The properties of bolted joint assembly with contact stiffness

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Abstract: In this paper, the real surface bolt connection model considering the contact characteristics of the joint surface is established by using the finite element simulation method. There is a non-linear segment in the initial stage of the angular preload curve. Flange model and two bolts mutual model under real contact surface are established. The contact characteristics of the joint surface will enhance the influence of bolt interaction. Considering comprehensively, cross tightening is the most suitable method in Wheel Disk Connection Structure.
Keywords: Threaded Fasteners; Contact stiffness; Torque-angle tightening; finite element analysis; Bolt interaction; Tightening sequence;

1 Introduction

As a critical basic component, bolt plays a crucial role in the mechanical industry. The advantages of bolt connection are simple structure, reliable connection, convenient assembly and so on. With the development of science and technology, mechanical equipment is developing towards precision, complexity and intelligence, and the accuracy of bolt assembly is also improved. The quality of bolt connection assembly has an important influence on the key performances of assembly component especially disk structures such as the dynamic stiffness dispersion, structural stability and durability. The improper assembly of disc bolts or excessive dispersion of preload will lead to poor neutrality, deviation of centroid line and asymmetry of radial stiffness of the disc, which will lead to excessive vibration of the whole machine and high cycle

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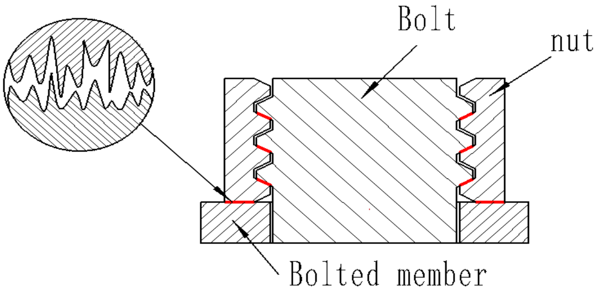
fatigue of the connecting components during the operation of the equipment, thus reducing the safety and reliability of the equipment. [1-7]

The uniformity of wheel disc bolt load is mainly determined by two factors: one is the accuracy of tightening preload of single bolt, the other is the influence of loading bolt between the former and the latter during sequential loading process, that is the elastic interaction of both bolts. The contact characteristics of the joint surface will affect the stiffness of the joint surface, so the above factors will affect the uniformity of the bolt load at the same time. Greenwood [8] et al. put forward the stress-deformation relationship of the surface micro-convex body by studying the micro-contact mechanism of the interface. Nassar [9] et al. studied the influence of bolt stiffness and connector stiffness on the single bolt torque angle method, but did not consider the contact stiffness caused by the contact characteristics of the joint. FUKUOKA [10] studied the stiffness of bolted connections under real contact surfaces, but only considered the contact stiffness between the connectors. In 1969, Campen [11] first proposed that subsequent loading bolts would change the loads of loaded bolts, that is, there was elastic interaction between bolts. Bibel [12] proposed that the elastic interaction was affected by flange size, joint and gasket stiffness, bolt number, bolt size and length, and tightening method and sequence. Bouzid [13] et al. proposed an elastic interaction model, in which the stiffness of gaskets and bolts was increased, which was verified by finite element analysis. But they did not consider the contact stiffness of the joint when they studied the elastic interaction of bolts.

In this paper, the theoretical model of contact stiffness of the joint surface is established according to the contact characteristics of the joint surface. The real surface bolt connection model considering the contact characteristics of the joint surface is established by using the finite element simulation method. At the same time, the ideal surface bolt connection model without considering the contact characteristics of the joint surface is established as a comparison. The tightening effect of the contact characteristics of the joint surface on the bolt torque method and the torque angle method is studied. The influence of process and contact characteristics of joint surface on the elastic interaction of two adjacent bolts. By establishing the six-bolt flange model of real contact surface, the dispersion of pretension force, the deformation relationship and neutrality of the connecting parts of the disc bolt connection structure under different tightening orders are studied.

2 Contact stiffness model of bolted joints



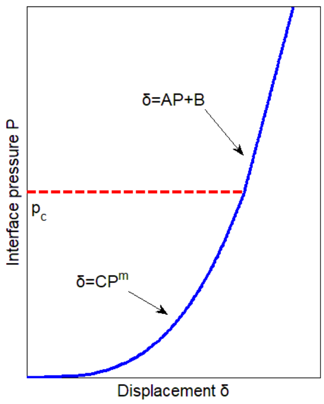


Figure 1 Relation between Contact Stress of joint Surface and Deformation of Micro-convex Body

The contact stiffness of the interface is caused by the elastic-plastic deformation of the micro-convex body on the contact surface under the action of contact force. As shown in the red line of Fig. 1, the contact stiffness of the joint surface is formed by contact and mosaic of the micro-convex body of the joint surface. When the contact stress reaches the critical stress, the deformation of the micro-convex body increases slowly and tends to be stable. The relationship between contact stress and deformation of micro-convex body is shown in Fig. 1.

