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Unbalance-induced rub between rotor and compliant-segmented stator

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ABSTRACT

Today, turbomachinery designers are trying to attain zero clearances for optimizing performance and efficiency of machine by designing advanced compliant-segmented seals. This trend involves secondary issues such as rotor-to-stator contact interaction which is to be treated with more technical knowledge in rotordynamic design and condition monitoring programs. The aim of this paper is to gain insight into dynamic interaction between a flexible rotor and a set of compliant arc-shaped segments as stator system. Specifically, the unbalanced-induced forward rubbing response is investigated in tight clearance condition during resonance-passing situations. A Jeffcott rotor modeling is used for representing the flexible rotor. A set of linear elastically-mounted rigid bodies with arc-shaped inner surfaces, which are arranged circumferentially around the rotor, are assumed as the model of the stator. The effects of mass, rotary inertia, translational and tilting stiffnesses are taken into account in the segment modeling. To compute the contact dynamic response, the equations of motion are coupled via Lagrange multiplier technique. The constrained equation of motion is solved by an implicit predictor-corrector time-marching numerical algorithm. Investigations reveal that the steady-state coupled rubbing solutions exist for the rotor interacting with the segmented stator. The solutions are classified with respect to stator properties, e.g. the number of segments and the stator stiffness. The synchronous rubbing solution covers various feature including shift in resonance speed, lower amplitude of rotor's vibration, smooth rise and fall in case of soft segments, jump phenomena in case of stiff segments, chaotic orbiting motion under effects of segment mass, etc. as are discussed in detail.

1. Introduction

Leakage in turbomachinery causes power loss and is usually controlled by appropriate design and placement of sealing systems in the prone locations such as between pressure stages or secondary airflow paths. Efficiency of turbomachinery can potentially be enhanced more and more until attaining zero clearances in sealing areas. Thus, clearance reduction is currently an industrial trend pursued via advanced compliant seals design [1,2]. Clearance reduction may increase possibility of contact between rotary part and stationary components of machine. This contact named “rub” can specifically occur during start-up or shut-down processes, when rotor's amplitude of vibration grows as it passes low frequency modes. For the purpose of rub

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avoidance, appropriate requirements are already fulfilled by turbomachine designers. As standardized in Ref. [3], anticipated clearances between rotary and stationary components have to be sufficiently large throughout the machine to let rotor freely run without any contact during rotor-stator gap closure events; i.e. passing through the resonances and thermal expansions. On the other hand, sealing performance of advanced compliant seals is critically tied to the ability of these seals to move radially relative to the rotor during transient events, and their ability to maintain a small running clearance at nominal condition [4]. Hence, contact phenomenon is one of major concerns in design of some advanced seals because of clearance closure during transient situations.

