Mechanical Systems and Signal Processing 116 (2019) 443–461

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Nonlinear dynamic analysis using the complex nonlinear modes for a rotor system with an additional constraint due to rub-impact

Jie Hong [a,b], Pingchao Yu [a], Dayi Zhang [a,c,*], Yanhong Ma [a,b]

[a] School of Energy and Power Engineering, Beihang University, Beijing 100191, PR China
[b] Collaborative Innovation Center of Advanced Aero-Engine, Beihang University, Beijing 100083, PR China
[c] Beijing Key Laboratory of Aero-Engine Structure and Strength, Beijing 100083, PR China

ARTICLE INFO

Article history:
Received 18 July 2017
Received in revised form 11 May 2018
Accepted 28 June 2018

Keywords:
Rub-impact
Additional constraint
Complex nonlinear modes
Stability
Dry whip

ABSTRACT

A rub-impact can bring the impact load and friction force onto the rotor, and in the meantime, it can also produce the additional effect of changing the stiffness of the rotor system. Past analysis and numerical simulation work related to rub-impact problems primarily focus on the complicated nonlinear vibration responses caused by the rubbing force. However, the influence of the additional effect on the rotor's modal characteristics is rarely studied. The present study investigates the modal characteristic of the rotor system with the additional constraint and how it affects the rotor's responses. The governing equation for a modified Jeffcott rotor system with a rub-impact is established first. Next, the complex nonlinear modes concept is introduced, and the corresponding solution method is derived. Finally, the modal characteristics are analyzed in detail, such as the modal frequency, the modal damping, the stability and the interaction between the nonlinear mode motion and rotor's responses. The results show that the rubbing rotor system possesses both forward whirl mode motion and backward whirl mode motion. The magnitudes of the modal frequencies for both the forward whirl and backward whirl increase with an increase in the amplitude of the mode motion (modal amplitude). Nevertheless, the magnitudes are limited to an interval range, which can be approximately determined through the linear rotor without rub-impact and the coupled linear rotor/stator system. Differing from the forward whirl mode motion, the backward whirl mode motion can be unstable, since its modal damping may be less than zero in certain cases. Moreover, the instability of the backward whirl mode motion is only the primary physical mechanism for the partial rub transmitting into dry whip.

1. Introduction

The high-performance requirements for rotating machines, such as aero-engines, gas turbines and compressors, always result in a decreasing clearance between the rotors and stators, which most likely results in a severe rub-impact during operation. Rub-impact in rotating machines will produce high impact forces and friction that may lead to severe vibration and even catastrophic failures in the worst-case scenarios [1,2].

* Corresponding author at: School of Energy and Power Engineering, Beihang University, Beijing 100191, PR China.
E-mail address: dayi@buaa.edu.cn (D. Zhang).

https://doi.org/10.1016/j.ymssp.2018.06.061

During the past several decades, a significant amount of research has been conducted on the mechanisms and the complicated phenomena of a rub-impact event. Muszynaka [3] presented an excellent review on the rotor-to-stator rubbing contact in rotating machinery. She noted that the rub-impact involves several physical phenomena, including most notably the impact, friction and stiffness increase. As a result, the rotor becomes highly nonlinear and will exhibit extremely rich dynamic behaviors, such as a partial rub, backward whirl, quasi-periodic and even chaotic motions [4–6]. Chu and Zhang [7,8] investigated the non-linear vibration characteristics of a Jeffcott rotor with a rub-impact. These researchers found that when the rotating speed was increased, the grazing bifurcation, quasi-periodic motion and chaotic motion occurred. Pennacchi studied the light and short arc rubs where the fixed part is less stiff than the rotor [9]. Roques investigated the speed transients during rotor-to-stator rubbing caused by an accidental blade-off imbalance [10]. Jiang explored the existence boundaries of different responses, e.g., a synchronous full annular rub, partial rub and dry whip for a rubbing rotor, and an overall picture of the global response in the parameter space was obtained using an analytic method [11]. Ma studied the rubbing-induced vibration responses based on contact dynamics theory under different rubbing types, such as a multiple-point rub [12] and a full annular rub [13]. Moreover, Ma built a comprehensive model of a rotational shaft-disk-blade system, and the effects of the rotational speed, stagger angle of the blade and the casing stiffness on the vibration responses were discussed in detail [14–17].

