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Nonlinear dynamics of mistuned bladed disks with ring dampers

Weihan Tang *, Bogdan I. Epureanu

Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI 48109, United States

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ABSTRACT

In turbomachinery applications, rotating bladed disks (blisks) are often subject to high levels of dynamic loading, such as traveling wave excitations, which result in large response amplitudes at resonance. To prevent premature high cycle fatigue, various dry friction dampers are designed for blisk systems to reduce the forced responses. Ring dampers are located in the disk, underneath the blades, and are held in contact with the blisk by centrifugal loading. Energy is dissipated by nonlinear friction forces when relative motions between the ring damper and the blisk take place. To investigate the dynamic responses of blisk–damper systems in the presence of the nonlinear frictional contacts, conventional methods based on numerical time integration are not suitable since they are computationally expensive. This paper presents a reduced-order modeling technique to efficiently capture the nonlinear dynamic responses of the blisk–damper systems. Craig–Bampton component mode synthesis (CB-CMS) serves as the first model reduction step. A novel mode basis that mimics the contact behavior under sliding and sticking conditions is developed to further reduce the CB-CMS model while maintaining its accuracy. The resulting reduced nonlinear equations of motion are solved by a hybrid frequency/time domain (HFT) method. In the HFT method, the contact status and friction forces are determined in the time domain by a three-dimensional contact model at each contact point, whereas the reduced equations of motion are solved in the frequency domain according to a harmonic balance formulation. Moreover, to investigate the effects of blade mistuning, which can lead to drastic increase of forced responses, an extension of the reduced-order models (ROMs) is developed based on component mode mistuning. Forced responses computed by the proposed ROMs are validated for both tuned and mistuned systems. A statistical analysis is performed to study the effectiveness of ring dampers under random blade mistuning patterns.

1. Introduction

Rotating bladed disks (blisks), when operating under severe conditions, are subject to high levels of static and dynamic loads, resulting in large amplitudes of forced vibrations at resonance. The high levels of forced responses can lead to prematured high cycle fatigue (HCF) that can cause substantial damages to the turbine blades. To prevent mechanical failures caused by HCF and to increase the working lifetime of blisks, extensive effort has been made to reduce the amplitudes of forced vibrations by introducing various designs of frictional damping sources to blisks, such as underplatform wedge dampers [1–8] and frictional shroud contacts [9–13].

However, integrally bladed disks are manufactured in a single piece. Thus, shroud contacts no longer exist. Also, integrally bladed disks possess very limited inherent contact interfaces for underplatform dampers to effectively dissipate vibrational energy. Therefore, ring-shaped frictional dampers have been proposed as an alternative damping source for single-piece rotating structures. Frictional ring dampers are located in dedicated grooves in the disk, underneath the blades, and are held in contact with the blisk by centrifugal loads. Energy dissipation by friction occurs when relative motions take place between the ring damper and the blisk.

To investigate the complex and nonlinear contact dynamics of dry friction damping, a variety of contact models have been developed and can be found in literatures. Due to its simplicity, one-dimensional (1D) marco-slip contact models have been widely used [14–16], and validated by data obtained from bench tests [17]. Arrays of 1D macro-slip models are constructed to capture the micro-slip phenomenon [5,18–20]. These 1D friction models are based on the assumption that the normal load acting on the contact surfaces is constant. However, in the presence of out-of-plane motions, this assumption no longer holds. Yang et al. [21] developed a 1D contact model that features normal contact stiffness to capture the variable normal loads between two

* Corresponding author.
E-mail addresses: weihant@umich.edu (W. Tang), epureanu@umich.edu (B.I. Epureanu).

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contact surfaces induced by relative motions in the normal direction. Transition criteria for contact status among stick, slip, and separation conditions were also suggested. Cigeroglu et al. [22] adopted this model, and proposed a multi-mode solution method.

The contact models described above focus on 1D relative motions between two contact surfaces. Sanliturk et al. [23] extended the 1D macro-slip contact model by allowing a single-spring point contact to travel on a 2D plane. Menq et al. [24] developed a 2D contact model that contains two coupled tangential contact springs, and derived analytical transition criteria for contact status. Yang et al. [25] addressed the issue of variable normal loads for 3D relative motions between contact surfaces. Their 3D contact model was further used to predict forced responses of nonlinear structures under periodic forcing [26].

Frictional contacts are nonlinear in nature. To solve the equations of motion of blisk–damper systems that carry nonlinear contact models, a variety of solution methods have been developed. Early studies focus on analytic derivations of the contact dynamics, and heavily rely on assumptions of the damper geometry [1,2]. Tanrikulu [27] proposed the technique of describing functions, which models the nonlinear contact forces as response-dependent equivalent damping and stiffness. Cigeroglu et al. [12] adopted this technique to study the dynamics of a friction-damped tip-shrouded blisk. Compared to describing functions, a more well-known and widely adopted solution method is the harmonic balance method (HBM). Cardona applied HBM to predict periodic responses of a frictionally damped system, and provided an analytical Jacobian for the Newton–Raphson solver [28]. Yang et al. [3] assumed two rigid contact surfaces between a blisk and a wedge damper, where each contact surface is modeled by a 1D macro-slip contact model that accounts for normal load variations. This work includes analytical transition criteria of contact status that involve simultaneous stick–slip motions of two contact surfaces. HBM was used to solve the nonlinear equations of motion [4]. A similar method is developed by Sanliturk et al. [6], in which a two-dimensional contact model is used to account for the relative motions in the axial direction of the blisk. Csaba [5] applied HBM to study the dynamic responses of a curve-shaped underplatform damper. HBM has also been adopted to study the periodic responses of blisks with frictional shroud contacts [9,10,29]. Variants of HBM have also been developed to improve its efficiency [30,31]. Cameron et al. [32] developed an alternating frequency/time (AFT) method. In the AFT method, the nonlinear friction forces are computed in the time domain, and transformed to the frequency domain, in which the equations of motion are solved by Newton–Raphson-like methods. A similar method, hybrid frequency/time domain method (HFT) is developed by Guillen [33]. This method has been adopted by Poudou et al. [34] to analyze friction damping in turbomachinery applications.

