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Nonlinear dynamics of a support-excited flexible rotor with hydrodynamic journal bearings

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ABSTRACT

The major purpose of this study is to predict the dynamic behavior of an on-board rotor mounted on hydrodynamic journal bearings in the presence of rigid support movements, the target application being turbochargers of vehicles or rotating machines subject to seismic excitation. The proposed on-board rotor model is based on Timoshenko beam finite elements. The dynamic modeling takes into account the geometric asymmetry of shaft and/or rigid disk as well as the six deterministic translations and rotations of the rotor rigid support. Depending on the type of analysis used for the bearing, the fluid film forces computed with the Reynolds equation are linear/nonlinear. Thus the application of Lagrange's equations yields the linear/nonlinear equations of motion of the rotating rotor in bending with respect to the moving rigid support which represents a non-inertial frame of reference. These equations are solved using the implicit Newmark time-step integration scheme. Due to the geometric asymmetry of the rotor and to the rotational motions of the support, the equations of motion include time-varying parametric terms which can lead to lateral dynamic instability. The influence of sinusoidal rotational or translational motions of the support, the accuracy of the linear 8-coefficient bearing model and the interest of the nonlinear model for a hydrodynamic journal bearing are examined and discussed by means of stability charts, orbits of the rotor, time history responses, fast Fourier transforms, bifurcation diagrams as well as Poincaré maps.

1. Introduction

Rotating machines are among the indispensable parts of the modern engineering industries. Due to the nature of the excitations applied to the machine rotors, most of them can be considered as on-board rotors affected mainly by both the mass unbalance and the support motions. Generator, pump, compressor and gas turbine rotors installed in power plants as well as vehicle turbochargers are examples of rotors on moving support. The unavoidable mass unbalance is due to the eccentricity of the center of mass along the rotor axis. The rotor balancing aims at reducing the mass unbalance but is not able to cancel it completely (see Xu et al. [1] and Kang et al. [2]). Rotors can also be subject to the frequent external movements of their support which can increase the flexural vibration of the rotors and create an unstable dynamic behavior.

In order to enhance the performances, the safety factor, the air-gap and the disk-stator gap have to be reduced. Therefore the prediction of dynamic behavior of the rotating machine components must be performed more and more carefully. In this context, the literature comprises numerous books studying a wide variety of phenomena related to the dynamics of

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symmetric/asymmetric rigid/flexible rotor systems mounted on linear/nonlinear elastic bearings in the case of a fixed support. Just few of them can be cited here (Lalanne and Ferraris [3], Genta [4], Bachschmid et al. [5]). Some works observed the instability of parametrically excited systems. Dufour and Berlioz [6] accomplished the study of Berlioz et al. [7] on the dynamics of a drill-string. They analyzed the time-varying parametric equations of motion of the system by employing the Rayleigh–Ritz method, the Floquet theory and the Friedmann approach. The design, using a computer, opened doors for a technique called "finite element method" to be applied to the rotor modeling and numerous studies contributed to this topic. The real breakthrough in the finite element modeling of a rotor was presented by Nelson and McVaugh [8], who studied a model called "Rayleigh beam", taking into account the rotary inertia of the shaft and the gyroscopic effects dependent on the speed of rotation of the rotor. Kang et al. [9] modeled rotor-bearing systems using Timoshenko beam finite elements and by taking into account the asymmetry of disk, shaft and/or bearing. They showed that the resonant speeds could change because of various angles between major axes of disk and shaft, the shaft asymmetry as well as the bearing characteristics. Nandi and Neogy [10] proposed an efficient analysis of stability for finite element models of asymmetric rotors and investigated whether an unstable rotor could be stabilized using an isotropic viscous damper. Theoretical and experimental investigations for the isolated and internal resonances of nonlinear forced and parametric oscillations of an asymmetric rotor with nonlinear spring characteristics were carried out by Ishida et al. [11].