The joint of bolted connection structure consists of two parts: the support joint of the connector and the thread joint. The contact stiffness of the joint has a very significant influence on the tightening process and the clamping force of the assembly. The contact stiffness of the interface can be defined as:

$$K = \frac{F}{\zeta}$$

Where F is the applied pretension force and ζ is the deformation of the interface. As shown in Figure 1, when the contact stress is less than the critical stress, it can be defined as:

$$\zeta = cp^{m}$$

where p is the pressure of the interface, c and m are the fitting coefficients of the pressure and deformation of the interface, which are determined by the surface roughness of the interface. According to the experimental study of TANIGUCHI [14], the variation of c and m with the surface roughness is shown in Fig. 2, which can be expressed as follows:

$$\mathrm{c} = 0.0674R_{mt} + 0.413$$
$$\mathrm{m} = 0.0155R_{mt} + 0.155$$

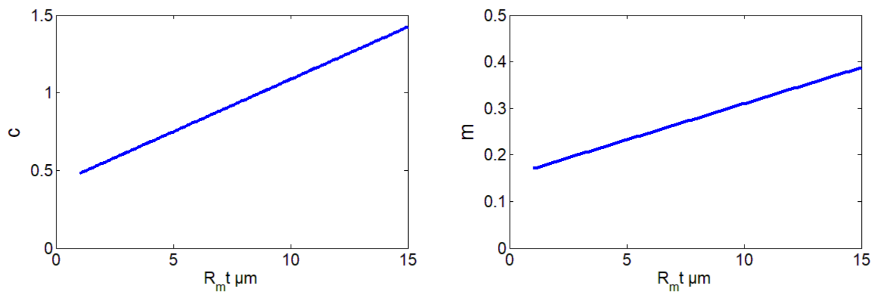


Figure 2 Fitting Coefficient of Pressure Deformation

Taking a rotor bolt connection structure as an example, the roughness of bolt head contact surface is R_a 1.6, converted into $R_z$standard roughness of 6.3 μm, the surface roughness of the other side joints is R_a 3.2, converted into R_z standard roughness of 12.5 μm, the total roughness of 18.8 μm, so $R_{mt} = 18.8\mu\mathrm{m}$, can be calculated as follows:

During the tightening process, the average stress of the bolt head under the initial preload is as follows:

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$$p_{hd} = \frac{4F_s}{\pi(B^2 - D_i^2)} = 80.48\text{MPa}$$

Therefore, the initial deformation ζ_s is calculated as follows:

$$\zeta_s = cp_{hd}^m = 0.0119\mu\text{m}$$

During the tightening process, the average stress of the bolt head under the target clamping force is:

$$p_{hd} = \frac{4F}{\pi(B^2 - D_i^2)} = 203.90\text{MPa}$$

The calculation of final deformation ζ

$$\zeta = cp_{hd}^m = 0.0180\mu\text{m}$$

Therefore, the contact surface stiffness of bolt head

$$k_{hd} = \frac{F - F_s}{\zeta - \zeta_s} \times 1000 = 3.7537\text{e}6 \ \ \text{N/mm}$$

Similarly, the surface roughness of bolt threads is R_a 0.8, converted into R_z standard roughness of 6.3 μm, the surface roughness of the other side joints is R_a 1.6, converted into $R_z$standard roughness of 6.3 μm, the sum of total roughness is 12.6 μm.

Thread contact surface stiffness:

$$k_{hd} = 4.5401\text{e}6 \ \ \text{N/mm}$$

According to the above principle, in order to realize the simulation analysis considering contact characteristics, the real contact surface modeling can use the known mechanical properties of the real contact surface to cut a thin layer on the joint surface of the model and endow it with approximate properties as an alternative material. The scale of the micro-convex body on the contact surface is Micro nano scale and the model size is millimeter. The mesh of the contact surface must be fine enough to obtain the real surface characteristics. The mechanical properties of the micro-convex body have been referred by many literatures. Therefore, the contact characteristics can be simulated by the Multilinear Isotropic Hardening method. This method is suitable for material in plastic stage, when the stress-strain curve is non-linear. At this time, the deformation of the micro-convex body is regarded as plastic deformation. For the surface roughness, 25 μm is chosen, the critical surface pressure is 10 MPa, and the A value is 10 nm. The relationship between the deformation and stress of the material is as follows

$$\delta = 2.0980p^{0.5}(p < p_c)$$

$$\delta = 0.01p + 7.3163(p \geq p_c)$$

In Multilinear Isotropic Hardening, the input parameters are stress and strain. In the above formula, we get the deformation, which needs to be converted into strain. The thin layer is taken as 25μm, and the contact stress-strain curve is shown in Figure 3.

