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The Best Preload of Bolted Joint Plate for Anti-resonance

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Abstract. Based on the problem of modal frequencies variation of bolted joint plate caused by the variation of bolt preloads, the purpose of this article is to propose a method of finding the best preload of bolted joint plate. Firstly, a modal analysis experimental system of bolted joint plates was set up. Subsequently, the modal frequency test of some bolted joint plates are completed. A method for designing the best preload of bolted joint plate was proposed in the end. Results indicate that the bolt preload has certain influence on modal frequency of bolted joint plate. The process of applying a preload to the bolt is regarded as the tightening of a bolt from loosen state to tighten state. As two loosen bolts are simultaneously tightened into tighten bolts, the modal frequencies is increased with a big magnitude. However, as one of loosen bolt is tightened to tighten bolt, but the other is unchanged, the modal frequencies is increased with a small magnitude. The sensitivity of first four modal frequencies of the jointed plate are different to the bolt preload. Therefore, working environment and working force of jointed plate must be considered in the dynamic design. Based on the experimental result, a best bolt preload design method of bolted joint plate in the dynamic design can be proposed.

1. Introduction
Due to the advantages of higher standardization, convenient to make, simple structure, lower cost and easier to disassemble and assemble, it is widely used in aerospace, vehicle and agricultural equipment. However, with the development of modern dynamic machinery, the force applied to the machinery is becoming to more and more complex. Vibration, shock, variable force and temperature is the inevitable working environment for many machineries. As a results, bolt looseness often occurs. Aiming at the loosening of bolted joints, researchers in the academic and engineering fields have proposed many factors that affect the looseness of bolted joints. For example, preload, temperature, and external loads. Among them, the bolt preload is particularly important for the bolted joints. If the bolt preload is applied too small, the component cannot bear the working force, and slipping will be introduced. This will affect the performance of the machine. But if bolt preload is too big, the bolt may be deformed plastically. Thereby, the strength of bolted joint structures is reduced. It will reduce the working life of the component. Therefore, a reasonable bolt preload not only can play a fastening, anti-slip effect, but also can improve working life of the component. Considering the impact mechanisms of preload on the dynamic characteristics, the study on the vibration, stiffness and strength of bolted joints have been focused by the scholars at home and abroad.

With the development of vibration theory, the measurement method of bolt preload based on vibration characteristics has been paid more and more attention. For the sake of monitoring the preload, Du F et al. proposed a virtual time reversal guided wave method to test the preload of the bolted
L-shaped joint[1]. In order to study the relationship between the bolt preload and the bolt elongation, Jimenez-Pena C et al. gave a proof of the concept of the relationship between bolt elongation and bolt preload based on the DIC method, and proposed a calibration method for the bolt preload-elongation relationship within a given clamping range[2]. Pakdil M et al. studied the effects of preload on the fail response of composite bolted joints with bolt hole clearances[3]. Esmaeili F et al. studied the effects of bolt clamping force on the fatigue life of double-lapped and hybrid-lapped bolt joints. The study revealed the positive effect of clamping force on the fatigue life of simple joints and hybrid joints[4]. Zhao T studied the effect of bolt preload on the bolted joints. It is found that if the fasteners are loosen, the fatigue life may be very short[5]. Liu F carried out random bolt load distribution test based on the single-lapped multi-bolt joints under different parameters. The results shown that the bolt preload and the bolt hole clearance have significant influences on the change of bolt load distribution[6]. Guang Z et al. carried out the influence of bolt preload on the modal frequencies of the bolted joints. It was found that the modal frequency of the bolted joint is increased with the increasing of the bolt preload[7]. Dravid S et al. conducted a research on the tightness of bolted joints by using different washers instead of torsional moments to explore the bolt's resistance to looseness[8]. Zhang M et al. conducted an experiment on the self-loosening behavior of bolted joints caused by thread wear under lateral cyclic load. Results indicated that reasonable preload can reduce the thread wear to improve the stiffness of the joint and enhance the tightening of the bolted joint[9]. Giannopoulos I K et al. studied the effects of preload on the tensile strength of composite plates with bolt hole. Results indicated that the reducing of preload can reduce the stress concentration around hole and increase the tensile and fatigue strength of the structure, and the increasing preload will cause the slippage on the surface of the mating bolt plate[10-11]. Dhote J X et al. used DIC equipment to extract the strain field of the joint surface of the bolted joint plate under lubrication and drying conditions. Chakherlou T N et al. analyzed the influences of preload on the laws of stress distribution around screw hole by finite element method. When the ratio of external load to bolt preload is too small, increasing the preload will shorten fatigue life[12-13]. Griza S et al. discussed the relationship between the bolt length and fatigue strength of bolt joints. It was shown that the increasing of the length of bolts can increase the fatigue strength of bolt joints, but this conclusion does not apply to short bolt joints[14]. Zhai Y et al. analyzed the influence of clearance between bolt and hole as well as the bolt torque on the strain of contact surface of the carbon fiber epoxy resin countersunk head bolt joint. Results shown that the increasing of the clearance will increase the strain of the contact surface and the increasing of the bolt torque is beneficial to alleviate the strain at the joint contact[15]. Benhamena A et al. studied the impact of the preload on the fretting fatigue characteristics of the bolted joint plate[16].

