Development of Concave Conical Gear Used for Marine Transmissions*

(1st Report, Principle of Generating Helical Concave Conical Gear)

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Conical involute gears used for marine transmissions are mostly helical ones. These gears are available in the form of not only intersecting axis gears but also nonintersecting-nonparallel axis gears. The contact between tooth surfaces of a pair of gears is the point contact. Tooth surface durability is generally low. In order to overcome this weak point, one of the authors invented a new type of conical gear called "Concave conical gear". Concave conical gear has higher tooth durability than the conventional conical involute gear. In this paper, a method to generate the helical Concave conical gear is newly developed. First, the principle of the generating method is introduced, and the tooth surface is analyzed theoretically. Second, test gears are ground. Tooth surfaces of the test gears are measured and compared with theoretical ones, and good agreement is observed.

Key Words: Gear, Conical Involute Gear, Concave Conical Gear, Helical Concave Conical Gear, Grinding, Niles-Type Grinding

1. Introduction

The composition of an angle-drive marine transmission is shown in Fig. 1. It consists of reduction gears and two clutches for forward and reverse motions. This transmission makes it possible to set the propeller at an inclination to a horizontal plane where the engine is installed.

Conical involute gears used for the angle-drive marine transmissions are mostly helical ones. The gear train of the angle-drive marine transmission is shown in Fig. 2. In this figure, the forward pinion and the output gear are intersecting axis gears, and the reverse pinion and the output gear are nonintersecting-nonparallel axis gears. In these cases, the contact between tooth surfaces of a pair of gears is the point

contact. Tooth surface durability is generally low⁽¹⁾. In order to overcome this weak point, one of the authors invented a new type of conical gear called "Concave conical gear". The tooth surface of Concave conical gear is called the "concave tooth sur-

Fig. 1 Angle-drive marine transmission

* Received 23rd May 2001. Japanese original: Trans. Jpn. Soc. Mech. Eng., Vol. 65, No. 638, C (1999), pp. 4179-4184 (Received 18th January, 1999)

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Fig. 2 Gear train

Fig. 3 Concave tooth surface in comparison with tooth surface of conical involute gear

face^{(2),(3)}. The concave tooth surface and the tooth surface of the conical involute gear are shown in Fig. 3, where the former is drawn by a solid line and the latter by a dotted line. In this figure, the concave tooth surface agrees with the normal tooth surface on the curved line v_0 , which is called the "locus of point of contact on tooth surface".

In this research, the authors aim at the establishment of the design and production system of Concave conical gears for marine transmissions. We have been carrying out the research and development of the production method of Concave conical gears. Finally, we have developed newly, the generating method of helical Concave conical gears. In this paper, first, the principle of the generating method is introduced and the theoretical tooth surface is analyzed. Second, test gears are ground. Tooth surfaces of the test gears are measured and compared with theoretical ones.

2. Contact between Tooth Surfaces of Concave Conical Gears

The contact between tooth surfaces of conical involute gears is shown in Fig. 4. Gear 1 comes into engagement with gear 2 through a rack. In Fig. 4, straight lines l_1 and l_2 are the contact lines between the rack and gears 1 and 2, respectively. Lines l_1 and

Fig. 4 Tooth surface contact of conical involute gears

(a) In the case of conical involute gear (b) In the case of concave conical gear

Fig. 5 Approximate view of tooth surface contact

l_2 are the generating lines of involute helicoids. The angle θ is the angle between lines l_1 and l_2 .

The contact between tooth surfaces of gears 1 and 2 in Fig. 4 is approximated by the contact between two cylinders shown in Fig. 5(a). On the other hand, the contact between the concave tooth surfaces can be approximated by the contact between two hyperboloids shown in Fig. 5(b). Therefore, the contact area between tooth surfaces of Concave conical gears becomes larger than that of conical involute gears⁽²⁾.

3. Generating Concave Tooth Surface by Conical Wheel

3.1 Tooth surface generating mechanism

The helical Concave conical gear is generated by a conical wheel, as shown in Fig. 6. This wheel has pitch radius r_c , normal pressure angle α_0 , and normal module m . Figure 7 shows a schematic view of the gear grinding machine. This grinding machine is based on a Niles-type gear grinding machine. However, the grinding stone of this machine generates the gear without reciprocation along the gear tooth trace⁽⁴⁾. The generation motion during this process is realized by rolling the pitch cylinder of the gear to the

pitch plane of the imaginary generating rack. Figure 8 shows the simulation of generating process. Figure 9 shows grinding of the test gear.

