Mechanical Systems and Signal Processing 118 (2019) 423–442

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Response evaluation of imbalance-rub-pedestal looseness coupling fault on a geometrically nonlinear rotor system

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ARTICLE INFO

Article history:
Received 24 February 2018
Received in revised form 30 June 2018
Accepted 30 August 2018

Keywords:
Dynamic performance
Rotor system
Rub
Pedestal looseness
Geometrical nonlinearity

ABSTRACT

In order to achieve the purpose of condition monitoring and the appropriate design of rotating structure, analyzing the dynamic performance associated with rotor-stator rub coupling fault is of high significance. Due to large imbalance excitation and pedestal looseness, the whirling motion appears with larger amplitude and then the geometrical nonlinearity of shaft becomes impossible to ignore. In order to reveal the inner interaction between coupling fault commonly appearing in the rotating machine and geometrical nonlinearity of shaft, a geometrical nonlinear rotor system with imbalance-rub-pedestal looseness coupling fault is proposed in this paper. The mechanical mechanism of rotor-stator normal impact is represented in terms of a novel force model and its different modifications. Meanwhile, the friction between them is assumed to be a tangential dry Coulomb force, which is proportional to the impact force. After that the vibration features of the rotor system are analyzed with respect to the effects of geometrical nonlinearity, rotor-stator rub and pedestal looseness. The change rules of resonant characteristic and rub region are revealed under different loose stiffness. What is more, the dynamic variation routes of the rotor system are analyzed by the bifurcation diagram, time waveform, whirl orbit, and Poincaré section, respectively. At last, the vibration experiment is performed on a rotor test rig and the typical signals of coupling fault are obtained at different rotational speeds.

1. Introduction

Thrust-weight ratio and efficiency of rotating machine can be enhanced via precisely manufactured bearings with reduced clearances. However, under this engineering circumstance, the probability of rotor-stator rub is increased sharply, which may result in decreased machine life and adverse thermal effects. The rub is termed as the contact between rotor and stator, which may be a dominant factor of rotordynamic behavior [1]. As one of secondary faults occurring in the rotating machine, rotor-stator rub is usually represented in the form of coupling failure. The sources for primary causes could be rotor imbalance, misalignment, fluid forces, shaft crack and pedestal looseness [2–6]. As far as the stability and safety of the rotating machine are concerned, the coupling failures are more harmful and uncertain than single faults.

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https://doi.org/10.1016/j.ymssp.2018.08.063
0888-3270/

That is to say it is essential to master the unique vibration signature of the rotor system with rub coupling fault from state monitoring point of view.

During the past decades, the rotor-stator rub coupling fault has been under comprehensive investigations. Considering this issue that the Jeffcott rotor was subjected to imbalance and rub, Chu et al. [7] revealed the distribution rule among periodic region, quasi periodic region and chaotic region at different rotational speed. As for an asymmetric double-disc rotor-bearing system, Xiang et al. [8] adopted the numerical method to study the nonlinear dynamic behavior of the system varying with the model parameters. The electromagnetic vibration of electrical machines with an eccentric rotor was addressed in the reference [9], in which the electromagnetic excitation, mass imbalance and rub were taken into account. Hou et al. [10] focused on the influence of aircraft hovering flight on the rub rotor system and they investigated the nonlinear dynamic phenomenon. AlZibdeh et al. [11] proposed a three degree-of-freedom extended Jeffcott rotor for describing the drill string, and then they captured the vibration response of the rotor system with rub fault in an approximate solution. Under the periodic excitation caused by the mass eccentricity of disc, Vlajic et al. [12] analytically and numerically investigated the torsional vibration of a Jeffcott rotor system subjected to continuous contact of stationary components. For a rotating continuous flexible shaft-disc system with rotor-stator rub, Khanlo et al. [13] emphasized the torsional coupling effect on the chaotic characteristic and gave the conclusion that this effect could primarily change the speed ratios at which rub occurred. Popprath and Ecker [14] presented the nonlinear dynamic response of a Jeffcott rotor system having intermittent contact with a stator and discussed the effect of the visco-elastically suspended stator on the rotor motion. Wang et al. [15] theoretically studied the sudden unbalance and rub-impact caused by blade loss, in particular investigated the response of the rotor on a rotor test rig. Cong et al. [16] proposed an Impact Energy Model (IEM) to evaluate the probability or severity of rub-impact fault. Meanwhile, they conducted the experiment in two steps i.e. hammer test and rub-impact fault validation. Based on variational mode decomposition, Wang et al. [17] gave a novel method of rubbing fault diagnosis and proved the effectiveness of the method. Ma et al. [18] investigated the fault characteristics of a single span rotor system with two disc when the rub-impact between a disc and an elastic limiter occurred. By using conventional scalograms and reassigned scalograms, Peng et al. [19] explained the cause of rubbings, its occurrence and phenomenon if the severity of rubbing became serious. Thus, there is no denying that the complicated nonlinear phenomenon is generally associated with a rub rotor and then this is supposed to be worthy of intensive study [20–25].