As above mentioned, a lot of researches on the bolt preload problems have been done. But few works were done on the impacts of different bolt preload on modal frequencies of the bolted joint plate. In the actual working process, once the modal frequency of the structure is close to the working frequency, resonance occurs, which is going to lead to lose bolts and unpredictable disasters. Therefore, in a dynamic design of the bolted joint plate, the modal frequency must be considered to avoid resonance during operation. Moreover, the modal frequency is usually related to the preload. Thus, a proper bolt preload helps the system to avoid resonance effectively and is beneficial to the vibration fatigue design.

In this article, the tests on the influences of different preload on the modal frequency of the bolted joint plate are carried out. Based on the influence mechanisms of preload on the modal frequencies, a preload design method of bolted joint plate is proposed. This method can provide optimization method of the bolt preload.

2. Experiment of bolted joint plate

2.1. Test piece

A single-lapped and double bolts joint plate is designed. The geometry and physical map are shown in Figure 1 and Figure 2. The dimensions are as follows: \( L_1 = 242 \text{mm}, \ L_2 = 242 \text{mm}, \ W = 55 \text{mm}, \ t = 5 \text{mm} \) and the bolt hole diameter \( D = 8.8 \text{mm} \). The major diameter of bolt \( d = 8 \text{mm} \). The distance from the center
of the plate hole to the end of the plate $e=24$ mm, and distance between the center of the two holes $c=10$mm. The bolted joint plate is made of SUS304 stainless steel, and the bolt and nut are made of LY12CZ aluminum alloy. The mechanical properties of SUS304 in room temperature are: elastic modulus $E=193$ GPa, Poisson's ratio $\nu=0.3$, material density $\rho=7870$ kg/m$^3$, yield strength $\sigma_s=260$ MPa, ultimate strength $\sigma_b=631$ MPa. The mechanical properties of LY12CZ aluminum in room temperature are: elastic modulus $E=69.5$ GPa, Poisson's ratio $\nu=0.33$, material density $\rho=2770$ kg/m$^3$, yield strength $\sigma_s=400$ MPa, ultimate strength $\sigma_b=443$ MPa.