Hydrodynamic bearings play a key role in the design of rotor systems and an accurate prediction of the vibration characteristics of the rotor-bearing systems must be made. Therefore the hydrodynamic bearing performance is predicted and reported in the extant literature by mathematical formulations firmly established. The fluid film forces are strongly nonlinear functions of the displacement and velocity of the rotor. Although they act locally on the system, rotordynamics is significantly affected and wholly nonlinear. Khonsari and Chang [12] showed that there was a stable region in the short bearing clearance circle, outside of which any initial conditions for the nonlinear transient dynamic problem would yield an unstable orbit even if the hydrodynamic bearing should be stable according to the linearized stability analysis. Zhao et al. [13] predicted the linearized stability and presented a comparison between linear and nonlinear mass unbalance responses of a flexible rotor-hydrodynamic bearing system modeled by the lump mass method to reduce the degrees of freedom. Li and Xu [14] studied a Jeffcott rotor supported on oil film infinite-length bearings to obtain periodic orbits, their periods and their stability using the generalized shooting method. Harmonic, sub-harmonic, quasi-periodic and chaotic responses and their Poincaré maps were investigated for a rigid rotor on hydrodynamic short bearings by Brown et al. [15], for a finite element rotor model on hydrodynamic elliptical bearings by Zheng and Hasebe [16] and for a rigid rotor on hydrodynamic elliptical bearings by Shen et al. [17]. Kishor and Gupta [18] used nonlinear analytical characteristics for hydrodynamic long bearings and introduced them in a rigid rotor-bearing model with a simplified spur gear model. Baguet and Velex [19] combined a finite element shaft model based on the Timoshenko beam theory with both gear and bearing nonlinearities, which were represented by spur gear mesh stiffness and hydrodynamic short bearing forces. Baguet and Jacquenot [20] extended the study presented in [19] to include helical gears as well as hydrodynamic finite-length bearings and analyzed parametrically the shaft orbits, the dynamic tooth loading factor as well as the hydrodynamic forces.

Some works focused on the dynamic behavior of a rotor under seismic, random or shock excitations of its support. Srinivasan and Soni [21] studied the effect of spin, support rotation as well as axial force and axial torque on the seismic response of a rotor-bearing system. Samali et al. [22] used the Monte Carlo simulation to simulate the non-stationary earthquake ground motions and to determine the statistics of rotating machinery response. Hori and Kato [23] examined a seismic response of a Jeffcott rotor mounted on oil film bearings to a real seismic wave and investigated its stability. Suarez et al. [24] observed that even for strong rotational inputs, the parametric terms in the equations of motion of a finite element rotor model subject to six components of support excitations could be neglected without affecting its seismic response. Subbiah et al. [25] obtained the amplitude power spectral density due to random excitations of the support for studying the rotor response using modal analysis methods. Lee et al. [26] proposed a finite element rotor model based on the Timoshenko theory by considering a shock excitation of the support and the state-space Newmark method and focused on the experimental behavior of a rotor under this excitation.

The effect of the flexible foundation on rotordynamics was investigated from theoretical and experimental points of view; see, for example, Bonello and Brennan [27]. Da Silva Tuckmantel et al. [28] represented the supporting structure (foundation) of a rotating system by coupled as well as uncoupled modes and tested the methods of mechanical impedance and mixed coordinates to calculate the system responses. The experimental tests of Feng and Hahn [29] showed that even with input data truncated to two significant digits, satisfactory identification was possible for a flexibly supported undamped rigid block foundation in rotating machinery.

Few works are referenced in the literature on the investigation of dynamic behavior of a rotor in the case of a harmonic motion of its support. Duchemin et al. [30] observed the motion stability of a rotor under a sinusoidal rotation of the support by employing the Rayleigh–Ritz and multiple scales methods. They also presented experimental results to validate the analytical study. The work of Driot et al. [31] was based on the model presented in [30], which described the numerical orbits of the rotor and compared them with experimental ones. El-Saeidy and Sticher [32] derived the equations of motion of a rigid rotor linear/nonlinear bearing system subject to rotating mass unbalance plus harmonic excitations of the support along or around lateral directions. They presented analytical frequency responses in the case of linear bearings, while they discussed numerical results with regard to the time domain, the fast Fourier transform as well as the Poincaré map in the case of a bearing cubic nonlinearity. Das et al. [33] investigated the active vibration control of a flexible rotor system modeled by Rayleigh beam finite elements and excited by a mass unbalance as well as a periodic rotational motion of the