Investigation on bolt tightening strategy for precision machine tool guideway considering linear accuracy

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Guideway is an essential component in machine tools which affects the accuracy and performance. The uneven deformation of the guideway during assembly can have a direct impact on the linear accuracy of machine tools. This effect is especially significant in in precision machine tools used for high-precision fields such as micro/nano manufacturing. Bolt tightening is an essential step in guideway assembly, where the large-scale group bolts tightening must ensure the linear accuracy of the guideway. The objective of this present research is to evaluate various bolt tightening strategies, explore bolt tightening strategies which offer both strong connection performance and high linear accuracy, thereby enhancing the machining precision of precision machine tools. First, finite element simulations modeled three different tightening strategies for the guideway, determining the straightness error and analyzing the influence of bolt preload and its uniformity on this error. Then, an experimental setup mimicking real machine tool specifications was created to validate the simulation's accuracy through practical assembly. Finaly, the findings indicate that uniform bolt preload is critical for guideway linear accuracy. The cross-tightening strategy not only ensures robust connection strength but also enhances linear motion precision. This research offers practical application references for guideway assembly and machine tool manufacturing, contributing to the enhancement of machining precision and assembly efficiency, and providing equipment support and precision assurance for micro/nano manufacturing.

1. Introduction

As the micro-nano manufacturing industry progresses, precision and ultra-precision machining technologies have experienced rapid growth. The application of these technologies has resulted in an enhancement in the consistency of part machining and surface accuracy, thereby increasing the significance of precision machine tools within the manufacturing industry. In this context, the assembly phase of machine tools, particularly the assembly of bolted joint structures, has become increasingly pivotal to the overall performance of the machine tool. The guideway, as the core component of the machine tool's linear feed axis, are typically secured to the bed by a series of bolts. The quality of the bolted connection not only influences the stability of the guideway but also significantly affects the machine tool's linear accuracy and machining precision [1, 2]. Straightness error is one of the principal metrics for assessing the linear accuracy of machine tools. Such errors often originate during the assembly of the guideway, and achieving the desired linear accuracy typically requires iterative adjustments or even reassembly of the guideway [3]. Different tightening strategies may lead to varying degrees of straightness error, which can only be measured after the guideway assembly is complete [4]. Therefore, exploring the bolt tightening process, which is the source of error generation, to understand its effect mechanism on the linear accuracy of machine tools, and clarifying the merits and drawbacks of various bolt tightening strategies, is of significant importance for predicting straightness errors in the guideway and enhancing the linear precision of machine tools.

This research takes the guideway of precision machine tools as the subject, and explores a bolt tightening strategy that Combines both performance and precision to enhance the linear accuracy and machining quality of precision machine tools. The organization of the main research in this research is as follows: In Section 2, the finite element model of the guideway is established, and three bolt tightening strategies are determined.; In Section 3, an experimental platform for guideway bolt tightening is independently constructed to perform actual assembly for different tightening strategies; In Section 4, the finite element and experimental results are analyzed and discussed, exploring the factors affecting the accuracy of the guideway and comparing different tightening strategies. This research provides practical guidance for machine tool manufacturers in selecting appropriate bolt tightening strategies, thereby enhancing the machining precision of precision machine tools.

2. Finite element simulation of bolt tightening

2.1 Finite element model establishment

Considering the intricacies involved in directly measuring the preload force and deformation of bolts during the tightening process, finite element simulation analysis proves to be highly effective for simulating the preloading of bolts and the deformation of guideway. This research has selected hexagonal head bolts with cylindrical shanks as the research subjects and has conducted a detailed analysis of the relevant dimensions and parameters of the bolts and their connecting components, with the specific data presented in Table 1. Based on the actual assembly relationship of the guideway, bolts, and the bed, this research has constructed an accurate three-dimensional solid model, as depicted in Fig. 1, which includes 23 bolts.

Table 1 Bolt parameters

Parameter	Value
Bolt nominal diameter d	8 mm
bolt mid-diameter d_1	7.89 mm
Thread hole diameter d_0	9 mm
Thread pitch P	1.25 mm
Bolt contact diameter D	12.35 mm
Thread angle λ	60°

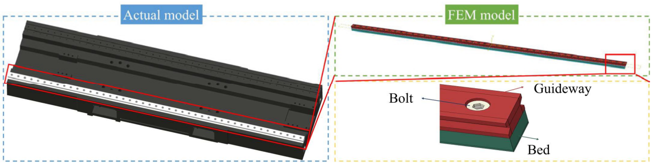

Fig. 1 Finite element model

2.2 Preload calculation

The formation of bolt preload is typically achieved by tightening with the torque method. In the actual bolt assembly process, torque is a parameter that is easily measured and controlled, whereas directly measuring the bolt preload is relatively difficult and complex. In finite element simulation analysis, to enhance the efficiency and accuracy of the simulation, it is common to convert the torque into bolt preload. The relationship between the torque T and the bolt preload F [5] can be expressed by Equ. (1).

