621.923.4:621.822

Paper No. 192-26

A Study of Thread Grinding Using an Optical Standard Scale

By Jiro OTSUKA*, Takehiko NOMURA**

Fumitaro SEKINE*** and Yuichi NAKANO****

Leadscrews used for machine tool or length measuring machine often act as a standard scale. At the same time high level precision is needed.

In this paper the table feed error in the thread grinding machine and the lead error in the ground leadscrew are discussed by use of Fourier analysis. To reduce such errors, a newly designed system is constructed. As a result, a leadscrew with high pitch accuracy can be obtained.

1. Introduction

In machine tools or measuring instruments, combinations of leadscrews and nuts are widely used as feeding mechanism and positioning mechanism. With the development of NC machine tools and with the improvement of precision measuring instruments, positioning accuracy is required to be within several micron meters per 1 m length and the leadscrews of higher pitch accuracy are needed.

In order to prevent lowering of accuracy by wear during use, leadscrews are ground after heat treatment of quenching. Accordingly, the accuracy of leadscrews to be ground owes much to the accuracy of the thread grinding machine. Many kinds of studies have been made about improvement of the thread grinding machine and thread grinding methods. (1)~(4)

As the result, leadscrews of several micron meters accuracy of 750 mm thread length can be obtained and such a value is comparatively small. However as for elimination of drunkenness, a good result cannot be obtained and such an important problem is left unsolved as yet.

It is one purpose of this paper to show that the accuracy of the ground screw thread is much influenced by the table feed error which contains a rotational transmissive error between the main spindle and the leadscrew axis and also much influenced by the fact that a correct table feed cannot be obtained depending on

the revolutions of the main spindle. It is another purpose of this paper to design and construct a new feeding mechanism which eliminates such errors and improves the accuracy of the thread grinding machine, giving a leadscrew of high pitch accuracy.

The grinding machine used in this study is a MITSUI EXCELL-0 precision thread grinding machine and it is equipped with an oil showering system to keep the workpiece temperature constant during grinding and also with an NC lead error compensating device.

2. Causes of Lead Error Generated during Grinding of Leadscrew

Both cumulative pitch error and drunkenness usually express accuracy of screw thread. This paper adopts the definitions of both errors in reference (5). According to this reference, cumulative pitch error is expressed as a difference between maximum value and minimum value of pitch errors in each pitch. Drunkenness is expressed as a difference between maximum value and minimum value of lead error within one pitch and Fig. 1 shows a schematic diagram of error definitions in screw thread. Combination of cumulative pitch error and drunkenness can express a lead error which is continuous. Table 1 indicates some causes of a lead error generated in thread grinding.

Table 1 Causes of lead error

Lead error	
Cumulative pitch error	Drunkenness
1. Tilting motion and out-of-straightness of the table	1. Table feed error caused by rotational transmissive error of gears between the main spindle and the leadscrew
2. Pitch error peculiar to the thread grinding machine	2. Table feed error due to drunkenness of the leadscrew
3. Thermal deformation of the workpiece due to grinding heat	3. Run-out and going in-and-out of the main spindle
4. Thermal expansion of the leadscrew due to frictional heat	4. Errors due to grinding conditions

Received 1st February, 1979.

* Associate Professor, Research Laboratory of Precision Machinery and Electronics, Tokyo Institute of Technology, Nagatsuta, Midori-ku, Yokohama 227.

** Graduate student, Tokyo Metropolitan University.

*** Assistant, Research Laboratory of Precision Machinery and Electronics, Tokyo Institute of Technology.

**** Associate Professor, Sagami Institute of Technology.

Fig.1 Schematic diagram of error definitions in screw thread

From the reference (3) which is a study about drunkenness, the following conclusion can be obtained. A correct table feed cannot be obtained depending on the revolutions of a main spindle and both table feed error and run-out of the main spindle cause a large amount of drunkenness.

Statistical treatment in the reference (3) considers the amplitude of drunkenness per one pitch in the ground screw thread according to the above mentioned definition of drunkenness. However, the experimental amplitude of drunkenness has the tendency of some dispersion, which leaves the room for discussion. The conclusion from this reference does not explain how these two factors affect drunkenness. Accordingly, it is necessary to discuss the qualitative causes of drunkenness in detail.

