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Determination of sensor positions for predictive maintenance of revolving machines

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Abstract

The monitoring by measurement and analysis of vibration is largely used to detect the defects in revolving machines. The determination of the best sensor positions is one of the main research goals in the field of predictive maintenance. This paper proposes a numerical methodology based on a finite element model and a spectral analysis in order to find optimum sensor positions. The bearing is a key component for the vibration propagation from the moving parts to static ones. An analytical bearing model and its numerical implementation in a finite element code are presented. The tangent stiffness matrix of the bearing element is obtained by the Newton–Raphson method and then used for the modal and spectral analyses. Several techniques are used to find the most sensitive zones to common defects. The proposed numerical approach correlate well with the experimental results. The numerical modeling of a grinder shows the interests in industrial applications. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Ball bearing; Finite element of bearing; Modal analysis; Experimental validation; Conditional maintenance

1. Introduction

The follow-up of the damage of some parts in a rotating machine by vibration analysis is a widely used technique in the predictive maintenance. The purpose of this type of maintenance, advantageous to the curative and periodic maintenance, is to carry out an intervention on a part just before its mechanical failure (AFNOR, 1995). This requires the monitoring and analysis of the evolution of vibration spectrums at one or several points on the machine in order to detect the characteristic peaks of common defects (Max, 1987). For the vibration follow-up of the bearings, it is possible to calculate in advance the frequencies of ring or ball defects according to the bearing geometry and its rotating speed (Morel, 1992). In most cases, the ideal measurement points are situated near the parts to be followed up, but the size of some machines and the accessibility to certain areas makes it difficult, even impossible, to take the measurements in these places.

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Although the reliability of defect detecting in the predictive maintenance has made enormous improvements, mainly due to the computer treatment of vibratory signals, it is nevertheless greatly dependant on the quality of signal analysis and positioning of sensors.

This study proposes a methodology based on a numerical approach in order to find an optimum sensor implementation on a revolving machine. The numerical modeling allows to determine the number and the location of measurement points. Particular consideration is given to a common component on revolving machines: the bearing which is the only material link between the moving part and the immobile part in the vibration transmission.

Firstly an analytical model for the rolling ball bearing is presented. The relations between the displacements (rotations) and the forces (torques) are obtained by using the cinematic relations and the Hertz contact theory. The formulation of the bearing element and its implementation in a finite element software are described. The model and the spectral analyses are used to determine the most sensitive zones for given defects. This numerical methodology is validated with an experimental academic example. Moreover, the comparison between the numerical and experimental results of an industrial grinder shows the interest of this application in the sensor monitoring setting for the predictive maintenance.

2. Bearing modeling and its numerical implementation

The numerical modeling of an elementary cell of a revolving machine (the whole shaft-bearing-housing) in detail is very tedious and complicated because of the contact treatment. An analytical model is presented here to obtain an equivalent stiffness of the ball bearing and then its finite element implementation in order to carry out the vibration analysis.

2.1. Definition of the bearing stiffness matrix

Numerous problems are involved in analytical models of the bearing because of its strongly non-linear elastic behavior. This non-linearity is due to the Hertzien contact and the clearance between the rolling elements and the rings. Moreover, the load intensity, supported individually by each ball, depends on the internal geometry of the bearing as well as the type of the applied load.

Many publications have been presented on the evaluation of the life duration of the ball and roller bearings in function of the applied excitations (Palmgren, 1959; Jones, 1960; Harris, 1991).

Several researchers have also studied the equivalent stiffness of bearings (Lim and Singh, 1990; Demul et al., 1989). They proposed an analytical model and a stiffness matrix with 5 degrees of freedom on the inner ring (3 translations and 2 rotations; the rotation around the shaft is free). The proposed matrix included coupling of the bending movements between the shaft and housing and take into account the effects of the centrifugal forces and the gyroscopic moments.

For the studied case, the effects of the centrifugal forces and gyroscopic moments have only a little influence on the coupling coefficients because of the low angular speed of the shaft. Our approach is based on the above works but without considering these effects. The analytical bearing model consists in determining the relations between the displacements (rotations) and the applied forces (torques) at the center O of the bearing.

The geometry of a ball bearing with oblique contact are presented in Fig. 1 where a_{i} and a_{e} are the curvature centers of the inner and outer rings, A_0 and A_j are the distances between these two centers before and after loading, δ_{rj} and δ_{zj} are the effective displacements in the radial and axial directions for the ball number j, δ_i and β_i, are the displacement and rotation at the center O. Fig. 1 also shows the external forces $\{F\}$ acting on the gravity center of the radial ball bearing. The components of this force in the global cartesian system (XYZ) are: