Method for Inspection of Spiral Bevel Gears in Klingelnberg Cyclo-Paloid System*

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In this paper, an inspection method for detecting machine setting errors such as tool setting and workpiece setting errors in spiral bevel gear cutting in a Klingelnberg cyclo-paloid system is proposed. In this method, the coordinates of many points on the gear tooth surface are measured and a theoretical gear tooth surface expressed as a function of the machine settings is estimated by the method of least squares so that the surface fits the measured data. The deviations of the estimated machine settings from the design settings are considered to be the machine setting errors. The machine setting errors in gear cutting were detected using this method and corrective cutting which compensated for the errors was carried out. As a result, more accurate gears could be obtained.

Key Words : Measurement, Machine Element, Gear, Inspection, Spiral Bevel Gear, Klingelnberg Cyclo-Paloid System, Method of Least Squares, Machine Setting Error, Coordinate Measuring Machine

1. Introduction

The pair of spiral bevel gears in a Klingelnberg cyclo-paloid system^{(1),(2)} can be expected to have a good contact pattern because the tooth surfaces are fundamentally conjugate. In practice, however, a gear pair with a good contact pattern is difficult to obtain because of machine setting errors such as tool setting and workpiece setting errors in bevel gear cutting. In order to develop a good contact pattern, it is necessary to recut on the basis of contact pattern observation. Such recutting depends heavily on skillful workmanship or on trial-and-error cutting methods.

One of the authors has proposed an inspection method for detecting machine setting errors in order to obtain an accurate gear without recutting based on the contact pattern observation. The errors are detected from tooth surface measurement data using

a coordinate measuring machine (CMM)⁽³⁾⁻⁽⁵⁾. In the previous paper⁽⁵⁾, the machine settings in which errors may occur were called error factors and the selection method of the error factors to be detected was presented. In this selection method, an error factor having significant influence on the gear tooth surface must be selected. This method was applied to hypoid gears and the machine setting errors were successfully detected. However, this method was not successful in application to spiral bevel gears in a Klingelnberg cyclo palloid system. It was clear that the method broke down in the case that the error of the selected error factor was small. We found that the previous result was acceptable when the error of the error factor happened to be large.

In this paper, a new method for finding the error factors from the tooth surface measurement data, namely, a selection method of error factors, is proposed, and the inspection method is applied to spiral bevel gears in a Klingelnberg cyclo-paloid system.

2. Basic Concept of Inspection Method

In spiral bevel gear cutting, machine setting errors such as tool setting and workpiece setting

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errors are unavoidable. Each machine setting error influences the gear tooth surface. This study is based on such concepts. The coordinates of many points on the gear tooth surface are measured using a CMM and a theoretical gear tooth surface expressed as a function of the machine settings is estimated by the method of least squares so that the surface fits the measured data. The deviations of the estimated machine settings from the design settings are considered to be the machine setting errors in gear cutting. These errors can be fed back to the gear cutting process, so that more accurate gears are obtained.

3. Inspection of Spiral Bevel Gears

For measurement, the spiral bevel gear is set arbitrarily on a CMM. The positions of the gear axis and the datum plane must be determined by measurement independent of the tooth surface measurement because the gear is set arbitrarily. We can make the origin O_g and gear axis z_g in the coordinate system $O_g-x_g y_g z_g$ fixed to the gear coincide with the origin O_m and axis z_m in the coordinate system $O_m-x_m y_m z_m$ fixed to the CMM, as shown in Fig. 1. However, the angle by which the gear is rotated about its axis is uncertain. Therefore, we must define an unknown angle Φ between axis x_g and axis x_m .

Figure 2 shows that the tooth surface X_m and the spherical probe of radius r_0 are in contact with each other at point Q_m . The coordinates of the probe center P_m are theoretically expressed as a position vector $\mathbf{P}(P_x, P_y, P_z)$ in $O_m-x_m y_m z_m$:

$$\mathbf{P} = \mathbf{X}_m + r_0 \mathbf{N}_m \quad (1)$$

On the other hand, the coordinates of the probe center P_m are measured by the CMM. The measured coordinates are expressed as a position vector $\mathbf{M}(M_x, M_y, M_z)$.