Figure 10 shows a helical Concave conical gear, a conical wheel, and the imaginary generating rack to generate the helical conical involute gear. This rack is realized by reciprocating this wheel along the z_2 axis, and this rack generates the helical conical involute gear. Figure 10 also shows motions of the

Fig. 6 Conical wheel

Fig. 7 Schematic view of gear grinding machine made for testing

Fig. 8 Simulation of generating process of Concave conical gear based on the Niles method

Fig. 9 Grinding of test gear 1

Fig. 10 Helical Concave conical gear, conical wheel, and imaginary generating rack

gear and the conical wheel. The gear rotates about the z axis with an angular speed ω . The conical wheel rotates about its axis (Y_2) and translates along the y' axis with translating speed ωr_b at the same time. During these motions, the conical wheel generates the helical Concave conical gear.

3.2 Coordinate systems

Expressing an arbitrary point P as $P(X, Y, Z) = P(X_2, Y_2, Z_2)$ in Fig. 10, the relationship between these coordinates is obtained as follows. Here, M_{04} is a square matrix of coordinate transformation. Angle ϕ is the angle of rotation of the gear.

$$\begin{bmatrix} 1 \\ X \\ Y \\ Z \end{bmatrix} = M_{04} \begin{bmatrix} 1 \\ X_2 \\ Y_2 \\ Z_2 \end{bmatrix} \quad (1)$$

$$M_{04} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ X_{04} & A_{11} & A_{12} & A_{13} \\ Y_{04} & A_{21} & A_{22} & A_{23} \\ Z_{04} & A_{31} & A_{32} & A_{33} \end{bmatrix}$$

$$\left. \begin{aligned} X_{04} &= (r_b + r_c \cos \delta) \cos \phi + r_b \phi \sin \phi \\ Y_{04} &= -(r_b + r_c \cos \delta) \sin \phi + r_b \phi \cos \phi \\ Z_{04} &= r_c \sin \delta \\ A_{11} &= \cos \delta \cos \phi \\ A_{12} &= \sin \delta \sin \phi \cos \phi + \cos \phi \sin \phi \\ A_{13} &= -\sin \delta \cos \phi \cos \phi + \sin \phi \sin \phi \\ A_{21} &= -\cos \delta \sin \phi \\ A_{22} &= -\sin \delta \sin \phi \sin \phi + \cos \phi \cos \phi \\ A_{23} &= \sin \delta \cos \phi \sin \phi + \sin \phi \cos \phi \\ A_{31} &= \sin \delta \\ A_{32} &= -\cos \delta \sin \phi \\ A_{33} &= \cos \delta \cos \phi \end{aligned} \right\} \quad (2)$$

3.3 Generating tooth surface

Figure 11 shows the conical surface of the conical wheel for generating the right tooth surface of the gear. Let vector r_2 be the position vector of an arbitrary point Q . Position vector r_2 in Fig. 10 is expressed by Eq. (3), where angle u and distance v are parameters to express the conical surface.

Fig. 11 Conical face for generating right tooth surface

$$\left. \begin{aligned} r_2 &= X_2 I_2 + Y_2 J_2 + Z_2 K_2 \\ X_2 &= X_2(u, v) = v \cos \alpha_0 \cos u \\ Y_2 &= Y_2(u, v) = v \sin \alpha_0 - a \\ Z_2 &= Z_2(u, v) = v \cos \alpha_0 \sin u \end{aligned} \right\} \quad (3)$$

Figure 12 shows the conical surface of conical wheel for generating the left tooth surface of the gear. Vector r_2 can be obtained in the same way as the right tooth surface.

$$\left. \begin{aligned} r_2 &= X_2 I_2 + Y_2 J_2 + Z_2 K_2 \\ X_2 &= X_2(u, v) = v \cos \alpha_0 \cos u \\ Y_2 &= Y_2(u, v) = a - v \sin \alpha_0 \\ Z_2 &= Z_2(u, v) = v \cos \alpha_0 \sin u \end{aligned} \right\} \quad (4)$$

