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Experimental study on influence of different tightening positions on bolt preload

QingZhou Zhao[1, a],Juntang Wang[1, b]， Mingfu Liao[1, c,*]

[1]Northwestern Polytechnical University School of power and energy Xi'an,China

[a]qzzhao@mail.nwpu.edu.cn，[b]2021261947@mail.nwpu.edu.cn,[c]mfliao@nwpu.edu.cn

Abstract: Aiming at the typical bolted flange connection structure in aero-engine, based on the principle of acoustic elasticity, the supersonic method is used to measure the bolt f preload, and the influence of different tightening positions on the bolt preload and stability is studied. The tightening positions are divided into bolt head and nut, and each tightening position is set with several tightening torques and different lubrication conditions. The test results show that in the full torque range of the bolt without lubrication, the torque coefficient is smaller when the bolt head is tightened, and the distribution of preload under each torque is more uniform and the standard deviation is smaller. Lubricating bolts and nuts, the torque coefficient is also smaller when tightening the bolt head, but under each torque, the preload distribution is more uniform when tightening the nut, and the standard deviation is smaller.

Keywords: Aero-engine;Connection structure;Preload; Tightening positions

1. Introduction

Bolted joint has become the most common connection method in the stator and rotor structures of aero-engines because of its simple structure, convenient installation and good connection rigidity. The connection quality (reliability, stability and uniformity) of bolted joint directly affects the dynamic and static stiffness, critical speed, dynamic characteristics and sealing performance of rotor structure and casing support structure, and then affects the safety and stability of aero-engine. [1-5]In the actual assembly process of the aero-engine, due to the compact structure and limited space, the torque wrench is generally used manually to tighten, which will cause a relatively large deviation in the Preload, resulting in prominent engine vibration problems. Therefore, it is necessary to study the parameters influence law of bolt preload to control the deviation of preload.

Domestic and foreign scholars have studied the influence of preload parameters from many aspects, including surface roughness, lubrication conditions, tightening strategies and process parameters. Fukuoka et al. [6,7] studied the mechanical and physical state of bolted connection structure in the process of pre-tightening by torque control method through experiments and numerical simulation, and proposed the relationship model between bolt preload and nut rotation angle. Persson et al. [8]compared and analyzed different tightening control methods through relevant tests for the single bolt connection structure of hard steel materials. The results show that the tightening method that causes the maximum deviation of bolt preload is the torque method, followed by the angle method, and the yield point control method has the smallest dispersion. Zhao Bing et al [9] studied the influence of tightening times, lubrication mode and bolt nut quality on the consistency of bolt connection preload by using the torque control method for the fastening control of flat nuts in the typical connection structure of aero-engine rotor flanges. A modified model of torque-pretightening force relationship with self-locking torque of the necking is proposed, and it is found that multiple tightening will lead to continuous reduction of surface roughness, while full lubrication can reduce the fluctuation of preload. Zou et al. [10] experimentally studied the effects of tightening times, tightening speed, lubricant type and lubrication positions on the magnitude of preload and friction coefficient, and found that sufficient lubrication will reduce the magnitude of preload and friction coefficient. Based on the single bolt connection process test of TC4 titanium alloy, Xiaoqiang Li et al. [11] studied the influence of tightening method, step tightening and tightening speed on the magnitude and stability of preload, and explored the short-term attenuation

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law of bolt preload. It was found that the fluctuation of preload can be stabilized by using the torque-angle method, step tightening and increasing the speed, and the control accuracy of preload can be improved.

In this paper, the influence of different tightening positions on the size and uniformity of bolt preload is studied for the bolt flange connection structure tester. The bolt head and nut are selected as different tightening positions, and the preload changing trend of multi-torque and multi-tightening times is studied under the condition of with or without lubrication, which provides guidance for engine assembly.

2. Bolt flange connection structure test system

2.1 The design of tester

As shown in Figure 1, the bolted flange connection structure consists of a flange disk and an elastic support with a flange structure. The connection structure uses bolts with a nominal size of M8 and a strength grade of 12.9, with a yield limit of 1090Mpa. The fitting place of flange disk and elastic flange is processed with a rabbet joint structure. This design can avoid the tangential displacement of the connection structure under load and avoid affecting the measurement of bending deformation. The flange is connected to the support through the tenon and fixed on the support. The physical diagram of the bolt flange connection structure tester is shown in Figure 2.