$\mathbf{P}$ and $\mathbf{M}$ expressed in the rectangular coordinate system $O_m-x_m y_m z_m$ are transformed into a cylindrical coordinate system $O_m-r_m \theta_m z_m$ the cylindrical axis of which is z_m as shown in Fig. 3:

$$\begin{aligned} \mathbf{P} &= (P_r, P_\theta, P_z)^T \\ \mathbf{M} &= (M_r, M_\theta, M_z)^T \end{aligned} \quad (2)$$

Under this transformation, each component (P_x, P_y, P_z) of $\mathbf{P}$ is expressed in the following form⁽⁵⁾:

$$\begin{aligned} P_r &= P_r(\nu, \psi; C_1, C_2, \dots, C_k) \\ P_\theta &= P_\theta(\nu, \psi; \Phi, C_1, C_2, \dots, C_k) \\ P_z &= P_z(\nu, \psi; C_1, C_2, \dots, C_k) \end{aligned} \quad (3)$$

where ν and ψ are the parameters expressing the tooth surface and are variable. On the other hand, $C_1, C_2, \dots, C_k$ are the parameters expressing the machine settings and are invariable because the machine settings do not change during the gear cutting process. When the values of $C_1, C_2, \dots, C_k$ are different from the respective design values, we consider that there

are machine setting errors in bevel gear cutting. In this section, we also express the error factors corresponding to these errors as $C_1, C_2, \dots, C_k$.

Let the components P_r and P_z be equal to the components M_r and M_z respectively:

$$\begin{aligned} M_r - P_r(\nu, \psi; C_1, C_2, \dots, C_k) &= 0 \\ M_z - P_z(\nu, \psi; C_1, C_2, \dots, C_k) &= 0 \end{aligned} \quad (4)$$

From Eq. (4), parameters ν and ψ can be determined, being independent of Φ but being dependent on $C_1, C_2, \dots, C_k$.

The determined parameters ν and ψ are substituted into P_θ . Then, the residual E is defined as the difference between the arguments M_θ and P_θ :

Fig. 1 Relation between coordinate systems $O_m-x_m y_m z_m$ and $O_g-x_g y_g z_g$

Fig. 2 Measurement of tooth surface

Fig. 3 Transformation into cylindrical coordinate system

$$E = M_\theta - P_\theta(\Phi, C_1, C_2, \dots, C_k) \quad (5)$$

The coordinates of n points on the gear tooth surface are measured and each residual $E_i (i=1, 2, \dots, n)$ corresponding to the coordinates of the i -th measured point M_i is calculated from Eq. (5). We generally cannot obtain the values of $\Phi, C_1, C_2, \dots, C_k$ so that all the $E_i (i=1, 2, \dots, n)$ are equal to zero. Therefore, we estimate the values of $\Phi, C_1, C_2, \dots, C_k$ so that the sum of the squares of $E_i (i=1, 2, \dots, n)$ can be minimized, namely, we estimate these values by the method of least squares. The sum of the squares of E_i , denoted by F , is as follows:

$$F(\Phi, C_1, C_2, \dots, C_k) = \sum_{i=1}^n E_i^2. \quad (6)$$

However, the extent of the real gear tooth surface is limited compared with the theoretical gear tooth surface, the gear tooth surface is a generated complex surface, and the errors of $C_1, C_2, \dots, C_k$ are small, so that the following two cases may occur. (i) One is that some of the errors in gear cutting have similar influences on the real tooth surface. In this case, it is difficult to distinguish the influences of those errors. (ii) The other is that errors having very significant influences and errors having slight influences on the tooth surface are both contained in $C_1, C_2, \dots, C_k$. In this case, the errors with slight influences are sometimes concealed by the errors with significant influences, so that the errors with slight influence cannot be distinguished. In either case, it is difficult to estimate all the values of $C_1, C_2, \dots, C_k$ simultaneously. In the previous paper⁽⁵⁾, the case (i) was evaluated in terms of the independence among plural error factors, the case (ii) was evaluated in terms of the influence coefficients, and we selected the error factor to be detected according to these two evaluation criteria.

