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Research paper

Forced responses analysis of a rotor system with squeeze film damper during flight maneuvers using finite element method

Bingbing Han[a,b], Qian Ding[a,b,*]

[a] Department of Mechanics, Tianjin University, Tianjin 300350, China
[b] Tianjin Key Laboratory of Nonlinear Dynamics and Chaos Control, Tianjin 300072, China

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ABSTRACT

The rotor system of aero engine will endure a severe bad working condition when aircrafts do flight maneuvers. This process can result in Multi-period or irregular transient vibration. In this paper a rotor/ball bearing system model is first established by using the finite element method. The dynamic characteristics of the system during maneuvers, with linear damping supports and squeeze film damper supports at the shaft ends respectively, are subsequently studied by adopting a corresponding hybrid numerical method. Time histories of velocity and displacement are employed to analyze the transient response during maneuvers. Frequency/waterfall spectra are used to reveal the sub- and super resonance in flight maneuvers. The results indicate that transient responses can be induced by both the commencement and the termination of the maneuvers. The squeeze film dampers (SFD) perform effectively on suppressing the amplitude of transient responses. Its damping effect is enhanced by flight maneuvers. The stiffness of central spring structure is found playing an important role on the damping behavior of SFD. Sub- and super-harmonic resonances can happen during flight maneuvers for linear damping supports but be suppressed significantly by the SFD.

1. Introduction

Flight maneuvers, including instantaneous turn, climb-diving, acceleration, sustained turn and roll performance, are the common performance of an aircraft in aerobatic displays and air combats, which can significantly influence the dynamics of aero engine rotor system [1–8].

In recent years, much work has been reported on dynamic properties of rotor/ball bearing systems in flight maneuvers. Literatures are mostly based on simple Jeffcott rotor or lumped parameter rotor models. Xu and Liao [9] investigated the performance of Jeffcott rotor system with SFD in maneuver flight, in which the flight maneuvers were simulated by a modified centrifugal force and a modified gyroscopic moment. SFDs at left and right ends of the rotor were found to move with different orbits due to gyroscopic moment. The transient vibration amplitude was increased during maneuvering process. Zhu et al. [10] built a general motion model of an aero engine rotor system in flight maneuvers, in which additional damping effect, stiffness effect and un-periodic external exciting force were considered. The investigation indicates that the vibration amplitude will increase and the center of motion will shift to a new position that may result in particle impact. The modeling method was adopted in dealing with the flight maneuvers recently [11,12]. Jeffcott and lumped parameter rotor model

* Corresponding author.
E-mail address: qding@tju.edu.cn (Q. Ding).

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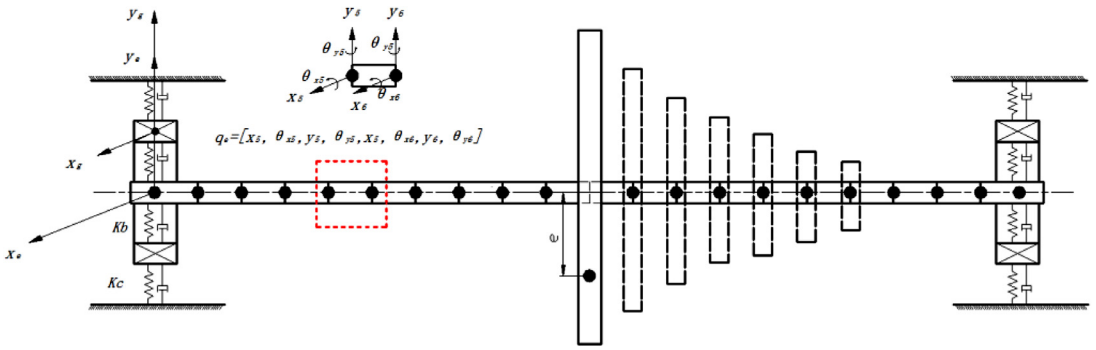

