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Bolt loosening at rotating joint interface and its influence on rotor dynamics

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ABSTRACT

The rotors of large rotating machinery involve multiple stages of disks supported by drums and shafts, where bolted joints are commonly employed to connect the adjacent disks and drums. Those connecting bolts, subjected to numerous combinations of loads during normal operation, tend to get loose, which will affect the rotor dynamics and even results in structural failures. However, little research has been done on the bolt loosening at the rotating joint interfaces of rotor systems. Thus, the influence of the bolt loosening on the rotor dynamics is studied in this paper. First, the time-varying stiffness at the joint interface with bolt loosening is investigated by means of three-dimensional (3D) nonlinear finite element (FE) models. Then, the motion equations for the rotor with bolt loosening are deduced accounting for the local stiffness variation caused by the bolt loosening. By taking a simple drum rotor with bolted joints as an example, the time-varying joint stiffness resulting from the bolt loosening and its influence on steady-state response of the rotor are calculated. The studies in this paper provide the fundamental understanding about the influence of the bolt loosening at the rotating joint interface on the rotor dynamics, and are helpful for the bolt loosening detection of rotating components in heavy-duty rotating machinery.

1. Introduction

In large rotating machines, bolted joints are widely used to fasten the rotating components together at the mating surfaces. Fig. 1 shows a typical disk–drum joint interface in an aero-engine rotor, where the adjacent disk and drums are connected by bolts distributed in the circumference of joint interface. Those joint interfaces rotate along with the shafts during normal operation of the rotating machines. Though high levels of preload are applied to the bolts to prevent joint separation and provide sufficient strength to maintain the integrity of the rotor systems, bolt loosening may occur due to severe loading conditions. The bolt loosening will change the local stiffness at the joint interfaces, which in turn affect the rotor dynamics and even result in structural failures. Investigation of the bolt loosening and its influence on the rotor dynamics will assist in the early detection of the bolt loosening before damage occurs. However, this issue has been generally disregarded up to now.

Bolt loosening is the major failure form for bolted joints. Much research has been performed to investigate the loosening mechanism and its influence on the joint stiffness and structural dynamics [1–5]. However, those works focused on the bolted joints in the stationary, namely non-rotating structures. The studies of bolt loosening in rotor systems dealt with looseness of the pedestal, which were also non-rotating [6–8]. To the authors' best knowledge, the bolt loosening of the rotating joint interfaces has not been yet studied.

Although no published literature has been found on the looseness of bolts connecting rotating components, a so called bolt-removal method was utilized to investigate the dynamics of the cracked rotors experimentally, where parts of the connecting

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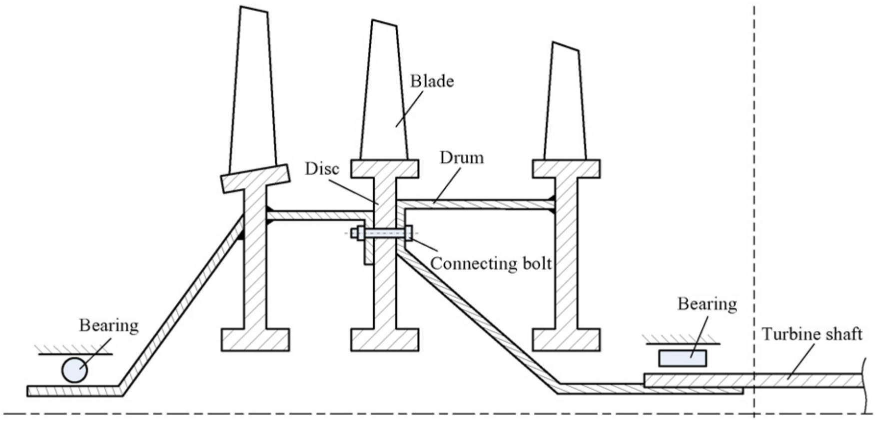

Fig. 1. Sketch of fan rotor of a certain type of aero-engine.

bolts were removed from the joint interface to simulate the breathing mechanism of a transverse crack [9–11]. Keiner et al. compared the experimental results using the bolt-removal method with the response of a real crack rotor, where good agreement was achieved [11]. The bolt removal can be treated as the limiting case of the bolt loosening, where those bolts are loosened completely providing no constraint to the mating surfaces. Thus, the consistency of the experimental results indicates the similarity of the bolt loosening signature to the breathing mechanism of the transverse crack to some extent. However, since the purpose of those studies was to simulate the breathing mechanism of the transverse crack experimentally through the bolt-removal method, no theoretical studies were carried out, and the experiments were limited to the complete loosening case without considering relatively lower degrees of loosening.

The aim of this work is to provide fundamental understanding of the dynamic characteristics of rotors with bolt loosening at the rotating joint interface. Taking a simple drum rotor as an example, quasi-static numerical simulations are performed on a 3D FE model accounting for the nonlinearity caused by the mating surface contact to investigate the variation of the local deformation and stiffness in a full revolution of the rotor primarily. Three degrees of loosening, together with different numbers of the loosened bolts, are discussed. Then, the time-varying joint stiffness is incorporated into the rotor dynamic model. The steady-state response of the rotor is calculated using harmonic balance method (HBM) to evaluate the influence of bolt loosening on the rotor dynamics.

2. Local stiffness at joint interface with bolt loosening

2.1. Quasi-static finite element analysis

A typical disk–drum joint interface is shown in Fig. 2, where two drums with inner flanges are fastened to one disk by a same set of connecting bolts distributed in the circumference of the joint interface. A stationary local coordinate system is used for calculating the deformation at the joint interface as shown in Fig. 2. In industrial applications, the spigot positioning is commonly adopted at the disk–drum joint interface to resist the relative lateral slippage between the contact surfaces of the disk and drum as shown in the zoom plot in Fig. 2. Owing to the constraint of the mating surfaces, the joint interface can be assumed to be rigid in the lateral direction, experiencing only bending deformations under external loads.

To evaluate the local stiffness caused by the bolt loosening, a 3D FE model shown in Fig. 3 is developed on the platform of ANSYS, on which nonlinear quasi-static simulations are performed. In the FE model, the disk, drums and connecting bolts are all modeled using brick elements SOLID95, and the frictional contact is simulated between the contact surfaces of the joint components using contact elements CONTA173 and target segment elementsTARGE170, where a uniform friction coefficient of 0.1 is assigned. To simulate the constraint of the mating surfaces in the lateral direction, the radial degree of freedom (DOF) of the corresponding nodes of the disk and drums at the outer edge of the contact areas are coupled together. The boundary conditions of the model are defined as follows: all DOFs of the nodes at the left edge surface of the left-side drum are constrained; all DOFs of the nodes at the right edge surface of the right-side drum are coupled together to form a rigid region with an auxiliary node defined at the region center as the master node shown in Fig. 3. The auxiliary node has six DOFs, on which external loads are applied to realize loading of the joint interface during simulations. The displacements of the auxiliary node will be used to calculate the local stiffness of the joint interface.

This work focuses on the influence of bolt loosening on the rotor dynamics, rather than the mechanisms of bolt self-loosening. Therefore, with no concern of the loosening process, the loosening phenomenon is simulated by reducing the preload level of those loosened bolts in the FE model. As the limiting case, the loosened bolts generate no constraint to the joint interface, and those bolts are removed from the FE model.

According to the discussions of the bolt-removal method in Section 1, it can be predicted that the local stiffness at the joint interface with bolt loosening varies periodically with respect to the rotation angle when the static deflection of the rotor is