Precision Engineering 49 (2017) 344–353

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

An improved accuracy-measuring method in manufacturing the lead screw of grating ruling engine

Xuefeng Yao[a,b,*], Jicheng Cui[a], Haili Yu[a], Xiangdong Qi[a], Xiaotao Mi[a,b], Yimin Jiang[c], Mingjia Wang[a], Xiaotian Li[a]

[a] Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Dongnanhu Road, 3888#, 130033, Changchun, PR China
[b] University of Chinese Academy of Sciences, Yuquan Road, 19#A, 100049, Beijing, PR China
[c] The Civil Aviation of China, Jinbei Road, 2898#, 300300, Tianjin, PR China

ARTICLE INFO

Article history:
Received 22 December 2016
Received in revised form 13 March 2017
Accepted 16 March 2017
Available online 24 March 2017

Keywords:
Lead screw
Grating ruling engine
Axial displacement
Error analysis
Non-contact measurement
Laser interferometer

ABSTRACT

A measuring method was studied to further improve the manufacturing accuracy of the lead screw. Firstly, factors that can axially displace the screw shaft were analyzed and a relationship between factors and axial displacement was given. The axial displacement of the screw shaft was measured using a laser interferometer, and results show that the variation amplitude of the screw-shaft axial displacement was about 80 nm while the variation period was consistent with the rotation period of the screw shaft. Next, two methods of measuring the manufacturing accuracy of the lead screw were considered: a traditional method that measures the absolute position of the nut and an improved method that measures the displacement between the nut and screw shaft. A No. 4 screw shaft was manufactured under the guidance of results obtained using the improved measuring method. Experimental measurements were then made; results show that the pitch displacement errors obtained using the traditional and improved measuring methods were 0.6 and 0.4 μm, respectively, indicating that the improved measuring method is more exact. Finally, an echelle grating ruled by a grating ruling engine that used the No. 4 screw shaft as a macro-positioning element was introduced. Its excellent parameters indirectly show that the improved measuring method has better accuracy.

1. Introduction

With the development of micro-displacement technology, new positioning technologies, represented by piezoelectric ceramics, have been developed in recent years [1]. These technologies can reach the nanometer level of position accuracy, but they also have shortcomings, such as a small travel range and weak bearing capacity [2,3]. The traditional lead screw drive form therefore remains irreplaceable in some large-travel and heavy-load-transmission applications. The positioning accuracy of the lead screw is usually at the micron level. However, for large-travel precision instruments, such as grating ruling engines, diamond lathes and ultra-precision grinding machines, the required positioning accuracy is usually tens of nanometers, and it is difficult to reach this precision level using the lead screw drive alone [4,5]. For these instruments, the usual practice is to position the lead screw as a macro positioning element and to realize an accuracy of tens of nanometers using micro positioning devices, such as those made from piezoelectric ceramics [6,7]. The precision of the macro positioning will directly affect the control accuracy and difficulty of micro positioning, which is more obvious in the case of an open-loop control system [8]. How to improve the positioning accuracy of the lead screw has therefore become an important challenge for engineers and technicians to overcome.

Generally speaking, methods of manufacturing lead screws can be divided into three types: cutting, grinding and lapping methods. Most ultra-precision lead screws are manufactured by lapping at present. In the lapping process, the transmission accuracy of the lead screw must be measured frequently, and the measurement results are used as feedback to guide the lapping of the lead screw [9–14]. A high-precision measuring method is therefore indispensable to obtaining a high-precision lead screw. Large-travel and nanometer-level-accuracy measurement has become possible in recent years with the emergence of laser interferometer technology, which is being increasingly adopted by lead screw measuring machines [15–17]. According to conventional engineering experi-

* Corresponding author at: Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Dongnanhu Road, 3888#, 130033, Changchun, PR China.
E-mail address: yaoxf@ciomp.ac.cn (X. Yao).

http://dx.doi.org/10.1016/j.precisioneng.2017.03.004

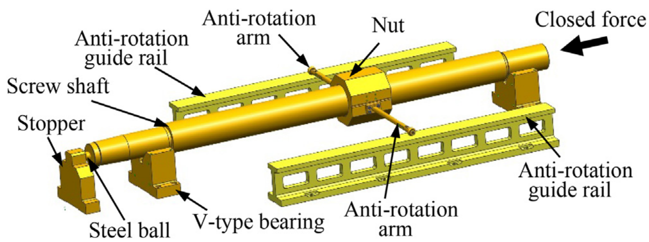

Fig. 1. V-type bearing installation that is widely used for lead screw measuring machines and grating ruling engines.

ence, it is generally believed that the transmission error of a lead screw is mainly due to the pitch distance error and mismatch of the pitch size between the screw shaft and nut. In the past, attempts to improve the transmission accuracy of a lead screw were made by continuously increasing the machining accuracy of the screw shaft and nut, but it was later found that when the machining accuracy reaches a certain level, continuing to improve the precision of manufacturing does not increase the transmission accuracy proportionally, especially in the sub-micron accuracy range. To explain this phenomenon, the present article proposes factors that affect the transmission accuracy of the lead screw from other perspectives and carries out related research.

