ABSTRACT

Bolted joints are widely used in the auto industry, energy field and Construction, and so on. Due to the wide use of the bolted joints, the degradation of bolts has significant effect on the performance of a whole machine. Under transversal vibration, the self-loosening of bolted joints, which is the biggest form of failure ranked only second to fatigue failure [1], will happen, due to the cyclic shear load. This paper is to study the mechanism of bolted joints’ self-loosening.

Aiming at analyzing the self-loosening mechanism of bolted joints under vibration, a three dimensional FEA model of bolted joints, which had taken thread into consideration, was built with the application of APDL, and the preload was applied on the bolted joints by dropping temperature, then FEA transient analysis of the bolted joints under transverse cyclic excitation was conducted. Effect of transverse cyclic excitation’s amplitude, initial preload, thread and bearing friction coefficients, the joints’ surface friction coefficient, the thread pitch and the hole clearance on self-loosening was investigated. The results show that the complete thread slip occurs prior to the complete bearing surface slip under transverse vibration; the smaller amplitude, the smaller thread pitch and the smaller hole clearance is, and the greater initial preload, thread and bearing friction coefficients are, the more difficult self-loosening is to happen; the joints’ surface friction coefficient has little relationship with self-loosening, however, the larger joints’ surface friction coefficient makes the needed shearing force, which induces the transversal vibration, larger. These are of great significance for understanding of fasteners’ self-loosening and designing of bolted joints’ anti-loosening.

Keyword: Bolted joints; Vibration; Transient Analysis; Preload; Friction Coefficient

INTRODUCTION

The self-loosening of bolted joints will cause leakage, failure due to the uneven stress, the lowering of the complete machine dynamic performance, and other bad effects, even lead to accident. Thus it is of significant for studying on self-loosening.
The self-loosening and anti-loosening of bolted joints has been studied by many scholars. Junker [2] designed the famous tester, called Junker tester, to study the loosening behavior of bolted joints and found that the bolted joints under transversal vibration relaxed more easily, due to the transversal cyclic shearing load, than under other conditions. Hess and his co-workers [3] [16] studied the self-loosening of bolted joints under transversal cyclic shearing load by using experimental and FEA method, and they put forward that there are four apparent stages in the self-loosening. Nassar, Housari and other co-workers [4]-[6] studied the effects of the thread pitch, the initial preload, the hole clearance, the thread and bearing friction coefficients on self-loosening through the application of line linear model. Then, Nassar, Yang and other co-workers [1], [7]-[11] proposed a more accurate analytical model to analyze the self-loosening under transversal vibration, and designed a series of corresponding experiments to validate the analytical model. The scholars mentioned above got plenty of achievement on self-loosening study, however, both their theoretical models and the experimental models were based on the Junker tester, which did not match the actual for ignoring the frictional condition of the joints’ surface.

Jiang and his co-workers [12]-[14] designed a new experimental facility to study on self-loosening. They studied the self-loosening of bolted joints under transversal cyclic load by using experimental and FEA method and proposed that self-loosening should be divided into two stages: the first loosening due to the short-time and acute plastic ratchet effect of the material of thread, the second loosening due to the clamping force loss caused by the nut’s turning back. Jiang and his co-workers considered the frictional condition of the joints’ surface, nevertheless, they didn’t consider the spiral effect of the thread in their finite element simulation, so their study cannot explain the self-loosening due to nut’s turning back clearly. Yang Guangxue and her co-workers [15] studied the effects of the addition bending moment, initial preload and anti-loosening nut on loosening of bolted joints under transversal vibration with the application of 3D FEA method in their research on anti-loosening mechanism of a new type of nut.

On the foundation of the former scholars, this paper built a three-dimensional finite element model of bolted joints, applied preload on the bolted joints model by using cooling pre-tightening algorithm, then conducted the FEA transient analysis of the bolted joints under transversal cyclic excitation, and investigated the effects of the transverse cyclic excitation’s amplitude, the initial preload, the thread and bearing friction coefficients, the joints’ surface friction coefficient, the thread pitch and the hole clearance on self-loosening.

