Research on control method of pre-tightening load based on moment method and strain gauge method

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Abstract. The most commonly used method to control the pre-tightening load of the bolt is torque measurement method and strain gauge method. The torque measurement method is convenient to use but usually leads to large control error, even up to ±25%. The strain gauge method is able to provide adequate control accuracy but is not convenient to use and costs are high. This study attempts to combine the advantages of the torque measurement method and the strain gauge method to form a kind of bolt pre-tightening force control method which is convenient for engineering application.

1. Introduction
The control methods of pre tightening force in engineering include torque measurement method, control angle method, bolt elongation control method, strain gauge method and so on. The most commonly used is torque measurement method, which controls the axial pre tightening force through the torque wrench. The method is easy to use and costs are low, but usually leads to low control accuracy, the error is generally considered to be ±25%. The strain gauge method is a method of controlling the tension of a bolt by applying a strain gage to the threaded portion of the bolt, which can improve the precision of measurement, but the method is not convenient to use and cost is high. According to the analysis, it is concluded that the cause of the error in the measurement based on the torque is that it is not easy to obtain the equivalent friction coefficient accurately. In this paper, the strain gauge method is used to obtain the exact equivalent friction coefficient of specified contact condition, through which the high accuracy control of bolt pre-tightening force can be realized with low cost. The experimental results show that the above method can be used to control the precision error of bolt pre tightening force control based on the torque measurement method within 5%, which has a great value in engineering application.

2. Torque Measurement Method
The relationship between the bolt preload T_bolt and the torque applied to the torque wrench M_{b Bolt} is the following:

\[ M_{b Bolt} = K_{pl} T_{b Bolt} D \]  \hspace{1cm} (1)

K_{pl} is the tightening coefficient, usually obtained by empirical formula as follow:
\[ K_{pl} = \left( 0.161p_{\text{bolt}} + 0.585\mu_G D_2 + 0.25\mu_K D_{km} \right)/D \] (2)

\( p_{\text{bolt}} \) is the pitch of the bolt, \( \mu_G \) is the thread friction coefficient, \( \mu_K \) is the friction coefficient of the fastener head or nut support surface, \( D_2 \) is the average diameter of the thread flank, and \( D_{km} \) is the effective diameter of the friction torque of the fastener head. Because the spring gasket is installed between the head of the fastening bolt and the fitting surface, the value of the \( D_{km} \) is related to the size of the spring gasket. The average diameter of thread flank \( D_2 \) can be obtained by equation (3) and equation (4).

\[ D_2 = \frac{D}{2} - \frac{3}{8}H \] (3)

\[ H = \frac{\sqrt{3}}{2} P_{\text{bolt}} \] (4)

Therefore, the bolt pre tightening force can be expressed as follow:

\[ T_{\text{bolt}} = \frac{M_{\text{bolt}}}{\left( 0.161p_{\text{bolt}} + 0.585\mu_G D_2 + 0.25\mu_K D_{km} \right)} \] (5)

For most type of bolts, the parameters in the above formula can be obtained through the engineering manual, however some of the parameter values are usually given over a wide range, which makes it difficult to determine the exact relationship between the bolt preload and the tightening torque. Take 12.9 M8 screws as an example, the parameters are shown in table 1, the geometric parameters of the equation (5) can be obtained by equation (3) and equation (4) or the basic geometric parameters of the bolt except the values of \( \mu_K \) and \( \mu_G \), obtained are provided in the form of range from engineering manual. The range of \( \mu_G \) is 0.1–0.18, and the range of \( \mu_K \) is 0.16–0.22, which extends the error to \( \pm 25\% \). Therefore, it is very difficult to obtain more accurate tightening torque base on the engineering parameters.

| Parameter name                             | Symbol | Value  |
|--------------------------------------------|--------|--------|
| Nominal thread diameter [mm]               | \( D \) | 8      |
| Pitch of the Bolt [mm]                     | \( P_{\text{bolt}} \) | 1.25   |
| Thread depth [mm]                          | \( H \) | 1.0825 |
| Average diameter of the thread flank [mm]  | \( D_2 \) | 7.188  |
| Effective diameter of the friction torque [mm] | \( D_{km} \) | 10.2   |
| Diameter of the bolt without thread        | \( D_3 \) | 7.8    |
| Thread friction coefficient [mm]           | \( \mu_G \) | 0.1–0.18|
| Friction coefficient of the fastener head or nut support surface | \( \mu_K \) | 0.16–0.22|

In order to improve the control precision of bolt pre tightening force, strain gauge method is used to obtain the exact values of \( \mu_G \) and \( \mu_K \) in the specified contact surface roughness condition.

