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Research on Tightening Technique of Turbopump Shaft System Based on Elongation Method

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Abstract: As the key role of turbopumps in spacecraft engines becomes increasingly prominent, accurate control of their shaft system tightening force is significant to ensure the stable operation of the engines. Although the traditional torque method has been widely used in the tightening of threaded connections, the tightening force is easily affected by the quality of threads and lubrication conditions, and the accuracy and consistency are poor. This paper investigates the elongation method based on the turbopump shaft system tightening force control method. It is applied to the turbopump rotor assembly scenario for the first time. The performance of the torque and elongation methods under different thread qualities and lubrication conditions is compared through experiments. The experimental results show that the elongation method has significant advantages in improving the consistency and accuracy of the tightening force, especially under poor thread fit or different lubrication conditions.

Keywords: turbopump; elongation method; tightening force control

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1. Introduction

With the rapid development of the aerospace industry, the status of aerospace is increasing. The safe launch of rockets is closely connected with the smooth operation of the engine [1], and the turbopump [2], as the core component of the space engine, is key to ensuring regular operation of the engine [3]. Bolt tightening [4] is one of the most widely used processes in the engine assembly.

During the test run for a specific rocket engine, abnormal vibrations and noise were observed, which experimental analysis revealed to be associated with insufficient clamping force. Studies [5,6] have shown that appropriate clamping force is crucial for ensuring the stability of turbine pump shafts, as it enhances rotational stability and reduces vibrations, thereby mitigating abnormal noise during turbine pump operation.

The tightening force on the turbopump rotor is crucial to the regular operation of the turbopump, and controlling the axial tightening force is an important measure to improve the quality of the connection of the rear aerospace structure [7], and the appropriate tightening force can ensure that the turbopump maintains sufficient mechanical rigidity during high-speed operation, preventing vibration, air leakage, and failure caused by looseness or excessive clearance. If the tightening force is insufficient, the turbopump may produce abnormal noises, exhibit reduced power output, or operate with diminished efficiency. At the same time, a tightening force that is too large may lead to excessive stress and fatigue damage to the rotor or other parts, thus shortening the service life of the equipment; therefore, precise control of the tightening force [8] is a key factor in ensuring the turbopump's stable and efficient operation.

Turbopump assembly using the torque method of tightening the shaft nut proceeded as follows: In the first installation of the turbine pump, the operator replaced a section of the rotor shaft system's parts with a pressure sensor in the bushing. Then, through the use of automatic tightening equipment, the shaft nut was tightened to 150 N·m as a pre-tightening step. This was subsequently uninstalled and then reloaded again to 120 N·m while simultaneously monitoring the tightening force and the angle of rotation. After this initial tightening, the operator disassembled the shaft system parts and replaced the pressure sensor with the original bushing, followed by the second tightening. The second tightening also consisted of a pre-tightening to 150 N·m, followed by unloading and reloading to 120 N·m. These two tightening operations were performed to ensure the stability and consistency of the threaded connection, ultimately resulting in a stable turbopump operation.

Figure 1 shows the turbopump rotor shaft system structure, which includes the rotor, multi-section sleeve, shaft nut, flywheel, and pressure sensor. The tightening force on the turbine pump rotor is provided by threading the shaft nut to the top of the rotor, and the shaft nut is tightened by tightening the hexagonal sleeve.

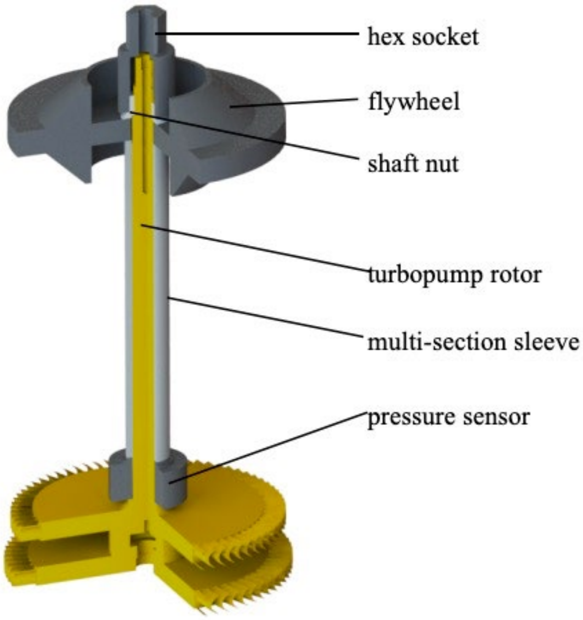

Figure 1. Turbopump shaft system structure.