In the following, the right tooth surface is discussed. Substituting X_2, Y_2, Z_2 of Eq. (3) into Eq. (1), the conical surface can be expressed in the coordinate system $O-XYZ$ as follows.

$$\left. \begin{aligned} X &= X(u, v, \phi) \\ Y &= Y(u, v, \phi) \\ Z &= Z(u, v, \phi) \end{aligned} \right\} \quad (5)$$

When angle ϕ is varied, the conical surface generates an enveloping surface in the gear blank. From Eq. (5), we have

$$\begin{vmatrix} \partial X / \partial u & \partial Y / \partial u & \partial Z / \partial u \\ \partial X / \partial v & \partial Y / \partial v & \partial Z / \partial v \\ \partial X / \partial \phi & \partial Y / \partial \phi & \partial Z / \partial \phi \end{vmatrix} = 0 \quad (6)$$

From Eq. (6), we have $\phi = \phi(u, v)$. Substituting $\phi = \phi(u, v)$ into Eq. (5), we get this enveloping surface by Eq. (7).

$$\left. \begin{aligned} X &= X(u, v, \phi(u, v)) \\ Y &= Y(u, v, \phi(u, v)) \\ Z &= Z(u, v, \phi(u, v)) \end{aligned} \right\} \quad (7)$$

Equations (8) and (9) are detailed expressions of Eq. (7).

$$\left. \begin{aligned} X &= X(u, v, \phi(u, v)) = A_1 \cos \phi + A_2 \sin \phi \\ Y &= Y(u, v, \phi(u, v)) = -A_1 \sin \phi + A_2 \cos \phi \\ Z &= Z(u, v, \phi(u, v)) = A_3 \\ \phi &= A_4 / A_5 \end{aligned} \right\} \quad (8)$$

Fig. 12 Conical face for generating left tooth surface

$$\left. \begin{aligned}
 A_1 &= v(\cos \alpha_0 \cos \delta \cos u + \sin \alpha_0 \sin \delta \sin \phi \\
 &\quad - \cos \alpha_0 \sin \delta \cos \phi \sin u) \\
 &\quad + r_c(\cos \delta - \tan \alpha_0 \sin \delta \sin \phi) + r_b \\
 A_2 &= v(\sin \alpha_0 \cos \phi + \cos \alpha_0 \sin \phi \sin u) \\
 &\quad - r_c \tan \alpha_0 \cos \phi + r_b \phi \\
 A_3 &= v(\cos \alpha_0 \sin \delta \cos u - \sin \alpha_0 \cos \delta \sin \phi \\
 &\quad + \cos \alpha_0 \cos \delta \cos \phi \sin u) \\
 &\quad + r_c(\tan \alpha_0 \cos \delta \sin \phi + \sin \delta) \\
 A_4 &= v(\sin \delta \sin u - \cos \delta \cos \phi \cos u) \\
 &\quad + r_c \tan \alpha_0(\sin \alpha_0 \cos \delta \cos \phi \cos u \\
 &\quad - \sin \alpha_0 \sin \delta \sin u) + r_c(\sin \alpha_0 \cos \delta \sin \phi \sin u \\
 &\quad - \cos \alpha_0 \cos \delta \cos \phi) \\
 A_5 &= r_b(\sin \alpha_0 \cos \delta \cos u - \cos \alpha_0 \sin \delta \sin \phi \\
 &\quad - \sin \alpha_0 \sin \delta \cos \phi \sin u)
 \end{aligned} \right\} \quad (9)$$

Equations (8) and (9) are for the right tooth surface of the gear generated by the conical wheel. The left tooth surface can be obtained in the same way as the right tooth surface.

4. Theoretical Tooth Surface of Generated Gear

The tooth surface of the conical involute gear is an involute helicoid. Therefore, the tooth profile in the direction of the generation line becomes a straight line l , as shown in Fig. 3. On the other hand, the generation line of Concave conical gear becomes a curved line l' . Lines l and l' are section profiles of the tooth surface cut through the plane in contact with the base cylinder of the conical involute gear.

