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Dynamic stability and nonlinear vibration analysis of a rotor system with flexible/rigid blades

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In this paper, the primary resonances of a coupled flexible rotor with rigid disk and flexible/rigid blades are investigated. The Euler-Bernoulli beam theory is used to model the blade and shaft. The equations of motion are derived with the aid of the extended Hamilton principle. To simplify the equations of motion, the Coleman and complex transformations are used. The multiple scales method is used to analyze the primary resonances of the system. The influences of mass eccentricity and the damping of the surrounding medium on the steady state responses of the system are studied. It can be seen that rotor's damping values that guarantee the stability of system with flexible blades are higher than those that impose stable conditions in system with rigid blades. In addition, the system with rigid blades becomes completely stable in higher values of the mass eccentricity compared to the system with flexible blades.

1. Introduction

The rotary system is an important machine component numerously used in many industrial applications such as turbines, compressors and aircraft engines. On the other hands, in recent years for higher efficiency in the industrial design, rotating machineries become thinner and more flexible with upper rotational speed. A dangerous interaction may be happen between the blades and the rotor. Therefore, investigation of blades effect on the stability and bifurcations of the steady state responses of the system is necessary. Genta [1] considered the stability of a rotating blade arrays. The model had an array of rotating pendulums, rigid disk, and dashpot as a suspension system by considering dynamical properties of the bearings. The stability of the system was studied considering the effects of interaction between blades, suspension system, and rotating and non-rotating damping. It was shown that in the undamped in-plane vibration of the long blades, the system loses stability due to the interaction between lades and suspension system. In addition, it was shown that rotating structural damping of blades has a stabilizing effect.

Khadem et al. [2] examined primary resonances of a simply supported in-extensional rotating shaft. The nonlinearity of the shaft was due to the geometrical nonlinearity and large amplitudes of the vibrations. To study the free and forced vibrations of the rotating shaft, the multiple scales method was applied. Two mode combination resonances were also analyzed by the same authors [3].

Vatta et al. [4] probed a linear asymmetrical rotating shaft with dissimilar flexural rigidities. The equations of motion were derived using the Bernoulli-Euler beam theory. The effect of asymmetry ratio on the stability regions was considered. However, the

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effect of nonlinearities on the stability of the system was neglected. Sorge et al. [5] studied the effect of internal damping on the whirling motion of a rotor in the supercritical region. The effect of external dissipative sources and anisotropic suspension system on the instability of the system was investigated using the perturbation method. For this purpose, dry friction and viscous damping were used. Samantaray et al. [6] investigated the stability of the rotor with polynomial nonlinear internal damping. They studied the effect of nonlinear damping on the distortion of the critical orbit and the orbital path. It was shown that nonlinear damping could be stabilize the behavior of the system at normally unstable operating conditions.

Grolet and Thouverez [7] analyzed the nonlinear dynamics of a system with a cyclic symmetry. The nonlinearity of the system was due to large deflection of the blades. The harmonic balance method was employed for solving the coupled equations of motion. They obtained forced responses and various bifurcation points of the nonlinear system under several types of excitations. Sanches et al. [8] investigated a helicopter ground resonance in isotropic and anisotropic multibladed rotor configurations. In order to analyze the nonlinear system, the Floquet theory was used and the bifurcation points of the system were determined.

Wang et al. [9] examined nonlinear dynamics of a blade-rotor-bearing system. The blades were modeled as a rotating pendulum and a discrete rotor was mounted on the journal bearings. Parametric equations of motion were transformed to equations with constant coefficients, using nodal diameter coordinates and periodic transformations. Nonlinear dynamic behavior of the system was studied using Poincare maps, three-dimension spectral plots, and bifurcation diagrams.

Santos et al. [10] considered the nonlinear dynamic of a coupled rotor-blade system. The system was composed of a rigid rotor mounted on a flexible foundation and the four flexible blades. The blades were modeled using the Bernoulli-Euler beam theory. In various angular velocities, theoretical results were validated by experimental ones.

