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A 5-DOF Model for Aeroengine Spindle Dual-rotor System Analysis

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Abstract

This paper develops a five degrees of freedom (5-DOF) model for aeroengine spindle dual-rotor system dynamic analysis. In this system, the dual rotors are supported on two angular contact ball bearings and two deep groove ball bearings, one of the latter-mentioned bearings works as the inter-shaft bearing. Driven by respective motors, the dual rotors have different co-rotating speeds. The proposed model mathematically formulates the nonlinear displacements, elastic deflections and contact forces of bearings with consideration of 5-DOF and coupling of dual rotors. The nonlinear equations of motions of dual rotors with 5-DOF are solved using Runge-Kutta-Fehlberg algorithm. In order to investigate the effect of the introduced 5-DOF and nonlinear dynamic bearing model, we compare the proposed model with two models: the 3-DOF model of this system only considering three translational degrees of freedom (Gupta,1993, rotational freedom is neglected); the 5-DOF model where the deep groove ball bearings are simplified as linear elastic spring (Guskov, 2007). The simulation results verify Gupta's prediction (1993) and show that the rotational freedom of rotors and nonlinear dynamic model of bearings have great effect on the system dynamic simulation. The quantitative results are given as well.

Keywords: aeroengine; dual-rotor; ball bearing; nonlinear dynamics; five degrees of freedom

1. Introduction

The spindle dual-rotor system is very common in aerospace field. Because of complicated dynamics and coupling between dual rotors, the system features complicate nonlinear dynamics, which is crucial to stability of the aeroengine and plane.

A spindle dual-rotor system is investigated in this paper. In this system, the dual rotors have co-rotating speeds and are connected by the intershaft bearing—a deep groove ball bearing. The intershaft bearing inner race is mounted on the low-pressure rotor while the outer race is mounted on the high-pressure rotor. The high-pressure rotor has higher rotational speed.

Important progress has been made on studies of dynamics of dual-rotor system. Early in 1975, Hibner[1] put forward the application of the transfer matrix method in order to compute the critical speeds and nonlinearly damped response. In 1986, Li, et al.[2] analyzed the dynamics of the dual-rotor system which was connected by intershaft squeeze film damper. In 1993, Gupta, et al.[3] studied through experiment the critical speeds, mode shape and unbalanced response of the dual-rotor system whose rotors were connected by a deep groove ball bearing and developed theoretically an extend transfer matrix procedure in complex variable to obtain dynamic response. The experimental results were in reasonable agreement with theoretical results in the case of two degrees of freedom (2-DOF) model. In 1996, Ferraris, et al.[4] made theoretical research on dynamic behavior of non-symmetric coaxial

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co- or counter-rotating rotors. In his research, a 2-DOF model was built using finite element, and the natural frequency and mass unbalance responses were investigated. However, the displacements of rotors at the bearing points were assumed the same and calculation was simplified in his model (The equations can be solved by hand calculations). In 2007, Guskov, et al.[5] presented a numerical 4-DOF model to study unbalanced response of a dual-rotor test rig system where two coaxial shafts were supported on deep groove ball bearings and connected by an intershaft bearing.

Basing on the above works, we numerically investigated a spindle dual-rotor system with five degrees of freedom (5-DOF) in this study. This work differs from the previous work[5] in two main aspects. Firstly, the bearing type is different. The rotors in Ref.[5] were supported on deep groove ball bearings, while the rotors in our work are supported on two angular contact ball bearings and two deep groove ball bearings. Therefore, besides translational degrees of freedom along x, y and rotational freedoms around x, y, we also consider the translational degree of freedom along z. Secondly, Ref.[5] simplified the bearing models as linear elastic spring elements so it ignored the influence of nonlinear stiffness and the rotational freedoms of rotors. In contrast, we formulate the bearing nonlinear displacements, elastic deflections and contact forces mathematically considering 5-DOF of the dual rotors. After contact forces of all the bearings are obtained, the equations of dual rotors motion are proposed according to rotor dynamics.