The contact of rotor with a stationary element involves friction, impacting, modification of the system stiffness due to the physical coupling, all of them additionally affected by thermal effects [5]. Generally, dynamic behavior of the rubbing contact falls into two categories: the first is full annular rub in which the rotor keeps contact with the stator continuously during its whirling motion. The second is partial rub in which the rotor contacts with the stationary surfaces only during a portion of its orbiting motion. In another classification, the rub is said to be “synchronous” if the rotor whirling path known as “orbit” is fully traversed during every revolution of the rotor. The rub is said to be “subsynchronous” with $1/n\times$ frequency component if the orbit is traversed once in every “n” revolutions of the rotor. These terminologies are from rotordynamic view point [5]. Subsynchronous solutions are named as “period-n” from nonlinear dynamics concepts [6], and they feature fraction “$1/n$” of rotational speed as a frequency component of the vibration. Muszynska [5] collected previous studies on the rotor-to-stator rubbing contact phenomena, which concerned with true modeling and consequent mechanical and thermal features. Black [7,8] presented a linear multi-degree-of-freedom model in which inertia, stiffness and damping are imputed to both the rotor and the stator interacting across a clearance annulus. He assumed a continuous steady interaction, and used polar receptances to analytically define speed zones within which interaction may occur. Choy and Padovan [9] assumed a Jeffcott rotor characteristics, an annulus casing approximated by a rigid massless casing supported by radial springs, and a Coulomb type of frictional relationship. They described the contact force as a linear elastic restoring force being proportional to casing deformation, and performed analytical simulations of rotor transient rub motion under the effects of sudden induced imbalance excitations. Considering such simplified model with a clearance annulus between the rotor and the stator, many researchers studied behavior of rotor-stator system under effects of different parameters in response to various initial conditions, and excitations as follow. Erich [10] used a simple piecewise linear model for rotor being in contact with the stiff stator and showed that the response is a series of pseudo-critical peaks at whole-number multiples of the rotational speed. Goldman and Muszynska [11] improved an oversimplified rotor/stator contact model to account the impact effect. They simulated more accurately the rotor's orderly subsynchronous and chaotic vibrations specifically when the supports are anisotropic. Chu and Zhang [12] assumed an elastic impact and the Coulomb friction relationship to show that a rub-impact rotor system supported on oil film bearings can exhibit periodic, quasi-periodic and chaotic vibrations when rotational speed, damping and unbalance are used as control parameters. Edward et al. [13] included the torsion flexibility in the rotor/stator contact model and highlighted its effects on the periodic nonlinear response. Al-Bedoor [14] constructed a rubbing model using impact-contact idealization and considered torsional degree-of-freedom, and then found a split in resonance during start-up condition. Bartha [15] worked on the friction-induced backward whirl of the rotor and found that a high modal damping and a reduced coefficient of restitution for impacts of the rotor with the stator also increase the plant's robustness towards frictional excitation. Bently et al. [16,17] experimentally and analytically studied forward rub jump phenomena, reverse rub triggering mechanism, transition between these two, and also the effects of mass unbalance, surface lubrication, shaft speed, and seal stiffness. Pavlovskaia [18] showed analytically and Karpenko [19] verified experimentally that the vibration behavior of Jeffcott rotor preloaded by a snubber ring can fall into five different contact regime. They used bifurcation diagram, phase portrait and Poincare maps to interpret the results. Child and Bhattacharya [20] extended the Black's model with a multimode rotor model to predict a complicated range of backward whirl and dry whip possibilities. Chu [21] demonstrated that the stiffening effect of the stator during rub changes the natural frequency of the rotor. Lahriri [22] investigated the rub dynamics between a rotor driven by a non-ideal drive and two backup stator guides: a conventional circular stator one and a disk-pined one. Varney and Itzhak [23] studied the bifurcation and rout-to-chaos of a rotor-stator system, and noticed that the gravity effect is not to be ignored. There are situations where the clearance around the rotor is not annular. A jammed or off-centered seal is an example well-known as “normal-tight” condition [24,25]. Childs (1981) performed an analysis based on Jeffcott model to explain subsynchronous rubbing vibration occurring in rotors which are subjected to periodic normal-loose or normal-tight radial stiffness variations. Muszynska [26,27] experimentally and analytically studied on rotor partially rubbing to a flexible obstacle via modeling friction, impacting, and a system stiffening effect. Choi [28] and Abuzaid [29] studied partial rotor rubbing occurring when an obstacle on the stator of rotating machinery disturbs the free whirling motion of the rotor.

Besides the simplified models, the need for high machine efficiency necessitated more realistic descriptions of fully flexible structures as an emerging field of researches on rotor-to-stator contact phenomena. Legrand et al. [30] investigated the modal interaction of bladed disks and outer casings of an aircraft engine by developing two-dimensional (2D) models using Euler–Bernoulli straight and curved beam elements, and then solving the governing equation using a time-stepping method in conjunction with the Lagrange multiplier method. Batailly et al. [31] showed that reduced-order modeling technique especially Craig–Martinez component mode synthesis method have computational efficiency and can be used for fast parameter studies. Legrand et al. [32] presented a fully three dimensional (3D) model for the prediction of blade-to-casing contact by using a smoothing procedure including bicubic B-spline patches together with a Lagrange multiplier based contact strategy. Such developed numerical models are later used for solving practical engineering problems like unexpected