It is seen from experimental results that a lead error of the ground screw thread has a cyclic component. This phenomenon may be solved by the structure of the thread grinding machine as shown in Fig. 2. Feeding methods of the table and driving method of the main spindle are as follows: In Fig. 2, the revolution of a hydraulic oil motor is transmitted to the revolution of the main spindle and to that of the leadscrew over change gear trains. A leadscrew engages with a nut which is fixed to the bed and the leadscrew revolution is converted to table feed. Ac-

Fig.2 Structure of thread grinding machine

Fig.3 Measuring methods of table feed error Δx and rotational transmissive error $\Delta \theta$

cordingly, considering change gear trains as well as the supporting method of the leadscrew, the cyclic movement grows during the revolution of the main spindle and the table movement. It is thought that the cyclic movement is transmitted to the screw thread to be ground and that it is the cause of a cyclic error in lead error.

As mentioned above, only the amplitude of drunkenness is discussed in the reference (3). The method of expressing drunkenness is one of the methods to estimate the lead error within one pitch of screw thread. To discuss the amplitude of drunkenness is equal to discussing only the amplitude component of a cyclic error with no consideration of the cyclic component.

Accordingly, it is necessary to analyse both of the amplitude and the continuous lead error which is cyclic about more than one pitch of the ground screw thread. Fourier analysis method is applied in this study and considerations about it are made. Three of the causes of drunkenness in Table 1 are considered below.

The workpiece screw used in this study is as follows:

Thread length: 100 mm; outer diameter: 50 mm;
Pitch : 5 mm; thread profile: trapezoidal

and Fourier analysis is tried on this size of workpiece.

2.1 Comparison between practical error of table feed and rotational transmission error of main spindle-leadscrew

After measuring table feed error against the revolution of the main spindle (practical error of table feed) and rotational transmissive error between the main spindle and the leadscrew, respective relations are discussed below. The measuring method is shown in Fig. 3. After measuring rotational angle θ of the leadscrew and table feed x against the rotational angle of the main spindle, the difference between θ and θ_0 and the difference between x and x_0 can be obtained, where θ_0 and x_0 are an ideal rotational angle and an ideal table feed respectively. Then, cumulative values $\Delta \theta$ and Δx are calculated by their differences using a cumulative computable counter.

An optical and electrical linear scale (analysis faculty $1 \mu\text{m}$, measuring length 100 mm) is used as standard scale to measure table feed and a rotary encoder (ana-

Fig. 4 Comparison between rotational transmissive error of table feed and practical error of table feed

lysis faculty 2 minutes) measures the rotational error. Now, a rotational error is converted to a rotational transmissive error of table feed, considering the pitch of the leadscrew (6.35 mm) of the thread grinding machine.

Fig. 4 shows comparison between practical error of the table feed and rotational transmissive error of table feed which is calculated from rotational error.

In Fig. 4, amplitude of rotational transmissive error of table feed is at most 7 μm. On the contrary, practical error of table feed is at most 4 μm which is smaller than rotational transmissive error. However, wave profile of practical error almost agrees with that of rotational transmissive error in cyclic motion and it is obvious that the cyclic component of practical error of table feed is much influenced by the rotational transmissive error between the main spindle and the leadscrew.

Following are the results of Fourier analysis about this cyclic component. Fig.

(a) Result of Fourier analysis of table feed error calculated from rotational transmissive error

(b) Result of Fourier analysis of practical error of table feed

Fig. 5 Fourier analyses of table feed error calculated from rotational transmissive error and practical error of table feed

Fig. 6 Comparison between lead error of the ground leadscrew and practical error of table feed

5(a) and (b) show the results of rotational transmissive error of table feed and practical error of table feed respectively. In both figures of Fourier analyses of rotational transmissive error and practical error of table feed, coefficients of 10th are larger and the former value is 1.5 μm and the latter value is 1.0 μm. Hereupon, an FFT method is applied in Fourier analysis and input data are 256 points of errors measured at every 1/20 rotation of the main spindle.

Since the pitch of the leadscrew in the thread grinding machine is 6.35 mm and the pitch of the workpiece screw is 5 mm, the value A of rotational cycle in the leadscrew is expressed as

$$A = \frac{256}{20} \times \frac{5}{6.35} = 10.1 \approx 10 \quad (1).$$

Accordingly, the numbers of 10th seen from Fig. 5(a) and (b), where there exist large coefficients in Fourier series, are cyclic errors synchronized with the revolution of the leadscrew and these are a controlling component of cyclic error in rotational transmissive error of table feed and practical error of table feed.

