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Reliability Analysis on Bolt Connection Structure of Compressor Rotor

Tienan Cao*, Fusen Ji

AECC Shenyang Engine Research Institute, Shengyang 110015, China

Abstract: The loosening of the aero-engine compressor rotor bolt may change the pre-tightening force of the rotor connection structure, which leads to the weakening of the local stiffness of the rotor system, and resulting in the serious loss of the vibration exceeding the limit. In present paper, the finite element method was imported to establish the analysis model of the bolt connection structure of a compressor rotor. Rotation displacement was applied to the nut, to describe the distribution of the stress and displacement field under the pre-tightening force. On this basis, the bolt loosening of the compressor was analyzed under the action of transverse loading. And then, the influence of transverse load frequency was analyzed, by considering the working condition of aero-engine. According to the present analysis results, measures for preventing and controlling bolt loosening of aero-engine compressor rotor were put forward.

Keywords: compressor rotor; threaded fastener; pre-tightening force; bolt loosening; transverse vibration

1 Introduction

The structure of the aero engine compressor rotor system is widely used in the form of rabbets centering, bolt connection and friction torque transmissions. This structure has the advantages of reliable centering, easy assembly and decomposing, reusable and so on. However, the fastener loosening as subjected to dynamic loads in the transverse cyclic loading seems to be inevitable. The vibration of the rotor will cause the loosening of the connecting bolt, which leads to the change of the local stiffness of the rotor system, and then affects the vibration characteristics and the vibration response of the rotor system.Some researches intended to make clear of the phenomenon of self-loosening of bolt based on the vibration theory, and the results showed that when the pre-tightening force of bolts drops to 90% of the initial pre-tightening force, the local stiffness of the engine rotor has been significantly affected[1].

Much research has been performed to investigate the loosening mechanism and its influence on the joint stiffness and rotator dynamics. Goodier[2] investigated the mechanisms of the loosening process due to shear loading in his issues.

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*Corresponding author: (jasoncao1987@126.com)

Junker[3]investigated the relationship between bolt loosening and transverse cyclic loading and the experimental resultst showed that the transverse cyclic loading was the main cause of bolt loosening. Based on the elastic beam theory, Nassar and Yang [4-8] established a mathematical model for different relative sliding relations between friction surfaces, and the result was compared by FEM. Nassar and Yang’s results showed that the results of mathematical model calculation and finite element calculation have a good agreement. Based on the finite element method, Yasuo Fujioka and Tomotsugu Sakai [9-10] investigated the effect of friction coefficient on bolt loosening. According to their results the friction coefficient between the threads and the friction coefficient between the bearing surfaces have a great influence on the loosening of bolts. And at the same time, the loosening rate of bolts was determined by two friction coefficients. Yasumasa SHOJI et.al [11] analyzed bolt loosening resistance with different nut and gasket structure. A simplified dynamic model is established by Zhao[12]], and an early warning index of bolt connection failure was proposed according to the comparison of the numerical simulation and experimental results. Based on experiment method, Li et.al [13] established a double exponential function of bolt loosening and the influence of transverse vibration amplitude and pretension force on bolt loosening was discussed in his issue. Jiang et.al[14] studied the phenomenon of bolt loosening on flange under cyclic torsion load.

To the authors‘ best acknowledge, the research methods of bolt loosening mainly included conventional theories based on material mechanics and with experimental and finite element simulation. The establishment of mathematical analytical model required a series of hypotheses on the object. Due to the differences in contact position, contact area and relative sliding conditions, the corresponding mathematical model of bolt loosening should be established according to the different types of thread[7]. 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 loosening of the pedestal,whichwere also nonrotating [6–8]. To the authors' best knowledge, the bolt loosening of the rotating joint interfaces has not been yet studied. In terms of experimental research, different screw structures can be targeted, but it can only be used to describe the situation of bolt loosening in an intuitive test, thus it is difficult to explore the mechanism of bolt loosening. However, the finite element analysis can solve the above problems well. Through finite element analysis, the object can be studied on the phenomenon and mechanism of release. In present report, we investigated the mechanisms of the tightening process and the loosening process due to transverse loading using the framework of the finite element method. To describe the deformation and the stress of bolt, the angular displacement along the bolt axis was applied to simulate the bolt pretightening force. Then, the loosening of the bolt under lateral loads of different frequencies and amplitudes and was investigated, at the same time the loosening of bolted connections with different initial pre-tightening forces was studied. Finally, an engineering method for preventing loosening of rotating mechanical rotor bolt connection is presented by combining with the research work in this paper.