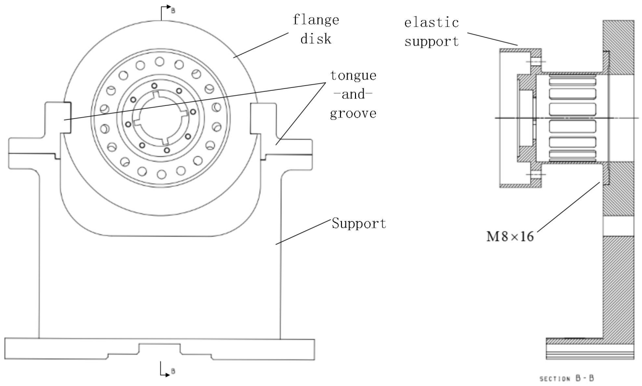

Fig1. Model of bolt flange connection structure tester

Fig2. Tester object

The surface treatment process of the joint surface of the flange and the flange disk is milling, the surface roughness is Ra1.6, the joint surface is cleaned with 75% alcohol solvent, no metal chips, no lubricating oil.

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Fig3.The surface state of the joint surface

2.2 Preload measurement system

During the test, the bolt preload is measured by supersonic method. The basic principle is shown in Fig. 4. The use of tightening before and after the supersonic wave in the bolt internal transmission time difference to calculate the bolt preload changes, also known as the sonoelastic effect. The preload of the bolt can be calculated by measuring the acoustic time difference during the test by measuring the relationship between the preload of the bolt and the supersonic propagation time difference. However, the bolt material, strength grade and other factors will affect the propagation speed of supersonic wave inside the bolt. Therefore, before measurement, it is necessary to calibrate the relationship between preload and acoustic time difference for specific batches of bolts. The technical parameters of the supersonic testing system are listed in Table 1

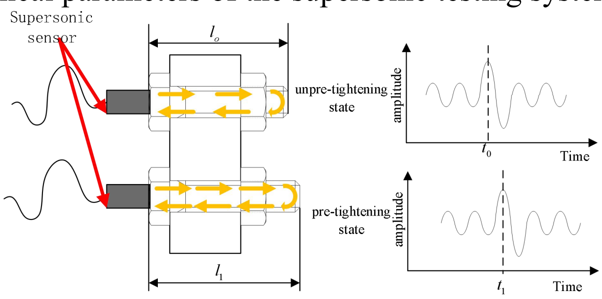

Fig4.Basic principle of supersonic measurement of elongation

Table 1. Technical parameters of supersonic testing system

	parameter	value
1	resolution	0.01ns
2	precision	≤1%
3	Applicable bolts	≥M3
4	working environment	-20℃~50℃; 10%~80%RH
5	Maximum number of channels	8

3. Study on the influence of different tightening positions on bolt preload

In domestic aero-engines, the most widely used bolt tightening method is torque control method. Therefore, this section uses the torque method to preload the bolted flange connection structure, and compares the influence of the two tightening positions on the change of the preload force through experiments.

3.1 Relationship between preload and tightening torque

When the tightening torque is applied, the tightening torque is used to overcome the thread resistance torqueT1 of the thread pair and the end face friction torqueT2 between the tightened position and the supporting surface of the connector. The formula for calculating tightening torque

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$$T = T_1 + T_2 = F\tan(\phi + \rho_v)\frac{d_2}{2} + \frac{F\mu}{3} \times \frac{D_w^3 - d_0^3}{D_w^2 - d_0^2} = KFd \tag{1}$$

$$K = \tan(\phi + \rho_v)\frac{d_2}{2d} + \frac{\mu}{3d} \times \frac{D_w^3 - d_0^3}{D_w^2 - d_0^2} \tag{2}$$

d : nominal diameter

F : preload

d_2 : medium diameter

Φ : lead angle

ρ_v : thread equivalent friction angle

μ_v : equivalent friction factor of thread

μ : friction coefficient of support surface

K : torque coefficient

D_W : nut outer diameter(the definition is shown in figure 5)

d_0 : screw hole diameter(the definition is shown in figure 5)

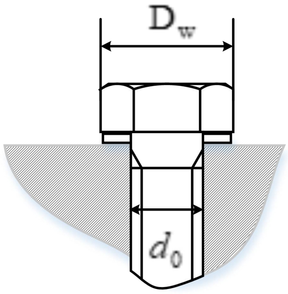

Fig5.Structural parameters of bolt joint

Torque coefficient directly determines the ability to convert tightening torque into preload, affecting the reliability of the connection structure. The size of the torque coefficient is related to many factors.Only through the theoretical expression, it can be seen that the torque coefficient will be affected by factors such as lubrication conditions, tightening positions, surface machining accuracy of positions, and size layout of the connection structure. Therefore, the bolt tightening process should try to ensure the stability of the torque coefficient, so as to ensure the stability and uniformity of the preload value.