When we consider estimation of the value of C_1 as an example, the value of Φ (Fig. 1) must also be estimated simultaneously because it is an uncertain angle independent of the machine setting errors. The simultaneous equations (7) are obtained by the method of least squares:

$$\frac{\partial F}{\partial C_1} = 0, \quad \frac{\partial F}{\partial \Phi} = 0 \quad (7)$$

4. Selection Method of Error Factors

In the previous paper⁽⁵⁾, we selected the error factor having most significant influence on the tooth surface beforehand and estimated it. In the previous method, however, the estimated theoretical gear tooth surface does not always fit the measured data well and accuracy of fit is not satisfactory in the case when the error of the error factor selected beforehand is small and the errors of other error factors are large. In this

case, if the deviation of the estimated value from the design value is considered to be the machine setting error and the deviation is fed back to the gear cutting process, more accurate gears cannot be obtained. Therefore, the error factors of the occurrence of errors must be found from the measured data. In this section, a method for finding the error factors of the occurrence of errors, namely, a selection method of error factors, is proposed for the first time.

We estimate the values of error factor C_1 and angle Φ from Eq. (7) by assuming that the errors of other error factors are zero. Then, we estimate the values of $C_2, C_3, \dots, C_k$ in the same manner as for C_1 . After these estimates, we calculate Δt according to Eq. (8) for each $C_1, C_2, \dots, C_k$. Δt corresponds to standard deviation in statistics and means the accuracy of fit which expresses whether the estimated tooth surface fits the measured data or not. Δt is calculated using the following equation:

$$\Delta t = S_r \sqrt{\frac{F}{n}} \quad (8)$$

where S_r denotes the mean radius of the gear. When the mean cone distance of the gear is denoted by R_m and the pitch cone angle of the gear is denoted by η , $S_r = R_m \sin \eta$. When the estimated tooth surface fits the measured data $M_i (i=1, 2, \dots, n)$ exactly, Δt is zero. In other words, when the value of Δt is small, we consider that the tooth surface is estimated well by the measured data M_i . Hence, the error factor indicating the smallest Δt is considered first as an error factor to be detected.

However, it is uncertain whether the errors of other error factors are small or not. Therefore, we estimate the values of other error factors separately and calculate each Δt using the estimated value of the first error factor. If there is another error factor for which Δt is smaller than the first one, this error factor is also considered as an error factor to be detected. Otherwise, only the first error factor is considered as an error factor to be detected.

As mentioned above, the deviations of the estimated values of the selected error factors from the design values are considered to be the machine setting errors and corrective cutting which compensates for the errors is carried out.

5. Tooth Surface of Spiral Bevel Gear in Klingelnberg Cyclo-Paloid System

It is necessary to express the equation of the generated gear tooth surface X_m and that of its unit normal N_m in this method. Therefore, X_m and N_m are expressed mathematically in this section.

Since the spiral bevel gear in a Klingelnberg cyclo-paloid system is generated by an imaginary crown

gear whose tooth trace is a trochoid curve, the equations of the generated gear tooth surface and of its unit normal can be expressed by using the equation of the tooth (tool) surface of the crown gear. The concave tool surface of the crown gear is considered in this section, but a similar analysis may be applied to the convex tool surface.

Figure 4 shows the geometrical interrelations of a Klingelnberg cyclo-paloid system. A rolling circle R rolls on a base circle Q which is on the pitch surface of the imaginary crown gear. r and q denote the radii of the circles R and Q respectively. $O-xyz$ is the coordinate system fixed to the crown gear and axis z is the crown gear axis. Axis y coincides with the pitch surface generator⁽⁶⁾. P is a point fixed to the circle R . When the rolling circle R rolls on the base circle Q , the locus on the pitch surface described by the point P is a trochoid curve.