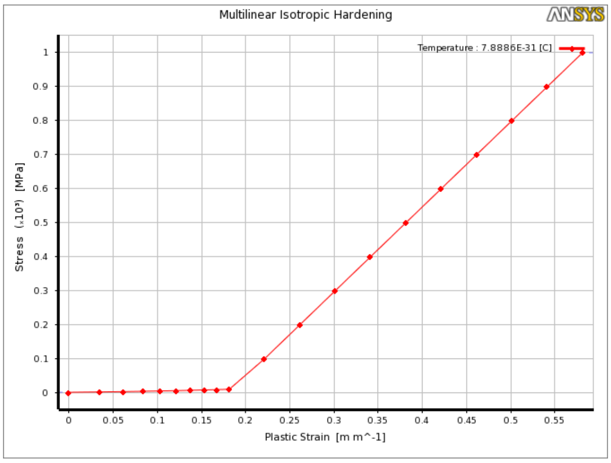

Figure 3 Surface Contact Stress-Strain Curves Based on Virtual Materials

3 The influence of contact stiffness on tightening process

There are two main methods for bolt tightening: torque method and torque angle method. The bolt torque tightening is mainly affected by the friction coefficient of the contact surface between the nut and the thread, which is independent of the stiffness of the bolt joint. In the process of tightening by torque-angle method, the angle of the nut is mainly related to its clamping force, joint stiffness and pitch, which can be expressed as follows:

$$\theta = \theta_{cl} + C_{TM}T + C_{TB}T_{tp} + \frac{360F}{PK}$$

where θ_{cl} tightening shaft clearance error, C_{TM} tightening shaft flexibility error, C_{TB} bolt torsional flexibility, K is the total equivalent spring constant of the connection structure, F is the clamping force, P is the pitch. The first two items of the formula are not analyzed in theoretical calculation as the clearance of the device; because the length of GH4169 M10 bolt is small, the torsional deformation under shear stress can be neglected, so we only consider the influence of spring constant of the connecting structure on the preload.

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Assuming that the whole connecting system is connected in series with several springs, the equivalent total spring coefficient can be expressed as:

$$\frac{1}{K}=\frac{1}{K_B}+\frac{1}{K_C}+\frac{1}{K_{TH}}+\frac{1}{K_{mthd}}+\frac{1}{K_{mtth}}+\frac{1}{K_{mtc}}+\frac{1}{K_{mtn}}$$

where K_B is the spring constant of the bolt, K_C is the spring constant of the connecting part, K_{TH} is the spring constant of the thread pair. K_{mthd}, K_{mtth}, K_{mtc}, K_{mtn} are the contact stiffness of the bolt head joint, the thread joint, the connecting part joint and the nut end joint respectively.

There are two factors affecting the non-linear section of tightening by torque-angle method: 1. the surface roughness of the joints; 2. the non-linearity of stress and strain on the real contact surface. In order to study the relationship between contact stiffness and clamping force, a finite element model of tightening process is established as shown in figure 4. The standard thread of bolt and nut is M10×1.25. It is assembled on a circular connector with a diameter of 10.7 mm and a thickness of 25 mm. The outer surface of the nut is simplified as a cylindrical surface. The bolt head is simplified, and the fixing constraint is applied on the bolt section and the connector, because the bolt head is fixed on the connector,. There are two kinds of real contact surface of bolt connection: the real contact surface between nut and connecting part is set on the connecting part, the real contact surface between threads is set on the bolt thread. The high strength bolts of grade 12.9 are selected. The material properties of bolts and nuts are: Young's modulus 200 GPa, Poisson's ratio 0.3 and yield strength 950 MPa. The joints are made of ordinary carbon steel with Young's modulus of 200 GPa, Poisson's ratio of 0.3 and yield strength of 450 MPa. The contact conditions of the upper surface of the bolt thread and the lower surface of the nut thread, the lower surface of the bolt thread and the upper surface of the nut thread, the end face of the nut and the fastener are all sliding with friction coefficient of 0.15. Apply 80Nm torque to the nut, output bolt connection torque, rotation angle and preload.