Among the different contact responses of a rubbing rotor system, dry whip is the most destructive motion to rotating machinery. During dry whip, the rotor undergoes a large deformation and is subjected to high-frequency stress, which will initiate a break or fatigue damage of the shaft and cause a failure of the machine [18,19]. Black built a general model for a synchronous rub to investigate dry whip and concluded that it was only possible in the frequency band, extending from an individual rotor/stator natural frequency to the next higher combined system frequency [20]. Applying Black's model to a long-cantilevered disk, Zhang [21] accounted for multiple rotor modes in dry whip and dry whirl and identified the same whirl regions as Black. Jiang studied the physical reason for the onset of dry whip and revealed that the rotor in resonance at a negative frequency to the rotor-to-stator system results in a dry whip [18]. Childs and Kumar developed analytic dry whip and dry whirl solutions for a rigid-rotor/rigid-stator model with contact at two rubbing locations [22].

In addition to the complicated dynamic behaviors caused by the impact and friction forces, the transient stiffness of the rotor will also be increased in the process of the rub-impact. This phenomenon is usually called the stiffening effect [23] or additional constraint effect [24,25]. Making use of this characteristic, Chu quantitatively analyzed the change of the transient stiffness of a rotor based on the parameter identification theory and put forward an effective method to detect the rubbing positions [23,26]. Ma built a constraint mechanical model of a full annular rub and their study showed that the constraint effect made the rotor's resonant range expand [24]. After that step, Hong proposed a dynamic modeling for the rotor system with a non-smooth constraint in the case of an intermittent rub-impact and studied the effects of the non-smooth constraint on the modal characteristics and vibration response of the rotor system [25,27]. Bently [28] and Child [29] demonstrated that a partial rub causes a periodic variation of the rotor's stiffness, which could lead to an instability of the rotor's vibration.

When a rub-impact occurs, the modal frequency and modal shape of the rotor system change due to the additional constraint. However, there are a limited number of papers that attempt to analyze the modal characteristics of a rubbing rotor. One important reason is that the traditional linear normal modes cannot be applied to this strong nonlinear system. Fortunately, the nonlinear normal modes (NNMs), originated by Rosenberg [30] and developed by Shaw and Pierre [31], provide a mathematical and practical framework for the analysis of the rubbing rotor system. Since the concept of nonlinear normal modes were proposed, many approximate methods [32–34], such as asymptotic methods, multiple scale methods and numerical methods, have been advanced and adopted to construct NNMs, which has strengthened the relevant theoretical background. More recently, the nonlinear normal modes for the practical engineering systems with non-smooth nonlinearities were investigated by several scholars [35,36]. D. Jiang built a numerical method for calculating the NNMs of piecewise linear autonomous systems and investigated the existence, stability and bifurcations of the NNMs [37]. Jiang analytically derived the nonlinear normal modes of a rubbing rotor, but the modal damping was ignored in his study [38]. Considering the energy dissipation in non-conservative systems, Denis Laxalde defined the complex nonlinear modes that can include the damping dissipation of the mechanical system and applied the concept to analyze turbo-machinery blades with friction [39].

As the influence of the additional constraint on modal characteristics of the rubbing system is not well-understood to date, this paper aims at revealing the modal characteristics of the rubbing rotor system with additional constraints, as well as how the modal characteristics affect the rotor's rubbing motions. First, the governing equation of a widely used Jeffcott rotor system with an additional constraint is established. Next, the eigen problem is derived in the frequency-domain by introducing the complex nonlinear modes concept, and modal frequency and damping characteristics are determined through numerical solving methods. The modal frequency and modal damping of the rubbing rotor system are obtained, and the interaction between the nonlinear mode motion and rotor's responses is analyzed in detail.

2. Governing equation for a rotor system with additional constraints

The rubbing rotor system used in the paper consists of a Jeffcott rotor and a stator, which is modeled with an added stiffness as shown in Fig. 1. This model is widely used in the mechanism study of the rotordynamics [7,11,24,38] due to its simplicity and its ability to reveal the basic mechanical characteristics of the rotor system. The rotor has a massless shaft carrying a mid-span disk with mass m. The mass center of the rotor is located at a distance e from its geometrical center. The