Numerical Studies on Time-Varying Stiffness of Disk-Drum Type Rotor with Bolt Loosening

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Abstract. Disk-drum type rotors are widely used in industry for their high stiffness and low weight properties. In disk-drum type rotors, the adjacent disks and drums are commonly connected by bolted joints. Those rotating joint interfaces are subjected to numerous combinations of loads during normal operation, where loosening of the connecting bolts might occur. The bolt loosening will change the local stiffness of the rotor, which in turn affect the rotor dynamics and even result in structural failures. In this paper, the local stiffness of a disk-drum rotor with bolt loosening is investigated numerically. A three-dimensional (3D) finite element (FE) model for the bolted disk-drum joint is established in ANSYS, where the bolt loosening is simulated by reducing the preloads of certain bolts, and removing those bolts as the limiting case. Simulations are performed on the FE model to evaluate the joint behaviour under static loads. Periodic variations of the joint deflections with respect to the rotation angle of the shaft are obtained, which implies the appearance of the time-varying local stiffness in the rotor system. The studies in this paper help accurate prediction of the rotor dynamics and early detection of bolt loosening.

1. Introduction

Disk-drum type rotors are commonly employed in heavy rotating machines, such as aero-engines, gas turbines, and so on. The configuration of a typical disk-drum type rotor is shown in Fig. 1, where the adjacent disks and drums are fastened together through bolts distributing in the circumference of joint interfaces. Preloads are applied to those bolts to prevent joint separation and provide sufficient strength to maintain the integrity of rotor systems. Despite the strict control of preloads, bolt loosening may occur due to the severe loading conditions in the course of normal operation. The bolt loosening will change the local stiffness of the rotor, which in turn affect the rotor dynamics and even result in structural failures. Investigating the joint behavior with bolt loosening may help accurately predicting the rotor dynamics, which assists in the early detection of the bolt loosening before damage occurs.

As one of the most common means to fasten substructures in industry applications, bolted joints have been extensively studied in decades, most of which deal with the joints in non-rotating structures [1-5]. When investigating the dynamics of rotor systems, the bolted joints assembling rotor components are usually assumed to be rigid connections. The few studies on bolted joints in rotor

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systems focused on evaluating the nonlinear influence of the joints on the rotor dynamics without taking into account the loosening phenomenon [6-10].

![Figure 1 Sketch of fan rotor of a certain type of aero-engine.](image)

Although no report has been found on bolt loosening in rotating structures, some researchers [11, 12] suggested that the dynamics of a rotor with a transverse crack could be simulated by the removing parts of the connecting bolts equally distributing in the circumference of the joint interface of rotating components. Treating the bolt removal as the limiting case of the bolt loosening, the rationality of the bolt-removal method implies that the bolt loosening shares similar signatures with the so called crack breathing subjected to static loads.

FE method is the most commonly used tool in structure design and analysis, especially for those structures involving joints, since it can deal with contact problem accurately and conveniently, which is one of the primary characteristics of the joint structures [4, 13-14]. In this paper, the time-varying stiffness of the disk-drum type rotor with bolt loosening is studied using FE method. Initially, a 3D FE model of the joint interface is constructed in ANSYS. The bolt loosening is taken into account by degrading the preload level of certain bolts or removing those bolts. Nonlinear static simulations are performed to evaluate the joint behavior with bolt loosening. It is revealed that the deflections of the joint interface and the corresponding joint stiffness are varying along with the rotation angle of the shaft periodically. The deflection amplitude is proportional to the preload decrement and the number of loosened bolts.

2. Finite Element Modelling of Disk-Drum Type Rotor with Bolt Loosening

2.1. Rotor description
The disk-drum type rotor studied here consists of three disks, two drums and two shafts supported by a rolling element bearing at each end, as shown in Fig. 1. In the rotor, the connections between the components are assumed to be rigid, except that the middle disk and two drums are connected by inner bolted flanges with 20 M4 bolts distributed uniformly in the circumference of the joint interfaces. The values of the dimensional parameters of the rotor are illustrated in Fig. 2. The materials of the disks, drums and shafts are identical, of which the density, elastic modulus and Poisson ratio are 7800 kg/m3, 210 GPa and 0.3, respectively.
Finite element modelling

A 3D FE model for the local joint interface, involving the middle disk and one drum in each side fastened with bolts, is developed in ANSYS as shown in Fig. 3. The disk, drums and bolts are all modeled using 8-node solid elements SOLID185, and the frictional surface-to-surface contact is defined between joint components using contact elements CONTA173 and target segment elements TARGE170. The model involves 58995 nodes and 55025 elements.