Fig. 1. The multi-disks rotor model with nonlinear bearing elements.

is efficient and can better reveal characteristic of nonlinear forces in rotor system. However, details of structure and complicated forces in shaft are all neglected [13]. Some researches were reported in recent years based on complex dynamical models, such as the finite element model combined with nonlinear bearing elements, to reveal nonlinear dynamics of real rotor systems. To efficiently simulate the complex models, hybrid numerical methods were adopted for traditional numerical method cannot deal with finite element rotor model with implicit nonlinear force in bearing supports. Ma and Wang [14] established a 3D finite element model with asymmetric rotor structure in which the bearing parts were simulated by time-varying coefficient differential equation. Hybrid numerical method based on Floquet theory and Hill expansion method were applied to obtain the set of equivalent linear time-invariant equations. Brouwer and Sadeghi [15] built a rotor-cartridge model by using a combined explicit finite method and discrete element method. The motions of shaft and bearings as the system traverses through the critical speeds were investigated. Chen [16] established a generalized complex rotor-support-casing coupling dynamic model. The rotor and bearing elements were included, and a numerical integral method, was used to simulate the system's responses.

Some literatures have proven that flight maneuvers can affect the response of rotor system orbits, transient response and periodic properties. Considering the inclining of shaft when a rotor moves in the space based on Jeffcott rotor model, Lin and Meng [17,18] found that the aircraft acceleration, especially its vertical component, affected significantly the response of rotor system. In designing the parameters of SFD, the aircraft's maneuver has to be considered. Xu and Liao [9] found that the transient vibration amplitude was increased during maneuvering process. However, there is no detail research on how transient vibrations are influenced by flight maneuvers and effectiveness of SFD on suppressing the vibrations. Wang and Liao [19] carried out experimental investigation on a setup, in which two electromagnetic force devices were used to simulate the additional centrifugal force and gyroscopic moment in flight maneuvers. They found that flight maneuvers could weaken damping effectiveness of the SFD. However, an opposite result was obtained in our paper in case the supporting central spring of SFD was with a relatively small stiffness.

Sub-harmonic resonance and irregular motions subjected to turning flight maneuvers were found by Hou et al. [20] recently. Two typical alternating patterns induced by maneuver load, motions alternating between period 2 and period 1 and motions between quasi-periodic and period 2, were presented. Besides, 1/2 sub-harmonic resonance happening during flight maneuver was also investigated by Hou [21]. They found that larger eccentricity and maneuver load will result in higher vibration amplitude of sub-harmonic resonance. Squeeze-film damper was usually used in aero-engine rotor system to provide extra nonlinear damping for rotor system, but not considered in Hou's research [22–24]. Therefore, the motivation of this work is to investigate the effectiveness of SFD on suppressing the occurrence of sub-harmonic resonance of the rotor during maneuvering process.

In this paper the finite element model and a hybrid explicit and implicit numerical method are adopted to better reveal the characteristics of rotor system in flight maneuvers. A rotor/ball bearing system with SFD supporting is investigated by constructing a composed model using the FE method. A hybrid numerical method is adopted to solve the model. Finally, Transient responses, sub-harmonic resonance, super-harmonic resonance and properties of SFD in flight maneuvers are discussed in details.

2. FE modeling of rotor system in flight maneuvers and hybrid numerical method

A rotor model with multi-disks, supported on ball bearings with SFDs at two ends, is investigated in this paper as shown in Fig. 1.

The Finite Element method is common used for modeling complicated structures, by which the inertia moment, gyroscopic moment and shear force can be considered using different finite elements. To model the multi-disks rotor model of Fig. 1, the shaft is divided into 20 sections with 21 points and 84°-of-freedom (DOF) in total. Each shaft section is described by a finite element of Timoshenko beam with 8 DOFs, and four of which are shared with the neighbor element. The disks attached on the shaft are simplified as lumped masses, and the polar moment of inertia and the radial moment of inertia