DEVELOPMENT OF HIGH ACCURATE GEAR ARTIFACT MEASURING INSTRUMENT BASED ON LASER INTERFEROMETRY

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Abstract: (250 Words)

A specialized high accurate gear artifact measuring instrument based on laser interferometry is developed in National Institute of Metrology (NIM, China), to fulfill the increasing demand for high accurate calibration of gear artifacts. This measuring instrument mainly consists of three linear guide rails, a rotary table, a 3D scanning probe and a laser measuring system. In the laser measuring system, laser beam from laser head is splited along two paths, one is arranged tangent to the base circle of gear for the measurement of profile deviation, another is arranged parallel to the gear axis for the measurement of helix deviation, both laser measurement performed with a resolution of 0.3nm. To minimize the influence of Abbe error, two cube-corner reflectors are placed close to the tip of probe. This measuring instrument operated automatically, during the measurement of gear artifact, all the signals from guide rails, rotary table, probe and laser measuring system are obtained synchronously. A software collects all the data for further calculation and evaluation. Development of this instrument makes it possible to guarantee the measurement of profile and helix direct traceable to the standard laser wavelength.

Keywords: gear measuring instrument, Abbe error, gear artifact, traceability, laser interferometry

1. INTRODUCTION

Gear artifacts including involute, helix and pitch artifact comprise a known involute contour, helix contour or pitch contour separately. They are usually manufactured accurately for performance verification of gear testing machines and of coordinate measuring machines. Since the gear artifacts possess the high authority in the calibration chain [1], they should be calibrated with a high accuracy. A typical well-known involute artifact measuring device was developed by Beyer of PTB [2], which operated according to the involute generation principle. The traceability of this device was based on the accuracy of measurement for the roll cylinder diameter and the accuracy of the tactile probe. From then on, different types of high accurate measuring devices for the calibration of gear artifact were developed and improved by some national metrology institutes (NMI) [3]-[5]. The high accurate measuring devices are essential since the gear produces are more high precise than before, and the calibration uncertainty of gear artifacts should be reduced as much as possible.

National Institute of Metrology (NIM) is the national metrology institute of China, which is responsible for providing metrology services of the highest accuracy and reliability to customers. NIM had established a serial of measuring devices for the calibration of involute, helix and pitch from 1976. However each device is exclusive to one type of gear artifact, and the measuring capability is not sufficient. Therefore, the NIM is developing a high accurate gear artifact measuring instrument based on laser interferometry.

2. CONCEPT OF MEASUREMENT AND CONFIGURATION OF INSTRUMENT

2.1 Concept of measurement for involute artifact

The classic method for involute measurement is based on the generative principle (Fig.1) [6], in which, an involute can be generated by a beam and base circle rolling with each other without slip. The involute calibration concept in coincide with the principle described above, that is a reference profile is created to compare to the actual gear profile, and the discrepancy would be detected by a sensitive probe. In this combined movement, the probe moves along a path which is tangent to the base circle of gear, and the displacement equals to the length of roll L_a, a corresponding rotational angle of gear is θ_a. The mathematica relationship between L_a and θ_a is defined as the following equation:

$$L_a = r_b \theta_a \quad (1)$$

Where r_b denotes the radius of base circle.

The most common type of involute measuring instrument today is the CNC instrument. These instruments consist of a rotary axis and a linear axis. Each axis is fitted with a high resolution scale respectively, and a numerical servo system would keep these two moments above simultaneously identical to equation (1). In this case, the probe deflection represents the deviation of gear profile from the nominal involute curve. If the gear profile is a perfect involute curve, the probe deflection would keep constant after contact with gear flank from root to tip.

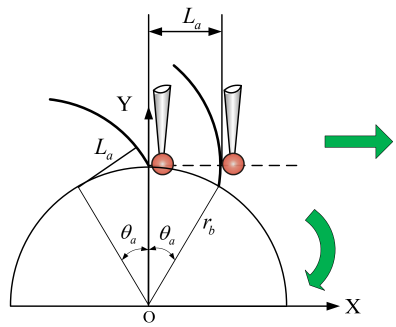

Fig.1: The generative principle for involute measurement

It is important to analyze the error sources of this measuring principle. One critical error is Abbe error arised by geometric error of guideway, the probe carrier slide on this guideway. For each translation movement, there are six geometric errors, they are defined as position error, straightness error in two directions, roll angle error, pitch angle error and yaw angle error . These angle errors have a negative effect on Abbe error, and the size of Abbe error depends on the Abbe offset which defined as the distance between the reference linear encode and the center of probe as shown in figure 2. The larger this distance the larger translation error would be induced by angle error. The mathematica relationship for translation error Δe , Abbe offset L_{offset} and pitch angle error ρ can be described as the following equation:

$$\Delta e = L_{offset}\rho \tag{2}$$

Since it is not possible to design an instrument without any Abbe offset, the objective is thus to minimize it or maintain it as a fixed distance which can be compensated by a kinematic model.