Li et al. [9] detected the axial bolt tightening force by measuring the luminescence intensity of SrAl2O4:Eu (SAOE) thin films. The SAOE membrane was coated on the washer, and the luminous area was experimentally determined to be proportional to the square of the tightening force, which realized the real-time control of the thread tightening force. The polymer film cannot be incorporated into the shaft components, nor is it convenient to detect its luminance; therefore, this method is not applicable. Guofang Jin et al. [10] proposed and developed a set of split connecting rod screw elongation digital measuring instruments, using inductive displacement sensors to achieve the displacement measurement of the connecting rod screw on the automotive internal combustion engine, and developed a digital inspection system with a measurement error of less than 10 µm. The structure and precision requirements of this equipment are not suitable for this system. Miao Rusong et al. showed that it is possible to calculate the axial compression of bolts based on the principle of acoustic elasticity of the ultrasonic measurement method, the detection of the time of the incident wave and the reflected wave [11]. The turbine pump shaft system features a compact structure with numerous components, making it impossible to use ultrasonic sensors; therefore, this method is difficult to apply. Jang S et al. designed an in situ bolt preload monitoring system based on a Linear Variable Differential Transformer (LVDT) [12] to estimate the bolt preload of a truck wheel assembly by detecting the distance between the end face of the nut and the bolt. Each of these methods has its advantages, but none of them applies to this structure. Since this method requires additional components to be attached to the nut surface of the shaft system, and the turbine pump shaft structure cannot accommodate such components, this method is also not applicable.

In summary, with the continuous development of the thread-tightening process, the precision of controlling the thread-tightening force is getting higher and higher. In order to ensure the regular operation and reliability of the turbopump, the accurate tightening of the nut according to the assembly process and the precise control of the size of the tightening force applied to the turbopump rotor are the keys to improving the stability of the system operation [13]. To address the applicability, stability, and practical operability of turbine pump shaft systems under complex working conditions, further systematic research and validation are required. Therefore, this study focuses on the turbine pump shaft system and systematically explores the clamping force control method based on elongation. Through experimental and theoretical analysis, the study aims to validate the linear relationship and control accuracy of the method, providing theoretical support and practical reference for high-reliability assembly processes.

2. Deficiencies

The relationship between bolt tightening force and torque [14,15] is as follows: the factors affecting the size of the bolt tightening force are mainly thread friction, thread rise angle, and friction at the end of the bolt.

$$T = KdF = \left(\frac{P}{2\pi d} + \frac{\mu_{th} r_{th}}{d\cos\beta} + \frac{\mu_b r_b}{d}\right) dF \tag{1}$$

where T is the tightening torque (N·m), K is the torque coefficient, d is the nominal diameter (mm), F is the tightening force (N), P is the pitch (mm), β is the tooth side angle (°), μ_{th} is the thread equivalent friction coefficient, rth is the thread equivalent friction radius (mm), μ_b is the end face equivalent friction coefficient, and r_b is the end face equivalent friction radius (mm).

When tightening through a torque spanner, torque and tightening force are linearly related; however, the torque-to-tightening force ratio is affected by various factors, such as thread quality and lubrication. These factors cause significant measurement errors during tightening, and the tightening force error can be up to 25%. Such a high error rate makes the torque method perform poorly when high precision is required, especially in aerospace, automotive, and large-scale machinery manufacturing, where bolt-tightening accuracy is strictly required.

The original assembly process used the torque method. It involved two tightenings, whereby the tightening force of the shaft system was controlled by setting the tightening tool to a specific torque value. In the tightening process, the tightening torque that can be converted into tightening force is about 10%. The rest of the tightening torque is used to overcome the friction, of which the friction on the support surface is about 50% and the friction between the threads is about 40% [16]. Still, due to the fluctuation of the torque coefficient of the bolts, the dispersion of the conversion into tightening force is relatively large. The accuracy of the tightening force is low. There was no pressure sensor in the second tightening process. The size of the actual tightening force was not known. The thread quality, fit, and lubrication might change, resulting in a change in the tightening force. In the actual tightening process, occasionally, the tightening force on the rotor during the second tightening was less than the set value. The tightening force on the rotor was too large a deviation from the set value, which may have affected the operation of the turbine pump.

3. Principle of the Displacement Method

Based on the above defects, the turbopump shaft tightening force detection method needs improvement. Currently, there are two commonly used detection methods for screw bolt tightening force: one is to use strain gauges [17], installing strain gauges to the axial position of the bolt and using Hooke's law to measure the clamping force; however, based on the structure of the turbopump shaft system, this method is not applicable. The second is to use ultrasonic measurement [18], installing an ultrasonic generator at one end of the bolt and calculating the path taken by the ultrasonic wave during this time by accurately measuring the time it takes for the reflected wave to return from the other end and converting the resulting clamping force from this distance. This method is not applicable because the turbopump's shaft system comprises numerous complex components, making it impossible for the ultrasonic sensor to obtain valid measurements.