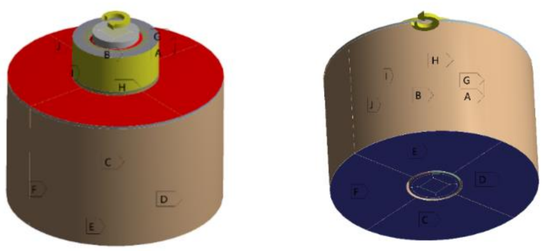
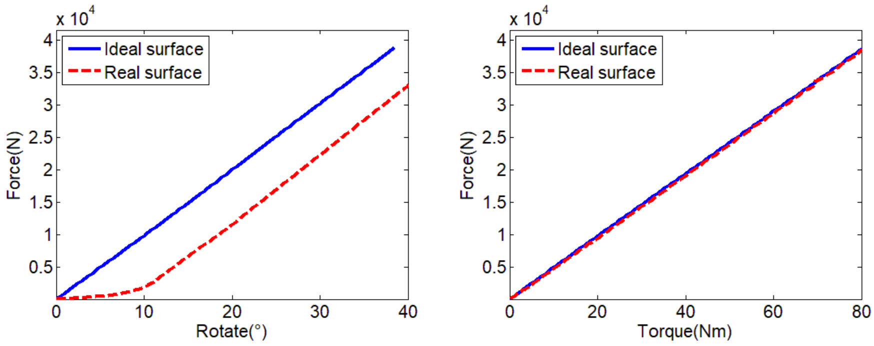


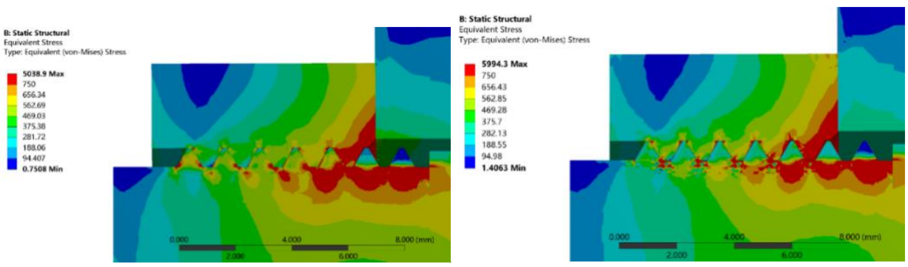
Figure 4 Finite Element Model for Tightening Process of Bolted Connections Considering Real Contact Characteristics

The simulation results are shown in Fig. 5. According to the curve of Rotate-Force, there is a non-linear segment in the simulation of real contact surface, which is consistent with the theory. Because the torque method tightening is affected by the friction coefficient and friction radius of the contact surface and not by the stiffness of the bolt joints, the surface contact stiffness will not affect the Torque-Force curve. But in theory, the stiffness of bolted joints considering the real contact surface is less than that without considering the real contact surface. However, the simulation results show that the stiffness of bolted joints is very close, even after considering the real contact surface, the stiffness of bolted joints is slightly larger. As shown in Figure 6, the stress distribution of the threads is more uniform and the stiffness of the bolted joints is increased by adding a real contact surface to the threads.



(a) (b)

Figure 5 Comparison of bolt tightening characteristics under different contact stiffness [a]: Rotate-Force curve, [b]: Torque-Force curve



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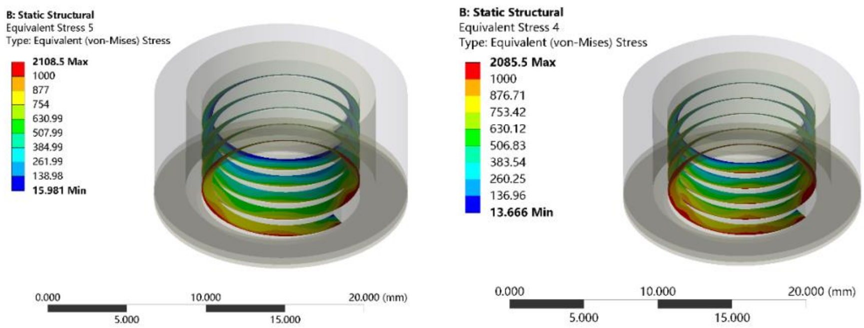


(c) (d)

Figure 6 Thread Stress Distribution

[a]: Stress Profile of Ideal Surface Thread, [b]: Stress Profile of Real Surface Thread, [c]: Stress Distribution of Ideal Surface Nut Thread, [d]: Stress Distribution of Real Surface Nut Thread