The coordinate system $O_c-x_cy_cz_c$ fixed to the circle R is introduced in order to express the equation of the tool surface of the crown gear. The cutter is attached to the rolling circle R . OO_c is the machine distance and is denoted by M_d . The radii r and q are represented by the equations:

$$r = \frac{Z_w M_d \sin \eta}{Z_b + Z_w \sin \eta}, \quad q = M_d - r, \quad (9)$$

where Z_b is the number of teeth of the generated gear and Z_w is the number of starts of the cutter head.

The cutter and the coordinate system fixed to the cutter are shown in Fig. 5. Although a cutter with linear cutting edges is considered in this paper, a similar analysis may be applied to a cutter with circular cutting edges⁽⁵⁾. r_c is the cutter radius, γ is the pressure angle of the cutter blade, and λ is the parameter representing the linear cutting edge. The edge X_c is expressed in $O_c-x_cy_cz_c$ by the following equation:

$$\mathbf{X}_c(\lambda) = \begin{bmatrix} 0 \\ r_c + \lambda \tan \gamma \\ \lambda \end{bmatrix} \quad (10)$$

The surface of the locus described by $\mathbf{X}_c$ in $O-xyz$ is expressed as:

$$\mathbf{X}(\nu, \lambda) = \mathbf{C}(\theta_1) \mathbf{X}_c(\lambda) + \mathbf{D}(\nu) \quad (11)$$

where

$$\begin{aligned} \theta_1(\nu) &= M_d \nu / r + \theta_0, \\ \mathbf{D}(\nu) &= \begin{bmatrix} -M_d \sin(\nu - \theta_0) \\ M_d \cos(\nu - \theta_0) \\ 0 \end{bmatrix}, \end{aligned} \quad (12)$$

$$\cos \theta_0 = (M_d^2 + R_m^2 - r_c^2) / 2 M_d R_m,$$

$$\cos \theta_0 = (R_m^2 + r_c^2 - M_d^2) / 2 R_m r_c$$

and $\mathbf{C}$ is the coordinate transformation matrix with respect to the rotation about axis z :

$$\mathbf{C}(\theta_1) = \begin{bmatrix} \cos \theta_1 & -\sin \theta_1 & 0 \\ \sin \theta_1 & \cos \theta_1 & 0 \\ 0 & 0 & 1 \end{bmatrix}. \quad (13)$$

Fig. 4 Tooth trace of imaginary crown gear

Fig. 5 Cutter with linear cutting edges

Fig. 6 Locus of cutting edge

In Eqs. (11) and (12), ν is a parameter which represents the swivel angle of the cutter around axis z (see Fig. 6). $\mathbf{X}$ expresses the equation of the tooth (tool) surface of the imaginary crown gear whose tooth trace is a trochoid curve in a Klingelnberg cyclo-paloid system. The unit normal of $\mathbf{X}$ is expressed by $\mathbf{N}$.

The imaginary crown gear is rotated about axis z by angle ψ and generates the tooth surface of the spiral bevel gear. We call this rotation angle ψ of the crown gear the generating angle. When the generating angle is ψ , the coordinate system $O-XYZ$ is rotated about axis z by ψ in the coordinate system $O-xyz$ fixed in space. Therefore, $\mathbf{X}$ and $\mathbf{N}$ are rewritten as $\mathbf{X}_\psi$ and $\mathbf{N}_\psi$ in $O-XYZ$:

$$\mathbf{X}_\psi(\nu, \lambda; \psi) = \mathbf{C}(\psi) \mathbf{X}(\nu, \lambda) \quad (14)$$

$$\mathbf{N}_\psi(\nu, \lambda; \psi) = \mathbf{C}(\psi) \mathbf{N}(\nu, \lambda)$$

When ψ is zero, $O-XYZ$ coincides with $O-xyz$. Assuming the relative velocity $\mathbf{W}(\mathbf{X}_\psi)$ between the crown gear and the generated gear at the moment when generating angle is ψ , the generating condition of the gear teeth is as follows:

$$\mathbf{N}_\psi(\nu, \lambda; \psi) \cdot \mathbf{W}(\nu, \lambda; \psi) = 0, \quad (15)$$

from which the following equation is obtained:

$$\lambda = \lambda(\nu; \psi) \quad (16)$$

Substituting Eq. (16) into Eq. (14), $\mathbf{X}_\psi\{\nu, \lambda(\nu; \psi); \psi\}$ which expresses the generating line of the gear tooth surface and its unit normal $\mathbf{N}_\psi\{\nu, \lambda(\nu; \psi); \psi\}$ in $O-XYZ$ can be obtained.

