Development of On-Machine Measuring System for Pitch Deviation of Large Gears

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***Abstract*—According to the processing principle of large-scale CNC gear hobbing machine, a high-precision on-machine measurement method for large gear pitch deviation using relative method and absolute method simultaneously is proposed. The mechanical body of high-precision on-machine measuring instrument with two-stage positioning system are designed to improve the positional accuracy of on-machine measurement. The system structure with upper and lower computers is proposed, which uses the high speed IO port of NC and Ethernet network for communication, so as to make full use of the function of NC system of gear hobbing machine. A large number of repeated experiments show that the range of 10 measurements of the pitch deviation and the cumulative deviation of the pitch in the developed machine are within 1/10 of the tolerance of the 3-grade precision worm specified in the national standard GB10089-88.**

Keywords-Component; on Machine Measurement; Pitch Deviation; Measuring Method; Side-by-side Construction

I. INTRODUCTION

Large gears generally refer to gears with large diameters and large modulus, but mainly depend on the gear diameter[1]. As a key or important basic component of large-scale equipment, large gears are mainly used in important departments such as machinery, transportation, electric power, metallurgy, mining, building materials, national defense, and aerospace. In order to ensure the geometric accuracy of machined parts, the detection of machined parts is very important[2]. Compared with processing equipment, large gear measuring equipment is relatively backward. Sometimes we even lacks the necessary means to large gear measurement[3]. The main characteristics of the development history of gear measurement technology are that it has gone through several stages of development, such as "comparative measurement", "meshing motion measurement" and "model measurement" in the principle of gear measurement[4]. Therefore, the ability to measure the big gear is an important part to check whether the accuracy of the processed gear is up to the standard. In the field of gear measurement, for large gears, analytical measurement is mainly based on the measurement of tooth profile, helix and pitch[5].

On-machine measurement refers to measurements made directly on the machine. This measurement can be carried out during the machining process or after the machining is completed. Because of the no need to carry the gear to other measurement equipment, it has higher efficiency [6].

The pitch deviation is one of the items that must be checked in the gear detection. In the national standard, the three items, the pitch deviation fpt, the K tooth pitch cumulative deviation Fpk and the pitch cumulative total deviation Fp are usually used to characterize the pitch deviation. The pitch deviation fpt is one of the main factors affecting the smoothness of the gear transmission, mechanical vibration and noise. The cumulative deviation Fpk and the cumulative total deviation Fp mainly affect the transmission accuracy of the gear pair [7].

There are two methods to measure pitch deviation: relative method and absolute method. The relative measurement method uses two probes to contact the middle and the middle of the tooth on the same side of any one of the pitches, and based on the pitch, and then sequentially measures the deviation of the other pitches from the reference pitch. The actual pitch deviation is determined by the principle of circumferential closure. When the relative method is used, the measurement uncertainty of the accumulated pitch error increases with the increase of the number of teeth due to the error accumulation effect. The absolute measurement method uses a single probe and a high-precision angular displacement sensor to measure the pitch deviation. When absolute method is used, the influence of uncertainty of angle measuring element on pitch deviation measurement increases linearly with the increase of measured gear diameter.

Because the two methods are difficult to achieve high accuracy when they are used in the measurement of large gears. a high-precision on-machine measurement method for large gear pitch deviation is proposed, which can be used for both relative and absolute measurement simultaneously. It can be selected by gear diameter and modulus. At the same time, the measuring instrument has adopted two-stage positioning in the radial direction (X-axis) to ensure the positioning accuracy. Therefore, the on-machine measurement system developed has improved the measurement accuracy of the large gear pitch deviation.

II. Principle of On-Machine Measurement of Pitch Deviation of Large Gear

A. *Measurement method of on- machine measurement*

The measurement method used in this study is shown in Figure 1.