2.2. Test procedure

In order to simulate a free-free state of the bolted joint plate, the tested specimen is supported by two balloons during the modal test, as shown in Figure 3. The system mainly includes an incentive hammer, a piezoelectric acceleration sensor, a bolted joint plate, a modal analysis system and a dynamic data acquisition as shown in Figure 4. Place the tested bolted joint plate on two light-weight and soft balloons, install an acceleration sensor at a suitable position on the surface of the test specimen, and use a hammer to strike it. The direction of tap of hammer must be consistent with the vertical direction of sticking position of the acceleration sensor. Then, the measured signal is imported into the YMC9800 modal analysis software by using acquisition equipment. The modal frequency response curve is obtained by fast Fourier transform. The vibration mode, damping, and modal frequency of the tested specimen are obtained. The flow chart of the test is shown in Figure 5.
3. Results and discussion

3.1. Preload setting

The bolt preload is limited by the strength of the two bolts and the loading condition of the bolted joint. The bolt preload is usually calculated by

\[ F_0 = \eta \times \sigma_s \times A_s \]  \hspace{1cm} (1)

Where: \( \eta \) is set as 0.5-0.7; \( \sigma_s \) is the yield strength of bolt; \( A_s \) is the cross-sectional area of the bolt in minor diameter.

The torque is usually calculated by

\[ M_i = K \times F_0 \times d \]  \hspace{1cm} (2)

Where: \( K \) is the tightening torque coefficient; \( F_0 \) is the bolt preload; \( d \) is the middle diameter of the bolts; \( K \) is set as 0.1-0.3. The working environment is approximated as a lubricating surface oxidation with \( K=0.2 \) in this article.

Thus, the relationship between the bolt preload \( F_0 \) and torque \( M_i \) is

\[ F_0 = 625 \times M_i \]  \hspace{1cm} (3)

The applied torques can be estimated by the equation (3). The torque applied to the bolt are 1.0 N.m, 1.5N.m, 2.0 N.m, 2.5 N.m, 3.0 N.m, 3.5 N.m, 4.0 N.m, 4.5 N.m, 5.0 N.m. And the corresponding preload are 625N, 937.5 N, 1250 N, 1562.5 N, 1875 N, 2187.5 N, 2500 N, 2812.5 N, 3125N.

3.2. Discussion on Factors Affecting Modal Frequency of Bolted Joint Plates

In order to better describe the relationship between bolt preload and modal frequency, the definition of frequency reduction rate is introduced, which is defined by the following formula.

\[ \tau = \frac{f_i - f_0}{f_0} \times 100\% \]  \hspace{1cm} (4)
Where: $\tau$ is the rate of decline of the modal frequency; $f_0$ is the initial modal frequency of the test piece; $f_i$ is the modal frequency of each stage of the test piece.

In order to describe the effect of different bolt preload, the bolt preload is divided into the bolt preload of the upper bolt and lower bolt, and the ratio of the torsional moment of the upper bolt at each stage and the maximum torsional moment of the upper bolt is described by dimensionless $m$. The definition formula is

$$m = G_i(G_{\text{max}})^{-1}$$  \hspace{1cm} (5)

Where: $G_{\text{max}}$ is maximum torsion moment of upper bolt; $G_i$ is the torsion moment of the upper bolt at each stage of the test piece.

Use the dimensionless $n$ to describe the ratio of the torsion moment of the lower bolt at each stage and the maximum moment of the lower bolt, and define the formula.

$$n = T_i(T_{\text{max}})^{-1}$$  \hspace{1cm} (6)

Where: $T_{\text{max}}$ is the test piece maximum lower end bolt torsion force; $T_i$ is the torsion moment of the lower end bolt at each stage of the test piece.

![Figure 6](image_url)

**Figure 6.** Influence of bolt preload on the first four order modal frequencies.

Figure 6 shows that the modal frequencies varies with the increasing of the preload. The variation law is nonlinear. When the preload of upper and lower bolts are applied simultaneously is compared with the preload of one of two bolts is applied, it is found that the former has a greater influence on the modal frequency of the member. The process of applying the preload to the upper or the lower bolts, it is regarded as the tightening from the "loosen" bolt to the "tighted" bolt. As two "loosen" bolts are tightened to the "tightly" bolt, the modal frequencies is increased and the amplitude is up to 3.3%. As a "loosen" bolt is tightened to “tighten” bolt, but the other is unchanged, the modal frequency is...
increased but the amplitude is only 1.5%. In dynamic design, as the excitation frequency is equal to the modal frequency of the specimen, resonance occurs. In order to avoid the resonance by adjusting the preload of the bolted joint plate to change its natural modal frequency, the modal frequency is far from the excitation frequency to avoid resonance. These bolt preload can make the modal frequency of the test specimen away from the external excitation frequency, which is called the best bolt preload. The frequency variation of each step of the joint plate is also different. The second-order frequency falling rate is up to about 3%, and the fourth-order frequency falling rate is only about 0.4%. This shows that the sensitivity of each order modal frequency to bolt preload is different. Under different orders of the same test piece, the value of the best bolt preload is also different, which indicates that the working environment of the test piece should be considered in the design, anti-resonant best bolt preload design under the actual working condition provides a basis for anti-resonance design.

