Research on Tightening Process of Bolt Group in Aeroengine Rotor

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Abstract: Named Data Networking(NDN) is a typical representative of the next-generation Interest architecture. In NDN, due to the existence of multi-source transmission, the traditional congestion control schemes cannot be applied to NDN directly. Aiming at the transmission features of NDN, we proposed a probability forwarding strategy based on congestion level of inter-face(PFS-CLI). Through calculating the congestion contribution of each flow passing by the router, PFS-CLI can calculate the congestion level of each interface, then probabilistically select the optimal interface for forward-ing interest packet. The simulation results show that PFS-CLI is effective for congestion control in NDN.

Keywords: Named data networking, Congestion control, Interface congestion, Probabil-ity forwarding

1 Introduction

Bolted joint is widely used in connection structures in aeroengine. The reliability of the bolt connection has a significant impact on the overall assembly quality and service performance of the engine.

The bolt tightening accuracy is limited by two problems. On the one hand, pre-tightening force is obtained by applying a torque to the bolt In the actual assembly process, so there is a difficulty that how to accurately control the torque to get the aim pre-tightening force. On the other hand, due to technical and cost constraints, the bolts can not be tightened at the same time. When the bolts are loaded in a certain sequence, the loading of bolts which are tightened before would be affected by the current tightening press. The phenomenon is called elastic interaction of bolt group. After tightening the bolt group, the pre-tightening force of bolt will relax and the pre-tightening force of the bolt group will diverge in a period. The former are mainly determined by the geometric parameters of the bolt and the latter depends on the elastic interaction of the bolt group, including the tightening steps/sequence/method[1-4].

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A lot of research has been done about the elastic interaction when the bolt group is tightened. Takaki[6,7] simulated the tightening process and found that the pre-tightening force of some bolts is higher than the target pre-tightening force when the one round of tightening is used. Considering the tightening rounds, using multiple rounds loading to avoid the extortionate pre-tightening force was proposed. Japanese scholar Fukuoka[8] considered how to make the residual pre-tightening force of the bolt group more uniform by adjusting the initial pre-tightening force with the finite element method. All of the above research is aimed at obtaining consistency and uniformity of residual pre-tightening force and target pre-tightening force and some scholars have analyzed the rationality of the tightening process from other aspects. Chapman[10] considered the strain on the surface of the workpiece as an evaluation index to analyzing the influence of different tightening processes on the stress and strain of the bolt joints surface. J. Wileman[11] analyzed the distribution of the contact stress of the joint surface and the tightening process of bolt group in the engine connection structures is optimized based on it.

However, the above research is mainly based on the simple structure by using theoretical and finite element method. There is no effective process for ensuring uniform pre-tightening force in the bolt group with regard to a structure with a complicated boundary condition such as an aeroengine rotor. In this paper, the influence of the tightening process on the residual pre-tightening force in the bolt group is studied.

2 Tightening Process of Single Bolt

2.1 Aim Pre-tightening Force Calculation

Among the various standards related to bolt, the German 《VDI2230》 standard is the most credible and the required pre-tightening force of bolts is estimated according to the standard.

Preload calculations need to meet the following four conditions:

- In the case of bearing varietious of working loading, the joint surface does not separate;
- The joint structure should not be broken by pre-tightening force of the bolt;
- The bolted joint has sufficient service life;
- The static and dynamic performance demand should be satisfied[9].

Considering the actual structure and demand, the 1st separation condition is the most import condition that needs to be satisfied. Because of the limition of the paper, we just listed the calculation of separation condition.

The pre-tightening force F_{KAB} is composed of two parts: (1) with the acting of the axial tensile load and the bending loading, the pre-tightening force F_{KA} should ensure that the joint surface does not separate; (2) with the acting of the torsional load, pre-tightening force F_{KQ} should ensure that the contact surface does not separate.