The boundary conditions of the model are defined as follows: all degrees of freedom (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. Multiple load steps are defined, where preloads are imposed to the bolts using the virtual thermal deformation method in the first load step. In the subsequent load steps, bending moments are applied at the master node.

To simulate the bolt loosening phenomenon in the FE model, certain bolts bear the preload of lower levels; whereas, the preloads applied to other bolts are identical with the desired magnitude. The preload for those normal bolts is 0.5kN, and 2 preload levels of 0.25kN, and 0 are applied to the loosening bolts, respectively. As the limiting case, the joint interface with some bolts removed is also discussed. Note that the deflection at the right side of the FE model is caused by both the elastic deformation of the joint components and the bolt loosening. To eliminate the deflection caused by the elastic deformation, a FE model of the joint interface with all components rigidly connected is also constructed, of which the deflections is subtracted from those of the joint interface with bolt loosening.

As mentioned in Section 1, if the rotor is mainly subjected to static loads, such as the gravity, the joint stiffness at the interface with bolt loosening would vary periodically with the shaft revolution, just like the breathing mechanism of the cracked rotors. To evaluate the varying joint stiffness, relative deflections of the disk and drums at the joint interface are calculated for one full revolution with the increment of 9° with the directions and magnitudes of the external loads remaining unchanged. The initial position of the joint interface and the load directions are illustrated in Fig. 4.
3. Simulations and Discussions
Subjected to the bending moment of 10kNm, the deflections of the joint interface with a single bolt loosening are investigated. The horizontal and vertical deflections versus the rotation angle $\Phi$ are shown in Fig. 5, where periodical variations of the deflections along with the rotation angle can be observed.

![Figure 5](image)

**Figure 5** Deflections with a single bolt loosening (a) under the preload of 0.25kN, (b) with no preload and (c) with bolt removed.

Considering that the bending moment is constant as the shaft rotates, the upper portion of the joint structure is always in the compression state, and the lower one is subjected to tension with the application of the bending moment. At the initial stage, the region involving the loosened bolt is in compression. In this case, the bolt loosening has little influence on the joint stiffness, which is equal to the one without bolt loosening. As the shaft rotates, the bolt loosening region will move into the tensile stress region, where the disk and drums tend to open up and the joint stiffness in the vertical direction decreases. The joint stiffness will reach its minimum as the loosened bolt reaches the bottom...
of the interface. Further rotation enlarges the joint stiffness again. Thus, along with the shaft revolution, the vertical joint stiffness varies periodically, so does the vertical deflection, which quite resembles the breathing mechanism of the crack shafts. The horizontal deflection of the joint interface also changes periodically due to the structural asymmetry resulting from the bolt loosening. The horizontal deflection shifts from one side to the other at $\Phi = 180^\circ$, where the maximum vertical deflection takes place.

Comparing the curves of Fig. 5 (a)-(c), it can be seen that the aforementioned signatures of the deflections appear in all the cases of 50% preload degradation, no preload and bolt removal. However, it should be noted that although the deflections of the joint interface are enlarged with the decreasing of the loosened bolt preload, the deflections without removing the loosened bolt are extremely small. This means that unless severe loosening, that is, the loosened bolt provides no constraint regardless of the joint interface deformations, takes place, the single bolt loosening causes no obvious variations of the joint stiffness.

The deflections at the joint interface with loosening of multiple adjacent bolts are also calculated. The simulation results corresponding to 1, 2, and 3 loosened bolts are compared in Fig. 6. It can be seen that the deflection signatures remain unchanged for the multiple bolt loosening cases. As the number of loosened bolts increases, the deflection amplitudes are amplified. Correspondingly, the variation of the joint stiffness becomes more significant. Due to the definition of the initial position in the numerical simulations, a slight shift of the deflection peaks to the right side for more loosened bolts is observed in Fig. 6.

4. Conclusions

In this paper, the time-varying stiffness of the joint interface in a disk-drum type rotor with bolt loosening was investigated using FE method. A nonlinear 3D FE model for the joint interface of the rotor was developed in ANSYS. The bolt loosening was simulated by reducing the bolt preload levels or bolt removal. Nonlinear static simulations were performed to calculate the deflections at the joint interface with bolt loosening. An analysis of the simulation results led to the following conclusions.

(1) The deflections of the joint interface varied periodically along with the shaft rotation angle, which implied the time-varying stiffness of the rotor with bolt loosening as the shaft rotates.

(2) The amplitude of the stiffness varying was proportional to the severity of the loosening and the number of loosened bolts.

(3) Only severe loosening, that is, the loosened bolt(s) provided no constraint on the interface deflections, could induce significant varying stiffness.

In further studies, the time-varying stiffness should be incorporated into the rotor model to evaluate the influence of bolt loosening on the rotor dynamics.
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