2 Finite element analysis of bolted joint

2.1 Model description

A typical disk-drum joint interface is shown in Fig. 1, where two drums and one front journal with inner flanges are fastened to one disk by a same set of connecting bolts distributed in the circumference of the joint interface. We employed a threaded fastener involving a screw thread with standard 0.3125-24UNJF-3A/3B (diameter, height of bolt head and Length of thread, 7.95mm, 33.5mm, 18.8mm, respectively)

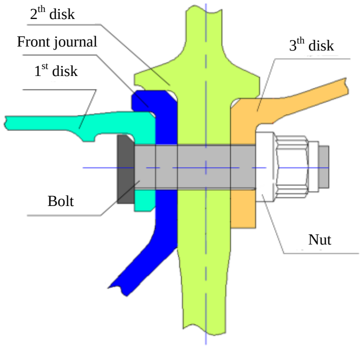
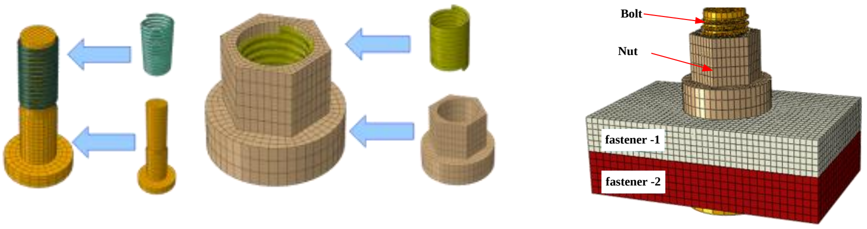


Fig.1. Sketch of the compressor rotator joint interface.

2.2 Model description

Based on the ABAQUS software, the finite element method (FEM) of the joint components was established, as shown in Fig.2. In the FE model, fastener, connecting bolt and the nut are all modeled using Hexahedron element C3D8I, and the screw thread is simulated by element C3D10M (shown in Fig.2 (a)). Fig.2(b) is the FE model which has 44356 element in total with 87563 nodes. A friction coefficient of the thread is assigned as μ_b=0.1 to simulate the constraint of the mating surfaces. The friction coefficient of the other part is assigned as μ=0.15.



(a) The FE model of bolt and nut (b) The FE model of the structure

Fig.2. The finite element model for joint components

In this paper, bolts and nuts are made of GH4169 material, the fastener part are made of TC17. The material of the bolt and the fastener are assumed to exhibit line elastic behaviors during clamping. The mechanical properties of the material used in the finite element analysis for the bolt are a Young's modulus of E=213GPa, a Poisson ratio of γ =0.31, for the fastener Young's modulusis 200GPa, the Poisson ratio 0.33.

2.3 Simulation of angular displacement of the nut

In the past investigation, the axial preload of bolt was simulated by applying bolt load on a section of bolt [8-10, 16-18]. And the calculation method is more suitable for the stress and deformation analysis of the joint or the connecting system. The deformation of bolts, nuts and fittings along the bolt axis is plotted in Fig.3. It can be obviously that the axial deformations of bolts will “abrupt” at the loading face of bolts, and the position of bolt axial deformation “abrupt” is related to the position of the loading section of bolt preload. It can be seen from Fig.3 that it is difficult to accurately describe the deformation of bolts by using the method of section loading to simulate the pre-tightening force.