**CORRELATIVE ALGORITHM**

**Augmented Lagrangian contact algorithm**

Contact algorithm is used to dealing with the relationship of the interaction between the contact body. Effective contact algorithm should be able to pass the contact force to ensure that there is no penetration between the two contact surfaces. General contact algorithms in ANSYS are Penalty Function algorithm, Lagrange algorithm and Augmented Lagrangian algorithm. The Augmented Lagrangian algorithm is an algorithm with easily converging and accurately calculating based on the former kinds of algorithms. Before calculating each load step, it will check the penetration between the contact surface and the target surface and manage the penetration. When there is a penetration, it will set up a normal contact force between the contact surface and the target surface, the size of the force is determined by the component proportionately to the contact stiffness and penetration size, and the Lagrange coefficient, being equivalent to set a spring which can be adjust its stiffness between the two surfaces to limit the size of the penetration and to prevent pathological integral stiffness, which will lead to the solving divergence, caused by excessive contact stiffness matrix. The algorithm is described as follows.

The finite element contact equation:

\[
[K][u] = \{P\} + \{R\}
\]

In Eq.(1), \(K\) is the stiffness matrix, \(u\) is the unit displacement matrix, \(P\) is the unit load vector, \(R\) is the unit contact force vector.

The portion \(R\) of \(R\) is determined by Augmented Lagrangian contact algorithm, as followed:

\[
R_i = \begin{cases} 
0 & , \delta > 0 \\
k_n \delta + \lambda_{r+1} , \delta \leq 0 
\end{cases}
\]

In Eq.(2), \(k_n\) is normal contact stiffness, \(\delta\) is the space between the contact surface and target surface, \(\lambda_{r+1}\) is Lagrange coefficient. If \(\delta \leq 0\), which means penetration, coefficient \(\lambda_{r+1}\) will modify \(k_n\) according to the actual contact stiffness, the concrete can be determined by Lagrange iterative method:

\[
\lambda_{r+1} = \begin{cases} 
\lambda_{r+1} + k_n \delta , |\delta| > e \\
\lambda_{r+1} , |\delta| \leq e 
\end{cases}
\]
In Eq.(3), \( \lambda_i \) is the Lagrange coefficient of the previous step, \( \varepsilon \) is the contact tolerance (the allowed maximum penetration for convergence).

So we can solve equation (1), and control penetration and transfer contact force between two contact surfaces.

**Cooling pre-tightening algorithm**

In FEA, the general pre-tightening algorithm are Preload Element algorithm, Equivalent Force algorithm and Cooling algorithm. The pretightening unit can't bear shear load, so it cannot be used in the transient analysis under transverse vibration; the loading by Equivalent Force algorithm is complex, and it cannot simulate the response of the joints under preloading [17]. To pre-tighten the bolt joints with shear force, the Cooling algorithm must be used. Cooling algorithm: setting the bolt material thermal expansion coefficient, then lowering the temperature of the pre-tightening bolt part, the bolt will elongate, while the joints will restrict the deformation of the bolt, which will cause the inside tension of the bolt, so the pretightening is simulated. The algorithm is described as follows.

As shown in figure 1, in the free stage, the temperature of the bolt part (length \( I \)), which will be pretightened, is lowered for \( \Delta T \). There will be a contraction deformation, whose size is \( \Delta l_0 \), due to the heat bilges cold shrink effect. In the cooling preloaded stage, the existence of joints reduces the deformation of bolt, there will be a clamping force between bolt and joints, this force decrease bolt shrinkage deformation for \( \Delta l_1 \) and cause the joints deformation for \( \Delta l_2 \).

\[ \Delta l_0 = \alpha_0 I \Delta T \]  

In Eq.(5), \( \alpha_0 \) is the linear expansion coefficient of bolt material.

As the deformation relationship of the bolt and joints under pre-tightening shows:

\[ \Delta l_1 = F / K_b \]  
\[ \Delta l_2 = F / K_c \]

In the above, \( F \) is the pre-tightening force on bolt connection, \( K_b \) is the stiffness of bolt, \( K_c \) is the stiffness of the joints.