3.3. The best preload of bolted joint plate

Under the action of dynamic load, the excitation frequency is close to the modal frequency of the structure to lead resonance has been a concern. In order to solve this problem effectively, this paper designs the best bolt preload of the bolted joint plate from the dynamic point of view based on the change of the modal frequency to achieve the anti-resonance purpose.

\[
\begin{align*}
&\text{Determine the range of excitation frequency} \\
&\quad \text{and loading form of the bolted joint plate} \\
&\text{Determine the appropriate vibration mode} \\
&\quad \text{and natural frequency order according to the} \\
&\quad \text{loading form} \\
&\text{Extract the 3D surface map of bolt preload and} \\
&\quad \text{modal frequency of bolted joint plate} \\
&\text{Extract the 2D contour map of the modal} \\
&\quad \text{frequency of the joint plate} \\
&\text{Find the intersection of the range of excitation} \\
&\quad \text{interval and contour line} \\
&\text{Select best bolt preload according to} \\
&\quad \text{actual working conditions}
\end{align*}
\]

Figure 7. The best bolt preload design based on modal frequency.

In order to explain the application of the scheme shown in Figure 7 in detail, the modal frequency analysis of the bolted joint plates are taken as an example. It is assumed that the single-lapped and double bolts joint plate is subjected to a lateral load. The actual working frequency is in the vicinity of the second-order mode. The operation frequency range is set as [285,288] Hz. In the dynamic design, the 3D map of the second-order modal frequency of the component is first extracted, and then the 2D contour map is drawn in the interval corresponding to the operating frequency. As shown in Figure 8, under the action of dynamic load, if the excitation frequency is in the working frequency range of the structural members, resonance is easy to be generated. As the bolt preload of the bolt is too small, the fastening property of the member is not guaranteed. Excessive preload is easy to cause the bolt to be broken, and the bolted joint are crushed, bitten, twisted or broken. In summary, the bolt preload should be reasonably selected based on the working environment.
in which the component is located. Then the maximum bolt preload of the two bolts of the bolted joint plate should be determined, and the actual bolt preload of the two bolts should be converted according to the relationship shown in Figure 8 to determine the best preload for anti-resonant of bolted joint plate. Through this optimization method, a new idea can be provided for the anti-resonant fatigue dynamics design of the bolted joint.

4. Conclusions
A single-lapped and double bolted joint plate was chose as the object, the influence of the preload on the modal frequency of the bolted joint plate is studied. A design method of the best preload for anti-resonant of bolted joint plate is proposed. The main conclusions are as follows:

- The preload has a certain influence on the modal frequency of the joint plate, and the preload applied to two bolts has a greater influence on modal frequencies. This property can be utilized to change the magnitude of the bolt preload so that the modal frequency is kept away from the excitation frequency to achieve anti-resonance purposes.
- The variation of modal frequency at each step of the bolted joint plate is different under the same bolt preload, which shows that the sensitivity of each mode modal frequency to the bolt preload is different. Under different orders of the same test piece, the value of the best preload of the bolt is also different, which indicates that the working environment of the test piece should be considered in the design.
- The design of the best preload of the bolted joint plate should be related to the actual working conditions. According to the actual working condition frequency, find the best preload of the bolt, and reasonably avoid the external excitation frequency to achieve anti-resonance purpose.

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