Under the acting of the working load, when the eccentric load F_A exceeds a limit value F_{Aab}, an opening will occur on the contact surface of the joint. Assume the minimum clamping force F_{KA} of the contact surface be:

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$$F_{KA} = F_{A\max} \frac{A_D \cdot \left(a \cdot u - s_{sym} \cdot u\right)}{I_{BT} + s_{sym} \cdot u \cdot A_D} \tag{1}$$

Where F_{Amax} is the maximum value of the axial tensile load; A_D is the clamping area of the single bolt; a is the eccentric distance of the load; S_{sym} is the eccentric distance of the clamp; μ is the distance between the bolt center line and the dangerous point; I_{BT} is the inertia momentum:

$$I_{BT} = \frac{b_T \cdot c_T^3}{12} \tag{2}$$

$$b_T = \min[\mathrm{G} \mid \mathrm{G}' \mid \mathrm{G}''; \mathrm{t}] \leq \mathrm{b}$$

Because the structure is bolt (not screw), there is $b_T = G$ and $G = d_W + h_{\min}$, d_w is the equivalent diameter of the bearing area of the bolt head. The specific single bolt connection structure dimensions are shown in Fig. 1.

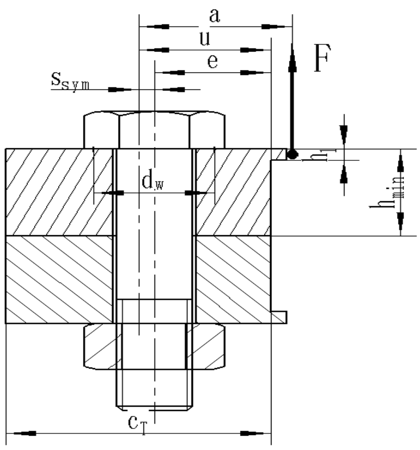

Fig. 1 Single bolt connection structure

Assume the remaining clamping force of the contact surface is F_{KQ}:

$$F_{KQ} = \frac{F_T}{q_F \cdot \mu_{T\min}} \tag{3}$$

Where q_F is the number of sliding interfaces under the acting of torque or shear force, and it usually is 1. μ_{Tmin} is the friction coefficient of the contact surface and its value is 0.32.

In summary, the bolt pre-tightening force which is satisfied the separation condition is $F_f = \max[\mathrm{F}_{KA}, \mathrm{F}_{KQ}] = 36999\,\mathrm{N}$.

2.2 Torque Method

The torque method controls the load of bolt by the relationship between the torque and the preload force when tightening the bolt. In tightening process, once the torque reaches the target value, the bolt is considered to have enough pre-tightening foce.

$$F_p = \frac{T_{in}}{\frac{P}{2\pi} + \frac{\mu_t r_t}{\cos\beta} + \mu_n r_n} \tag{4}$$

In eq. (4), F_p is the pre-tightening force of bolt; T_{in} is input torque; P is pitch; μ_t is friction coefficient of tooth surface; r_n is effective contact radius of the thread; β is half angle of the thread; μ_n is friction coefficient of end face; r_n is friction effective radius of end face.

In the process of assembly. the properties of the joint, such as machining accuracy, lubrication conditions, etc., will affect the final pre-tightening foce. For a certain structure, the friction coefficient is the most important factor affecting the torque control. Acting the same torque, the range of pre-tightening force affected by the change of friction coefficient reaches 30%. when the pre-tightening force is smaller, the bolt joint may not meet the requirements and when the pre-tightening force is larger, the bolts will be yielded and broken. The uncerinty of friction coefficient results quality and safety issues.

2.3 Torque/angle Method

In torque/angle method, both torque and angle are used to control the pre-tightening force. When the bolt is tightened, the nut does not contact with the connected structure at the beginning and there is no pre-tightening force. After a while, the pre-tightening force of the bolt increases as the tightening angle increases. In the tightening process, a certain torque is applied firstly, so that the nut is totally contacted with the connected structure. Then rotating the angle to a point measured before, called the torque/angle method.

In torque/angle method, the variety of pre-tightening force can be expressed as:

$$\begin{aligned} \Delta F_P &= \Delta F_T + \Delta F_\theta \\ \Delta F_\theta &= \frac{K_B \cdot K_J}{K_B + K_J} \cdot \frac{P}{360} \cdot (\Delta\theta_R - \Delta\theta_B) \\ \Delta\theta_B &= \frac{\Delta T_B}{GI_P} \end{aligned} \tag{5}$$

In the formula, ΔF_P is the deviation of pre-tightening force with torque/angle method; ΔF_T is the deviation of pre-tightening force with torque method and it can be calculated by eq(4); is the deviation of pre-tightening force with /angle method; K_B and K_J is the stiffness of bolt and connected structures respectively; P is pitch; $\Delta\theta_R$ is the

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variety of angle; $\Delta\theta_B$ is torsion deformation of the bolt; ΔT_B is the change in the thread torque during the tightening; GI_p is the torsional rigidity of the bolt.