4 Influences of Contact Stiffness on bolted joint assembly

The clamping force of the bolt will change when the bolt is tightened one by one, which is called the elastic interaction between the bolts. For group bolts with periodic distribution, the elastic interaction is more complex. As shown in Fig. 7, the simulation model of tightening process of 6-bolt flange connection is established. The diameter of the upper and lower flanges is 90 mm. Six bolts with uniform distribution are connected with the upper and lower flanges. A real contact surface is added between the two flanges. The real contact surface is set by using the plastic deformation of Multilinear Isotropic Hardening. The contact settings between the six bolts and the flange and the contact settings between the two flanges are bonds. The preload of each bolt is loaded to 3800 Nm. According to the existing research results, when the contact characteristics are not considered, the elastic interaction can be neglected in the finite element model without gasket flange connection. However, as shown in Fig. 10, when the contact characteristics are taken into account and the real contact surface is added, the variation of pretension force increases significantly. When six bolts are tightened sequentially, the adjacent bolts make the clamping force of the first tightened bolt decrease, while the bolts in the diagonal position increase. The clamping force of bolt No. 1 changes the most, and the maximum change rate is 10.5% in the tightening process. After all bolts are tightened, the change rate will be 6.6%. Fig. 8 is a curve of the clamping force distribution of all six bolts. The standard deviation of symmetrical pre-tightening force is the largest, 1837.26N, and that of cross tightening force is the smallest, 1165.39N. The distribution of bolt preload will affect the radial stiffness of the disk structure, so the multi-bolt assembly process with cross tightening will ensure the stability of the dynamic stiffness of the structure. In the process of tightening, besides the change of the clamping force of bolt group, the shape and center of flange are also changed.

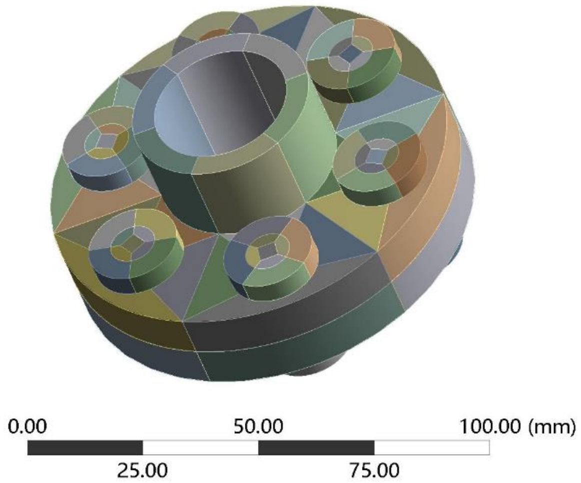
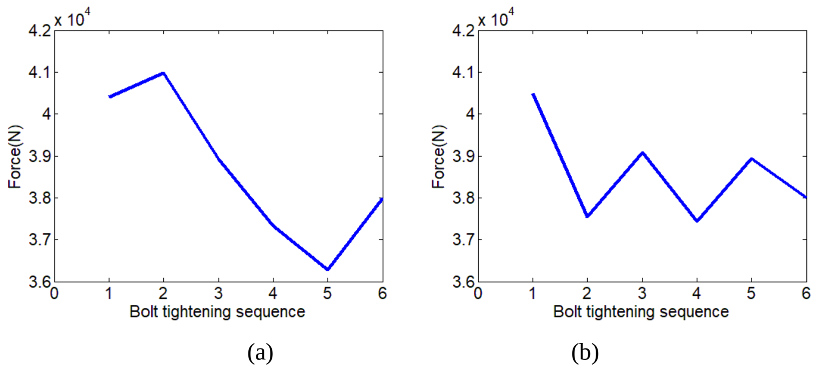


Figure 7 Simulation model of tightening process of six-bolt flange



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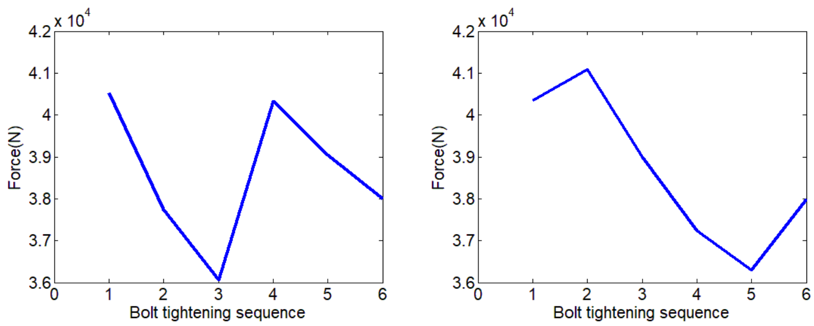
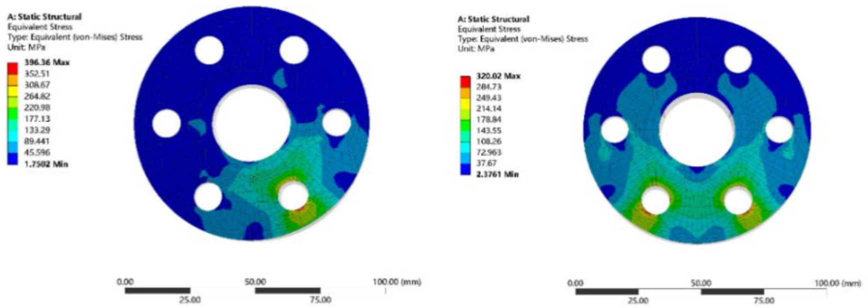