As shown in Fig. 7, $\mathbf{X}_\psi$ in $O-XYZ$ is transformed into $O_g-x_gy_gz_g$ and is denoted by $\mathbf{X}_g$. Since $O_g-x_gy_gz_g$ is rotated by angle $-\psi/\sin \eta$, $\mathbf{X}_g$ is represented by the equation:

$$\mathbf{X}_g(\nu, \psi) = \mathbf{C}^{-1}\left(\frac{-\psi}{\sin \eta}\right) \mathbf{A}^{-1}\left(\frac{\pi}{2} + \eta\right) \mathbf{X}_\psi(\nu, \psi), \quad (17)$$

where $\mathbf{A}$ is the coordinate transformation matrix with respect to the rotation about axis X :

$$\mathbf{A}\left(\frac{\pi}{2} + \eta\right) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\left(\frac{\pi}{2} + \eta\right) & -\sin\left(\frac{\pi}{2} + \eta\right) \\ 0 & \sin\left(\frac{\pi}{2} + \eta\right) & \cos\left(\frac{\pi}{2} + \eta\right) \end{bmatrix} \quad (18)$$

In Eq. (17), regarding ν and ψ as parameters, surface $\mathbf{X}_g$ expresses the equation of the generated gear tooth surface. The unit normal $\mathbf{N}_g$ of $\mathbf{X}_g$ is

$$\mathbf{N}_g(\nu, \psi) = \mathbf{C}^{-1}\left(\frac{-\psi}{\sin \eta}\right) \mathbf{A}^{-1}\left(\frac{\pi}{2} + \eta\right) \mathbf{N}_\psi(\nu, \psi). \quad (19)$$

$\mathbf{X}_g$ and $\mathbf{N}_g$ in $O_g-x_gy_gz_g$ are transformed into $O_m-x_my_mz_m$ and are denoted by $\mathbf{X}_m$ and $\mathbf{N}_m$ in Eq. (1). Equations (17) and (19) include M_d , r_c , γ , η , etc.

Fig. 7 Relation between coordinate systems $O-XYZ$ and $O_g-x_gy_gz_g$

Fig. 8 Gear setup on CMM

which correspond to $C_1, C_2, \dots, C_k$ in Eq. (3). When these values are different from the design values, there are machine setting errors in gear cutting.

6. Results of Inspection

An inspection of the spiral bevel gear in a Klingenberg cyclo-paloid system was carried out in order to confirm the validity of the proposed method. The dimensions of the inspected gear are shown in Table 1. The cutter and machine settings are shown in Table 2. A spherical probe of radius $r_0 = 0.997$ mm was used in the measurement shown in Fig. 8. We measured twenty six points on the tooth surface in order to avoid the influence of accidental errors.

The error factors in spiral bevel gear cutting may include machine distance M_d with respect to the gear cutting machine, cutter radius r_c and pressure angle γ with respect to the cutter, and pitch cone angle η , mounting distance L (see Fig. 7), and offset distance l_x along the X axis in $O-XYZ$, with respect to the workpiece setting.