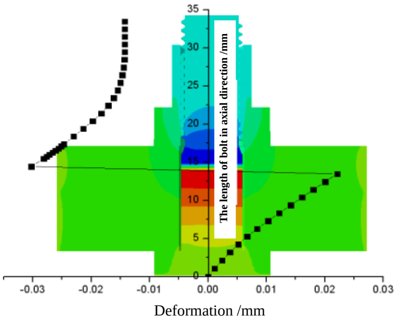


Fig.3. Deformation of parts under bolt cross section load

In order to the axial preload of bolt accurately, based on the engineering practice, the angular displacement of the nut is imported. In present analysis, all DOF of the boundary of bolt head, fittings 1 and 2 are fully constrained and the angular displacement is applied along the bolt axis to the nut. With the nut of the bolt axis rotation, due to the interaction between the threads, the nut moves down along the axis direction, and the bolt is drawn to produce a pre-tightening force. At the same time, the fastener is compressed due to the pre-tightening force of the bolt. In Figure 4, the deformation of the bolt's smooth section is linear. However, it is nonlinear deformation at the screw thread of the bolt, obviously. The amount of deformation increases gradually from the front to the end of the threaded connection contact structure (1# tooth to 11# tooth) and the strain of the 11# tooth equals zero. The average stress trend from 1# tooth to 11# tooth is plotted in Fig.5, the average stress decreases gradually, which is similar with the trend in Fig.4. It can be seen from Fig.4 and 5 that, when the bolt is subjected to the pretensioning force, the bearing capacity of the screw is mainly caused by the thread on the first few teeth before contact. With increase of teeth increases, the bearing capacity of the screw decreases gradually. Through the above analysis, it is shown that this pre-tightening loading method can clearly describe the force and deformation of bolts, nuts and joints.

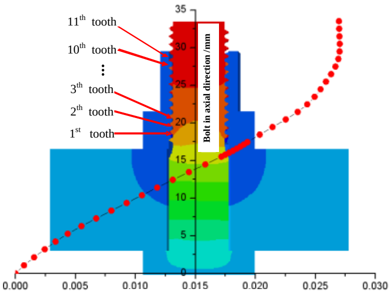


Fig.4. Deformation of each part under angular displacement

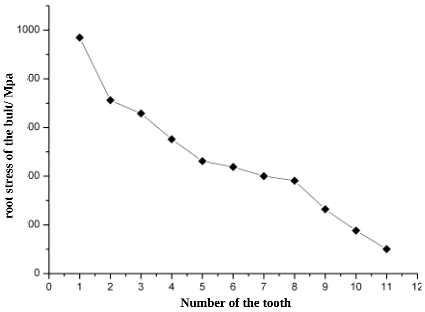


Fig.5. Average stress of bolted tooth root

In engineering fields, the tightening torque of the nut is designed according to the load condition of the bolt connection structure and the rotation angle can be determined via the engineering experience [11]. The relationship between rotation angle and pretension force is plotted in Fig.6. In Fig.6, the FE results are close to the theoretical results in the pretension range 12000N~16000N. Take the loading process when the nut's rotation Angle equals 0.25rad for example, at the beginning of the process (Φ ≤0.025rad), the contact surface is not in the complete contact state due to each part is in the initial contact, and the pretension force with the increase of rotation angle change slowly. Then the relationship between the rotation angle and pretension force is linear trend.

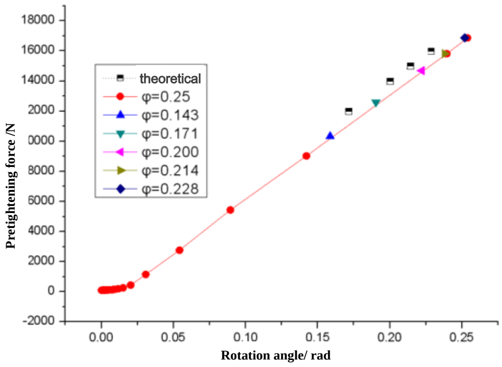


Fig.6. The curve of the rotation angular displacement and the pre-tightening force