Neither of the above two groups of methods applies to this structure. This paper proposes using a contact displacement sensor to measure the rotor elongation and determine the axial tightening force by dividing the turbopump rotor displacement by the elongation per unit of tightening force. It applies this method to turbopump rotor assembly for the first time. By measuring the elongation of the bolt, the tightening force applied to the bolt can be determined. Due to the limited clearance exposed at the upper end of the turbopump rotor, an indirect measurement of rotor elongation can be achieved by connecting a threaded rod. This approach is thus suitable for such a structural configuration. Based on the German VDI2230 specification [19], the relationship between tightening force and elongation is as follows:

$$F = \Delta l / \delta_s \tag{2}$$

where F is the tightening force (N) applied to the rotor, Δl is the rotor elongation (mm), and $\delta_s$is the bolt elongation per unit tightening force.

$$\delta_s = \frac{3.6}{E_s \pi d} + \frac{4 l_{sh}}{E_s \pi d_{sh}^2} + \frac{4 l_{ft}}{E_s \pi d_3^2} \tag{3}$$

where E_s is the modulus of elasticity of the bolt material (GPa), d is the outer diameter of the bolt thread (mm), l_{sh} is the length of the bolt light bar part (mm), d_{sh} is the diameter of the bolt light bar part (mm), l_{ft} is the length of the threaded non-screwed part (mm), and d_3 is the inner diameter of the thread (mm). It can be seen that the elongation method of tightening force control accuracy is only related to the geometry and material properties of the bolt and has nothing to do with the quality of the thread, lubrication status, and other factors. The elongation method indirectly measures the tightening force's size by measuring the threaded parts' axial elongation in the tightening process. The accuracy of the tightening force control is higher. However, the measurement process is complicated, and the bolt displacement elongation reaches the micrometer level, a higher requirement for the tightening system and the measuring device. Compared with the system stiffness of the threaded connection in the torque method, the stiffness of the bolt is easier to obtain and less affected by other conditions. The bolt tightening force is obtained with higher accuracy [20] by measuring the elongation displacement accurately. Therefore, the elongation method is suitable for important threaded connections.

Figure 2 shows the elongation method of measurement principle: bracket one end is fixed at the bottom of the turbopump rotor, with the other end installing a contact displacement sensor contact turbopump rotor top. When the torque is applied to the shaft nut, the turbopump rotor elongation drives the rod to move. The difference between the displacement sensor signals is the size of the rotor displacement.