(c) (d)

Figure 8 Pre-tightening Force Distribution of Bolts in Different Tightening Sequences

[a]: sequential tightening, [b]: cross tightening, [c]: triangular tightening, [d]: symmetrical tightening



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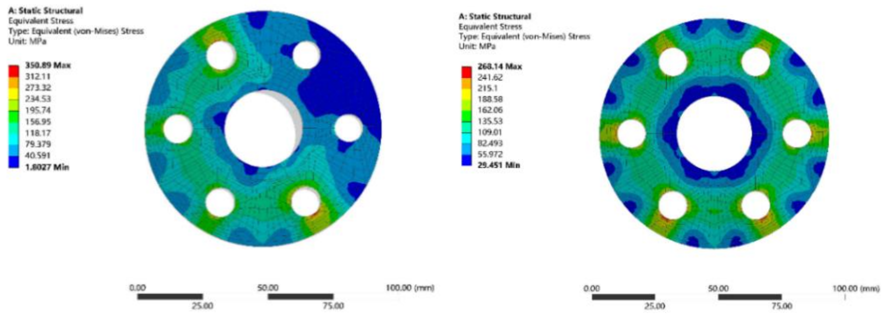

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(c) (d)

Figure 9 Stress Distribution on Sequential Tightening Contact Surface

[a]:one bolt, [b]: two bolts, [c]: four bolts, [d]: six bolts

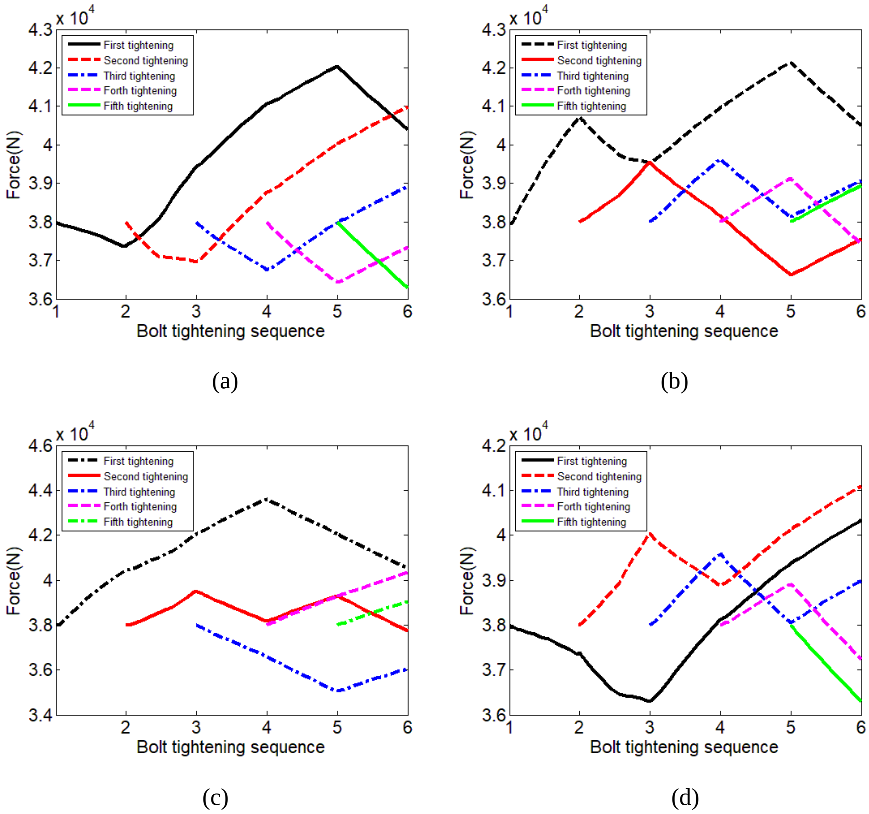

Figure 10 Variation of bolt preload considering contact characteristics

[a]: sequential tightening, [b]: cross tightening, [c]: triangular tightening, [d]: symmetrical tightening

As shown in Figure 11, the bolts are tightened sequentially in different tightening order, and the track of flange center is changed. As shown in Fig. 12, the final flange deformation under different tightening orders is enlarged 500 times for more intuitive deformation. As shown in Table 1, the calculated roundness deviates from the center of the circle. Among them, the flange roundness keeps the best under sequential tightening, but the position of the center of shape varies greatly, while the change of the center of shape is the smallest under triangular tightening, but the flange deformation is large; the roundness and the center of shape position are moderate under cross tightening.