Although HBM and its variants have proved efficiency in analyzing friction-damped systems, directly applying HBM to commercial finite element (FE) models of blisk–damper systems can be computationally expensive as the nonlinear equations of motion may contain many degrees of freedom (DOFs). To address this issue, reduced-order models (ROMs) have been introduced to reduce the size of the full-order models. Exploiting cyclic symmetry, it is possible to use the model of a single sector to obtain forced responses of blisks with frictional shroud contacts [11,13]. Classical model reduction methods, such as Craig–Bampton component mode synthesis (CB-CMS) [35], are used to condense full-order models into a relatively small subset of physical DOFs, including those on the contact surfaces, and modal coordinates of the system normal modes with fixed CB-CMS interfaces [34,36]. A modal superposition method was introduced by Cigeroglu et al. [22] to project the full-order models onto their free mode shapes. That approach adds rigid body mode shapes into the projection mode basis [7,8]. Ferhatoglu et al. [37] expresses frictional nonlinearity as equivalent stiffness. Normal mode shapes of systems that involve such additional stiffness are extracted for model reduction. Recently, Mitra et al. [38] proposed a method using adaptive micro-slip projection. This method is based on combining mode shapes of a set of linear systems with strategically chosen boundary conditions on the contact surfaces.

The frictional contact models, solution methods and ROMs described above have been extensively used to study underplatform wedge dampers, and frictional shroud contacts. Comprehensive reviews are also available in literature [39,40]. In contrast, limited work has been done to study ring dampers. In the early studies, Niemotka et al. [41] analyzed the stress–strain relationships of a split ring under static forcing. Laxalde et al. [42] constructed a lumped-parameter model of the blisk–damper system that features a 1D macro-slip contact model. The resulting nonlinear equations of motion were solved by the HFT method. The HFT method was further applied to a more realistic FE model of the blisk-ring system [43]. A dynamic Lagrangian method was used to predict the nonlinear contact forces. A nonlinear modal analysis approach was developed by Laxalde et al. [44], and applied to determine design parameters of ring dampers.

In this paper, a novel ROM is developed to predict the nonlinear steady-state forced responses of blisks with frictional ring dampers. The key difference between ring dampers and underplatform dampers is in the type of motion that leads to energy dissipation through friction. This difference leads to a substantial difference in the types of modes where dampers are effective. Ring dampers are most effective when modes with significant motion along the rim of the blisk are excited. These modes tend to be associated with low nodal diameters. In terms of modeling approaches, underplatform dampers can often be treated as rigid structures. In contrast, ring dampers are very flexible. Under external forcing, ring dampers deform (coherently) with the blisk. Their deformation must be accounted for accurately in order to estimate correctly the friction forces. In contrast, underplatform wedge dampers are very rigid and their deformation can be and is typically neglected in models. To capture the elastic deformation of the ring damper, the method proposed in this study utilizes two sets of system normal mode shapes, extracted for global sliding and global sticking contact conditions. The key observation we use is that ring dampers have a small amount of mass and low stiffness compared to the blisk. Thus, the two sets of mode shapes are nearly identical except for the difference along the contact DOFs. When the system is under external periodic forcing, such difference can capture the relative motions between contact surfaces, and the responses of the rest DOFs can be captured by either of the two sets of mode shapes. A small mode basis consisting of the two sets of mode shapes is formed for model reduction. The resulting ROMs are expressed in a HBM formulation. The frictional contact between the ring and the blisk contains contact node pairs that are distributed across the contact surfaces. Each node pair can be modeled by a 3D sophisticated contact model developed by Yang et al. [25]. However, to accelerate the computations, a simplified 3D contact model, consisting of two independent 1D macro-slip models and an additional spring accounting for normal load variations, is adopted in this study. The HFT method is used to solve the nonlinear equations of motion, where in the frequency domain, the nonlinear equations of motion are expressed using only a few coordinates.

The effect of mistuning on frictionally damped Blisks has not drawn much attention in the previous studies. Mistuning, defined as variations in structural properties of individual sectors, can lead to localization and drastic increase of forced responses. It is of interest to explore the effectiveness of ring dampers in dissipating vibrational energy when forced responses are amplified by the presence of mistuning. The interaction between frictional damping and mistuning has been studied in the past for blade-to-ground and blade-to-blade dampers, such as underplatform wedge dampers, and frictional shroud contacts with small motions [45,46]. blisk–damper systems are modeled with lumped-sum parameter models. The conclusion that the optimal slip load for a tuned system holds for mistuned system is important. In this study, a method based on component mode mistuning (CMM) is developed to construct the mistuning components of the blisk–damper systems directly in the ROM coordinates [47–49]. This method enables the developed ROMs to capture the forced responses of mistuned blisk–damper systems, and to explore the correlations between mistuning and the effectiveness of the frictional ring dampers.

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