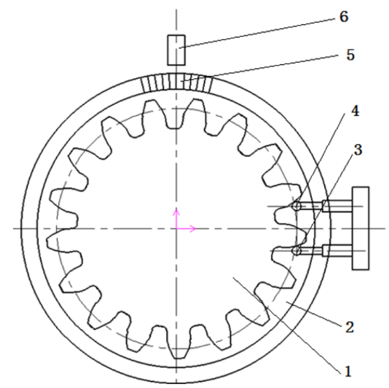

Figure 1. 1-Measuring method schematic measured gear; 2-rotary table; 3-probe 1; 4-probe 2; 5-circular grating; 6-grating reading head

In this measuring method, The measuring device is composed of a rotary table 2, a circular grating 5, a grating readhead 6, a Probe 1 and a Probe 2. The worm wheel to be tested is mounted on the rotary table of the machine tool, and the rotary table rotates at a constant speed during measurement.

1) When measuring by the relative method, 1, 2, 3, 4 can be selected and combined.

The relative method derivation formulas (1), (2), (3), (4) are as follows, where P_{2i} is the reading of the probe 2,P_{1i} is the reading of the probe 1, $\overline{p}$ is the average value of P_i, fpt is the pitch deviation, and Fpk is the cumulative deviation of the pitch:

$$P_i = P_{2i} - P_{1i} \tag{1}$$

$$\overline{P}_i = \frac{1}{n}\sum_{i=1}^{z} P_i \tag{2}$$

$$fpt_i = P_i - \overline{P_i} \tag{3}$$

$$Fpk = \sum_{i=1}^{k} fpt_i \tag{4}$$

2) When measuring by the absolute method, a combination of 1, 2, 3, 5 or 1, 2, 4, 5 can be selected.

Absolute method derivation formulas (5), (6) are as follows, where θ_i is the current reading of the grating, θ_{i-1} is the reading of the previous tooth grating, P_{1i} is the current reading of the probe 1, and $P_{1(i-1)}$ is the reading of the previous tooth probe;

$$fpt_i = (\theta - \theta_{i-1})r - \pi m + P_{1i} - P_{1(i-1)} \tag{5}$$

$$Fpk_i = (\theta_i - \theta_0)r - i\pi m + P_{1i} - P_{10} \tag{6}$$

B. Mechanical Structure Design

The overall scheme of the system is shown in Figure 2. The measuring system, as an independent integral part, is placed on the right side reserved position of the worktable of the worm gear hobbing machine to realize on-line measurement of the machined worm wheel.

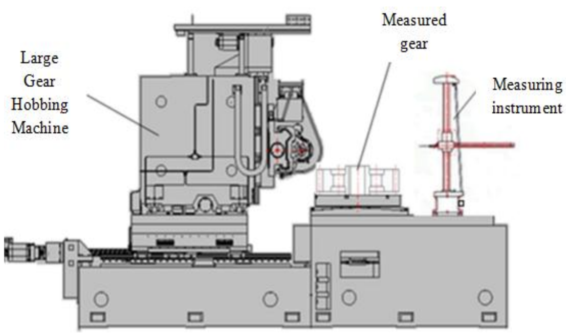

Figure 2. System overall plan

In the aspect of mechanical structure design , servo motor drive - ball screw drive - linear guide is adopted to realize linear motion in two directions: X1, X2 in radial direction and Z in axial direction. The double probes 1, 2 are mounted on the X1-axis of the side-mounted measuring machine, and the X1-axis drives the in-and-out slots to achieve measurement movement.

In order to improve the positioning accuracy of the measuring instrument, rough and fine two-stage positioning(namely X1,X2) is adopted in the radial (X-axis). In order to improve the positioning accuracy of the X1-axis, a high precision grating is used to realize the feedback of the probe position and to form a closed-loop control system with the servo motor.