Because of the poor quality of installation or long period of vibration, the pedestal looseness becomes one of the common faults that happen in rotating machine [26]. The looseness fault will reduce the elastic constraint stiffness of pedestal and cause the violent vibration of the rotor system. It is suggested that the work on the topic of pedestal looseness is indeed significant to aviation industry in terms of safe operation. Ma et al. [27,28] established a single-span rotor model with two discs, where the looseness fault was described by a piecewise linear spring-damper model, and analyzed the nonlinear vibration characteristic. For a rotating machine with only one pedestal looseness, Goldman and Muszynska [29,30] observed the synchronous and sub-synchronous frictional components referring to the numerical results and experimental data. Jiang et al. [31] developed a nonlinear measure to quantify the degree of nonlinear behaviors in a bearing-rotor system and predicted the dynamic behavior under different looseness clearances. In the reference [32], a method of multiple scales was adopted to analyze the free vibration and forced vibration of the nonlinear rotor-bearing system. Besides, the influences involved in this bearing pedestal model were also revealed in detail. According to the vibration sensitive time-frequency feature, Chen et al. [33] proposed a novel method to recognize the pedestal looseness extent of rotating machine and then successfully examined the validity of the method.

It should be noted that the looseness fault has a higher potential risk to induce the rotor-stator rub and causes the complicated nonlinear vibration. In other word, there is a close relation between pedestal looseness and rub in the most of actual cases. Meanwhile, the coupling fault of looseness-rub can easily aggravate the whirling motion, so that the geometrical nonlinearity of shaft should not be ignored. Meanwhile, it becomes an extremely crucial component in dynamic design of rotating machine. In the previous authors' work [34], the geometrically nonlinear relation between strain and displacement of flexible shaft was characterized by the equivalent spring and equivalent damper. However, the pioneering contributions to the dynamic response of the rotor system considering geometrical nonlinearity of shaft, rotor-stator rub and pedestal looseness have not been observed in existing literature.

In view of this case, the main contribution of this paper is to investigate the close interaction between geometrical nonlinearity and coupling fault acting on the rotor system. According to the Hamilton principle, a general dynamic model for geometrically nonlinear rotor system subjected to imbalance-rub-pedestal looseness coupling fault is established in this paper. To reveal the normal impact mechanism in the condition of thermal barrier coatings, a novel force model and its modified forms [35,36] are employed at the different penetration stages. In the tangential direction, the Coulomb model [37] is used to describe the friction characteristic. Then the numerical simulation is applied to obtain the nonlinear vibration response of the rotor system at different rotational speed. Briefly speaking, there are five parts in the present work, including (1) sweep frequency analysis of linear/nonlinear rotor system without any fault, (2) imbalance-rub coupling fault under different initial clearance, (3) imbalance-pedestal looseness coupling fault under different looseness stiffness, (4) nonlinear dynamic characteristic of the rotor system with imbalance-rub-looseness coupling fault, (5) hammering test and vibration test on the rotor test rig. To some extent, this work can enrich our understanding to the vibration mechanism of rotating machine and may promote the development of fault diagnosis.