluded that the radial force included a constant component and an oscillatory component. A Jeffcott rotor was modeled to simulate the effect of the radial eccentric force. Pennacchi [3] derived a more accurate expression for the air gap length under eccentricity. A generator was modeled with 153 beam elements to study the dynamical behavior due to the radial eccentric force. In [4], Frosini et al. improved the model by including the tangential flux density which was ignored in the papers above. They calculated the average tangential stress from motor torque and used that in obtaining the tangential flux density. The radial eccentric force was calculated using the Maxwell stress tensor at no load condition. A four poles turbo generator was modeled to show the nonlinear effect of the radial eccentric force. Wu et al. [5] included the mass unbalance in a Jeffcott rotor based on the results of [2]. Im et al. [6] combined the electrical and mechanical equations by using Lagrange's equation with generalized force for a brushless DC (BLDC) motor. All these papers were only focused on the radial eccentric force and the two assumptions mentioned above may reduce the accuracy of the model. The first assumption (infinite iron core permeability) results in a bigger force than its actual value since the air gap MMF drop was over-estimated and the machine saturation was not taken into account.

Dorell [7] modeled a cage induction motor by using winding analysis and the radial eccentric force was studied. The distributed stator windings were written in Fourier series expansion and used to calculate the machine impedances. Radial eccentric force was obtained using Maxwell stress tensor method. Smith and Dorell [8,9] continued the study for paralleled winding and compared their results with experiments. Al-Nuaim and Toliyat [10] improved the winding analysis method by developing a modified winding function which included the influence of eccentricity on MMF distribution. The characteristic of motor torque was investigated, which helped in identifying the eccentric motor fault. This motor model with winding analysis included all the MMF space harmonics due to winding distribution. However, machine saturation was not included in the model.

Stoll [11] used the basic method of Swann [12] for a two pole turbogenerator and included rotor eddy current effects. In the model, an eccentric motor was transformed into a concentric case by coordinates mapping. Both radial and tangential flux density were calculated and used in Maxwell stress tensor calculation. Similar as the literatures mentioned above, this method still follows the same assumptions. Chen and Hofmann [13] analyzed the radial eccentric force of bearingless switched reluctance motors (BSRM) based on turn angle of rotor. Magnetic inductance of the air gap was calculated using an equivalent magnetic path. The equivalent system stiffness was also derived.

The finite element method (FEM) is also used for the motor eccentricity problem. Belahcen et al. [14] calculated the radial eccentric force of a synchronous generator for noise analysis. Tenhunen et al. [15] studied the motor eccentric force – both radial and tangential – when the motor rotor was in a whirling motion. Rodriguez et al. [16] investigated the radial Maxwell stress tensor and wrote it in a double Fourier series expansion of induction motors. Then the vibration pattern due to radial eccentric force was identified under rotor whirling. FEM is generally considered to have high accuracy for magnetic field prediction. However, Amrhein [17] compared the results from FEM to experiment, together with magnetic equivalent circuit method (MEC), and pointed out that the FEM did not predict well when the machine had saturation. Also, FEM is time consuming to mesh the machine and solve the Maxwell equations, especially for dynamic eccentric simulation.

Mechanical system stability was studied and its considerable influence was pointed out by several researchers. Wang et al. [18] derived the equations of motion (EOM) of a Jeffcott rotor model with unbalanced mass and radial eccentric force. The radial eccentric force was calculated using the energy method under same assumptions as [1–6]. System instability of free vibration and forced vibration due to mass unbalance excitation were investigated. Their results showed the effect of the motor air gap flux density on the system natural frequency. Also the vibration jump phenomenon was observed in the whirling amplitude-frequency relationship for forced vibration. Gustavsson and Aidanpaa [19] studied the influence of radial eccentric force on hydropower generator. The expression of the constant component of the radial eccentric force was used. A four degrees of freedom (DOF) mechanical system was modeled. The results indicated the system could become unstable in certain operating condition. The same mechanical system was modeled in [20] with both radial and tangential eccentric forces. FEM was used to calculate the forces for no-load and full-load conditions. The results showed the eccentric force affected both system damped natural frequencies and stability significantly. In [21], Calleecharan and Aidanpaa further extended the hydropower generator model with importing the radial and tangential eccentric forces under whirling condition. Bifurcations, including jump were observed.

Since the motor eccentric force has significant influence in mechanical system vibrations, a calculation method capable for both radial and tangential eccentric force is required, which should also balance the required model accuracy and computation time. The literature indicates that the magnetic equivalent circuit method (MEC) can be a suitable way to analyze the eccentric motor field. It models an electric motor as a reluctance network and calculates the magnetic fields in the entire machine without loss of important magnetic characteristics. The computation time is fairly short relative to more detailed finite element analyses. Thus, it can give reasonably accurate results when requiring less modeling effort and shorter computation time compared to finite element method.