$$\begin{cases} T = \left[\dfrac{d_2}{2d} \tan(\lambda + \varphi_v) + \dfrac{f_c}{3d} \dfrac{D_1^3 - d_0^3}{D_1^2 - d_0^2} \right] Fd = KFd \\ \tan(\lambda + \varphi_v) \approx \tan\lambda + \tan\varphi_v = \dfrac{P}{\pi d_2} + \dfrac{f_t}{\cos\lambda} \end{cases} \tag{1}$$

Where K is the tightening torque coefficient.

Based on the specifications and strength grades, the bolts have a recommended tightening torque range of 35-45 N·m. A torque T=40 N·m is selected as the standard for tightening in this research. According to Equ. (1) and the parameters listed in Table 1, the initial preload F of the bolt is calculated to be 18000 N.

2.3 Preload calculation

In this simulation analysis, three distinct tightening strategies were defined for the tightening process of 23 bolts, with their specific implementation methods and schematic illustrations presented in Fig. 2. The strategies are detailed as follows:

(1) Tightening strategy-1 (sequential tightening): Initiating from one end of the linear guide, the tightening is sequentially conducted for the 23 bolts according to their linear arrangement.

(2) Tightening strategy-2 (symmetric tightening): Commencing at the midpoint of the bolt column (i.e., the 12th bolt), the strategy involves first tightening the 11 bolts on the right side in sequence, followed by the tightening of the 11 bolts on the left side, creating a symmetrical tightening pattern.

(3) Tightening strategy-3 (cross tightening): This strategy also begins at the midpoint of the bolt column but differs from strategy-2 by employing a staggered tightening method. After tightening a bolt on the right side, the adjacent bolt on the left side is skipped, and the next bolt on the right is tightened, continuing this alternating pattern to form an interlaced tightening path.

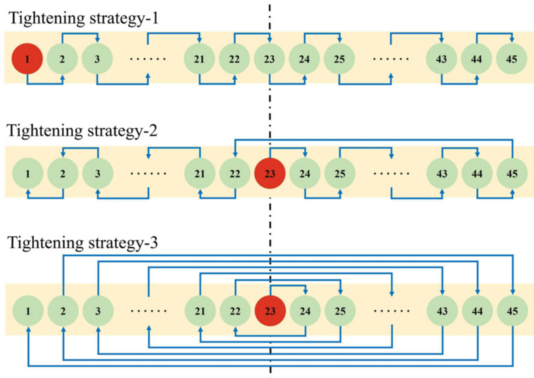

Fig. 2 Bolt tightening strategies

3. Experimental verification

3.1 Experimental platform construction

In actual machine tools, the process of disassembling and reassembling the guideways is complex, often failing to meet experimental requirements. To address this issue, the current research, grounded in the actual dimensions and structure of the machine tool, has independently designed and assembled a guideway bolt tightening experimental platform (Fig. 3). The two guideways of the experimental platform are designated as the driving side and the free side, respectively. The driving side guideway is connected to the ball screw and worktable, which ensures that the slider can perform precise feed motions with the ball screw. In contrast, the free side slider is unconstrained in the horizontal direction, allowing for unrestricted movement. During the experiment, testing is conducted solely on the free side guideway to eliminate potential interference from interactions between the two guideways on the experimental results. Prior to measuring the straightness error, the free side slider is connected to the worktable via a fixed wedge, enabling the free side slider to move accurately according to the instructions of the CNC system. In the measurement process for straightness error, the receiver of the laser interferometer is directly affixed to the free side slider, and the error data obtained is considered to be solely attributable to the pre-tightening of the guideway bolt on that side, thereby excluding interference from the driving side guideway and other factors.