The theoretical tooth surface of the generated gear is expressed by Eqs. (8) and (9) in the coordinate system $O-XYZ$ set on the gear. Here we express this tooth surface in the stationary coordinate system $o-xyz$ in Fig. 13.

$$\left. \begin{aligned}
 x &= X \cos \phi_0 - Y \sin \phi_0 \\
 y &= X \sin \phi_0 + Y \cos \phi_0 \\
 z &= Z
 \end{aligned} \right\} \quad (10)$$

$$\left. \begin{aligned}
 \cos \phi_0 &= r_g / r_b \\
 \sin \phi_0 &= \sqrt{r_b^2 - r_g^2} / r_b
 \end{aligned} \right\} \quad (11)$$

Next, we cut this tooth surface by the plane in contact with the base cylinder. This plane is expressed by Eq. (12).

$$x = r_g \quad (12)$$

Substituting Eq. (12) into Eq. (10), we get the relation between parameters u and v : $u = u(v)$. Then, substituting $u = u(v)$ into y and z in Eq. (10), we get a section profile drawn in Fig. 14. Finally, we express this profile in the coordinate system $O_2-x_2y_2z_2$ in order to compare it with the profile of the ground test gear.

$$\left. \begin{aligned}
 y_2 &= \left\{ (1/r_b)(A_1 V + A_2 W) - \sqrt{r_b^2 - r_g^2} \right\} \sin \beta_g \\
 &\quad - A_3 \cos \beta_g \\
 z_2 &= \left\{ (1/r_b)(A_1 V + A_2 W) - \sqrt{r_b^2 - r_g^2} \right\} \cos \beta_g \\
 &\quad + A_3 \sin \beta_g \\
 V &= \sqrt{r_b^2 - r_g^2} \cos \phi - r_g \sin \phi \\
 W &= \sqrt{r_b^2 - r_g^2} \sin \phi + r_g \cos \phi
 \end{aligned} \right\} \quad (13)$$

5. Experiments

5.1 Basic dimensions

Concave conical gear is based on the conical involute gear. The basic dimensions of the conical involute gear are normal module m , normal pressure angle α_0 , helix angle of tooth trace in plane of symmetry ϕ , generating cone angle δ which are on the generating rack, and number of teeth in gear z . Table 1 shows the basic dimensions of test gears. Here, r_c is the pitch radius of the conical wheel.

5.2 Measurement of tooth profiles of test gears

The section profile of the tooth that cut through a

Table 1 Basic dimensions of test gears

No.	m	α_0	ψ	δ	z	r_c
1	3	30°	15°	30°	32	72
2	3	30°	0°	30°	32	72

Fig. 13 Rotating coordinate system $O-XYZ$ and stationary coordinate system $o-xyz$

Fig. 14 Tooth section profile cut through plane of contact with base cylinder

plane in contact with the base cylinder is measured using a profilometer. The principle of this measurement is shown in Fig. 15, and the measuring apparatus is shown in Fig. 16. In this apparatus, an X - Y table is set on the base of the profilometer, and a gear support is placed on it. By feeding this support along the X axis, the plane in contact with the base cylinder

Fig. 15 Principle of measuring tooth section profile cut through plane of contact with base cylinder

can be set at the same position as the probe of the profilometer. The gear axis is tilted by angle β_g . The tooth section profile is measured by the probe fed along the Y axis.

Figures 17 and 18 show comparisons of the theoretical and measured profiles. Here the measured profiles are translated parallel from the theoretical ones for comparison, but they agree well with the

Fig. 16 Apparatus for measuring tooth section profile using profilometer

(a) Right tooth surface

(b) Left tooth surface

Fig. 17 Theoretical and measured profiles of test gear 1

(a) Right tooth surface

(b) Left tooth surface

Fig. 18 Theoretical and measured profiles of test gear 2

theoretical ones, if the former are superposed on the latter.

6. Conclusions

(1) A generation method for the helical Concave conical gear, which used a conical wheel, has been developed. This method makes it possible to generate the concave tooth surface as designed.

(2) This method can be applied even in the case when a hob cutter or a threaded wheel is used to generate the gear, because the conical wheel can be realized imaginarily by moving the threaded tool in space.

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