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Modal characteristics analysis for a flexible rotor with non-smooth constraint due to intermittent rub-impact

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Abstract Intermittent rub-impact, during which the contact between rotor and stator is characterized by a ''bouncing'' or intermittent type of behavior, is one of the most common rubbing forms in rotating machinery. When the intermittent rub-impact occurs, the non-smooth constraint, which is the phenomenon that the system stiffness changes with respect to the state of contact and noncontact, will appear. The paper aims at discovering the possible effects of the non-smooth constraint on the flexible rotor's modal characteristics by theoretical and experimental methods. The qualitative description for non-smooth constraint is given for the intermittent rub-impact process, and the dynamic modeling for a rotor system with non-smooth constraint is carried out. Meanwhile, the analysis method is developed by Floquet theory and Hill's method to obtain the rotor's modal characteristics. The results reveal that the non-smooth constraint produced by the intermittent rub-impact will increase the modal frequencies and critical speeds of the rotor system significantly. Due to the time-varying features of the constraint stiffness, the modal frequencies for the intermittent rub-impact rotor present fluctuant changes with the increase of rotation speed, which is different from the general linear rotor system. The non-smooth constraint is possible to lead the rotor's instability, and the rotor's instable regions can be expanded significantly for the increase of average constraint stiffness, constraint amplitude and contact time ratio. Non-smooth constraint could also expand the resonance speed and resonance sideband of the rotor system, which sometimes results in amplitude jump phenomenon.

1. Introduction

The high performance requirements for modern aero-engines always bring about the decrease of the clearance between rotors and stators, which probably results in the terrible rub-impact during operation.[1] Rub-impact is mostly a secondary

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failure for aero-engines[2], which may result from misalignment, unexpected imbalance, blade off, etc. When rub-impact occurs, severe vibration can be induced to the machinery, which can lead to the permanent bow of the shaft, and even damages to the whole system.[3] As a result, the rotor-to-stator rub-impact has always been the crucial problem affecting the reliability and integrity of aero-engines, and it is extremely beneficial to study the vibration characteristics for the dynamics analysis and safety design of the aero-engine rotor systems.[4–6]

Rub-impact involves several physical phenomena, such as the most notable impact, friction and a stiffness increase while the contact is maintained, and as a result, the system turns to be highly nonlinear.[7] During the past decades, a significant amount of researches have been done on the mechanisms and the complicated phenomena of rub-impact, and some representative works include the thermal effects[8–10], the possible dynamic behavior and corresponding response characteristics, the destructive dry-whip and its stability, and the stiffening effects.

Dynamic behavior of the rotor system excited by the impact force is one important research topic mentioned in many public references. Beatty introduced the piecewise linear rub-impact force model and investigated typical characteristics of rub-impact fault[11] for the first time. After his pioneering work, Choy et al. performed a detailed theoretical investigation to observe the effects of the casing stiffness, friction coefficient, etc. on the rub force and rotor orbit.[12] Goldman and Muszynska studied the dynamics of rotor systems with partial rub-impact. The orderly harmonic responses, sub-harmonic responses as well as chaotic responses were obtained in their simulation.[13] Chu and Zhang[14] investigated the non-linear vibration characteristics of a rub-impact Jeffcott rotor. They also found that when the rotating speed was increased, the grazing bifurcation, the quasi-periodic motion and chaotic motion occurred after the rub-impact. Ma et al. studied the rubbing-induced vibration responses based on contact dynamics theory, under different rubbing types such as single-point rubbing[15], multi-point rubbing[16], and full annular rubbing.[17] Some interesting fault features had also been extracted. Taking single-point rubbing as an example, different rotor motions, such as period-one motion P1, P2 and P3, could be observed with the increasing rotation speeds.[15]

Another emphasis of the researches is about the dry-friction whip and whirl characteristics of the rub-impact rotor system caused by the tangential friction force. During dry-friction whirl and whip, the rotor undertakes very large deformation and is subjected to high-frequency stress, which will initiate the break or the fatigue damage of the shaft and cause the failure of the machine.[18] In order to investigate dry-friction whirl, Black built a general model for synchronous rubbing and concluded that dry-friction whirl was only possible in the frequency band, extending from an individual rotor/stator natural frequency to the next higher combined system frequency.[19] Applying Black's model to a long-cantilevered disk, Zhang[20] accounted for multiple rotor modes in dry-friction whip and whirl and identified the same whirl regions as Black.[19,20] Jiang and Ulbrich presented a modified Jeffcott rotor with a given rotor/stator clearance and cross-coupling influences and carried out an analytical study on the stability of the full annular rubbing conditions.[18] Childs and Kumar developed analytic dry-friction whip and whirl solutions for a rigid-rotor/rigid-stator model with contact at two rubbing locations.[21]

On the other hand, the influence of stiffening effects for rub-impact is also investigated by many researchers. The stiffening effect, also called constraint effect in Ref. 22, is the phenomenon that rotor's displacement is constrained and the stiffness of rotor system increases when rotor contacts with stator during rub-impact. Making use of this characteristic, Chu and Lu analyzed the change of transient stiffness of rotor quantitatively based on parameter identification theory and put forward an effective method to detect the rubbing positions.[23,24] Generally, rubbing forms determine the constraint stiffness change process of rubbing rotor. In rotor system, the rubbing forms mainly include full annular rub-impact[17,20] and intermittent rub-impact.[16,17,25] Full annular rub-impact denotes that the rotor is in continuous contact with the stator[17], and consequently, constraint effect exists all the time. Ma et al. built a constraint mechanical model of full annular rub-impact and their study showed that constraint effect made the rotor's resonant range expand.[22] Intermittent rub-impact, during which the contact between rotor and stator is characterized by a "bouncing" or intermittent type of behavior[25], is one of the most common rubbing forms in rotor system. Due to the contact and separation of rotor with stator, constraint effect at that time is discontinuous and stiffness of rotor system is time-varying. As "discontinuous" is named "non-smooth" in non-smooth mechanics[26], this reference names the constraint effect or stiffening effect of intermittent rub-impact as "non-smooth constraint". Bently demonstrated experimentally that intermittent rub-impact causes a periodic variation in the rotor's stiffness, which could lead to Mathieu-Hill type of parametric instability.[27] Childs built a simple physical model and presented analysis of rotor's dynamic characteristics and stability by this kind of rub-induced parametric excitation.[28] Abuzaid et al. investigated effect of intermittent rub-impact on rotor's shaft vibration experimentally and analytically. In their study, rotor's stiffness with the influence of non-smooth constraint was analyzed and a new additional stiffness model considering time-varying characteristic was proposed.[29]

In the literatures described above, researchers mostly focused on the dynamic behavior and vibration response characteristics of rubbing rotor system excited by impact and friction forces. However, the discussion on the modal characteristics of intermittent rub-impact rotor system with non-smooth constraint was rarely reported so far. The additional constraint produced by the rub-impact has been preliminarily discussed in the authors' previous researches[2], in which the mechanism of the additional constraint is confirmed by an extremely simplified method; however the effects of non-smooth constraint on rotor modal characteristics, particularly on the rotor's stability, are not well studied. Meantime, it is also not well understood how the modal characteristics influence the rotor's vibration response. In view of the above mentioned work, this paper further studies the modal characteristics of an overhung flexible rotor system with non-smooth constraint more detailedly and systematically. A non-smooth constraint stiffness model is proposed based on the physical process of intermittent rub-impact, and the dynamic equation for an overhung rotor with non-smooth constraint is established. The time-varying parameters analysis