Taking Eq.(4), (5) and Eq.(6) into Eq.(7), and calculating them, the lowering temperature of bolts when loaded prestressing force \( F \) will be given:

\[ \Delta T = \left( \frac{1}{K_b} + \frac{1}{K_c} \right) \frac{F}{\alpha_0 I} \]  

**STUDYING ON THE SELF-LOOSENING SIMULATION**

**Finite element analysis modeling**

In order to study the self-loosening mechanism of bolted joints under transversal vibration based on FEA, the corresponding finite element model must consider the spiral effect of the thread, in other words, a three dimensional FEA model of bolted joints, which takes thread into consideration, must be built.

In this paper, the ANSYS parametric language is used to build the FEA model of bolted joints. As Fig.2 shows, the bolt is made up of two parts: haulm and thread, and is meshed after using the command VGLUE. The FEA model of the nut can be obtained in the similar way. The sizes of the model are follows: the nominal diameter \( D \) is 12mm, the bolt head diameter \( D_1 \) is 16.6mm, the height of the bolt head \( H_1 \) is 7.5mm, the height of the nut \( H \) is 13mm, the thread pitch \( p \) is 1.75mm, the length of the bolt L is 64mm, joints’ sizes is 80mm\( \times \)80mm\( \times \)20mm(both boards are the same), the hole clearance \( \delta / 2 \) is 0.5mm, the profile angle is 60 degree. In the model, the bolt material is high strength steel, whose Young’s modulus \( E_1 \) is 210GPa, Poisson ratio \( \nu_1 \) is 0.3, density \( \rho_1 \) is 7.9\( \times \)10\(^3\)Kg/m\(^3\), yield limit is 640Mpa. While the joints material is Q235 steel, whose Young’s modulus \( E_2 \) is 210GPa, Poisson ratio \( \nu_2 \) is 0.3, density \( \rho_2 \) is 7.9\( \times \)10\(^3\)Kg/m\(^3\), yield limit is 235Mpa.
**Fig.2: Three dimensional FEA model of bolted joints**

**Constraints applying**

This paper consider the slippage between contact surfaces, so the contact pairs is built by using TARGE170 as the target unit and the CONTA173 as the contact unit. When building the contact pairs, the friction coefficients of the thread engagement surface $\mu_1$, $\mu_2$ and $\mu_3$ by defining material friction factor. Each friction coefficients is obtained from literature [6] and literature [16], namely the paraffin lubrication (0.05), the MoS2 grease lubrication (0.1), mechanical lubricating oil (0.17) and dry friction (0.2).

**Bolted joints pre-tightening**

In the static solver, the normal temperature is setted by using command TREF, the temperature load according to Eq.(8) is loaded on the bolt by using command BFV to pre-tighten the bolt. Fig.3 shows the stress nephogram of nut thread after preloaded. As shows in the figure, the first circle thread stress is the largest, the followed decreases one by one, which fits to the actual stress distribution of bolt joints.

**Transversal vibration transient analyzing**

In order to conduct the FEA of bolted joints self-loosening, the transversal excitation $\delta_z$ should be loaded and the transient analysis should be conducted. The $\delta_z$ is determined by the formula:

$$\delta_z = \delta_0 \sin(\omega t) \quad (9)$$

In Eq.(9), the excitation amplitude is $\delta_0$ ($\delta_0 \leq \delta / 2$), $\omega$ is angular frequency.

Concretely, the joint surface friction coefficients are setted as $\mu_1 = \mu_2 = \mu_3 = 0.1$, the FEA model of bolted joints, showed in figure 1, is pre-tightened by the load of $F(F=10730N)$ to conduct static analysis. After the solution, the displacement load $\delta = 0.2\sin(3600t)$ is loaded, and the transient analysis is conducted for time step $t=0.0125s$ and end time=0.325s.

**ANALYSIS OF SELF-LOOSENING MECHANISM**

**Analysis of self-loosening process**

The curve in the Figure 4 shows the shearing load changing over transverse displacement, called shearing load hysteric curve. As the transversal stiffness of bolted joints can be explained by $K_{\text{transverse}} = F_{\text{shearing}} / \delta_0$ ($F_{\text{shearing}}$ means the biggest shearing load, which equals to the half the vertical span of the curve), thus the transversal stiffness of bolted joints can be measured by the vertical span of the curve: the bigger the vertical span is, the bigger the transversal stiffness is.