Shahgholi and Khadem [11] considered the primary and parametric resonances of an asymmetrical rotating shaft with simply support conditions. The sources of asymmetry were due to the difference between mass moments of inertia and flexural rigidity in the direction of the principal axes. A large amplitude vibration and the stretching effect were the sources of nonlinearities. The analytical solution of the equations of motion was obtained using the multiple scales method. They investigated the effect of the shaft asymmetry on the steady state responses of the system. The same authors [12] carried out these analyses by considering the in-extensional effect as the source of nonlinearity in an asymmetrical rotating shaft with simply support boundary conditions. Awrejcewicz and Dzyubak [13] studied nonlinear dynamics of a high-speed rotor symmetrically supported on the magneto-hydrodynamic bearing. The analytical solution of the equations of motion was employed using the multiple scales method. The non-resonant and primary resonance behaviors were surveyed.

Chang-Jian and Chen [14] investigated a dynamic behavior of a rub-impact rotor located on two couple stress fluid film journal bearings. The vibration amplitude of the rotor for various rotor speeds was obtained. It was shown that for various rotor speeds, periodic, quasi-periodic and chaotic motions existed in the system.

Al-Bedoor [15] analyzed the nonlinear phenomena of the shaft-disk-blade system. The multi-body dynamics, the Lagrange's equations of motion, and the assumed modes method were used to obtain the equations of motion. It was shown that interaction between the bending vibrations of blades and the torsional vibrations of the shaft is significant. Dai et al. [16] examined a rotor-bearing system with magnetic and hydrodynamic bearings and squeeze film damping. Using four degrees of freedom, the linear dynamic of the system was described. The response of the system subjected to rotating unbalanced mass was investigated. It was demonstrated that the squeeze film damping significantly decrease the amplitude of vibration and unstable region of the system.

Shahgholi and Khadem [17] studied the stability of an asymmetrical rotating shaft with in-extensional nonlinearities under speed fluctuations. The analytical solutions of the equations of motion were obtained using the multiple scales method. They investigated the effect of the speed fluctuations on the steady state responses and branching points of the system. Khader and Masoud [18] investigated the influence of a blade mistuning on the dynamic behavior of the flexible shaft, rigid disk and flexible blade. The equations of motion were obtained using the Lagrange's equations. The variation of the natural frequencies and mode shapes of the system as function of the blade-mistuned magnitude was obtained.

Silani et al. [19] studied the vibration behavior of the rotating system with cracks. They obtained the flexibility matrix of the cracked element and used it for investigation of the dynamic behavior of a rotor system containing open crack. These results were used as a feasible basis for an online monitoring system. Chiu and Chen [20] studied natural frequencies of a rotor-blade system. A coupled torsional vibration of a shaft and bending vibrations of blades were investigated. It was indicated that the natural frequencies and mode shapes of the system are a function of disk distances. Also, it was shown that the unstable region depends on the number of disks.

Shahgholi et al. [21] studied the dynamic behavior of a nonlinear slender rotating shaft with simply support condition. The system rotary inertia and gyroscopic effects were considered. Using the multiple scales method, the forward and backward linear natural frequencies were obtained. The same authors [22] probed the stability of a rotary system which was consisted of a simply supported nonlinear spinning shaft with multi-rigid disk. The sources of nonlinearity were stretching and large amplitude. Based on multiple scales method, the effects of different system parameters on the nonlinear behavior of the rotary system were analyzed. It was shown that in higher rotational speeds the backward frequency is ascending with respect to the number of disks and, in the lower rotational speeds the backward frequency descending with respect to the number of disks.

Wang and Luo [23] studied the stability and bifurcation of a rotating blade under a torsional excitation. Using the Galerkin method, the partial differential equation was converted to the ordinary differential equations. Based on the results of the harmonic balance method, periodic solutions and stability condition were analyzed.

Yaun et al. [24] presented a novel approach to analyze the nonlinear behavior of a turbofan aeroengine blade. Based on sensitivity analyses it was shown that the proposed method is so precise in predicting the trend of the variations of the natural