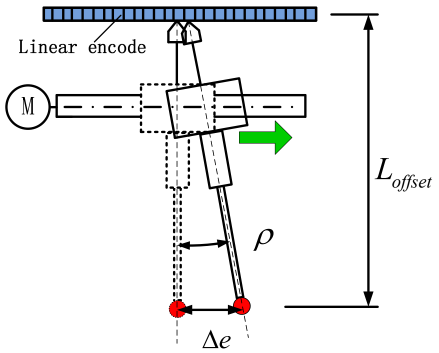

Fig.2: Illustration of translation error, Abbe offset and pitch angle error

To realize the Abbe offset, a laser measuring system with high resolution is applied. In which, the retroreflector is placed close to the probe, and the laser beam from laser head is arranged parallel to the linear axis. By this way, the laser measuring axis will replace the linear encode as the reference scale, which is more accurate and traceable to the standard laser wavelength.

2.2 Concept of measurement for helix artifact

The classic method for helix measurement is also based on the generative principle. A reference spatial helix can be created by the combined movements of rotation and translation along the axis of rotation. In the measurement of helix, a sensitive probe is brought into contact with the tooth near to pitch circle, and is then carried along a direction parallel to the gear axis while the gear is rotated. The gear rotation θ_b must be in a direct relationship with the axial motion of probe L_b according to the mathematical description as following:

$$L_b = \frac{r\theta_b}{\tan\beta} \tag{3}$$

Considering error sources of helix measurement, analogously, Abbe offset and angle error of axial axis led to the Abbe error. To minimize the influence of Abbe offset, a laser measuring axis is applied as well, and the retroreflector is also placed close to the tip of probe but installed in a vertical position.

2.3 Configuration of laser measurement system

Both the laser measuring axes for involute and helix should be arranged in one laser measurement system, each measuring axis requires an interferometer and associated retroreflector. The configuration with all components for this measurement system is as illustrated in Fig.3. The laser beam leaves the laser head, and is split into two laser beams along two directions. Two retroreflectors are attached near to the tip of probe. It is important to know that the optics arranged in Z axis (surrounded by a rectangle of dashed) should be moved together when the involute measurement is performing. Similarly, the optics arranged in X axis should be moved together when the helix measurement is performing.

The laser head and corresponding optics are chosen from Agilent company. The single beam interferometer is use the cube-corner as the measurement reflector. The basic resolution of an interferometer system is λ/2 (λ is the laser wavelength), but it can be electronically extended to λ/2048, that is a resolution of 0.3nm can be achieved.

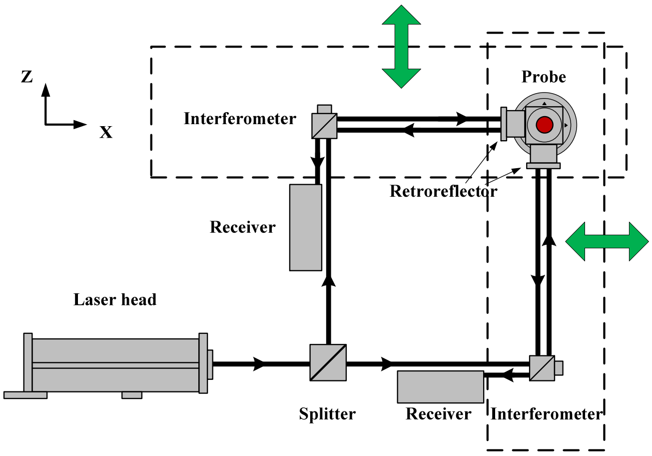

Fig.3: Configuration of laser measurement system

2.4 Configuration of measuring instrument

The main mechanism of measuring instrument for gear artifact is designed as a 4-axis CNC gear measuring instrument, which comprise 3 linear axes and 1 rotary axis (Fig.4). Linear axes are vertical, radial and tangential axes relative to rotary axis. According to the Eq.(1)and Eq.(2), the moving accuracy of the linear axis and rotary axis are critical for generation of reference involute or helix. To obtain a high geometrical accuracy, total of 4-axis are designed with granite guideways, and air bearing technology is applied in it. Sliders of 3 linear axes are driven by the ball screw driving system with zero backlash. A tailstock with a center is installed for between-centers mounting of gear artifact. The instrument`s main spindle axis should be coincident with the gear axis.

For simplify and improve the performance of rotary axis, a direct drive torque motor is applied to replace conventional multi-stage transmission rotary table.

Importantly, the accuracy of the rotary table can be improved up to 0.1" by the technique of self-calibration.