**Fig.4: The relationship between shearing load and transverse displacement**

What shows in Figure 5 are the contact status of thread engagement surface and bearing surface at point A, B, C and D in Figure 4. In the figure, we can know that the thread engagement surface slips completely, while the bearing surface slips incompletely at point A and C, and the slippage parts of bearing surface at point A and C are opposite, suggesting that the bearing surface can slip in a whole circle. However, both thread engagement surface and bearing surface slip incompletely at point B and D. It suggests that the slippage at the amplitude of transverse displacement is the acutest, and the complete slippage of thread engagement surface happens before that of bearing surface.
Fig. 5: The contact status of thread and nut bearing surface

The Curve in the Figure 6 shows the residual preload change over time. In the figure, we can know that the preload loses a little in a circle (for decreasing only 0.7% per circle). Integrating with the Figure 5, we can know that the incompletely slippage can also cause relaxation.

Fig. 6: Residue preload VS time

**Effect of excitation amplitude on self-loosening**

In order to investigate into the effect of amplitude of transversal vibration on self-loosening, referring to the simulation of section 3.4, we only modify the parameter δ₀ to 0.02, 0.1, 0.2, 0.3 and 0.4. Then the comparison simulation of bolted joints with different excitation amplitude under transverse vibration is conducted. The curves in the Figure 7 show residual preload change for different excitation amplitudes. In the figure, we can know that the curves of 0.02 and 0.1 are nearly parallel with the coordinate axis, which indicates that there is little preload loss when the excitation amplitude is 0.02 and 0.1. However, the preload loss is very visible when the excitation amplitude is 0.2, 0.3 and 0.4. It suggests that the self-loosening of bolted joints can happen only when the excitation amplitude is big enough. When comparing the preload loss of 0.2, 0.3 and 0.4, we can know that the greater the amplitude is, the more likely to happen the self-loosening is. The Figure 8 shows shearing load hysteretic curves under different amplitudes. In the figure, we can know that the greater the amplitude is, the bigger the shearing load needed is.

Fig. 7: Residue preload VS time under different amplitudes

Fig. 8: Shear load hysteretic curves under different amplitudes

**Effect of initial preload on self-loosening**

In order to investigate into the effect of initial preload on self-loosening, referring to the simulation of section 3.4, we only modify the parameter F to 3, 10.73, 21.32 and 29.93. Then the comparison simulation of bolted joints with different initial preloads under transverse vibration is conducted. The curves in the Figure 9 show the losing preload percentage change for different initial preloads. In the figure, we can know that the greater initial preload is, the smaller percentage of preload loss is, the less likely to happen the self-loosening is. The Figure 10 shows shearing load hysteretic curves under different initial preloads. In the figure, we can know that the greater initial preload is, the bigger vertical span is. It suggests that the greater initial preload is, the greater transversal stiffness of bolted joints is.

Fig. 9: Curves of losing preload percentage under different initial preloads
Effect of coefficients on self-loosening

(1) Effect of coefficient $\mu_1$ on self-loosening

In order to investigate into the effect of thread engagement surface friction coefficient ($\mu_1$) on self-loosening, referring to the simulation of section 3.4, we only modify the parameter $\mu_1$ to 0.05, 0.1, 0.17 and 0.2. Then the comparison simulation of bolted joints with different thread engagement surface friction coefficient under transverse vibration is conducted. The curves in the Figure 13 show residual preload change. In the figure, we can know that the bigger coefficient is, the greater preload loss is, when the bearing surface friction coefficient is 0.1, 0.17 and 0.2. However, there is little preload loss when the bearing surface friction coefficient is such small as 0.05, which is contrary to other scholars’ results, but is also correct. Because the bolt head’s and nut’s DOFs are not constrained in this paper, but constrained in other scholars’ analysis to fit with Junker test. When the bearing surface friction coefficient is very small, the slippage, caused by transversal movement of the board, will be very slight, thus the self-loosening speed is very slow. The Figure 14 shows shearing load hysteretic curves under different bearing surface friction coefficients. In the figure, we can know that the bearing surface friction coefficient has as small effect as thread engagement surface friction coefficient on the transversal stiffness of bolted joints.