Amplitude component of practical error of table feed is smaller than that of rotational transmissive error of table feed. However, their phases almost agree and it is thought that cyclic component of practical error of table feed grows from rotational transmissive error of table feed.

2.2 Comparison between lead error of the ground leadscrew and practical error of table feed

In this section, lead error of the ground leadscrew and practical error of

Fig. 7 Fourier analysis of lead error of the ground leadscrew

table feed are discussed below. Lead error of the ground leadscrew is measured by a laser interferometer screw lead checker (analysis faculty $0.1 \mu\text{m}$).⁽⁵⁾

Fig. 6 shows the comparison between lead error of the ground leadscrew and practical error of table feed and it is found that both are in good agreement with each other.

Fig. 7 shows the result of Fourier analysis of the ground leadscrew. It is seen from this figure that coefficient of 10th in Fourier series which corresponds to the revolution of the leadscrew is larger and at the same time coefficient of 13th is larger.

Considering the effect of the main spindle, the value B of rotational cyclic of the main spindle is expressed by the same formula (1) as

$$B = 256 \times \frac{1}{20} = 12.8 \approx 13 \quad (2).$$

From this value, the number of 13th in Fig. 7 is seen to be influenced by the main spindle.

Coefficient of 10th in Fourier series in practical error of table feed is $1.0 \mu\text{m}$ in Fig. 5(b) and that of 10th in lead error of the ground leadscrew in Fig. 7 is $0.8 \mu\text{m}$. From this result, it can be said that rotational transmissive error of table feed causes lead error of a ground leadscrew.

In Fig. 7, coefficient of 13th which corresponds to the revolution of the main spindle is $0.6 \mu\text{m}$. This value is smaller than the value of $0.8 \mu\text{m}$ which is coefficient of 10th in a leadscrew ground under practical error of table feed.

It is thought that the causes of this cyclic error, whose cycle agrees with the cycle of the main spindle, are run-out and going in-and-out of the main spindle. The grinding machine used in this study has run-out of the main spindle: $2.7 \mu\text{m}$ and going in-and-out of the main spindle: $0.4 \mu\text{m}$.

This cyclic effect is converted to at most $1.1 \mu\text{m}$ of pitch error in 30° trapezoidal thread, and it is thought that this value is the main cause of coefficient $0.6 \mu\text{m}$ of 13th which corresponds to the revolution of

the main spindle in Fig. 7.

As a result of Fourier analysis in sections 2.1 and 2.2, it is made clear that the cause of lead error in a ground leadscrew is almost due to practical error of table feed, especially due to cyclic error whose cycle in Fourier series agrees with the cycle of leadscrew revolution and this proves that the effect of practical error of table feed which causes a lead error of a ground leadscrew is smaller than that of main spindle which also causes a lead error.

3. Newly Designed Mechanism for Fine Table Feed

In order to get a leadscrew of higher pitch accuracy, it is necessary to reduce table feed error as clarified in Chapter 2. In this chapter, research is done about table feed error which contains rotational transmissive error of table feed. As mentioned above the rotational transmissive error much influences the lead error in a leadscrew to be ground.

As a countermeasure, a mechanism for fine table feed has been newly designed and constructed. Fig. 8 shows a schematic diagram and its explanation is given below.

In Fig. 8, a dividing disk whose axis is on the same axis of the main spindle divides the angle of main spindle finely and an optical and electrical linear scale (analysis faculty: $1 \mu\text{m}$) used as a standard scale measures the table feed accurately. Dividing disk of 300 mm in diameter has 40 holes which have the same interval of 9° and its interval of the main spindle is detected by a photo sensor. The linear scale can measure up to 100 mm in length.

While the angle of the main spindle is divided into some constant angles of θ by the dividing disk, the distance x which indicates table movement is measured by the optical and electrical linear scale.

On the other hand, when the main spindle rotates by θ , an ideal table movement is x_0 and the relationship is expressed by

$$x_0 = p \cdot \theta / 2\pi \quad (3)$$

where p is the pitch of the workpiece screw. Then, the table feed error Δx is expressed as

$$\Delta x = x_0 - x \quad (4),$$

and Δx is calculated together with each θ revolution by the cumulative computable counter.