The 5-DOF model of the dual-rotor system, which includes nonlinear formulations of bearings, has not been reported in the previous work.

In order to indicate the effect of our introduced 5-DOF and nonlinear dynamic bearing model on the system dynamics, not only the proposed 5-DOF model but also the other two models of the system are simulated simultaneously for comparison. One is 3-DOF model only considering three translational degrees of freedom, and the other is 5-DOF model where the deep groove ball bearings are simplified as linear elastic spring elements as Ref.[5] (5-DOF-Sim for short).

2. Mathematical Model of System

Fig.1 shows the schematic diagram of the dual-rotor system. The left hand of higher pressure rotor a is supported by two same angular contact Bearings 1, 2 and the right hand of lower pressure rotor b is supported by two different deep groove ball Bearings 3, 4, where Bearing 4 is the intershaft bearing. The dual rotors have different co-rotating speeds. The coupling between the two rotors through the intershaft bearing is also considered in the mathematical model.

The mathematical model follows two steps. First of all, the displacements, elastic deflections and contact forces of the bearings are calculated considering 5-DOF of the rotors. Then the motion equations of the dual rotors are formulated based on rotor dynamics.

Therefore, all the contact forces of bearings should be calculated firstly. For angular contact Bearings 1 and 2, calculations of their elastic deflections and contact forces only need consideration of freedoms of rotor a, thus many studies about formulations of angular contact bearing associated with one rotor as Refs.[6]-[15] can provide reference for our work. In this work, the earliest report about formulations of angular contact ball bearing under one rotor proposed by Aini[15] is adopted among all previous work. The calculation is listed out in Section 2.1.

The calculations of deep groove ball Bearings 3 and 4 differ from current research on some aspects. Although the current calculation[5] of intershaft bearing considered 4-DOF of rotors, the bearing is simplified as linear elastic spring element and disregarded nonlinearity. Furthermore, the nonlinear calculation of deep groove ball bearing is involved in Refs.[16]-[19], but it only considers two translational degrees of freedom of the single rotor. And last but not least, Zhou and Chen[20] calculated the nonlinear contact force of intershaft deep groove ball bearing considering 2-DOF of rotors. In our work, not only the rotational degree of freedom is considered, but also the nonlinear displacements, deflections and contact forces are formulated mathematically. Additionally, formulations of Bearing 3 differ from that of Bearing 4 because Bear-

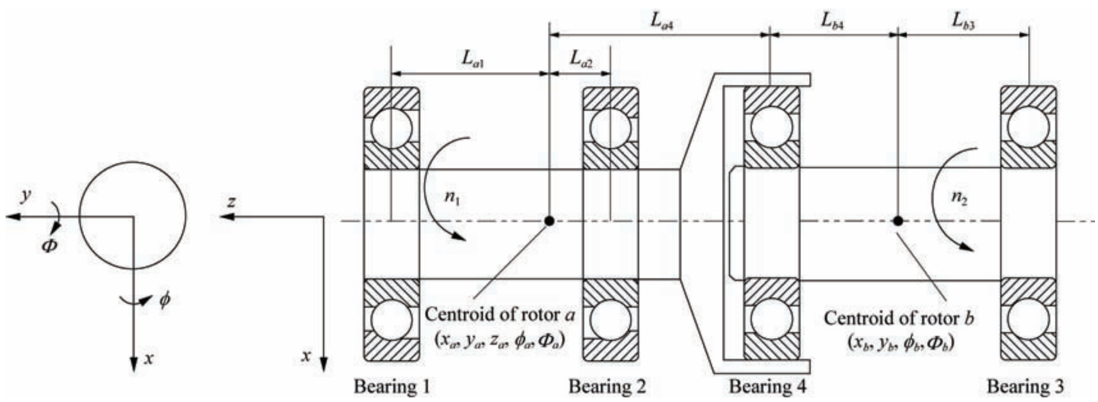

Fig.1 Schematic diagram of dual-rotor system.