3 Numerical results are discussed

3.1 Analysis of bolt loosening

On the basis of the above analysis, the influence of transverse load on bolt loosening is investigated in this part. In present analysis, the vibration is simulated by applying transverse sinusoidal displacement to fastener 1, and the DOF of fastener 2 is fixed. The relationship between of cycle- clamping force/initial pre-tightening force is plotted in Fig.7 under lateral loads. The bolt clamping force will increase sharply at the moment of the connected part 1 vibration. With the continuous effect of transverse cyclic loading, the clamping force of bolts decreases at the same time. During the process, the bolt pre-tightening force will increase slightly when the fastener 1 return to the initial position. The force condition of each part is plotted in Fig.8. In Fig.8, the X direction is the axial direction along the bolt, and the Y direction is the motion direction of the connector and Z is perpendicular to the x-y plane. The static friction force F_{NUT} of fastener 1 against the nut will increase dramatically when fastener 1 moves relatively horizontally with the nut. The force exerted by the bolt on the nut F_{BLOCK} increases to ensure the force balance of the nut. In this condition, the bolt buckled which lead to the sudden increase of the axial clamping force, which is consistent with the experimental results [7, 21].

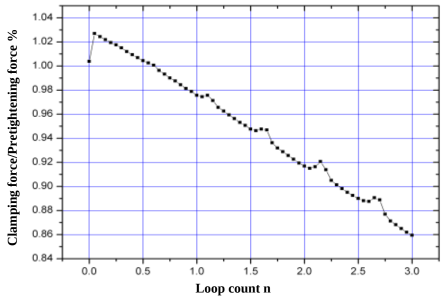


Fig.7. Cycle- clamping force/initial pre-tightening force

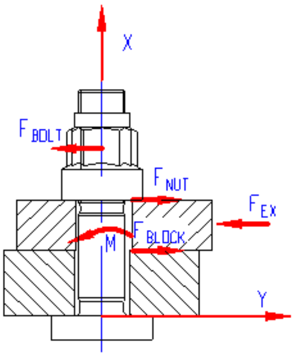
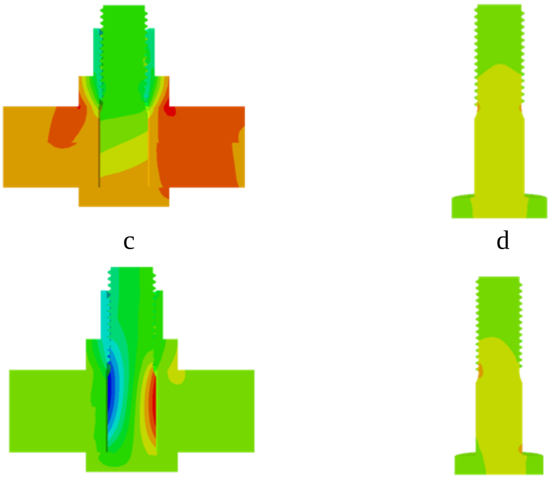


Fig.8. The stress condition of connection structure

The radial deformation of bolts and radial stress distribution of bolts during half a cycle ($-Y \rightarrow 0 \rightarrow +Y$) are plotted in Fig. 9. The axial deformation and stress distribution of bolts are plotted Fig. 9(a) and Fig. 9(b) respectively, and it is obviously that the bolt's smooth section is subjected to the bending moment in the Z direction. When the fastener 1 returns to the initial position, the bending moment on the bolts are weakened, and the axial stress is distributed symmetrically under this condition (shown in Fig.9 (d)). With the moving of fastener 1, the torque of the bolt will be reversed. When the fastener 1 is in 'Y' position, the bolt is subjected to a torque in the -z direction (shown in Fig.9 (e) and Fig.9 (f)).

a

b



c d

e f

Fig.9. Radial deformation and radial stress distribution of the joint structure

In the process of generating transverse displacement, the screw between bolt and nut is relatively "dislocated" due to the deformation of bolt under the action of bending moment, shown in Fig. 10. When there is no "dislocation" between the screw pair, the screw pair will generate friction self-lock between the screw wedges due to the pre-tightening force. And the relative "dislocation" will lead to the change of the contact angle between some threads, in addition, even lead to the separation of the threads from the contact surface. In this condition, the loss of friction self-locking between some pairs of threads may occur. The relative "dislocation" accumulates gradually under the cyclic loading, which will lead to the relative motion of the screw pair, and resulting in the loosening of the joint structure.

