Cutting Error Measurement of Harmonic Drive Gears Using Laser Probes

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1. Introduction
The harmonic drive is a precision mechanism that has a high reduction ratio with low backlash[1]. The dimensional tolerances required for the precision gears used in the harmonic drive are getting tighter and tighter[2]. To assure the quality of the machined gears, it is necessary to accurately measure cutting errors of hobbing machines for cut of the gears. It is also desired to perform the measurement efficiently so that the machining efficiency can be improved[3].

In this paper, we develop a new system of cutting error measurement for the flexspline(FS) gear of the harmonic drive. Two laser probes[4] are used in the measurement. The non-contact measurement avoids deforming the gear geometries, and leads to a high-speed measurement.

2. Principle of measurement
In the case of measuring the radial cutting error component, two laser displacement probes are employed to replace the conventional method of using Van Kuven wires and a micrometer[5]. Fig.1 shows a schematic comparison between the conventional method and the new method. In the conventional measurement method of using wires and micrometers, the wire is placed between two adjacent gear teeth, and the measurement over wires is obtained by the micrometer. If the teeth are over-cut, the tooth thickness decreases and the space interval between the gears increases. As a result, the contact points of the wire will move toward the gear center. The radial cutting error component can then be evaluated from the measurement over wires.

In the developed laser probe-based measurement system, the two laser beams are projected onto different tooth surfaces.

Fig. 1 A comparison between the conventional Van Kuven wire method and the new method
The incident light spots on the tooth surfaces function as the contact points of the wire on the tooth surfaces. The radial cutting error component can be obtained from the probe outputs. The measurement uncertainty can be greatly reduced through rotating the gear and performing the measurement over the entire teeth. The influences of the alignment errors as well as the rotational errors of the rotary gear stage can be removed by a differential data processing technique described as follows.

Fig. 2 shows the measurement model taking eccentricity error of alignment and rotation error of the gear stage into consideration. Assume that the eccentricity error of the when FS attached is \( d \), and X-, and Y-directional components of the rotation error are \( e_x(\theta_i) \), \( e_y(\theta_i) \), respectively. The probe outputs \( D_1(\theta_i) \), \( D_2(\theta_i) \) can be expressed as:

\[
D_1(\theta_i) = g_1(\theta_i) - \{d \cos \theta_i + e_x(\theta_i)\}\tan \phi_i(\theta_i) + d \sin \theta_i + e_y(\theta_i) \\
D_2(\theta_i) = g_2(\theta_i) + \{d \cos \theta_i + e_x(\theta_i)\}\tan \phi_2(\theta_i) + d \sin \theta_i + e_y(\theta_i)
\]

where \( g_1(\theta_i) \), \( g_2(\theta_i) \) are the probe outputs when eccentricity and rotation errors don’t exist.

Subtracting (2) from (1), the differential output \( \Delta D \) becomes

\[
\Delta D = D_1(\theta_i) - D_2(\theta_i) \\
= g_1(\theta_i) - g_2(\theta_i) - \{d \cos \theta_i + e_x(\theta_i)\}\{\tan \phi_1(\theta_i) + \tan \phi_2(\theta_i)\}
\]

It can be seen that the Y-directional components of eccentricity and rotation errors are removed. To reduce the influence of the X-directional error components, an average of the data over one rotation is carried out. The averaged result \( \bar{\Delta D} \) can be denoted as:

\[
\bar{\Delta D} = \frac{\sum_{i=1}^{N} \Delta D}{N} = \frac{\sum_{i=1}^{N} g_1(\theta_i) - g_2(\theta_i)}{N} - \frac{\sum_{i=1}^{N} \{d \cos \theta_i + e_x(\theta_i)\}\{\tan \phi_1(\theta_i) + \tan \phi_2(\theta_i)\}}{N}
\]

where, \( N \) is a sampling number over one rotation.

The residual error term \( \Delta E_X \), which is caused by non-synchronous rotation components of the X-directional rotation error, is expected to be smaller than \( \Delta G \). Average of data over multiple rotations can also be carried out to reduce \( \Delta E_X \) furthermore. As a result, the cutting error, which is a function of \( \Delta G \), can be evaluated from \( \bar{\Delta D} \) accurately.
3. Experiments

Fig. 3 shows a schematic of the measurement system. The system consists of two laser probes and a rotary stage on which the gear is mounted. Resolution of the laser probe is 10 nm. The displacement interval L was approximately 35mm. The probe outputs were taken into a personal computer through an AD board. The rotary stage is driven by a stepping motor. The radial error motion of the stage is approximately 5 µm. The time for the measurement of one rotation is 60 seconds. The eccentricity of the FS center is approximately 5 µm.

Three FS samples with cutting errors of 0, -5, +5 µm were used in the experiment. The samples are referred to as standard FS, -5 µmFS and +5 µmFS, respectively. The cutting errors were generated by adjusting the depth of cut when the samples were machined on the hobbing machine. Measurements were made after the laser probes and the rotary stage had been powered for an hour. The FS samples were cleaned by ethanol before the measurement. The temperature of the measurement room was approximately 23℃ and the humidity was under 30%.

Fig. 4 shows the measurement results of ΔD defined in Eq.(3) for different FS samples. The data of one rotation are shown in figure. The horizontal axis shows the rotary angle of the stage and the vertical axis shows the differential output ΔD. It can be seen that influences of the eccentricity and rotation errors are included in the differential output ΔD. The eccentricity errors were not constant for different FS samples since they were
mounted on the stage at different times.

Fig.5 shows $\overline{\Delta D}$ defined in Eq.(3), which is the average of the differential output $\Delta D$ over one rotation. The horizontal axis of figure shows the applied FS cutting error and the vertical axis shows $\overline{\Delta D}$. It can be seen that the cutting errors have a good correlation with $\overline{\Delta D}$, which indicates the feasibility of the developed measurement method.

Measurements were also made when a layer of cutting oils remained on the FS surface. Fig.6 shows the probe output with oils on the surface. The result after the oil was removed from the surface by compressed air is also shown in the fig.6. The horizontal axis shows the rotary angle of the rotary stage and the vertical axis shows one of the laser probe outputs. It can be seen that the laser probe did not function well for the sample with oil on its surface. However, the laser probe was able to measure the sample when the surface was cleaned by compressed air. This indicates that blowing off cutting oil from the sample surface with compressed air is an efficient method for cleaning the sample surface in practical use.

4. Conclusions

A new method has been developed for measurement of cutting errors of flexspline gears of the harmonic drive through using two laser displacement probe in stead of a Van Kuven wires and a micrometer. An averaging operation of the data over one rotation of the gear stage removes the influence of eccentricity and rotation errors. The effectiveness of using compressed air to remove the oil from the gear surface, which enables the measurement of laser probes, has also been confirmed.

References