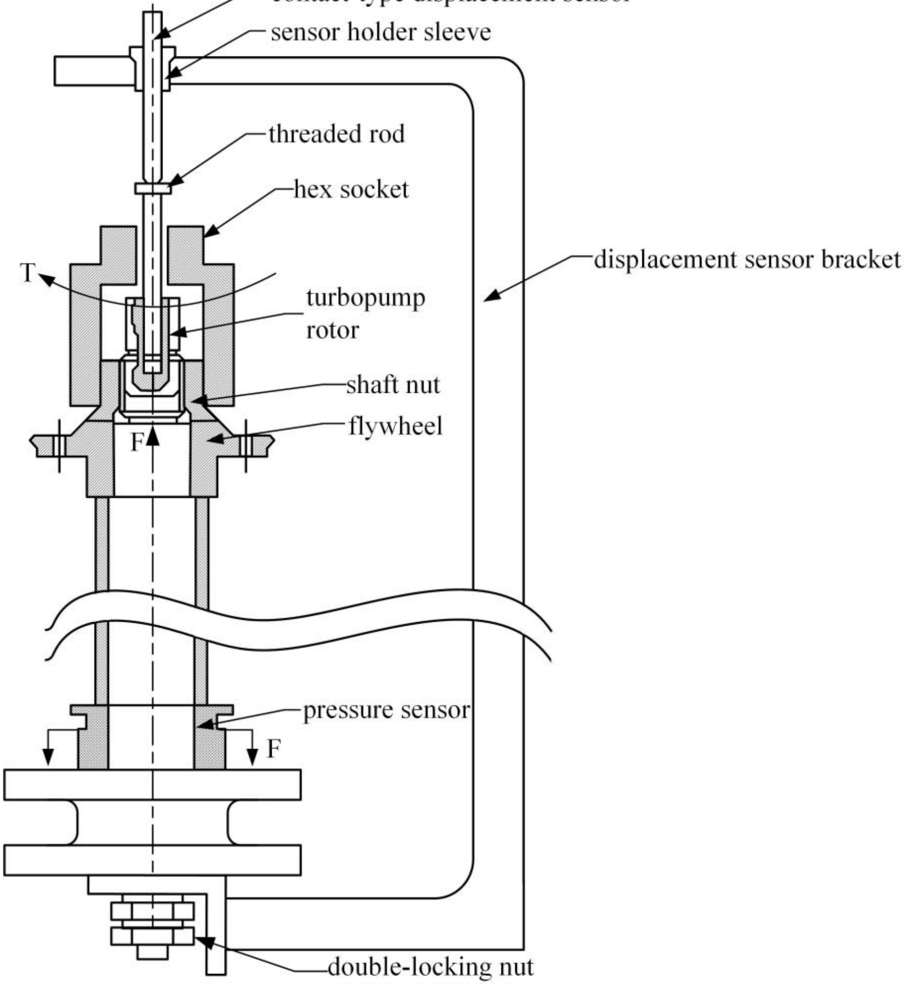

Figure 2. Principle of the displacement measurement method.

Based on this principle, an assembly procedure employing the displacement method presented in Table 1 was proposed. Before implementing the elongation-based assembly approach, it is necessary to subject the rotor to an additional load–pressure test to determine its stiffness.

Table 1. Displacement tightening process.

	Tightening Process
Step 1	stiffness of the same batch of rotors obtained by press test;
Step 2	the displacement x μm required for tightening is calculated by Equation (2)
Step 3: first tightening	pre-tightened 150 N·m; unloaded; control the tightening torque to 10 N·m; controlled rotor elongation to x μm
Step 4	verify that the pressure sensor value does not deviate from the set value
Step 5	replacement of the pressure sensor with a bushing of the same length
Step 6: second tightening	pre-tightened 150 N·m; unloaded; control the tightening torque to 10 N·m; controlled rotor elongation to x μm

During the initial tightening phase, slight vibrations occur as the nut first engages with the rotor. Due to the micron-level precision of the displacement sensor, these vibrations can cause data fluctuations during measurement. To mitigate the effects of such vibrations when using the elongation method for tightening, the tightening torque is first controlled to reach 10 N·m before recording displacement sensor data. This ensures that the relationship between bolt elongation and pre-tightening force reaches the linear phase, which is then used as the zero point to control elongation to the specified value.

4. Experimental Section

In order to investigate the impact of the torque and elongation methods on the axial tightening force, considering varying thread conditions and lubrication scenarios, multiple tightening tests were conducted using several turbopump rotors and shaft nuts.

The experimental environment is shown in Figure 3, and the hexagonal socket is tightened by an electric spanner to drive the shaft nut tightening. The tightening process is shown in Table 2.

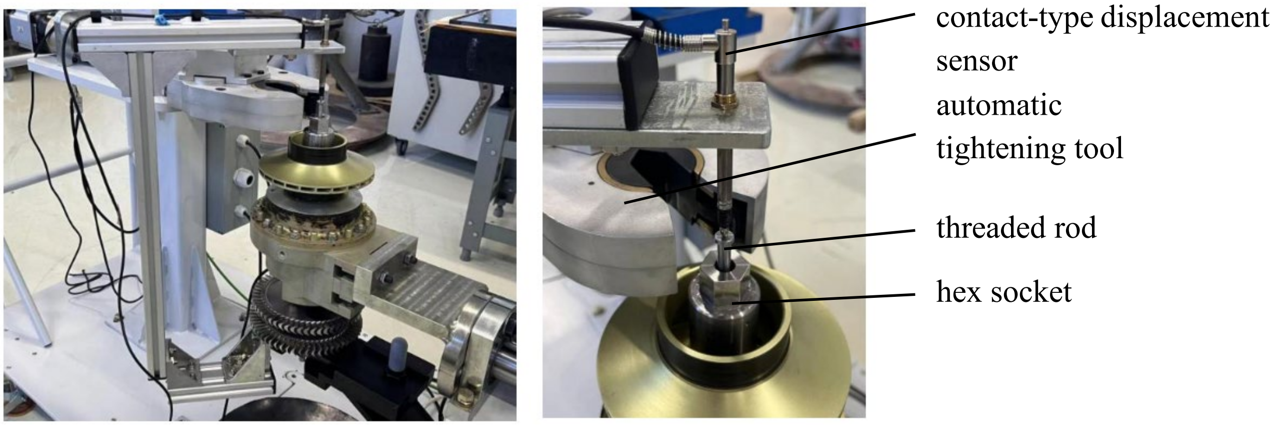

Figure 3. Tightening experiment environment.

Table 2. Tightening process.

Control Methods	Tightening Process
torque method	pre-tightened to 150 N·m; unloaded; rotor torque is controlled to reach 120 N·m
elongation method	pre-tightened to 150 N·m; unloaded; rotor elongation is controlled to reach 75 μm

4.1. Experimental Equipment

Torque was applied using an electric tightening wrench, as illustrated in Figure 4. The wrench primarily consists of a power source, a reduction and transmission mechanism, a dynamic torque sensor, and an open tightening head. The wrench is powered by a servo motor, with an initial reduction in speed and an increase in torque achieved via a reducer. The dynamic torque sensor measures the tightening torque in real-time, and the torque is redirected through a pair of bevel gears before being output by an open-type straight gear module.