3.2 Single bolt tightening nut

After the bolts are treated and patched, as shown in Figure 7. Firstly, the calibration of this batch of bolts is carried out to obtain the relationship between the preload and elongation of this batch of bolts.

Fig6.Patched bolt

For the above bolt flange connection structure tester, this batch of new bolts is selected to carry out the nut tightening test under unlubricated conditions. Test conditions are shown in Table 2. The tightening torque is set to five values, and the bolts are tightened for 10 cycles, from 27.5 Nm to 37.5 Nm as a cycle. Under five torques, the relationship between the preload of No.1 bolt and the number of tightening times is shown in figure 7.

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Table 2.Test conditions of No.1 boltTechnical parameters of supersonic testing system

Type	Test conditions and parameters
Specification of bolt	M8
Surface roughness	Ra1.6
Lubricated condition	unlubricated
Torque gradient	27.5/30/32.5/35/37.5
Tightening position	nut
cycle index	10

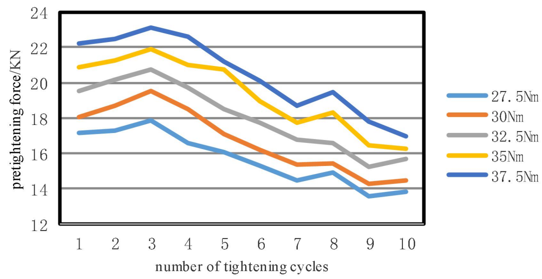

Fig7.Variation trend of preload of No.1 bolt

For the test piece bolts that tighten the nut and are not lubricated, the preload under each torque has the same change trend with the number of tightening times. The torque coefficient is 0.227 and the standard deviation is 0.0238 under full torque conditions. Under different tightening times, the preload fluctuates greatly and the overall trend is decreasing. The main reason is that the bolt is not lubricated, tightening the nut on the thread meshing damage is more serious. This assembly condition is not suitable for repeated tightening of the connection structure in a short time, which will affect the reliability of the connection structure.

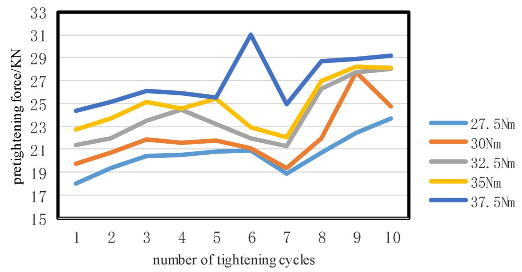

Fig8.Variation trend of preload of No.2 bolt

Figure 8 shows the same batch, the change of No. 2 bolt preload, test conditions compared with No. 1 bolt, No. 2 bolt lubrication. Under the five tightening torques, the change of preload is more consistent, showing a fluctuating upward trend. Compared with non-lubrication condition, the average preload is higher under the same tightening torque, especially under large tightening torque, the average preload is 31.8 % higher.

3.3 Single bolt tightening bolt head

Select the same batch of bolts as the tightening nut end, and also set five tightening torques as a cycle for ten cycles of tightening. The tightening position is the bolt head, and the other test conditions are the same as those of No.1 bolt, which is also not lubricated. The change of preload of No.3 bolt is shown in Figure 9. Under different tightening torques, the preload decreases with the fluctuation of tightening times, and the preload changes little from the 3rd to 8th test cycles.

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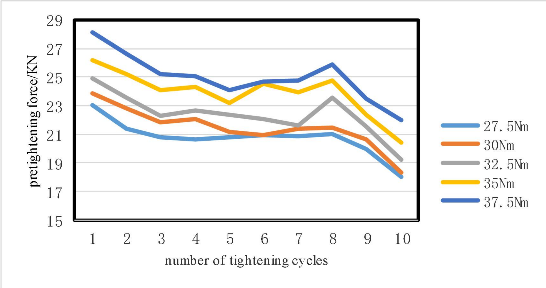

Fig9.Variation trend of preload of No.3 bolt

Figure 10 shows the change of preload of No.4 bolt. Unlike No.3 bolt, the bolt is lubricated, and the other test conditions are the same. According to the test results, the overall change trend of bolt preload under lubrication conditions is relatively stable. Compared with the bolts under non-lubrication conditions, the preload is greatly improved. Under the condition of large torque, the average preload increases by 41.8 %.