Table 1 Roundness and Centroid Location in Different Tightening Sequences

Tightening sequence	Roundness	Centroid position change (μm)
sequential tightening	0. 0015126	6. 095

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cross tightening	0. 0021489	3. 777
triangular tightening	0. 0046323	1. 821
symmetrical tightening	0. 0019778	5. 361

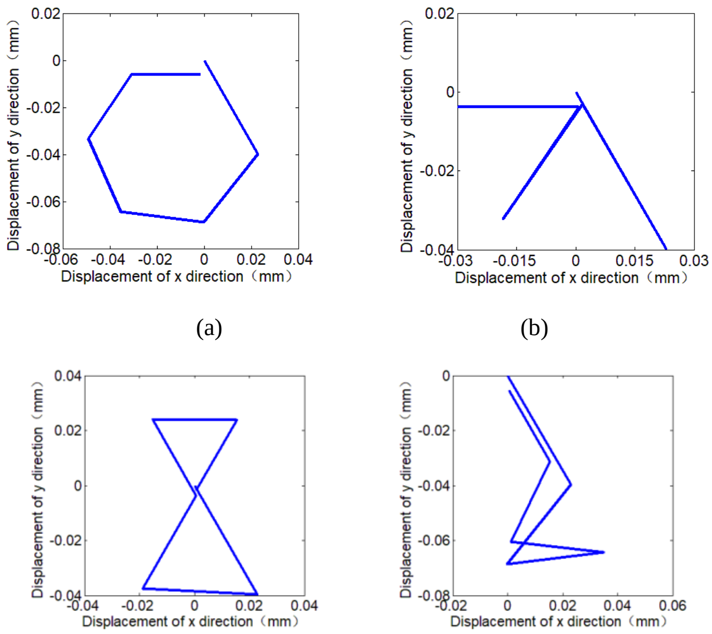
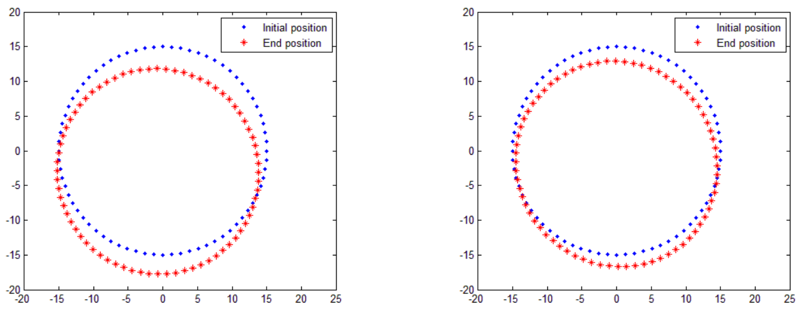
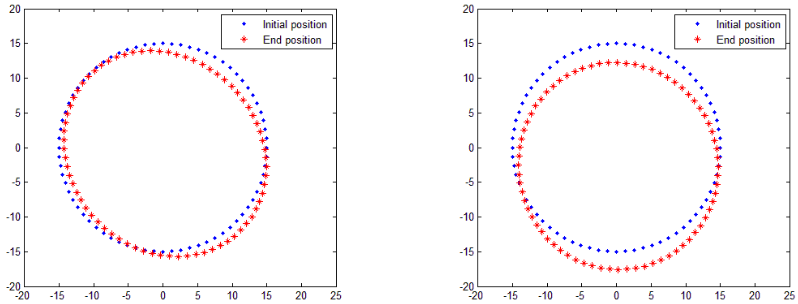


Figure 11 Change of flange center under different tightening sequence

[a]: sequential tightening, [b]: cross tightening, [c]: triangular tightening, [d]: symmetrical tightening



(a) (b)



(c) (d)

Figure 12 Deformation contrast of flange tightening under different tightening sequence (enlargement 500 times)

[a]: sequential tightening, [b]: cross tightening, [c]: triangular tightening, [d]: symmetrical tightening

In order to study how the real contact surface affects the elastic interaction of bolts, a simulation model of the tightening process of two bolts is established. The distance between two bolts is driven by parameterization, and the clamping force of two bolts is loaded to 3800 N in sequence. The elastic interaction of two bolts at different spacing is studied. The simulation results are shown in Fig. 13 and Table 2. When the bolt distance is 25 mm, the interaction between the second bolt and the first bolt is negative. The pretension force of the first bolt decreases to 36317N (-4.4%). When the bolt distance is more than 100 mm, the interaction is positive and decreases slowly with the increase of the bolt distance. The influence of positive interaction is less than that of negative interaction (+0.2%). Without considering the contact characteristics, when the bolt distance is 25 mm, the pretension force of the first bolt decreases to 377772 N (-0.6%), while when the bolt distance increases, the positive interaction between the bolts is very small. Therefore, the contact characteristics of the joint surface will enhance the influence of bolt interaction.