Now, the dividing angle of θ and an ideal table movement of x_0 are set on the cumulative computable counter.

In order to compensate for the calculated error Δx by a lead error compensating device⁽²⁾ using an electric pulse motor, an electric pulse motor control unit (in Fig. 8 EPM control unit) generates pulses and they rotate the pulse motor. Revolution of the pulse motor moves the table finely against the lead-

A: Mechanical part of lead error compensating device

X: Table feed

P: Pitch of workpiece

θ: Dividing angle

Fig. 8 Schematic diagram of table feed mechanism

Fig. 9 Schematic diagram of the compensating device of fine table feed

screw by use of a lead error compensating device which contains a fine table feeding device. One pulse compensates table feed as $0.035 \mu\text{m}$. Fig. 9 shows a schematic diagram of the compensating device of fine table feed and Fig. 10 shows a general view of experimental apparatus.

The characteristics of the compensating device are as follows;

- (1) Feeding mechanism and fine positioning mechanism are separated from the mechanism which consists of the gears, the leadscrew and the nut. There is no effect of rotational error of change gear trains or lead error of the leadscrew. Therefore, a very accurate and stable movement can be obtained.
- (2) There is no problem of aging about the optical and electrical linear scale as a standard scale.
- (3) The optical and electrical linear scale is a non-contact measuring instrument and there can be no lowering of accuracy due to wear.
- (4) The heat expansion coefficient of the linear scale is exactly the same as that of steel. Therefore, there is no problem of a pitch error being generated due to a heat expansion of the leadscrew in the thread grinding machine, when there is no temperature difference between the leadscrew and the workpiece.
- (5) The optical and electrical linear scale has no effect from induction motor or magnetic stand like a magnetic scale.
- (6) It must be noted that the optical and

Fig. 10 General view of experimental apparatus

Fig. 11 Performance of compensating device

electrical linear scale should be fundamentally set on the same axis as the main spindle of the thread grinding machine owing to Abbe's principle. However, owing to good alignment of the table movement, the linear scale is set on the edge of the machine bed as shown in Fig. 10.

4. Experiment and Consideration

4.1 Performance of the compensating device

Performance of the compensating device for fine table feed mechanism which has been newly designed and constructed as shown in Chapter 3 is described in this chapter.

Fig. 11 shows the result of displacement between the leadscrew and the table when command values are given to the pulse motor control unit. Measuring method is such that a plunger type electric micrometer measures the displacement between the table and the end of the leadscrew.

In the same figure (a) and (b), the results of fine movement are shown against command values of $1 \mu\text{m}$ and $2 \mu\text{m}$ during the table movement. However, when the pulse motor rotates in the opposite direction in the compensating device, a backlash of about $2 \mu\text{m}$ appears during the table movement but in this system, the pulses which correspond to a backlash are added to the control unit when the pulse motor rotates in the opposite direction and these pulses compensate

Fig. 12 Results of table feed error with and without compensating device

for the backlash. It is seen from Fig. 11 that almost fine movements of 1 μm and 2 μm can be obtained against command values.

Fig. 12 shows the values of table feed error in the presence and absence of a compensating device. In this experiment, 20 compensations per one revolution of the main spindle are made. The same figure (a) shows the table feed error and the compensating behavior of the compensating device. The figure (b) shows the table feed error not compensated.

Comparing the results with and without compensation, a cumulative pitch error of 6 μm in the 95 mm table movement can be seen to be yielded without compensation, but a cumulative pitch error when compensated is almost within 2 μm . Thus the compensating device is found useful.

From above mentioned result, the cumulative pitch error compensating device, which has been newly designed and constructed, has a good performance and it is certain that a value of 1 μm which is the accuracy of table feed by the optical and electrical linear scale can certainly compensate the table movement.

4.2 Thread grinding experiment using the compensating device

The workpiece screw is ground using a newly designed compensating device. Table 2 shows the experimental conditions. Twenty compensations of table feed error per one revolution of the main spindle are made here. The workpiece temperature is kept the same as the temperature of grinding fluid which is controlled at 20°C during grinding.

