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Nonlinear dynamic modeling of a simple flexible rotor system subjected to time-variable base motions

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ABSTRACT

Rotor systems carried in transportation system or under seismic excitations are considered to have a moving base. To study the dynamic behavior of flexible rotor systems subjected to time-variable base motions, a general model is developed based on finite element method and Lagrange's equation. Two groups of Euler angles are defined to describe the rotation of the rotor with respect to the base and that of the base with respect to the ground. It is found that the base rotations would cause nonlinearities in the model. To verify the proposed model, a novel test rig which could simulate the base angular-movement is designed. Dynamic experiments on a flexible rotor-bearing system with base angular motions are carried out. Based upon these, numerical simulations are conducted to further study the dynamic response of the flexible rotor under harmonic angular base motions. The effects of base angular amplitude, rotating speed and base frequency on response behaviors are discussed by means of FFT, waterfall, frequency response curve and orbits of the rotor. The FFT and waterfall plots of the disk horizontal and vertical vibrations are marked with multiplications of the base frequency and sum and difference tones of the rotating frequency and the base frequency. Their amplitudes will increase remarkably when they meet the whirling frequencies of the rotor system.

1. Introduction

Rotor dynamic problems have been extensively studied in the case of fixed supports over the past decades. However, turbo-machinery such as generators, pumps, compressors and gas turbines, which are installed in power plants as well as transportation systems, are examples of rotors on moving bases. Such rotor system might undergo large time-varying linear and angular base motions. The time-variable base motions would induce additional excitations to the rotor system, and then make the rotor's dynamic behavior differ distinctly from that of the rotor system under fixed supports. Thus, it is necessary to carry out studies to point out the effects of base motions on the dynamic behaviors of flexible rotor systems.

The effects of base motions on the rotor dynamics were first considered in the dynamic analysis of gas turbine rotors subjected to seismic excitations. Soni and Srinivasan [1,2] studied the seismic response of a rigid rotor and a flexible rotor mounted on fluid film bearings, respectively. The importance of including the base rotation in the dynamic analysis was pointed out. Using modal analysis methods, Subbiah et al. [3] obtained the amplitude power spectral density for rotor

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systems due to random support excitations. With the same model in [1], Samali et al. [4] used Monte Carlo simulation to investigate the random vibration of rotating machines under six-component nonstationary seismic excitations. Hori and Kato [5] examined the response of a Jeffcott rotor supported by oil film bearings under a strong artificial shock and a real seismic wave, and investigated its stability by calculating the locations of the disk and journal centers. Suarez et al. [6] applied non-linear interposition functions to improve the accuracy of the finite element model presented by [2]. Lee et al. [7] proposed an FE transient response analysis method to analyze the effect of base shock excitations on rotor-bearing system. The analytical results were verified by experiments. The model with only two degrees of freedom in [6] is too ideal. All the other models mentioned above have the same definition about the rotations of the base and the rotor. As described in [1], the rotations of the base are assumed to be small. Then, the rotational angles of the base could be linearly superposed upon the rotational angles of the rotor (see Eq. (3)–(5) in [1]). When the rotations of the base are not small, the expressions for base rotational velocities would become complicated and the superposition principle is no longer applicable. Moreover, the rotation of the base around the axis of the rotor is not considered (see Eq. (6) in [1]), which might cause the final equations of motion (EOMs) miss some terms.