Figure 4. Electric tightening wrench.

The system includes four types of sensors—displacement, dynamic torque, static torque, and pressure sensors—as detailed in the table below. The system includes four types of sensors: displacement, dynamic torque, static torque, and pressure sensors, with their parameters detailed in Table 3. The displacement sensor is used to detect rotor elongation, the dynamic torque sensor measures tightening torque in real-time, the static torque sensor calibrates the dynamic torque sensor, and the pressure sensor detects the clamping force applied to the rotor. The primary external factor affecting the experiment is potential external vibrations or impacts on the experimental equipment during measurement, which could cause slight deviations in the displacement sensor or the measured object, leading to measurement errors. To ensure accurate data, all experiments were conducted in a temperature-controlled environment (20 ± 2 °C), and no external vibrations or impacts occurred during the tightening process.

Table 3. Sensor model and parameters.

Type	Model	Range	Accuracy
Displacement Sensor	DP-10VA (Shensi)	10 mm	1 µm
Static Torque Sensor	SBT811A (Spator)	100 N·m	±0.1% FS
Dynamic Torque Sensor	Zhongnuo	250 N·m	±0.1% FS
Pressure Sensor	JHBM-4 (Zhongwan)	50,000 N	±0.1% FS

4.2. Experimental Study of the Relationship Between Elongation and Tightening Force

Multiple tightening experiments are carried out through the elongation method. Figure 5 shows the curve of a tightening experiment; the elongation and the tightening force are linear, and the goodness of fit R^2 is 0.99741. The goodness of fit of multiple tightening experiments is greater than 0.9955, indicating that the elongation and the tightening force are linear, which means that the elongation of the rotor of the turbine pump in the process of tightening the system can control the axial tightening force.

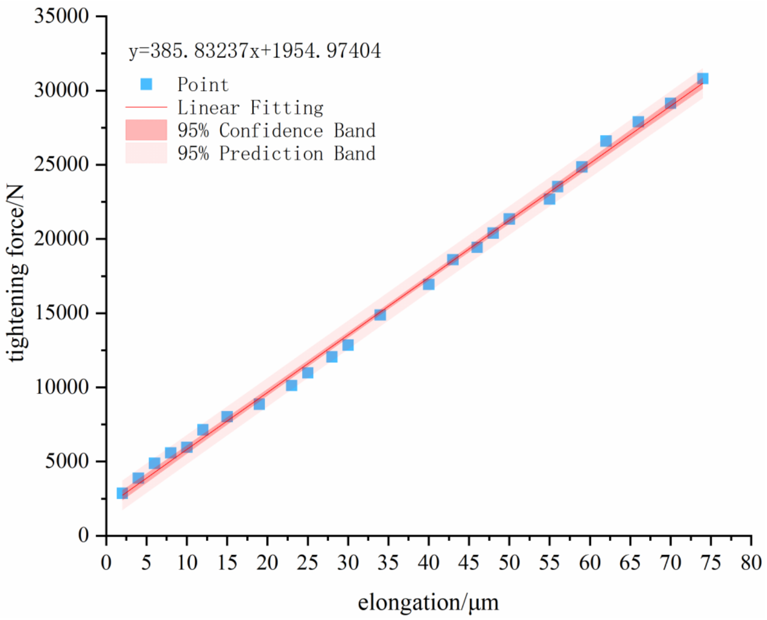

Figure 5. Compression force–elongation relationship curve.

Figure 5 illustrates the fitted curve along with its 95% confidence and prediction bands. The fitted curve represents the linear relationship between elongation and clamping force. The confidence band reflects the reliability of the mean estimates from the fitted curve, whereas the prediction band indicates the model's ability to predict the outcome of individual experiments. Based on multiple experimental analyses, the 95% confidence band of the fitted curve is relatively narrow, and the prediction band also maintains a reasonable distribution, further demonstrating that the linear relationship between elongation and clamping force is quite pronounced under the given experimental conditions.

4.3. Comparative Analysis of Tightening Quality Between Elongation Method and Torque Method

In order to compare and analyze the tightening effect of the two tightening control methods, four rotors and nine shaft nuts were tightened using the elongation method and the torque method, respectively, and the tightening force after tightening was measured.

According to the experimental data, the distribution of the tightening force of different tightening control methods is shown in Figure 6. The analysis of compressive force distribution under repeated tightening shows that, when using the torque method, the average tightening compressive force was 29,977.1 N with a standard deviation of 1798.1 N. In contrast, when using the elongation method, the average tightening compressive force was 29,747.4 N with a standard deviation of 884.2 N.

