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A novel semi-analytical method for the dynamics of nonlinear rotor-bearing systems

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ABSTRACT

A semi-analytical simulation of a rotor bearing system that consisted of a multi-segment continuous rotor and plain fluid film bearings with finite length is developed in this paper in order to investigate the system's response under the current proposal of simulation. The rotor is simulated using the continuous medium theory and the bearings with finite length follow a very recent analytical simulation that incorporates the analytical solution of the Reynolds equation for the plain, finite journal bearing. The boundary conditions combine the rotor's shearing force and the fluid film forces at the points where the bearings are located, which are expressed analytically with direct integration of the pressure distribution function.

A case study of simulating a multi-segment shaft is used in order to compare the current simulation with corresponding simulations using continuous rotor mounted on linear bearings, or finite bearings numerically simulated using the finite difference method. The time response, the amplitude of the response and the phase during passage through resonance are evaluated for these three cases of bearing simulation using numerical procedures and the differences are notified and remarked.

1. Introduction

An important matter with severe influence in rotor bearing system dynamics is the interaction between the rotating shaft and the fluid film forces of the bearings. A very recent achievement of the exact analytical solution of the plain journal bearing with finite length [1–4] is the base for the current investigation which can be defined as the comparison of the different ways of simulating the bearing reaction forces that mount a rotating shaft. The cases that are incorporated in this paper regarding the bearing forces that mount the continuous rotor are:

a) the exact analytical, where the nonlinear bearing forces are evaluated under the exact analytical solution of the Reynolds equation for the plain finite bearing [1–4] and they are expressed using closed form analytical formulas,
b) the numerical, where the Reynolds equation for the finite journal bearing is solved using the finite difference method (FDM) [5,6], and the nonlinear forces are evaluated as the numerical integration of the pressure in the pressure field,
c) the linear, under the use of the linear stiffness and damping coefficients that are extracted using numerical solutions of the Reynolds equation [7,8].

The need for the simulation of the highly nonlinear forces of fluid film bearings in combination with a continuous rotor model is considered in this paper and an analytical simulation technique about the rotor bearing system is suggested. Until now, the numerical methods and the high computational speeds achieved from the computers make the simulation of complicate

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multi-segment and multi-bearing systems feasible and confident, but in the current work the analytical path can yield an alternative method in the simulation of multi-segment rotors mounted in fluid film bearings.

The simulation of the interaction of the rotor with the fluid film is the main contribution of this paper. In cases of large amplitude vibrations of the journal, which approach the bearing radial clearance, linear bearing theory is judged insufficient to yield accurate results since the journal whirling amplitude can be yielded even larger than the radial clearance. This large vibration amplitude is not always a result of high unbalance excitation nor is it generally due to external loading, but it can be produced if the rotor bearing system passes through resonance. The magnitude of the shearing forces is becoming high during passage through resonance and it should be included in order to aid in an accurate modeling of the shaft's dynamic properties inside the bearings. This correlation between the dynamic properties of the entire continuous shaft, instead of the dynamics of the journal only, with the fluid film bearings makes the current simulation quite different in comparison with what has been made until now.

The rotor and bearing interaction has been treated in literature with various combinations of a shaft model with the fluid film bearings. The methods for transverse vibration analysis of rotor systems that have been developed can be divided into two major classes. The first contains discretization methods, such as FEM and the Transfer Matrix Method, in which the rotor system is approximated by a finite degree-of-freedom system whose motions are described by ordinary differential equations [9–13]. The second includes the analytical method in which a rotor system is treated as a distributed parameter system whose motions are described by partial differential equations [14–17]. Lee et al. [18] apply modal analysis to a continuous rotor system with various boundary conditions (isotropic and anisotropic); whirl speed and mode shapes (forward and backward) are obtained as spin speed and boundary conditions vary. The effects of asymmetry in boundary conditions on the system dynamic characteristics are also investigated. Also, Lee et al. [17] use a modal analysis technique to investigate the forced response analysis of an undamped distributed parameter rotating shaft. A study of the resulting non-self-adjoint eigenvalue problem is presented. Modal analysis of an asymmetrical rotor-bearing system, which consists of asymmetrical Rayleigh shafts, asymmetrical rigid disks, and isotropic bearings is performed by Jei and Lee [19]. Adams [20] models a rotor as a separate system with the use of finite elements. The central feature of his analysis is a proper handling of various highly non-linear effects of journal bearings, which dominate the dynamic phenomena encountered during large amplitude rotor-bearing vibrations. The Transfer Matrix Method is used in calculating the transient response of a large-scale rotor bearing system using strong nonlinear elements in a study by Gu et al. [21], who obtain the transfer matrix via the Newmark formulation and determine the dynamic characteristics by integration. A very recent work of Shen et al. [22] presents a fast and accurate model for the calculation of the bearing fluid film nonlinear forces using free boundary theory and the variation method.

Multi-span Timoshenko beams connected or supported by resilient joints with damping are used by Hong et al. [23,24], in order to achieve exact solutions for a distributed parameter system. An analysis of whirl speeds for rotor-bearing systems supported on fluid film bearings is presented in [25] by Kalita and Kakoty, using FEM to present the observation that the additional frequencies around half the spin speeds cannot appear when using the short bearing approximation, but appear only with finite bearing dynamic coefficients. Ehrich [26] observes sub-critical, super harmonic, and chaotic responses in rotor dynamics. An emphasis on oil whip phenomena in the non-linear dynamic behavior of rotor-bearing systems is given in [27] by JianPing et al., using FEM for the rotor motion and the short bearing approximation for fluid film forces.

The current paper aims in the analytical simulation of a rotor bearing system based on the analytical simulation of the continuous rotor, using the classic mechanics theory for the continuous medium, and the recently developed analytical solution of the finite journal bearing [1–4]. The paper is parted from 3 sections. In the first section the simulation technique is presented using two sub-sections, one for the rotor's equation of motion and one with the brief description of the analytical solution of the journal bearing. In the second section, the dynamic system for the rotor-bearing simulation is composed and a time-domain solution using a modified Newton–Raphson method is presented in detail. The use of a numerical procedure for the solution of the dynamic system of equations describes the method as semi-analytical. In the last section, a case study of a multi-segment shaft mounted in two journal bearings with finite length, is presented in order to notify the differences in the dynamic response of the system during passage through the first critical speed, in comparison to three other cases of journal bearing forces. The current paper is supposed to present a contribution to the simulation of the rotor bearing systems by incorporating analytical simulation both for the rotor and the finite journal bearing. The section of conclusions notifies the differences in the result of the time response and its amplitude during start-up, evaluated under different assumptions for the bearing forces.

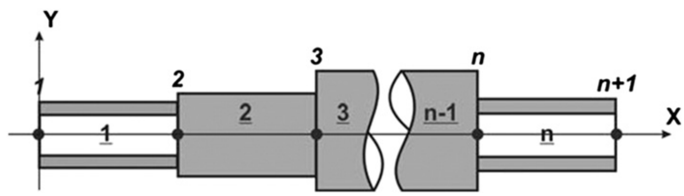

Fig. 1. Multi-segment shaft consisted from n segments and definition of the coordinate system.