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Nonlinear vibration analysis of a cracked rotor-ball bearing system during flight maneuvers

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ABSTRACT

This paper focuses on the nonlinear responses of a cracked rotor-ball bearing system caused by aircraft flight maneuvers. The equations of motion of the system are formulated with the consideration of the breathing mechanism of a transverse crack and the maneuver load of a climbing-diving flight. The fourth order Runge-Kutta method is employed to detect the nonlinear responses of the system, which are reflected by bifurcation diagrams, power spectrums, maximum Lyapunov exponent, phase portraits and Poincaré sections. It is shown that the super-harmonic responses of the system are affected significantly by the maneuver load under sub-critical speeds. Plenty of quasi-periodic motions are obtained, and a variety of complex nonlinear behaviors including bifurcations and jumping phenomenon are observed near 1/4, 1/3, 2/5 and 1/2 critical speeds when the maneuver load increases from 0 to 10 g. The nonlinear responses of the system influenced by crack stiffness, bearing clearance and rotor eccentricity are also investigated. Chaotic motions are demonstrated when the crack stiffness or the bearing clearance increases across a critical value. However, the responses maintain quasi-periodic when the rotor eccentricity changes. The results will contribute to a better understanding of the nonlinear dynamic behaviors of cracked rotors in flight maneuvers.

1. Introduction

Considerable attention has been paid to crack fault, which is one of the most serious damage in aircraft engines and other rotating machines, in the last three decades [1]. Wauer [2], Gasch [3] and Dimarogonas [4] reviewed the dynamical behavior of rotor systems with transverse cracks, in which, highly nonlinear vibrations were shown. Switching crack model (also known as hinge model) [3] and response-dependent breathing crack model [5,6] were proposed in early times, based on which, the dynamical comparison of the two models [7], the critical speed influenced by the nonlinear breathing of the crack and the imbalance orientation angle of the rotor [8], and the stability of periodic movements in cracked rotor systems [9–11] were investigated to detect the nonlinear dynamics of cracked rotor systems. Finite element models [12–14] were presented afterwards to study the dynamic behaviors of rotor systems affected by crack depth, position and type (transverse or slant). Harmonic balance method [15], alternate frequency/time domain approach [16] and experimental methods [17,18] were also developed to gain an insight into the dynamical characteristics of cracked rotors. From the above studies, the 2× and 3× super-harmonic frequency components are shown as distinct signals, based on which, the diagnostic tools that the changes in natural frequencies and evolution of the non-linear behavior of the system at the super-harmonic frequency components are proposed to gain crack detection strategies [19–24].

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In recent years, a significant amount of research has been conducted in the area of coupling problems [25–30] and multi-cracks [31,32] in cracked rotor systems. It is shown that the excitation in one mode may lead to an interaction between all the modes due to the coupling between longitudinal, lateral and torsional vibrations [25], and coupled modes induce a quasi-periodic motion or even non-periodic behavior in the region of internal resonance [26,27]. Unique features of nonlinear vibrations are shown in cracked rotor systems respectively coupled with rub excitation [28], bow [29] and misalignment [30], which are useful for the identification of crack faults. It is also shown that the dynamic response in the Jeffcott rotor system with two transverse surface cracks is affected significantly by the angular orientation of one crack relative to the other [31]. Sekhar [32] summarized the different studies on double/multi-cracks to bring out the state of the research on multiple cracks and their identification methods in vibration structures.

Generally, gravity that plays an important role named weight dominance in the crack breathing in normal rotor systems is a constant force [33,34]. In an aircraft rotor system, however, the maneuver load that plays the same role as gravity may increase from 0 to highly 10 times of gravity in flight maneuvers [35,36], which makes a great influence on the dynamic behaviors of nonlinear rotor system. Lin et al. [37] has investigated the nonlinear dynamics of a cracked rotor by considering the flight maneuver model with a constant flight speed or a constant acceleration, in which, it was shown that the climbing angle, acceleration, and other flight parameters make significant influences on the parameter range for bifurcation, quasi-periodic response and chaotic response as well as system stability. Yang et al. [38] found three different ways for the vibration response going to chaos: quasi-periodic, intermittence and period-3 bifurcation, in a cracked rotor system under the maneuver load of hovering flight. Hou et al. [39,40] found that sub-harmonic resonance is a nonlinear mode inducing rub-impact in maneuvering rotor systems.

The motivation of this paper is to detect the nonlinear dynamic behaviors of an aircraft cracked rotor-ball bearing system under maneuver load. The equations of motion proposed herein enable us to investigate the nonlinear responses of the system considering the effects of the maneuver load induced by the climbing-diving flight, which is a maneuver in the vertical plane. Numerical technique is employed to detect the nonlinear dynamic behaviors of the system when the crack is not very deep. Nonlinear behaviors such as super-harmonic resonances, jumping phenomenon, and plenty of quasi-periodic and chaotic motions are obtained due to the effect of the maneuver load.

The paper is organized as follows. Firstly, the model of a ball bearing supported rotor system with a breathing transverse crack is presented, in which, the crack breathing model combining both switching and cosine functions, and the maneuver load of a diving-climbing flight model are considered. Secondly, the super-harmonic responses of the system affected by the maneuver load are analyzed in detail from different aspects by using bifurcation diagrams, power spectrums, maximum Lyapunov exponent, phase portraits and Poincaré sections. Finally, the nonlinear responses of the system influenced by crack stiffness, bearing clearance and rotor eccentricity are respectively investigated to give an insight into the evolution of the system behavior as the increase of the parameters.

2. Mathematical model

2.1. Cracked rotor-ball bearing system

Consider the ball bearing supported rotor system with a transverse crack on the shaft at the bottom of the disk as shown in Fig. 1, where o is the left endpoint of the shaft, and it is assumed that o is also the gravity center of the aircraft, o' and o_m are, respectively, the geometric center and the mass center of the disk, and e is the rotor eccentricity between o_m and o'. The motion of the system is modeled by six degrees of freedom: the vertical displacement y and the horizontal displacement z of the disk, and the vertical displacement y_{b1} and y_{b2}, the horizontal displacement z_{b1} and z_{b2} of the two bearings. k and c are the stiffness and the damping of each side of the shaft. m, m_{b1} and m_{b2} are the masses of the disk and the two bearings respectively.

2.2. Maneuver load

Fig. 2 shows the flight maneuver model discussed in this study, where it is assumed that the angular velocity ω_{maneuver} and the speed v of the aircraft are constants in the climbing and diving flight, and o is the gravity center of the aircraft corresponded with Fig. 1. The maneuver loads of the system at the six degrees of freedom can be written as

$$F_{\text{maneuver}} = [m\omega_{\text{maneuver}}v \;\; 0 \;\; m_{b1}\omega_{\text{maneuver}}v \;\; 0 \;\; m_{b2}\omega_{\text{maneuver}}v \;\; 0]^{\mathrm{T}}. \tag{1}$$

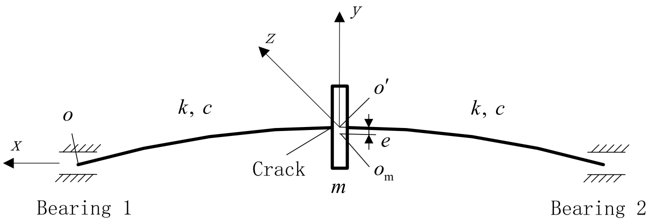

Fig. 1. Schematic diagram of a cracked rotor-ball bearing system.