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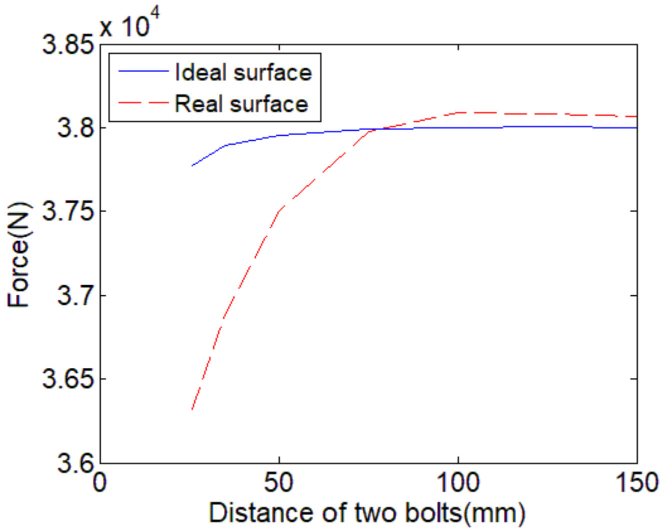

Figure 13 The relationship between bolt spacing and pre-tightening force variation

Table 2 The relationship between distance of the bolt and preload of the first bolt

Distance of the bolt (mm)	Clamping force under ideal surface (N)	Change of Clamping force under ideal surface (N)	Clamping force under true surface (N)	Change of Clamping force under true surface (N)
26	37772	228	36317	1683
35	37894	106	36887	1113
50	37956	44	37503	497
75	37993	7	37973	27
100	38002	−2	38086	−86
125	38004	−4	38082	−82
150	38002	−2	38070	−70

5 Conclusion

In this paper, single bolt tightening model, two bolts mutual model and flange model under real contact surface are established. Single bolt torque method and torque angle method considering contact characteristics of interface, flange joint Interaction in

Different Tightening Sequences are studied. The conclusions are summarized as follows:

(1) Through the stress-deformation relationship of the micro-convex body on the contact surface, the stiffness of the contact surface is studied Taking a bolt from a rotor as an example, the standard roughness of the contact surface of the bolt head is 12.5 micron, the standard stiffness of the contact surface of the bolt head is 3.7537e6N/mm, the standard roughness of the surface of the bolt thread is 6.3 micron, and the stiffness of the contact surface of the bolt head is 4.5401e6N/mm.

(2) In the process of tightening single bolt by torque-angle method, due to the contact stiffness of the contact surface, there is a non-linear segment in the initial stage of the angular preload curve, while the torque method tightening is affected by the friction coefficient of the contact surface, so the contact stiffness has little effect on the torque preload curve. Under the real contact surface, the stress distribution of bolt thread is more uniform than that of ideal surface.

(3). The different tightening sequence of flange bolts will affect the uniformity of clamping force and assembly accuracy. Among them, the centroid offset of sequential tightening is the largest, offset is 6.1 μm, but flange deformation is the smallest, roundness is 0.0015. The centroid offset of triangular tightening is the smallest, offset is 3.8 μm, but flange deformation is the largest, roundness is 0.0045. The standard deviation of discrete value of symmetrical tightening preload is the largest, 1837.26N, and that of cross tightening preload is the smallest, 1165.39N. Considering comprehensively, cross tightening is the most suitable method in Wheel Disk Connection Structure.

(4). The contact characteristics of the joint surface will enhance the influence of bolt interaction. Considering the contact characteristics of the joint surface, when the bolt distance is 25 mm, the negative interaction occurs. The preload of the first bolt decreases to 36317 N (-4.4%), while the positive interaction occurs when the bolt distance is more than 100 mm. The preload of the first bolt increases to 38086 (+0.2%).

In this paper, the influence of contact characteristics of joint surface on assembly accuracy of bolt connection is discussed from two aspects of single bolt tightening and bolt interaction. In practical engineering applications, there is no absolutely smooth ideal surface, so we should consider the effect of the contact stiffness of the real contact surface. Contact stiffness will make the first half of the angular preload curve of single bolt tighten appear non-linear, but has little effect on the torque preload curve. This is also because we will not tighten the bolt by angle method alone in engineering application, but by torque-angle method. Contact stiffness will enhance the elastic interaction between bolts, so in the bolt tightening of Wheel Disk Connection Structure, tightening order determines the accuracy of assembly. Cross tightening method is recommended to achieve the balance of assembly stiffness and accuracy.

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