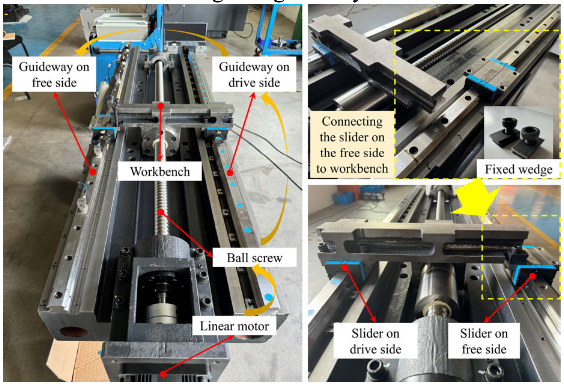

Fig. 3. Guideway bolt tightening experimental platform

3.2 Straightness error measurement of guideway

3.2.1 Bolt tightening

On the constructed experimental platform, the tightening of the guideway bolts was carried out following the same tightening strategies as in the finite element simulation, with a total of three distinct strategies. The bolts of the guideway were tightened according to the torque value (T=40 N·m) described in Section 2.3, and the on-site image of the bolt tightening is shown in Fig. 4.

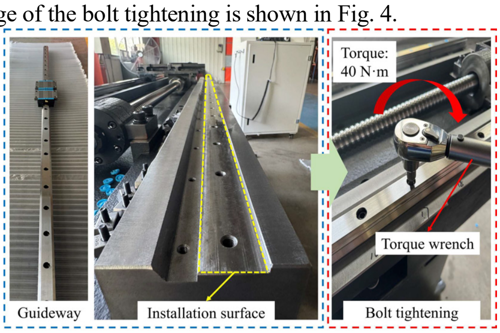

Fig. 4. Guideway bolts tightening

3.2.2 Straightness error measurement

The guideway's straightness error was measured after assembly using a Renishaw XM-80 multi-beam laser interferometer. The measurement range for the straightness error was determined based on the actual conditions of the experimental platform and the site. During the measurement process, the positions of the laser transmitter, and laser receiver were arranged as close as possible to the worktable surface, aligning the measurement optical path with the plane in which the grating ruler is located. This setup minimizes the impact of Abbe-Brennan errors on the actual measurement results. The measurement site and the arrangement of the instruments for straightness error are shown in Fig. 5.

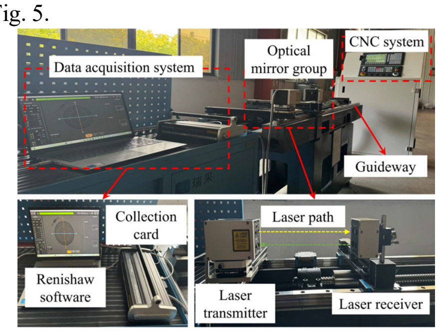

Fig. 5. Straightness error measurement

4. Results and discussion

4.1 Preload analysis based on FEM

In the tightening process of a group of bolts, the tightening action of an individual bolt can affect other previously tightened bolts, leading to a relaxation phenomenon, which is a reduction in preload. This research extracted the principal stress in the axial direction of the 23 bolts during the final analysis step and calculated the residual preload for each bolt after the completion of all tightening based on the cross-sectional area of the bolt threads.

The mean value $\overline{F}$ and the standard deviation σ_F of the residual preloads for the 23 bolts were calculated. The standard deviation of the residual preloads is utilized to assess the uniformity of the preloads, thereby analyzing the connection performance of the bolts under different tightening strategies. Table 2 presents the statistical results for the mean values and standard deviations.

Table 2 Mean value and standard deviation of bolt residual preload

Tightening strategy	$\overline{F}$ (N)	σ_F
1	14486.91	28.21
2	14579.43	81.05
3	14694.40	30.18

From the perspective of average residual preload, the average preloads for the bolts under the three tightening strategies are 14486.91 N, 14579.43 N, and 14694.40 N, respectively. Tightening strategy-3 demonstrates a relatively higher average residual preload, which is typically associated with stronger connection strength. In terms of the uniformity of the preload, tightening strategy-1 exhibits the smallest standard deviation of 28.21, indicating the best uniformity in preload; Tightening strategy-3 follows closely with a standard deviation of 30.18; whereas tightening strategy-2 has the largest standard deviation, reaching 81.05, suggesting relatively poorer uniformity. Taking into account both the average residual preload and the uniformity of the preload, tightening strategy-3 demonstrates the best overall performance. It not only provides a higher bolt preload to ensure connection strength but also maintains a good uniformity in preload.