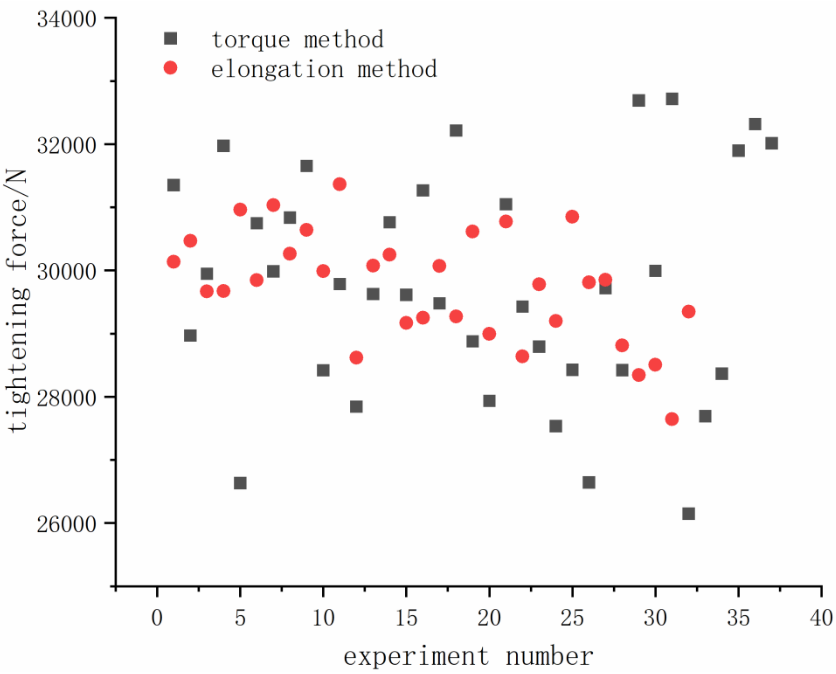

Figure 6. Distribution of compression force of different tightening methods.

Under such process conditions, the elongation method of tightening, the value of the compressive force, is closer to the set value than the torque method. Under such process conditions, the tightening force value of the elongation method is closer to the set value than that of the torque method, and the dispersion degree of the tightening force is also lower, so the elongation method has higher tightening accuracy than the torque method.

Perform a Jarque–Bera test on the experimental data:

$$JB = \frac{n}{6}\left(S^2 + \frac{(K-3)^2}{4}\right) \tag{4}$$

Here, n is the sample size; S is the skewness, which measures the symmetry of the data distribution; and K is the kurtosis, which measures the "peakedness" of the data distribution.

$$S = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^3}{\left(\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2\right)^{3/2}} \tag{5}$$

$$K = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^4}{\left(\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2\right)^2} \tag{6}$$

In these expressions, x_i is the i-th sample value, $\bar{x}$ is the sample mean, and n is the sample size. The results of the calculation are shown in the Table 4.

Table 4. Normality test.

	Sample Size	S	K	JB	p
torque method	37	−0.120	2.11	1.297	0.522
elongation method	32	−0.283	2.53	0.721	0.697

Neither of the two datasets showed statistical significance ($p > 0.05$), indicating acceptance of the null hypothesis (i.e., that the data follow a normal distribution). Accordingly, both sets of experimental data exhibit normality and are therefore considered valid.

4.4. Experimental Study of the Effect of Thread Condition on Tightening Force of the Turbopump Shaft System

In order to investigate the effect of the torque and elongation methods on axial tightening force under different thread conditions, the experimental subjects were divided into two groups, A and B, as shown in Table 5. Two consecutive tightening experiments were conducted for each group using the torque method for group A and the elongation method for group B. This procedure was repeated 5 times. Before each tightening, the nuts were disassembled and coated with a specified amount of grease.

Table 5. Comparative analysis of tightening quality experimental process.

Experimental Group	Nut Number	Thread Quality
A	#1, #2, #3	excellent thread quality and good fit
B	#4, #5, #6	partial thread damage and poor fit

The experimental results are shown in Figure 7. When using the torque method, the tightening force in experiment ② decreased by about 10–20% compared with that in ①, and the tightening force varied greatly due to the difference in the quality of the threads. In experiment ②, the thread quality is poorer, and the fluctuation of the friction coefficient during the two tightening processes leads to a more unstable tightening force, and the deviation of the tightening force between two consecutive tightening of the same shaft nut reaches 9–15%.

When the elongation method is used, the tightening force of experiments ③ and ④ can maintain high consistency, and the deviation of tightening force between two consecutive tightenings is below 6%. Even in the case of poor thread quality, the elongation method controls the tightening force by directly measuring the axial displacement of the threads, which reduces the uncertainty caused by the fluctuation of the friction coefficient.