The remainder of the paper is organized as follows. Section 2 introduces the V-type bearing installation of the screw shaft and the error analysis of deviation and nonperpendicularity is carried out. Section 3, on the basis of the laser interferometer, presents an optical schematic of a device used to measure the axial displacement of a screw shaft. Section 4 discusses the effect of the measurement environment and sets up the screw shaft axial-displacement system. After a method of adjusting the measurement mirror is introduced, error analysis is performed to calculate the off-axis error, which is the deviation between the center of the optical path and the rotation axis of the screw shaft, and the nonperpendicularity error between the measurement mirror and the rotation axis of the screw shaft. Section 5 measures axial displacements for forward and reverse directions and compares them with the axial runout of assembled radial rolling bearings of difference tolerance classes. Section 6 employs two different methods to measure the transmission accuracy of the lead screw, introduces two optical schematics and the structure of the measuring machine and compares the two measurement results. The measurements reveal a stick-slip motion phenomenon. Conclusions are presented in Section 7.

2. Analysis of the axial displacement of a screw shaft

Fig. 1 is a schematic diagram of the method of installing a lead screw that is widely used for lead screw measuring machines and grating ruling engines. As shown in the figure, the screw shaft is supported by two V-type bearings at the two journals of its, and the nut is connected with two anti-rotation arms that are always in contact with the anti-rotation guide rail to avoid rotating with the screw shaft. To limit the degree of freedom in the axial direction of the screw shaft, a closed force acting leftward is provided together with a steel ball and stopper that are located at the left end of the screw shaft. Under the effect of the closed force, the contact between the steel ball and the stopper is at a point, and the axial clearance that exists in the assembled radial rolling bearings does not exist for the V-type bearing.

Although the V-type bearing installation mentioned above reduces the axial clearance, it does not eliminate axial displacement. Fig. 2 shows how axial displacement occurs. During the process of manufacturing, assembling and adjusting, it is sometimes impossible to avoid deviation between the center of the steel ball and the rotation axis of the screw shaft as well as nonperpendicularity between the limit surface of the stopper and the rotation axis of the screw shaft. We define two coordinate systems for the convenience of analysis. In Fig. 2(a) and (b), the Z-axis is the rotation axis of the screw shaft and the Y-axis is the reverse direction of gravity. For analysis on the limit surface of the stopper, the Y′-axis is directed vertically upward and the X'-axis horizontally rightward, as shown in Fig. 2(c). According to the geometric relationship, if we ignore the size of the steel ball, it is reasonable to believe that the axial displacement of the steel ball is the same as that of the screw shaft. When the screw shaft rotates through one cycle, the ball will travel along an elliptical trajectory on the limit surface of the stopper. As shown in Fig. 2(c), the curve equation of the ellipse can be expressed as

$$\left(\frac{x'}{\delta}\right)^2 + \left(\frac{y' \cdot \cos\theta}{\delta}\right)^2 = 1 \tag{1}$$

where δ is the deviation between the center of the steel ball and the rotation axis of the screw shaft in the direction of the Y′-axis and θ is the angle between the limit surface of the stopper and the normal plane of the rotation axis of the screw shaft. The equation shows that the length of the major axis of the ellipse is 2δ/cosθ and the length of the minor axis of the ellipse is 2δ.

As shown in Fig. 2(a), when the steel ball rotates around the rotation axis of the screw shaft with angular velocity ω, we can deduce the polar-coordinate equation of the spatial trajectory of the steel ball as

$$\begin{cases} x = \delta\cos\omega t \\ y = \delta\sin\omega t \\ z = -\delta\sin\omega t\tan\theta \end{cases} \tag{2}$$

Eq. (2) reveals that the axial displacement of the steel ball varies with the same frequency of the screw shaft rotation, and its amplitude depends on δ and θ but is independent of ω. The trajectories of the steel ball in space and the Z direction are presented in Fig. 3(a) and (b) respectively. Fig. 3 shows that the trajectory of the steel ball in space is an ellipse, in the Z direction, the trajectory of the steel ball is a sinusoidal curve and the period of the steel ball trajectory is consistent with the rotation period of the screw shaft.

3. Optical schematic design for measuring axial displacement

Figs. 4 and 5 are respectively an optical schematic and three-dimensional diagram of the system for measuring the axial displacement of the screw shaft. The measurement mirror is perpendicular to the rotation axis of the screw shaft, the measurement mirror moves with the screw shaft in the axial direction while the reference mirror is fixed and stationary, and S_m is the axial displacement of the screw shaft.

4. Preparation for the measurement of axial displacement

Several factors outside the laser measurement system can affect system accuracy. These factors (i.e., the measurement environment, machine and material temperature and optics installation) and their interrelationships must be understood to predict the performance of the system. Because the system measures only the relative motion between the interferometer and reflector, measurements are not affected by vibration along the beam axis of the laser source or the receiver. When vibration of the laser head displaces the beam (perpendicular to the beam axis) at an interferometer or receiver, the beam signal power can fluctuate. An insufficient beam signal will arrive at the receiver if this fluctuation