C. Hardware Scheme of Measurement System

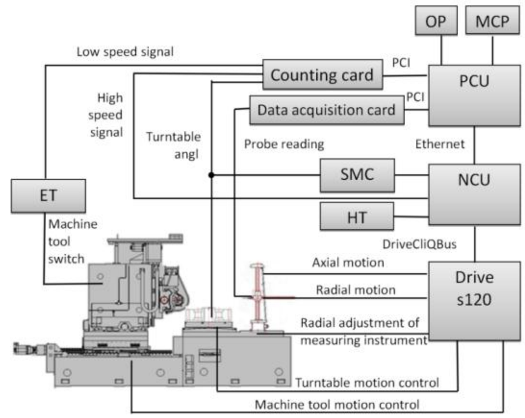

Figure 3. Hardware system diagram

As shown in Figure 3, the on-machine measurement system uses an industrial control computer as the measurement computer. The measuring computer is connected to the machine tool CNC system PCU via Ethernet. Measurement software is installed in the measurement computer to perform tasks such as data acquisition, error assessment, and management of measurement data. The measurement system controls the movement of the CNC table and the measurement movement of the measuring instrument through the NCU. The input and output control of the measurement system switching quantity is realized by the ET module of the numerical control system, and the real-time handshake between the measuring computer and the NCU is realized by using the IO channel on the counting card and the high-speed I/O port of the NCU.

D. Software scheme of measurement system

The measurement software is divided into two parts: on-machine measurement software and numerical control system man-machine interface software [8][9]. The entire measurement system software consists of 4 modules. The measurement module, The data processing module, The data management module, The debugging module.

The measurement module is responsible for data acquisition, parameter setting and control of manual or automatic measurement process.

The data processing module mainly completes the pre-processing of collected data, the calculation and determination of measured data, the evaluation of uncertainty, the generation of measurement reports and the calculation of Fp compensation data.

Data management module is responsible for the management of measurement parameters, measurement standards, measurement data and measurement reports.

The debugging module is mainly responsible for assisting debuggers to complete sensor calibration, IO debugging, motion control debugging and fault diagnosis.

III. MEASUREMENT EXPERIMENT

In order to test the performance of the whole machine, we carried out testing experiments on the worm wheel machined by WG37125CNC high-precision CNC worm gear hobbing machine. The parameters of worm gear tested are shown in Table 1:

TABLE I. BASIC PARAMETERS OF THE CHECKED WORM WHEEL

Attributes	parameter
Worm gear material	ZCuSn10Pb1
Hardness	HB170-215
Modulus	6.4
Number of teeth	111
Tip height coefficient	1
Tooth angle	15o
Lead angle	5o27’23”

In order to check the repeatability of the measurement results of the on-line measurement system under the same probe adjustment and the measurement effect of different measurement methods. We have completed one-time adjustment of the probe, and then use the probe with a diameter of 2mm to measure the same gear for 10 consecutive times .

Measurement results can be seen from the table 2:

TABLE II. SUMMARY OF THE UNCERTAINTY OF THE RESULTS OF REPEATED TEN TURNS EXPERIMENT ON THE LEFT TOOTH SURFACE

Relative method	deviati on	Standard deviation	Range	Tolerance ratio
Relative method	fpt	0.145	0.40	8.89%
	Fp	1.076	2.92	11.7%
Absolute method	fpt	0.242	0.81	18%
	Fp	0.220	0.72	2.88%

As can be seen from the above table:

1) The standard deviation of the left flank pitch deviation fpt with the relative method is below 0.2 microns, the range of 10 measurements is below 0.6 microns, and the ratio of the range of 10 measurements to the tolerance of the 3 grade precision worm gear is about 1/10. the standard deviation of the cumulative total deviation of the left flank pitch is basically below 1.5 microns, and the range of 10 measurements is below 5 microns, and the range of 10 measurements is less than 1/5 of the tolerance of the 3 precise worm. The above results show that the on-machine measurement system has better measurement repeatability.