When fastener 1 moves to the initial position, the threaded pair contacts all over again, and the bolt's pre-tightening force picks up slightly at the same time. The past research has shown that The extent of the bolt's pre-tightening response depends on the frictional force F_{BLOCK}, F_{NUT} and F_{EX} [20].

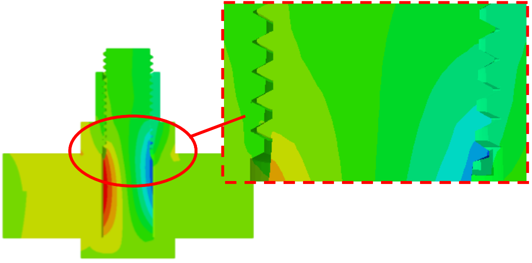


Fig.10. The relative "dislocation" of thread under transverse load

3.2 The influence of frequency on bolt loosening

The compressor rotor has a wide range of frequencies during operation. Due to the frequency is an important parameter of cyclic loading, it is necessary to investigate the effect of frequency on bolt loosening. In this paper, the initial bolt pretension is setting 16*kN* and the amplitude of transverse vibration of connector 1 is limited to 0.1mm. Four typical rotating conditions are considered, which are 60r/min, 600r/min, 6000r/min and 12000r/min. As shown in Fig. 11, the frequency of transverse load has less direct influence on the change rate of clamping force, which is similar with the experimental results [14].

In a single cycle, the frequency of transverse load has a significant influence on bolt loosening. It can be seen from Fig. 12, when the clamping force/initial pre-tightening force measuring bolt loosening reaches the same value, the higher the cyclic loading frequency, the more vibration frequency is required.

The decrease of cycle load frequency can increases the time of relative "dislocation" of screw pair in single cycle. As a result, the displacement of the threads in a single cycle is increased relative to the "dislocation", which releases more pre-stress between the pairs of threads, thus the tightening force of bolts decreases in a single cycle. It can be seen from this part that the bolting loosening caused by the long time low-frequency multiple vibration is greater than that caused by the short time high-frequency low-frequency vibration.

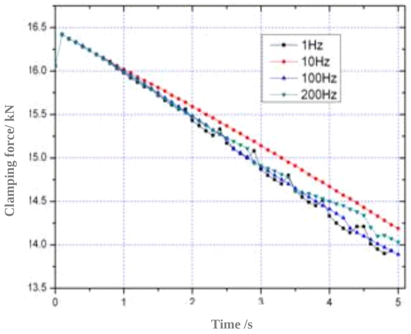


Fig.11. Loosening of bolts under different frequencies

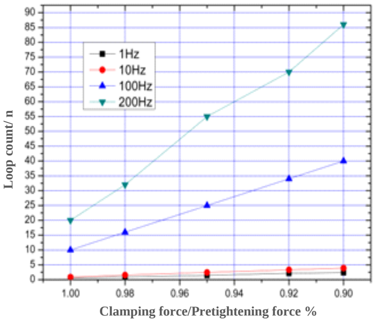


Fig.12. The relationship between the number of cycles and the clamping force

4 Conclusions

Considering the influence of the angular displacement along the bolt axis, the tightening and loosening processes of the threaded fastener were investigated by a finite element method and the following conclusions can be drawn:

The bolt pre-tightening force, stress and deformation of joints can be simulating by applying the angular displacement along the bolt axis. The result shows that simulation results have a good agreement with the results.

The periodic transverse load has a significant influence on the loosening of bolts in the connection structure. The reduction of transverse load frequency will accelerate the loosening rate of bolts in a cycle.

The relative "dislocation" between threads has an obvious influence on the pretension of the bolts. Thus, the nuts of compressor rotor must have the function of self-locking and the quality of the nut should be strictly control to reduce the "dislocation" between the bolt teeth. Adding the fit tightness of mounting edge and restricting the lateral relative motion between the connected parts can effectively reduce the rate of bolt loosening.

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