The values of error factors and Φ were estimated from the measured data separately in order to find the error factors of the occurrence of errors and each accuracy of fit Δt was calculated. These results are shown in Table 3. The deviations of the estimated values of error factors from the design values are shown as errors. Since the error factor whose Δt is the smallest is the mounting distance L , the theoretical gear tooth surface corresponding to the mounting distance $L + \Delta L = 101.00 - 0.25 = 100.75$ mm can be

Table 1 Dimensions of spiral bevel gear

Gears	Miter
Number of teeth	Z_b 31
Module	3.4031mm
Spiral angle	$35^\circ 0'$
Hand of spiral	Left hand
Pitch cone angle	η $45^\circ 0'$
Mean cone distance	R_m 91.07mm

Table 2 Cutter and machine settings

Cutter radius	r_c	55.00mm
Cutter blade module		3.60mm
Number of starts of cutter head	Z_w	5
Pressure angle	γ	$20^\circ 0'$
Base circle radius	q	74.62mm
Machine distance	M_d	83.13mm
Mounting distance	L	101.00mm

Table 3 Results of inspection

Error factor	Error	$\Phi(\text{deg})$	$\Delta t(\mu\text{m})$
M_d	0.094mm	$55^\circ 18'$	8.9
r_c	-0.334mm	$55^\circ 17'$	22.6
γ	7'	$55^\circ 17'$	23.1
η	7'	$55^\circ 22'$	14.2
L	-0.250mm	$55^\circ 20'$	3.7
l_x	-0.258mm	$55^\circ 04'$	4.4

Table 4 Results of inspection for $\Delta L = -0.250\text{mm}$

Error factor	Error	$\Phi(\text{deg})$	$\Delta t(\mu\text{m})$
M_d	-0.002mm	$55^\circ 20'$	3.6
r_c	-0.031mm	$55^\circ 20'$	3.6
γ	2'	$55^\circ 20'$	3.5
η	0'	$55^\circ 20'$	3.6
l_x	0.0mm	$55^\circ 20'$	3.7

Table 5 Results of inspection after corrective cutting

Error factor	Error	$\Phi(\text{deg})$	$\Delta t(\mu\text{m})$
L	0.004mm	$54^\circ 59'$	3.1

considered to fit the measured data best. In other words, the gear tooth surface is actually cut with the mounting distance L in which the error $\Delta L = -0.25\text{ mm}$ occurs although the surface should be cut with L equal to 101.00 mm. However, it is uncertain whether the errors of other error factors are small or not. Therefore, we estimated the values of error factors M_d , r_c , γ , η , l_x and each value of Φ separately, and calculated each value of Δt for L of 100.75 mm in order to determine the values of other error factors. These results are shown in Table 4 in the same manner as those in Table 3. No errors occur in M_d , r_c , γ , η , and l_x because each accuracy of fit Δt is nearly equal to $3.7\text{ }\mu\text{m}$ which is Δt of L in Table 3. In other cases, if one of the Δt shown in Table 4 is smaller than the smallest value $3.7\text{ }\mu\text{m}$ of Δt in Table 3, we consider that the error of the corresponding error factor will occur. From Table 4, we can consider that error occurs only in L . Therefore, corrective cutting increasing L by 0.250 mm was carried out. Then, the values of L and Φ were estimated, and the accuracy of fit Δt was calculated. The results after the corrective cutting are shown in Table 5. The value of Δt with respect to L is very small. Furthermore, the gear tooth surface is cut accurately because the estimated error of L is 0.004mm which is very small. These

results show the efficacy of the corrective cutting.

As mentioned above, the validity of the proposed method was confirmed.

7. Conclusion

Although the pair of spiral bevel gears in a Klingelnberg cyclo-paloid system can be expected to have a good contact pattern, the first accurate gear pair is difficult to obtain because of machine setting errors such as tool setting and workpiece setting errors in gear cutting. Therefore, gear recutting based on observation of the contact pattern, which depends heavily on skillful workmanship or on trial-and-error cutting methods is necessary in order to develop a good contact pattern.

In this paper, an inspection method for detecting the machine setting errors in spiral bevel gear cutting in a Klingelnberg cyclo-paloid system was proposed in order to obtain an accurate gear without recutting based on contact pattern observation. In this method, a theoretical gear tooth surface expressed as a function of the machine settings is estimated from the tooth surface measurement data using a coordinate measuring machine and the machine setting errors are detected.

In this study, we evaluated many error factors with respect to the machine settings from the measured data on the gear tooth surface. As a result, we could detect the machine setting errors. Furthermore, corrective cutting which compensated for the errors was carried out, so that more accurate gears could be obtained.

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