If the torque method is used in the formal assembly process, the threads may be damaged before the second tightening due to tightening torques of up to 150 N·m, resulting in insufficient tightening force and accidents.

This experimental result reflects the advantages of the elongation method. The thread quality has a greater influence on the torque method, which may lead to unstable tightening force and reduced tightening accuracy. In contrast, the elongation method ensures the consistency of the tightening force by directly measuring the axial elongation.

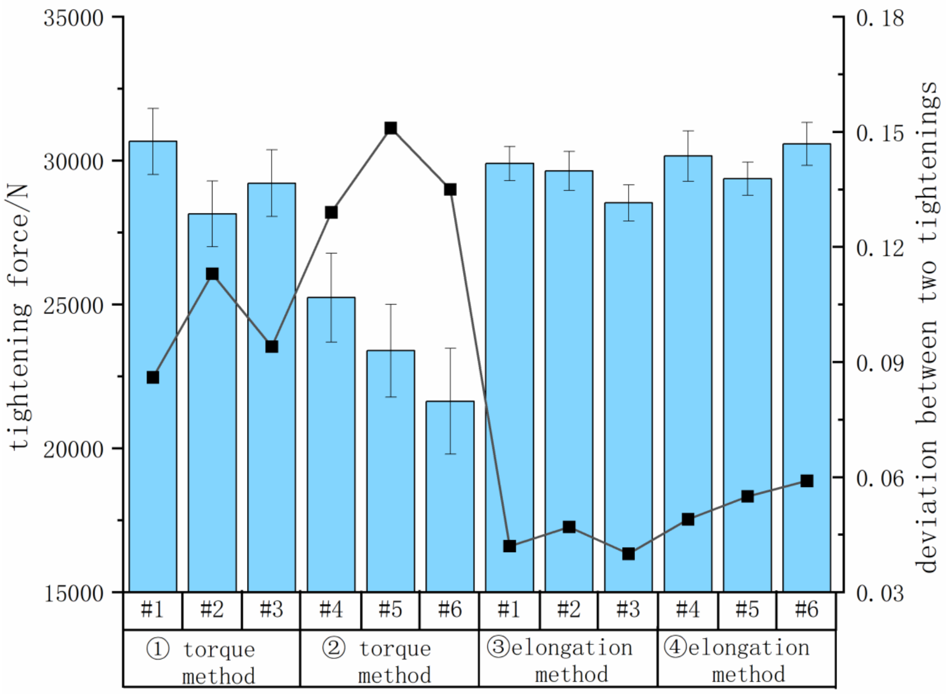

Figure 7. Distribution of tightening force for different thread conditions.

4.5. Influence of Lubrication on the Compression Force of the Turbo Pump Shaft System

In order to investigate the effect of torque and elongation methods on axial tightening force under different lubrication conditions, a rotor with three axial nuts (No. #1, #2, #3) was selected for tightening experiments under different lubrication conditions.

The lubrication conditions were divided into half-lubrication, normal lubrication, and over-lubrication. Normal lubrication was to apply grease with a volume of 0.5 cm^3 uniformly on the threaded surface and end face of the rotor, half-lubrication was to apply grease uniformly with a volume of 0.25 cm^3, and over-lubrication was to apply grease uniformly with a volume of 0.75 cm^3.

The experiment was repeated five times for each lubrication condition, with grease being cleaned and reapplied before each tightening. The results are shown in Figure 8.

When using the torque method, lubrication conditions significantly affect the tightening force. Particularly in the case of semi-lubrication, the friction between the threads decreases, leading to an increase in the tightening force for the same torque, which is approximately 12–15 percent higher in the normal lubrication case than in the semi-lubrication case. This difference is mainly attributed to a change in the coefficient of friction, where a change in lubrication conditions leads to a change in friction, affecting the final effect of the tightening force. When the torque method is used in the actual tightening process, the amount of grease applied by the operator before the second tightening is changed, resulting in a change in the lubrication conditions and a change in the tightening force of the shaft system. In severe cases, it may even affect the regular operation of the turbine pump.

In contrast, when using the elongation method, the difference in tightening force under different lubrication conditions is smaller. This is because the elongation method controls the tightening force by measuring the actual axial elongation of the thread. The effect of the lubrication conditions on the friction is effectively suppressed, and the stability of the tightening force is significantly improved.