In eq. (5), it can be found that during the tightening, the parameters hardly affected by friction coefficient except the ΔT_B and this is also the reason why the torque variation is often controlled during the implementation of the torque/angle method. The purpose is to reduce the influence of the dispersion of the friction coefficient and ensure the consistency of pre-tightening force.

3 The Tightening Process of Bolt Group

Elastic interaction causes the uneven distribution of load after the bolt group is tightened. There are many factors affecting the elastic interaction of the bolt group, such as the material properties of the joint, the structural, the number of bolts, the distribution of bolts and the tightening method. In the paper, we concentrated on the tightening process and mainly considering the tightening method, including the bolt pre-tightening sequence, the number of rounds, and the steps of load increment.

During the assembly process, when the existing tightening process (sequential and one round tightening) is used, the pre-tightening force distribution of bolt group is ununiform, compared to cross-tightening and 2/3 rounds tightening is widely used abroad. An optimum tightening process is required to make sure the pre-tightening force of the bolts less dispersive.

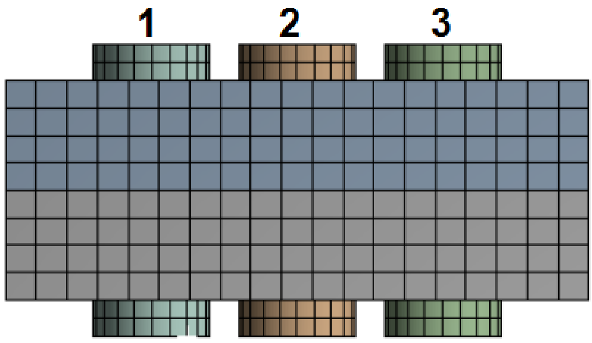

Fig. 2. Three bolt finite element model

To verify the elastic effect, a finite element model of bolts is created, shown in fig. 2. The model consists of two plate-shaped connected structures and three simplified bolts. Using finite element load step (step controls) to simulate the tightening sequence of bolt group. Firstly, two load steps are set. While the bolt 1 applies a preload, the bolt 2 is in a free state. Then a preload (load) is applied to the second bolt to ensure that the bolt 1 is locked. In the same state, the influence of the bolt 1 on the bolt 3 is the same as the bolt 1 on the bolt 2. The specific simulation results are shown in Table 1:

Table 1. Effect of elastic negative effect under different preloading conditions

pre-tightening force/N	the variety of Bolt 2	percentage	the variety of Bolt 3	percentage
10000	-251	2.51	18	0.18
15000	-376	2.51	23	0.15
20000	-503	2.52	25	0.13
25000	-624	2.5	28	0.12
30000	-813	2.71	32	0.11
35000	-869	2.5	39	0.11
40000	-1051	2.63	44	0.11
45000	-1109	2.46	47	0.1

According to table 1, it can be found that the bolt 1 has the greatest influence on the bolt 2 during the tightening process. In elastic effect, with the increase of the bolt pre-tightening force, the base will deform and affect adjacent bolts. The pre-tightening force of adjacent bolts is reduced, which is related to the distance between the bolts. The purpose of studying the elastic effect is to avoid the ununiform distribution of the pre-tightening force of the bolt group. If the deformation amount of the base body can be reduced during one tightening process, the pre-tightening force variety of bolt can be reduced together.

This paper proposes to use step-by-step tightening to reduce the variety of the pre-tightening force of the bolt group. In the simulation analysis, the previous three-bolt finite element model is still used. The simulation analysis only uses bolt 1 and bolt 2 and simulates one-round tightening and two-round tightening respectively. In one round tightening, firstly the bolt 2 is applied the target pre-tightening force to 30KN. Then the bolt 1 is applied the target pre-tightening force 30KN. In the two-round tightening, there are three cases containing three step size:30%, 50%, 70%. For example, when using 30%, firstly acting 30% (9KN) of the target preload on the bolt 2. Then the bolt 1 is applied 30% of the target preload to (9KN)). After the first round of tightening, the second round of tightening is similar to the first by tightening to 30KN. The data is shown in Table 2.

According to table 2, it can be found that the variety of pre-tightening force value of the two-round is less than one round. In the two-round tightening, the closer the pre-tightening force applied during the first-round tightening to the target pre-tightening force, the final pre-tightening force change smaller, which is the same as the previous analysis.