4.2 Straightness error analysis based on guideway deformation

A specific path on the guideway was selected for analysis and the deformation displacement in the Y direction of these nodes was extracted in FEM model. The deformation at the position of maximum error of the slider is selected to calculate the straightness error. Equ (2) describes the mathematical relationship between the deformation at various positions of the guideway and the straightness error [6].

$$\delta_y(x) = \frac{D(x_{n-1}) + D(x_{n+1})}{2} \tag{2}$$

Incorporating the simulated deformation data and Equ (2), the calculated straightness errors are depicted in Fig 6. Analyzing the results from Fig. 7 reveals that tightening strategies 1 and 3, which exhibit better uniformity in preload, perform similarly in terms of straightness error, while tightening strategy-2, with its poorer uniformity, demonstrates a larger straightness error. This phenomenon highlights the impact of the uniformity of the residual preload on the deformation of the guideway: a higher degree of uniformity in preload ensures that the deformation of each node remains within a smaller fluctuation range after deformation, resulting in a smoother actual motion trajectory of the slider and, consequently, a smaller straightness error. Therefore, the uniformity of the bolt preload is a key factor affecting the straightness error of the guideway. Good uniformity in preload contributes to maintaining a lower straightness error, thereby ensuring the machining accuracy and stability of the machine tool.

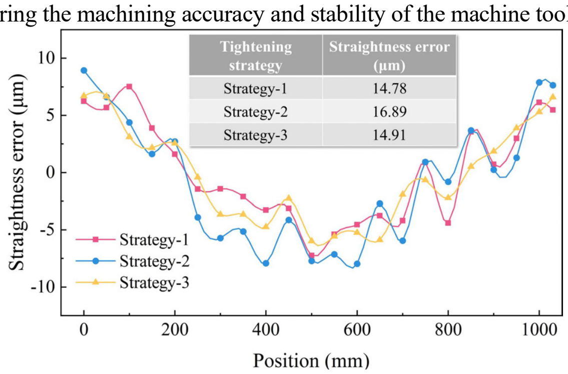

Fig. 6. Straightness error of guideway under different tightening strategies (simulated)

Figs. 7 and 8 display the straightness errors of the guideway under different tightening strategies in the experiments, along with a comparison between experimental measurements and simulation analysis results. It can be observed from the figures that the ranking of straightness errors for the different tightening strategies is consistent with the simulation analysis, with tightening strategies 1 and 3 exhibiting relatively smaller straightness errors. However, taking into account the requirement for high preload, tightening strategy-3 is still considered the optimal solution in terms of overall performance.

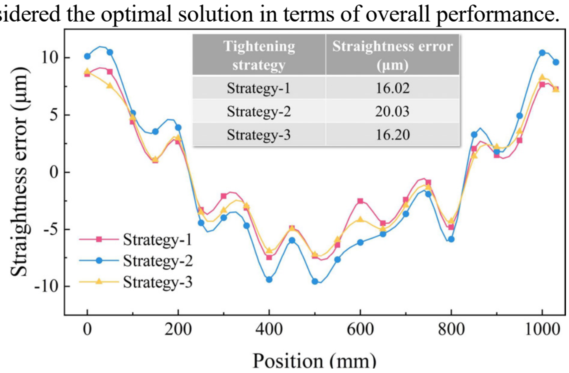

Fig. 7 Straightness error of guideway under different tightening strategies (experimental)

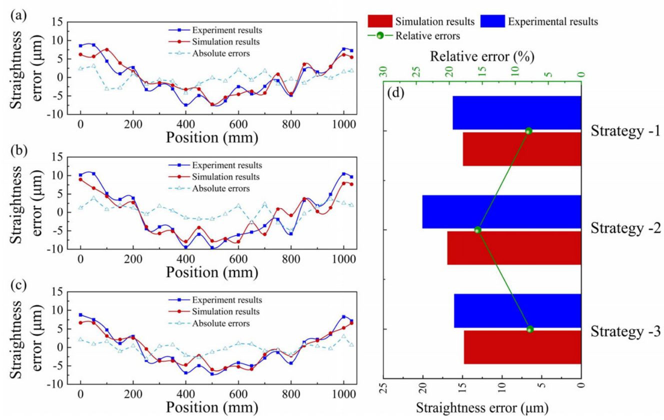

Fig. 8 Straightness comparison: (a) strategy-1; (b) strategy-2; (c) strategy-3; (d) relative error

5. Conclusions

This research integrates finite element simulation with experimental validation to compare the advantages and disadvantages of three tightening strategies. It analyzes the impact of bolt preload and its uniformity on the straightness error of guideway. The main findings and conclusions are as follows:

(1) Among the three initial strategies, the cross-tightening strategy demonstrated the best overall performance in terms of guideway characteristics.

(2) The results from both simulation and experimentation demonstrate that the straightness error of the guideway is reduced with the cross-tightening strategy, thereby proving that uniformity of residual pretension force is a more pivotal factor influencing the straightness error of guideway.

(3) The interaction between group bolts will result in inconsistent residual preload at each bolt of the guideway after tightening. This inconsistency can cause local stress concentration or uneven deformation of the guideway, thereby affecting the straightness and overall rigidity of the guideway.

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