In additional to the 3-axis measuring system, a 3-axis CNC moving system is designed for adjustment of laser measuring system. As described in section 2.3, the two laser measuring axes in Z axis and X axis should work during the process of measurement. For example, to keep the laser beam in Z axis can be reflected when probe moving along X axis, the corresponding interferometer should moves synchronously, thus a slide and a guideway are necessary. It should be noticed that, gear artifacts could be a variety of pitch diameter, thus the whole laser measuring system including laser head need to be moved as the probe moves in Y axis.

To improve the real-time accuracy of scanning measurement, a 3D high accuracy scanning probe is applied in this measuring instrument, which is manufactured by Renishaw and named as SP80H. The SP80 is a passive measuring probe with serial kinematics and optical sensing of displacement. The movement of the stylus is transferred to a cube with precise gratings and recorded by three digital reading heads with a measuring resolution of 20 nm. Importantly, this probe is capable to maintain the operating range even when using the heaviest stylus mass (300g), thus the two retroreflectors can be attached to stylus holder directly.

The major specifications of this measuring instrument are listed in Tab.1.

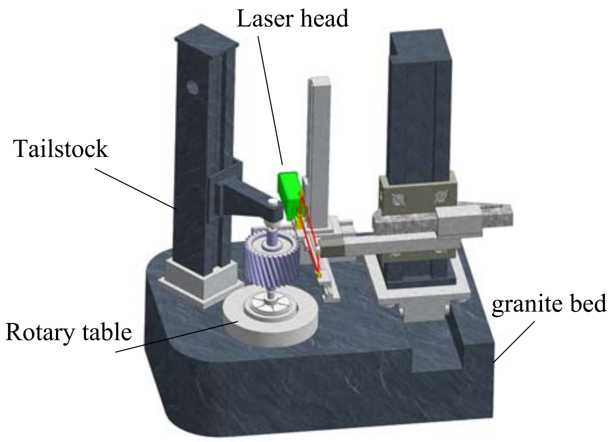

Fig.4: Configuration of measuring instrument

Table 1: Major specifications of measuring instrument

characteristics	value
Gear outer diameter	max.650mm
Gear module range	1-12mm
Gear weight	Max.10kg
Measuring speed	Max.10mm/s
Measuring accuracy of probe	＜1.0μm
Measuring accuracy of rotary table	＜0.1"
Resolution of linear scale	20nm
Resolution of rotary scale	0.035"
Resolution of laser interferometer	0.3nm

3. FIRST MEASUREMENTS

In order to verify the efficiency of this measuring instrument, first measurements on gear artifact were carried out according to the generative principle. In the first measurement, two types of gear artifacts were used, which are involute artifact and helix artifact and their parameters are shown in Tab.2.

Table 2: Major parameters of gear artifacts

parameters	value	
type of artifact	involute	helix
Pressure angle α_n	20 °	20 °
Helix angle β	0 °	31 °
Pitch diameter d_0	419.888mm	209.578mm
Base diameter d_b	394.566mm	200mm
Face width b	25mm	160mm

According to the ISO 1328-1:1995 and ISO/TR 10064-1:1992, the deviations need to be evaluated for involute artifact are total profile deviation (F_α), profile form deviation ($f_{f\alpha}$), profile slope deviation ($f_{H\alpha}$). The deviations for helix artifact are total helix deviation (F_β), helix form deviation ($f_{f\beta}$), helix slope deviation ($f_{H\beta}$).

The involute artifact was measured in four positions successively which are more or less uniformly distributed on the circumference to determine the eccentricity of gear axis, in each position, 5 measurements will be repeated in a short time. The evaluation results are shown in Tab.3

The helix artifact was measured in two directions to determine the alignment error of the tailstock center. In each direction, 5 measurements will be repeated in a short time. The evaluation results are shown in Tab.4

It can be observed from Tab.3 that total of the results in four uniformly distributed positions are coincide to each other almost, the discrepancy small than 1μm. The results of helix illustrate that the gear datum axis of rotation is coincident with the instrument`s spindle axis.

Table 3: Measurement results of involute artifact

measurand	result(μm)			
	0 °	90 °	180 °	270 °
F_α	1.7	1.5	1.5	1.2
$f_{f\alpha}$	1.5	1.3	1.3	1.2
$f_{H\alpha}$	0.7	0.5	0.6	0.3

Table 4: Measurement results of helix artifact

measurand	result(μm)	
	normal	inverse
F_β	3.8	3.3
$f_{f\beta}$	3.0	2.7
$f_{H\beta}$	3.4	-3.1

4. CONCLUSIONS AND OUTLOOK

NIM has developed a high accurate measuring instrument for gear artifact measurement. Both elements of involute and helix can be measurement. The measurement is based on classic gear generative principle, the reference involute and helix are created by a 4-axis CNC mechanism.

A laser interferometer is applied to create two laser measuring axis for involute and helix separately. By this way, the Abbe offset would be minimize as much as possible, the result of measurement would be improved and traceable to the standard laser wavelength.

In future, most experiments will be performed under different measuring speed, and the results will illustrated the consistency and stability of this instrument.

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