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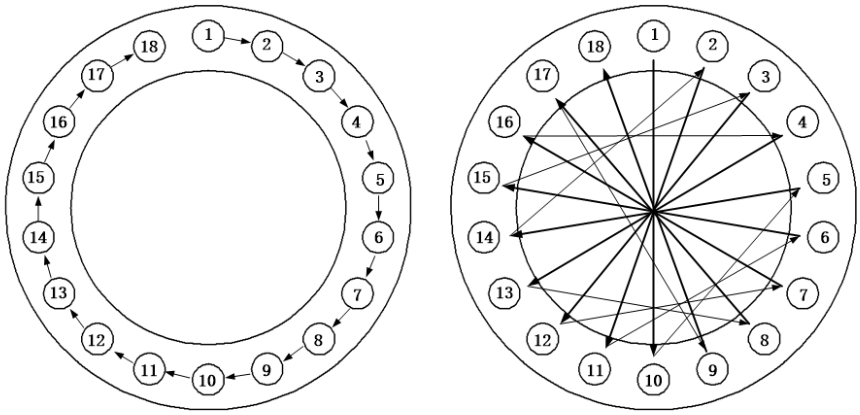
Table 2. The influence of the number of tightening wheels on elastic negative effect

round	1-round	2-round(30%)	2-round(50%)	2-round(80%)
pre-tightening force variety of Bolt 2/N	-823	-622	-445	-178

In addition, since the tightening bolts have the greatest influence on the bolt which have a closer distance, diagonal tightening, shown in fig.4, can be used instead of sequential tightening.



(a) Sequential (b) diagonally

Fig. 3. tightening sequence

4 Experiment

4.1 Experiment System and Method

The aero-engine rotor experiment system is shown in Fig. 4. The system consists of a rotor test piece, a clamping system and a measuring system. The ultrasonically measurement is used to obtain the bolt residue pre-tightening force. In the experiment, we changed tightening method/round/step to obtain the pre-tightening force of bolt group. At first, the experiment about tightening sequence is carried and the detailed about the other experiments' design is shown in table.3.

For example, in table. 3, torque 4 contains the following steps:

1) Tightening all of bolts to 50% of target torque in diagonally loading
2) Tightening all of bolts to target torque in diagonally loading
3) Loosen one bolts and tightening it to 50% of target torque and repeat it for last bolts
4) Tightening all of bolts to target torque in diagonally loading

Table. 3 Experimental design

tightening method	NO.	tightening rounds	tightening step(50%)/round
torque method	1	1	1
	2	1	2
	3	2	1
	4	2	2
torque-angle method	1	1	1
	2	1	2
	3	2	2

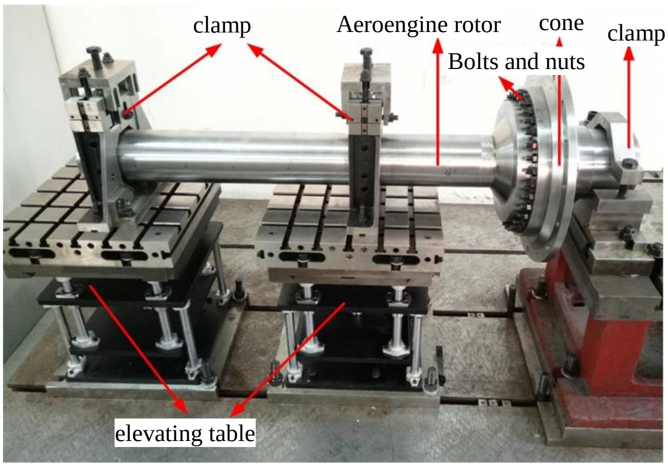


Fig. 4. Fixture map of assembly platform rotor assembly platform

4.2 Data Analyze

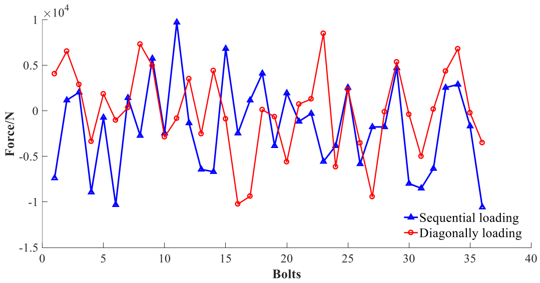


Fig. 5. tightening sequence effect

As shown in fig. 5, there is approximate no difference between sequential and diagonally and their variance are 2.3452 E+07 and 2.1223E+07 respectively. In general, diagonally loading is better than sequential loading. But in aeroengine rotor, maybe the