Although the literatures mentioned above consider the random or shock base motions, rotors running in moving vehicles (ships and aircrafts) are another important situation to be concerned in the rotordynamic analysis. Lin and Meng [8] first studied the dynamic characteristics of a rotor located in a maneuvering aircraft. The results showed that the rotor's unbalanced response is obviously influenced by flying status of the aircraft. Xu et al. [9] found that maneuvering flight will add centrifugal force and gyroscopic moment on the rotor and make the rotor vibrate transiently. Using Lagrange's equation, Zhu and Chen [10] developed a general differential equation of motion of an unbalanced flexible rotor system during maneuvering flight. Yang et al. [11,12] analyzed the nonlinear response of a cracked Jeffcott rotor in an aircraft with hovering and diving-hiking actions respectively. Recently, Hou and Chen et al. [13–16] devoted much effort to the investigation of the effect of constant maneuver load on a nonlinear rotor system. The sub-harmonic and super-harmonic resonance phenomena due to the maneuver load were especially studied. In addition, Hou and Chen also examined the nonlinear dynamic and bifurcation characteristics of a rotor under sine maneuver load [17] and Herbst maneuvering flight [18]. In the above researches on the dynamics of the rotor during maneuvering flight, the base motions just cause additional external excitations. Due to the effects of the nonlinearities from cracks or bearings, typical nonlinear characteristics (such as chaos, bifurcations, sub-harmonic and super-harmonic resonances) occur in the response of the rotor and are influenced by the additional external base excitations. It should be noticed that the investigations in [8–18] focus on the transient or aperiodic base motions.

In recent years, the investigations of dynamic behaviors of a rotor excited by harmonic base motions are drawing more and more attention. Duchemin et al. [19] derived the EOMs based upon the Rayleigh-Ritz method to study the dynamic behaviors of a simple rotor subjected to sinusoidal rotation of the support. The method of multiple scales was applied to observe the stability of the rotor. The analytical results were validated by experimental results. Then Driot et al. [20] calculated the orbits of the rotor by employing normal form approach and Runge-Kutta method, and found them in good agreement with experimental results. Driot et al. [21] also studied the stochastic dynamic behavior of an asymmetrical rotor under random base translational motions. EI-Saeidy and Sticher [22] developed a formulation of a rigid rotor linear/nonlinear bearing system subjected to mass imbalance plus base excitations along or around lateral directions. The sum and difference tones of unbalance frequency and base excitation frequency were observed in the rotor-nonlinear bearing system. Based upon the finite element modeling of an unbalanced rotor-shaft system under a periodic base rotation, Das et al. [23,24] proposed an electromagnetic actuator for active control of the vibrations excited by periodic base rotations. The EOMs were written with respect to the non-inertial reference frame (the moving base) and the shaft was modelled using Euler beam elements. The effectiveness of the actuator was then confirmed by detailed numerical simulations. Dakel et al. [25] considered the geometric asymmetry, and improved the model of Das et al. [24] by using the Timoshenko beam element for the flexible shaft. The dynamics of two different rotor configurations (symmetric and asymmetric) under various support motions were numerically investigated. Later, the nonlinearity of hydrodynamic journal bearings was further considered in [26]. The influence of support motions and nonlinear bearings were examined and discussed by means of stability charts, bifurcation diagrams as well as Poincaré maps. Asgarisabet et al. [27] studied the nonlinear behavior of a symmetrical rotating shaft under mass unbalance and periodic base excitations in the vicinity of the main resonance. Zhang et al. [28] investigated the effect of the pitching and rolling motion on the nonlinear dynamic characteristics of journal bearing-rotor system for marine turbo machinery. The results indicated that the additional stiffness matrix, additional gyroscopic and additional exciting force vector due to base motions have significant influences on the system by affecting the nonlinear oil film force. Wang et al. [29] established a rotor model of a centrifugal pump with a pair of oil lubricated bearings subjected to base movements and investigated its dynamic behaviors under the EI Centro seismic wave and periodic translational base motions, respectively. In the above literatures, the flexibility of the rotor is not considered in [29] and simply concerned in [19–21] (the use of Rayleigh-Ritz method instead of finite element method). The investigations conducted by Das et al. [23,24] focus on the active vibration control of the rotor. Other literatures mainly concern the nonlinearity induced by the oil film bearings [26,28,29]. The direct effects of the harmonic angular base motions on the rotor's dynamics are still not clear.

Recently, Han and Chu [30] developed a nonlinear finite element model for the base excited flexible rotor-bearing system with open or breathing transverse cracks. An imposed harmonic balance method was introduced to obtain the steady-state response of the system under both transverse cracks and base excitations. Later, Han and Chu [31] applied the discrete state