2) The standard deviation of the left tooth surface pitch deviation fpt with absolute method is basically below 0.25 microns, the range of 10 measurements is below 0.9 microns, the ratio of the range of 10 measurements to the tolerance of the 3 grade precision worm gear is 1/ 5 or less; the standard deviation of the cumulative total deviation of the left flank pitch is about 0.3 μm, the range of the 10 measurements is about 1 μm, and the tolerance of 10 measurements is less than 1/20 of the tolerance of the 3 grade worm. The above results show that in the case of absolute evaluation, the on-machine measurement system has better measurement repeatability than the relative method.

The measurement results of each tooth when the left flank is evaluated by the relative method (a, b)and the absolute method (c, d)are shown in Fig.4:

As can be seen from the figure 4:

The relative method measures the maximum difference of the left flank fpt to 1.15um (22 teeth), the maximum difference of Fpk is 6.30um (47 teeth), and the maximum difference of the right flank fpt is 1.18um (48 teeth), Fpk The maximum range is 4.06um (94 teeth).The extreme difference of Fpk is due to the cumulative effect of the pitch error when measured by the relative method.

Absolute method measures the maximum difference of left flank fpt to 1.40um (55 teeth), the maximum range of Fpk is 1.86um (105 teeth), and the maximum difference of right flank fpt is 1.36um (86 teeth), Fpk The maximum range is 1.61um (55 teeth).Compared with the relative method evaluation, The results indicate that the range difference of the pitch cumulative deviation Fpk is much smaller than that in the relative method evaluation。the absolute method has no cumulative effect of error，but the range difference of fpt in each tooth surface absolute evaluation is slightly larger than the extreme difference of fpt in the relative method evaluation.

IV. CONCLUSION

In view of the limitation of absolute and relative methods in pitch deviation measurement, a high-precision on-machine measurement method for large gear pitch deviation using relative method and absolute method simultaneously is proposed. The accurate positioning of the secondary positioning mechanism of the mechanical body and the reliable operation of the software and hardware in the mechanical measuring instrument system provide the guarantee for the accuracy of the measurement method based on the diameter and modulus of the gear to be measured. Through repeated measurement It is found that the maximum range of the pitch error measurement method selected according to the diameter and modulus of the measured gear is about 10% of worm gear tolerance for 3 grade precision, which shows that the whole on-line measurement system has high repeatability.

V. ACKNOWLEDGMENT

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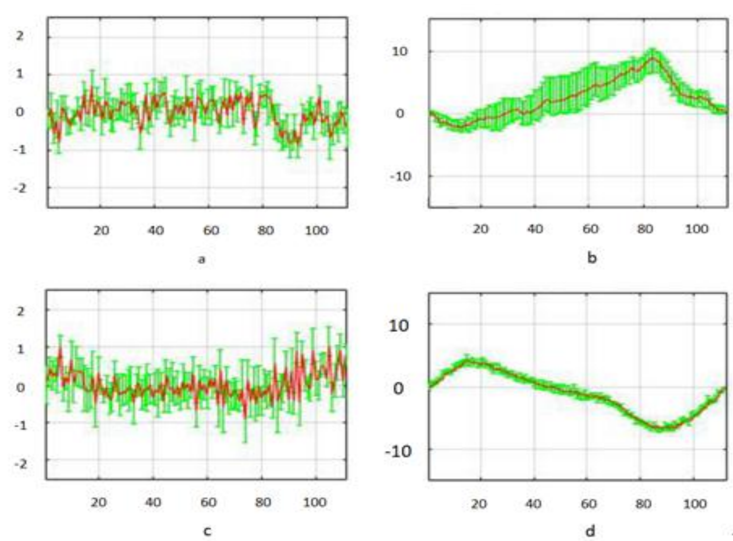

Figure 4. The measurement knot of each tooth when evaluating the left tooth surface by the relative method and the absolute method of 10 turns measurement(a)Relative method to measure the deviation of left tooth surface pitch; (b)Relative method to measure the accumulated deviation of left tooth surface pitch; (c)Absolute method to measure the deviation of left tooth surface pitch; (d)Absolute method to measure the accumulated deviation of left tooth surface pitch