### 3. Strain Gauge Method
The basic principle of the strain gauge method is to stick the resistance strain gauges along the screw axial direction in the bolt non threaded part. The tension force of the screw is controlled by controlling
the axial strain of the screw rod, so as to achieve the purpose of controlling the pre-tightening force of the bolt.

Assuming $\mu G = \mu K = \mu_{tot}$, where $\mu_{tot}$ is the equivalent friction coefficient, the equation (5) can be simplified as follow:

$$T_{b Bolt} = \frac{M_{b Bolt}}{\left(0.161p_{b Bolt} + \mu_{tot} \left(0.585D_2 + 0.5D_{km}\right)\right)}$$ \quad (6)

The equivalent friction coefficient $\mu_{tot}$ can be obtained by experiment based on Strain Gauge Method, which would greatly improve the accuracy of the expression between the tightening torque and the bolt pre tightening force.

The equivalent friction coefficient $\mu_{tot}$ can be expressed as follow:

$$\mu_{tot} = \frac{1}{\left(0.585D_2 + 0.25D_{km}\right)} \left(\frac{4M_{b Bolt}}{E\varepsilon D_2^3} - 0.161p_{b Bolt}\right)$$ \quad (7)

4. **Experiment for Equivalent Friction Coefficient**

In this experiment, the torque value $M_{b Bolt}$ can be measured by torque wrench, which is used to load the bolts. The corresponding strain $\varepsilon$ is obtained by strain measuring instrument. Therefore, the relationship between preload $T_{b Bolt}$ and tightening torque $M_{b Bolt}$ could be expressed as the function of strain $\varepsilon$, which is expressed as follow:

$$\mu_{tot} = \frac{4}{48\pi \left(0.585D_2 + 0.25D_{km}\right)ED_2^3 \sum_{i=1}^{8} \sum_{j=1}^{6} \frac{M_{b Bolt}}{\varepsilon}}$$ \quad (8)

The experiment module including 2 pre tightening surfaces and 8 M8 bolts, is shown in Figure 1, in which 4 bolts are applied to each fastening surface. The 8 bolts are numbered as shown in figure 1, the bolts L1~L4 are used for fastening surface L, the bolts R1~R4 are used for fastening surface R. Before experiment, tighten and loosen the bolts and nuts repeatedly, in order to make the friction between the bolt and the screw stable.

**Figure 1.** Sketch of installation position of strain gauge

The strain gauges are attached to the no threaded region of each pre tightening bolts. The strain values during the experiment were measured by SDY2102 dynamic and static strain measuring instrument. During the test, the torque wrench were adjusted to 5 Nm, 5.5 Nm, 6.0 Nm, 6.5 Nm, 7.0
Nm, 7.5 Nm, the corresponding strain are read from static strain measuring instrument, the results shown in figure 2. R1~R4 and L1~L4 are the numbers of the experimental bolts, ε is the strain measurement value of each bolt. Bring the test values of strain ε and the corresponding tightening torque M_{bolt} into equation (8), the corresponding average equivalent friction coefficient μ_{tot} is obtained by calculation. In this contact condition, μ_{tot} = 0.181.

![Figure 2. Relationship between tightening torque M_{bolt} and strain](image)

**Table 2.** Parameter of 12.9 M8 standard metric thread

| T_{bolt}[MPa] | M_{bolt}[Nm] |
|---------------|--------------|
| 11.8          | 3.28         |
| 13            | 3.62         |
| 14            | 3.90         |
| 15            | 4.17         |
| 16            | 4.45         |
| 17            | 4.73         |

**5. Summary**

In this paper, the reason of the error of bolt pre-tightening force control based on moment measurement is analysed and an effective method to improve the control precision of the pre-tightening force is presented, which can be summarized as follows:

- The analysis results show that the main reason is that it cannot determine the equivalent friction coefficient of the contact surface.
- In order to realize the high precision control of bolt pre-tightening force, the accurate equivalent friction coefficient must be obtained.
• The strain gauge method is an effective method to obtain the effective friction coefficient under the specified contact condition, which can greatly improve the accuracy of the torque measurement method.
• The experimental results show that the above method can be used to control the precision error of bolt pre-tightening force control based on the torque measurement method within 5%, which has a great value in engineering application.

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