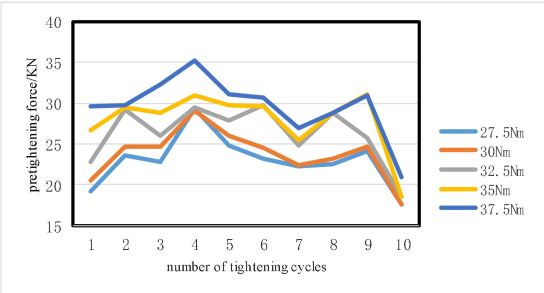

Fig10.Variation trend of preload of No.4 bolt

3.4 Comparative analysis of bolt preload and stability with tightening positions

For the same batch of bolts, the difference of bolt torque coefficient under different tightening positions are analyzed and compared. Fig. 11 shows the comparison of bolt torque coefficient K and its standard deviation under different tightening positions without lubrication. It can be clearly seen from the diagram that the bolt torque coefficient is approximately a straight line, that is, the bolt tightening torque is approximately proportional to the preload. When tightening the nut, the bolt torque coefficient is higher than tightening the bolt head under full torque conditions. That is to say, under this test condition, with the same tightening torque, tightening the bolt head will obtain greater preload. In addition, the standard deviation of the bolt torque coefficient of the tightening bolt head is smaller, which is half of the standard deviation of the tightening nut under the same conditions.

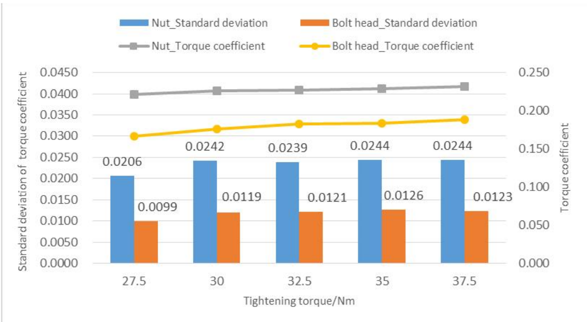

Fig11.Comparison of torque coefficient and standard deviation of different tightening positions (no lubrication)

Fig. 12 shows the comparison of bolt torque coefficient K and its standard deviation under different tightening positions with lubrication.The bolt torque coefficients under the two conditions are not much different, and the K value is higher when the nut is tightened. Different from

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non-lubrication condition, the standard deviation of torque coefficient of tightening bolt head under full torque is larger than that under nut tightening condition. After lubricating the bolt, tightening the nut will make the preload change more stable.

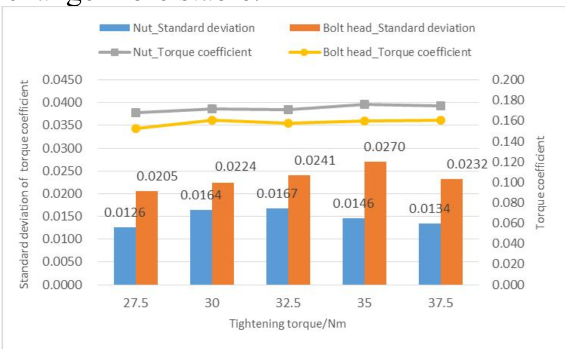

Fig12.Comparison of torque coefficient and standard deviation of different tightening positions (with lubrication)

4. conclusion

In this paper, the bolt flange connection structure tester is taken as the research object, and the bolt head and nut are selected to carry out the experimental study on the parameters influence law of the tightening positions on the bolt preload with or without lubrication conditions. The main conclusions are as follows:

The preload of different bolts varies with the number of tightening times, but the change of the same bolt under different torques is generally consistent. The bolt preload of this batch is approximately proportional to the tightening torque.

Under the same tightening torque, the preload of bolt lubrication is larger than that of unlubricated, especially under large torque, the average preload is 41.8 % higher.

The preload changes differently under different tightening positions. Under the condition of no lubrication, the torque coefficient of tightening bolt head is smaller, the distribution of preload under each torque is more uniform, and the standard deviation is smaller. Under lubrication conditions, the torque coefficient is also smaller when tightening the bolt head, but under each torque, the preload distribution is more uniform and the standard deviation is smaller when tightening the nut.

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