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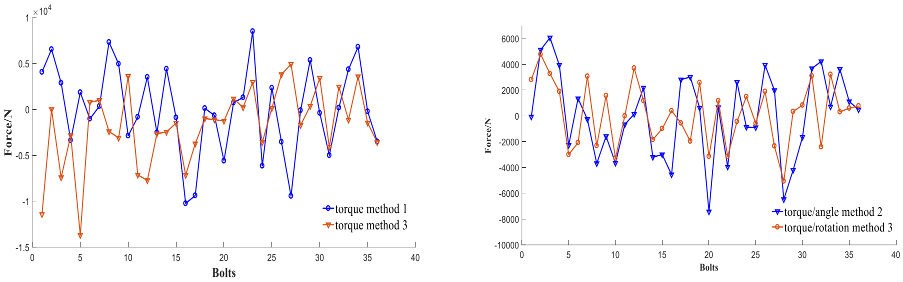
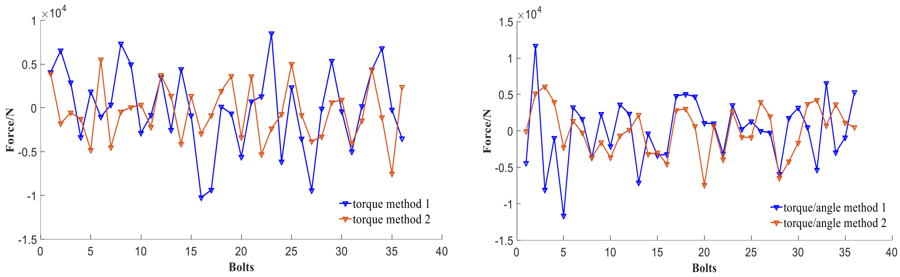
specifically structure and material make the sequential loading is almost as good as diagonally loading.



(a) (b)

Fig. 6. tightening round effect



(a) (b)

Fig. 7. tightening step effect

As shown in fig.6 and fig. 7, more rounds or steps in a round make the distribution of pre-tightening force of bolt group more uniform, especially when the torque/angle method is used. The trend corresponding with the analyze of FEM in above. But when using torque/angle method, the influences of tightening rounds and steps is more significant, compared to the torque method.

Finally, we used the optimal tightening process which obtained from above test (diagonally, 2-rounds, 2-step/round) to compare the difference between torque and torque/angle method. As shown in fig. 8 and table 4, the distribution of pre-tightening force of bolt group with torque/angle method is better than the torque method and the influences of tightening method is more remarkable than other factors.

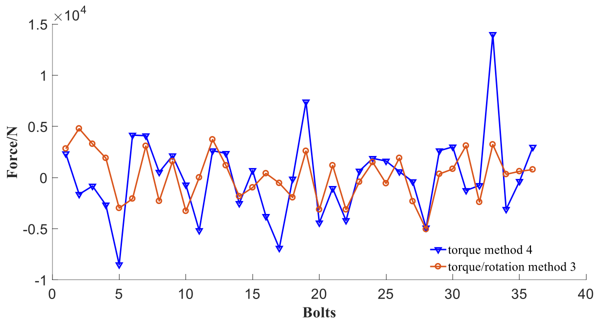


Fig. 8. tightening method effect

Table 4. variance comparison of methods

Tightening method	Final preload force dispersion (variance)
torque method 1	2.24E+07
torque method 2	1.23E+07
torque method 3	1.82E+07
torque method 4	1.52E+07
Torque/angle method 1	1.02E+07
Torque/angle method 2	1.07E+07
Torque/angle method 3	8.68E+06

5 Conclusion

In this paper, the single bolt and bolt group tightening process are studied to get the influence of the tightening process parameters when tightening the bolt group of rotors. The following conclusions were mainly drawn:

1) Since the uncertainty of friction coefficient, when a large number of bolts need to be tightened, the torque/angle method which is not sensitive to friction coefficient could get more uniform pre-tightening force.

2) Because of the influence of elastic interaction, the tightening parameters of assembly process need to consider the tightening sequence/rounds/steps. In particularly, diagonal method and 2-rounds are more suitable for bolt group of aeroengine rotor based on the experiment data.

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