Fig. 13(a) shows a lead error of a ground leadscrew with compensation as measured by a laser interferometer screw lead checker. From this result, cumulative pitch error and drunkenness are found to be 1.5 μm and 2.5 μm respectively. It

Table 2 Grinding Conditions

Grinding wheel	WA80J8V
Circumferential speed of grinding wheel	1800 m/min
Dressing conditions	single point tool: Diamond feed: 20 μm feed rate: 60 $\mu\text{m}/\text{rev}$
Workpiece	Material: SCM 415 (H _{RC} 50 Induction hardening) Outer diameter: 50 mm Profile: 30° trapezoidal Pitch: 5 mm Thread length: 94 mm Center hole: Ground

Fig.13 Lead error of the ground leadscrew

Fig.14 Result of Fourier analysis of lead error after compensating grinding

is seen from this figure that the lead error of this workpiece screw is very small.

As shown in the same figure (b), cumulative pitch error and drunkenness are 4.0 and at most 5.5 μm respectively in case of grinding without compensation. It is clear that, comparing with thread grinding with and without compensation, cumulative pitch error and drunkenness are decreased to 1/2~1/3.

In the same figure (a), the amplitude is smaller, but a cyclic component can be seen. Fourier analysis is applied about this phenomenon and Fig. 14 shows the result.

Comparison is made between Fig. 14 and Fig. 7 which is the result of Fourier analysis of lead error in case of grinding the leadscrew without compensating for the table feed error. Coefficient of 10th in Fourier series which corresponds to the revolution of the leadscrew is 0.8 μm in Fig. 7, and that of 10th with compensation is negligibly small in Fig. 14. However, in Fig. 14, coefficients of 13th and 14th in Fourier series are comparatively large and that of 13th is caused by the main spindle as described in Chapter 2.

As for the number of 14th, when the revolution of the main spindle is set at 1, the cycle C of 14th is expressed as

$$C = \frac{256}{14} \times \frac{1}{20} = 0.91 \quad (4).$$

Fig. 14 shows the result of Fourier analysis of 256 points of errors measured at every 1/20 rotation of the main spindle. Therefore, it is thought that coefficient of 14th is due to the lead error of the main spindle. In Fig. 7, coefficient due to the main spindle is 0.6 μm in case of grinding without compensation and in Fig. 14, coefficient due to the main spindle is 0.5 μm in case of grinding with compensation. Accordingly, a small cyclic component which is shown in Fig. 13(a) is due to the main spindle.

It is thought that the aim to eliminate table feed error due to rotational error and also the aim to get a ground leadscrew of high pitch accuracy can be fully achieved.

5. Conclusions

As the result of experiments and discussions, the following conclusions can be obtained.

(1) It is made clear by analysing the experimental data that table feed error and run-out of the main spindle are the main causes of the lead error in a ground leadscrew.

It is also made clear that table feed error is mainly caused by the rotational transmissive error between the main spindle and the leadscrew and that the effect of table feed error which causes a lead error in a ground leadscrew is larger than that of the main spindle.

(2) In order to compensate for practical error of table feed using an optical and electrical standard scale, a newly designed pitch error compensation device has been installed on the thread grinding machine. Using this device, a high accuracy of the leadscrew of 100 mm in length can be obtained with cumulative pitch error and drunkenness 1.5 μm and 2.5 μm respectively.

Acknowledgement

Authors express their sincere thanks to Professor Akira Yamamoto of Tokyo Denki University, Professor Akira Toyama, Professor Isamu Yoshimoto and Doctor Matataro Tsubone of Tokyo Institute of Technology for their valuable advices and assistances. Thanks are also due to Mitsui Seiki Co., Ltd. for its considerable assistance.

References

- (1) R. H. Turner & G. Sweeney, Some Problems Associated with the Development of Ball Screw and Ball Nut Grinding Machine, Int. J. Mach. Tool Des. & Res., No. 7 (1967-9), p. 409.
- (2) J. Otsuka et al., A Study of a Newly-Developed Precision Thread Grinding Machine, Proc. 17th Mach. Tool Des. & Res. Conf., No. 17 (1977-9), p. 157.
- (3) Y. Nakano et al., Bull. of the JSME, Vol. 17, No. 150, (1977-4), p. 1637.
- (4) J. Otsuka, Bull. of the Japan Soc. of Prec. Engg., Vol. 11, No. 3 (1977-9), p. 109.
- (5) A. Yamamoto et al., Seimitsu-Kikai (J. Japan Soc. of Prec. Engg.), Vol. 41, No. 9 (1975-9), p. 919. (In Japanese)