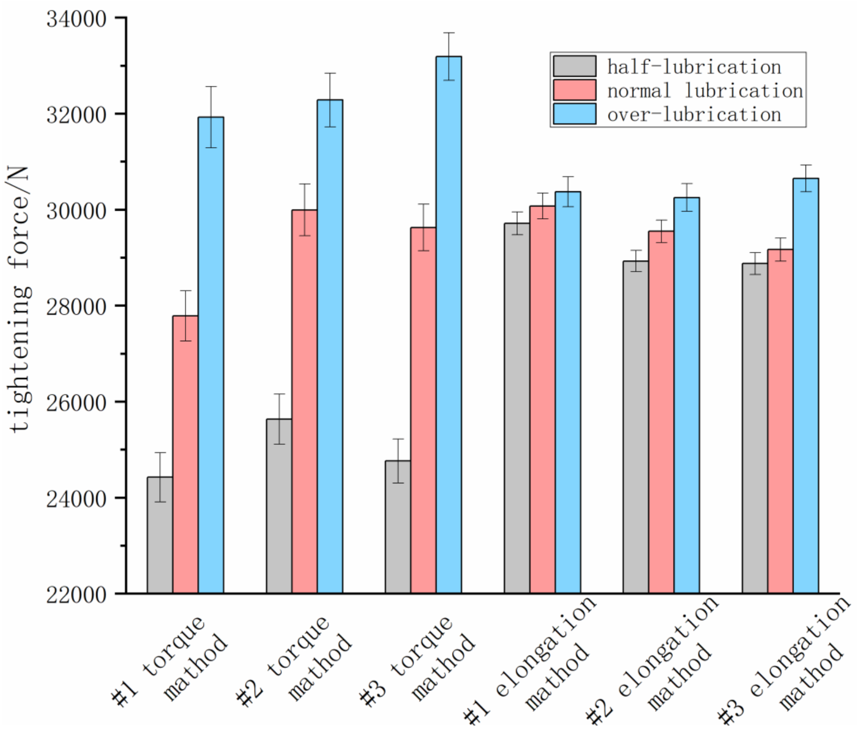

Figure 8. The magnitude of tightening force under different lubrication conditions.

5. Discussion

Despite the significant advantages of the displacement method in controlling clamping forces for turbopump shaft assemblies, certain limitations remain in practical applications. Compared with the conventional torque method, the displacement method requires additional measurement devices and operational procedures—for instance, the installation and calibration of displacement sensors. These complexities not only increase costs but also impose higher training requirements on technical personnel, potentially reducing industrial production efficiency. Furthermore, displacement sensors necessitate sufficient installation space and require high precision in their contact with the measured surface. In scenarios where space is cramped or the geometries are complex, sensor misalignment or installation challenges may arise, thereby affecting measurement accuracy.

In response to these limitations, several improvement measures can be considered:

(1) Modular and Easy-to-Install Design: By developing more modular and compact sensor mounts, the complexity of sensor installation and calibration can be reduced. Improved designs can also lower the training requirements and workload for operators.

(2) Automated Displacement Measurement Systems: The development of intelligent, automated displacement measurement equipment can minimize errors introduced by human operations while enhancing efficiency and measurement reliability in industrial settings.

(3) Adaptability in Confined Spaces: In constrained or curved environments, flexible connection structures or magnetic mounting devices can be employed, allowing sensors to adapt more readily to various installation positions. This approach improves applicability in complex settings.

It is important to emphasize that the displacement method is mainly suited for critical bolt connections with high-precision and high-reliability requirements, such as those in turbopump shaft assemblies. Not all bolt connections necessitate control via bolt elongation. For general applications with lower accuracy demands, the traditional torque method remains more cost-effective and better suited. Therefore, the displacement method should be judiciously applied to fully leverage its technical merits while avoiding unnecessary expense and complexity.

6. Conclusions

Through the above experiments, we can draw the following main conclusions: The elongation method has significant advantages over the traditional torque method in controlling the tightening force of the turbopump shaft system. Especially in the case of poor thread quality or large changes in lubrication conditions, the elongation method can provide more stable and accurate control of the tightening force, avoiding the fluctuation of the tightening force due to changes in the coefficient of friction, which is a common problem in the torque method. Strain gauge and ultrasonic methods, despite their capability of measuring clamping force during the tightening process, are constrained by practical application conditions and the structural characteristics of the target object. As a result, these methods are not suitable for the present system.

The elongation method can reduce fluctuations in tightening force due to thread damage or improper lubrication, thus significantly improving the assembly quality of the turbopump shaft system and the reliability of system operation. Especially in areas where high precision is required, such as spacecraft, the elongation method can better ensure the proper operation of critical components. The elongation method is recommended for tightening operations requiring high-precision tightening force control, especially where thread quality may be problematic or lubrication conditions cannot be easily controlled. This not only ensures precise control of the tightening force but also improves the efficiency and reliability of the overall assembly process.

In summary, the application of the elongation method in turbopump shaft system tightening technology shows advantages. Future research can further optimize the elongation method's application scenarios and measurement tools to better suit various complex industrial requirements.

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