(2) Effect of coefficient $\mu_2$ on self-loosening

In order to investigate into the effect of joints’ surface friction coefficient ($\mu_2$) on self-loosening, referring to the simulation of section 3.4, we only modify the parameter $\mu_2$ to 0.05, 0.1, 0.17 and 0.2. Then the comparison simulation of bolted joints with different joints’ surface friction coefficient under transverse vibration is conducted. The curves in the Figure 15 show residual preload change. In the figure, we can know these curves are nearly the same. It suggests that the thread engagement surface friction coefficient has small effect on the transversal stiffness of bolted joints.
can know that the bigger the joints’ surface friction coefficient is, the bigger vertical span is. It suggests that the bigger the joints’ surface friction coefficient is, the bigger transversal stiffness of bolted joints is, the less likely to happen self-loosening is.

**Effect of thread pitch on self-loosening**

In order to investigate into the effect of thread pitch on self-loosening, referring to the simulation of section 3.4, we only modify the parameter $p$ to 1.5 (Fine thread) and 1.75 (Coarse thread). Then the comparison simulation of bolted joints with different pitches under transverse vibration is conducted. The curves in the Figure 17 show residual preload change for different thread pitches. In the figure, we can know that the preload of fine thread loses slower than the coarse thread’s. It suggests that the anti-loosening performance of fine thread is better than coarse thread. The Figure 18 shows shearing load hysteresis curves under different thread pitches. In the figure, we can know that the shearing load hysteresis curve of fine thread has the same vertical span with the coarse thread. It suggests that the thread pitch has small effect on the transversal stiffness of bolted joints.

**Effect of hole clearance on self-loosening**

In order to investigate into the effect of hole clearance on self-loosening, referring to the simulation of section 3.4, we only modify the parameter $d'/2$ to 0.5, 0.75 and 1.25. Then the comparison simulation of bolted joints with different clearance under transverse vibration is conducted. The curves in the Figure 19 show residual preload change for different hole clearance. In the figure, we can know that the bigger the hole clearance is, the faster the preload loses, which proves that the better the assemblage is, the better anti-loosening performance is. The Figure 20 shows shearing load hysteresis curves under different hole clearance. In the figure, we can know that the shearing load hysteresis curve of bigger hole clearance has the smaller vertical span than the smaller ones’. It suggests that the bigger hole clearance has smaller transversal stiffness of bolted joints. At the same time, the difference between three shearing load hysteresis curves is not conspicuous. It suggests that the hole clearance has small effect on the transversal stiffness of bolted joints.

**CONCLUSIONS**

The self-loosening mechanism of bolted joints under
transversal vibration is studied based on FEA. And the transverse vibration amplitude, the initial preload, thread and bearing friction coefficients, the joints’ surface friction coefficient, the thread pitch and the hole clearance on self-loosening is investigated. The results show that:

(1) Both the slippage of thread engagement surface and the slippage of bearing surface can lead to the preload loss of bolted joints under transversal vibration. The complete slippage of thread engagement surface is priority to bearing surface.

(2) The greater the vibration amplitude is, the more likely to happen the self-loosening is.

(3) The greater initial preload is, the smaller percentage of preload loss is, the less likely to happen the self-loosening is.

(4) The greater thread and bearing friction coefficients is, the less likely to happen the self-loosening is. The joints’ surface friction coefficient has small influence on self-relaxation under the same transversal vibration. But it has a big impact on the transversal stiffness of bolted joints.

(5) The self-loosening of bolt with coarse thread is more likely to happen than that with fine thread.

(6) The paper proves that the better the assemblage, the better locking performance of fine thread.

In conclusion, when designing bolted joints’ anti-loosening, we should put how to change the thread engagement surface friction first. We should also consider bearing surface friction. We should give the biggest preload within the strength and increase joints’ surface friction without leakage.

All in all, this paper is of great significance for understanding of fasteners’ self-loosening and designing of bolted joints’ anti-loosening.

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REFERENCE


