



Reduced-order modeling for mistuned centrifugal impellers with crack damages



Shuai Wang, Yanyang Zi*, Bing Li, Chunlin Zhang, Zhengjia He

State Key Laboratory for Manufacturing and Systems Engineering, School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China

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ABSTRACT

An efficient method for nonlinear vibration analysis of mistuned centrifugal impellers with crack damages is presented. The main objective is to investigate the effects of mistuning and cracks on the vibration features of centrifugal impellers and to explore effective techniques for crack detection. Firstly, in order to reduce the input information needed for component mode synthesis (CMS), the whole model of an impeller is obtained by rotation transformation based on the finite element model of a sector model. Then, a hybrid-interface method of CMS is employed to generate a reduced-order model (ROM) for the cracked impeller. The degrees of freedom on the crack surfaces are retained in the ROM to simulate the crack breathing effects. A novel approach for computing the inversion of large sparse matrix is proposed to save memory space during model order reduction by partitioning the matrix into many smaller blocks. Moreover, to investigate the effects of mistuning and cracks on the resonant frequencies, the bilinear frequency approximation is used to estimate the resonant frequencies of the mistuned impeller with a crack. Additionally, statistical analysis is performed using the Monte Carlo simulation to study the statistical characteristics of the resonant frequencies versus crack length at different mistuning levels. The results show that the most significant effect of mistuning and cracks on the vibration response is the shift and split of the two resonant frequencies with the same nodal diameters. Finally, potential quantitative indicators for detection of crack of centrifugal impellers are discussed.

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1. Introduction

Centrifugal compressors are important equipment in industrial production and are widely used in the fields of petrochemical, steel and electric power owing to their ability to achieve higher pressure ratios per stage compared with axial compressors. However, accidents due to mechanical failures may cause enormous economic loss or even endanger the life safety of field personnel. Thus, to ensure the operation safety of compressors is of great importance in industrial applications. In addition, the impellers, as key components of centrifugal compressors, may suffer from crack damages due to high cycle fatigue after several years of service. With the advances of centrifugal compressor, this issue has been the main safety concern of the reliability of systems [1].

* Corresponding author. Tel./fax: +86 29 82663689.

E-mail address: ziyy@mail.xjtu.edu.cn (Y. Zi).

Most of the previous research on vibration analysis of turbomachinery was focused on axial compressors, which was reviewed in literature [2,3]. However, few papers were reported, to date, to deal with the nonlinear vibration analysis of cracked centrifugal impellers, which exhibit different features compared with bladed disks due to their unique structures. Then, a brief review of the progresses on modeling techniques for cracked bladed disks will be given. Among the studies, papers dealing with the vibration response and mode localization of cracked bladed disks can be roughly divided into two categories according to the simplifications of blades and the assumptions of crack.

Firstly, models in literature [4–8], which simplified blades as Euler–Bernoulli beams and treated the crack as local disorder of the system or local stiffness loss, were employed to analyze the vibration response and the stability of cracked bladed disks. The results showed that crack may change the vibration response significantly and may introduce an additional unstable zone near the localization frequency. Other investigations by applying simplified bladed disk models can be found in [9,10]. Qualitative results obtained from these models helped to gain general understanding of the influence of crack on the vibration of bladed disks. However, these simple models have limitations when quantitative predictions are needed for specific industrial applications. Moreover, the nonlinear effect caused by crack breathing was not considered, which may change the dynamic response of bladed disk significantly.

The second approach is realized by introducing finite element-based reduced order methods to avoid various assumptions during the modeling process [11–15]. By using finite element model and order reduction method, it is possible to generate a compact, yet, accurate model for analysis of the nonlinear vibration of cracked structure. Saito et al. [12] utilized a hybrid component mode synthesis method to obtain a reduced-order model for cracked mistuned bladed disks. Kharyton et al. [11] introduced the notation of relative DOFs and regarded the crack surface as interface between two substructures. Marinescu et al. [13] exploited the idea of Kharyton and used the component mode mistuning method to construct an efficient ROM. Though, it is much computationally expensive compared with the lumped parameter models, this approach can be used to accurately predict the forced response of cracked structures and can describe the nonlinear effects of crack breathing.

Due to the nonlinearities induced by cracks, the response of cracked structures differ from their uncracked counterparts. Natural frequencies which are notations of linear systems may not be used to precisely describe the vibration characteristics. Then, resonant frequencies obtained by the nonlinear forced response are needed. It can be realized by applying the hybrid frequency–time (HFT) method proposed by Poudou [16]. Another computational efficient approach for predicting the nonlinear resonant frequencies is the bilinear frequency approximation (BFA) which was first used for single-DOF piecewise linear systems [17]. This technique was employed and generalized to approximate the resonant frequencies for three-dimensional cracked structures [18,19]. In this paper, the bilinear frequency approximation is employed to investigate the statistical characteristics of resonant frequencies of an impeller with random mistuning and crack damage.

A centrifugal impeller is fabricated via welding different components, including blades, cover and disk. The existence of cover makes the impeller inherently resistant to alternating forces at normal flow conditions and greatly increases the reliability [20]. However, such a feature renders the impeller insensitive to structural damages, leading to no significant change in the vibration response unless the damage is severe. An impeller tends to present strong structural coupling between the blade, cover and disk components. Moreover, the modes of a centrifugal impeller are mostly disk-dominated or cover-dominated modes, and the modes of interest for a bladed disk are blade-dominated modes. Thus, a comprehensive study should be conducted to gain some general insights into the effects of cracking and mistuning on the vibration response of impellers.

This paper presents an efficient method for vibration analysis of impellers with crack damages. Mistuning is also taken into account to investigate its effects on the forced response and on the resonance frequencies. Firstly, a finite element model of a sector of the realistic impeller is obtained and used to generate the whole model by rotation transformation. Due to the large amount of DOFs on the interfaces between substructures, a hybrid-interface component mode synthesis method [21] is employed to generate a compact ROM while assuring high accuracy. During the model order reduction process, a computational procedure is proposed to save the memory space when calculating the inversion of a large sparse matrix. The DOFs on the crack surfaces are retained in the ROM for evaluation of the nonlinear boundary conditions. Mistuning is implemented by introducing small variation in Young's modulus of each blade. Then, the effects of cracks and mistuning on the nonlinear forced response are investigated, and the similarities and differences are pointed out. Moreover, statistical analysis is performed using the Monte Carlo simulation to study the statistical characteristics of the resonant frequencies versus crack length at different mistuning levels. Finally, the potential applications of the frequency-based indicators for detection of crack are discussed.

This paper is organized as follows. In Section 2, the mathematical formulation of the reduced-order modeling method is presented. Section 3 contains the numerical results of the vibration response of a mistuned impeller with a crack. In Section 4, a frequency-based method for detection of crack is discussed. Conclusions are given in Section 5.

2. Mathematical formulation

An impeller can be divided into one cover component, one disk component and several blades. The finite element model of an impeller and its sector model are depicted in Fig. 1. In most cases, according to many experienced engineers, fatigue cracks initiate at the weld toe on cover sides of the blade as is shown in Fig. 1. Therefore, effects of a crack located at such a

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