Topology of Modified Helical Gears and Tooth Contact Analysis (TCA) Program

Faydor L. Litvin and Jiao Zhang
University of Illinois at Chicago
Chicago, Illinois

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Abstract

The contents of this report covers: (i) development of optimal geometry for crowned helical gears; (ii) method for their generation; (iii) tooth contact analysis (TCA) computer programs for the analysis of meshing and bearing contact of the crowned helical gears and (iv) modelling and simulation of gear shaft deflection.

The developed method for synthesis is used for determination of optimal geometry for crowned helical pinion surface and is directed to localize the bearing contact and guarantee the favorable shape and low level of the transmission errors.

Two new methods for generation of the crowned helical pinion surface have been proposed. One is based on application of the tool with a surface of revolution that slightly deviates from a regular cone surface. The tool can be used as a grinding wheel or as a shaver. Other is based on crowning pinion tooth surface with predesigned transmission errors. The pinion tooth surface can be generated by a computer controlled automatic grinding machine.

The TCA program simulates the meshing and bearing contact of the misaligned gears. The transmission errors are also determined.

The gear shaft deformation has been modelled and investigated. It has been found the deflection of gear shafts has the same effects as those of gear misalignment.
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<tr>
<td>( a^* )</td>
<td>half the length of major axis of contact ellipse</td>
</tr>
<tr>
<td>( a )</td>
<td>coefficient of parabolic function</td>
</tr>
<tr>
<td>( b )</td>
<td>addendum of cutting tool or coefficient of linear function</td>
</tr>
<tr>
<td>( b^* )</td>
<td>half the length of minor axis of contact ellipse</td>
</tr>
<tr>
<td>([d_{ij}])</td>
<td>3x3 auxiliary matrix</td>
</tr>
<tr>
<td>( C )</td>
<td>Operating center distance</td>
</tr>
<tr>
<td>( \tilde{C} )</td>
<td>operating center distance vector</td>
</tr>
<tr>
<td>( C^0 = \frac{N_1}{2P} + \frac{N_2}{2P} )</td>
<td>nominal center distance</td>
</tr>
<tr>
<td>( \tilde{C}^0 )</td>
<td>nominal center distance vector</td>
</tr>
<tr>
<td>( d )</td>
<td>height of generating cone or level of transmission error.</td>
</tr>
<tr>
<td>( e^{(i)}<em>I, e^{(i)}</em>{II} )</td>
<td>unit vectors along principal direction of surface ( \Sigma_i ) if principal directions of two surface coincide, ( i ) is neglected.</td>
</tr>
<tr>
<td>( f_i(X_1, X_2 \ldots) )</td>
<td>function expression with respect to variables ( X_1, X_2 \ldots )</td>
</tr>
<tr>
<td>( F_i(X_1, X_2 \ldots) )</td>
<td>function expression with respect to variables ( X_1, X_2 )</td>
</tr>
<tr>
<td>( F )</td>
<td>magnitude of force ( \tilde{F} )</td>
</tr>
<tr>
<td>( \tilde{F} )</td>
<td>acting force between gear tooth surfaces</td>
</tr>
<tr>
<td>( \tilde{F}_t )</td>
<td>acting force in transverse section</td>
</tr>
<tr>
<td>( \tilde{F}_z )</td>
<td>acting force in axial direction</td>
</tr>
<tr>
<td>( g(\phi_1) )</td>
<td>auxiliary function of ( \phi_1 )</td>
</tr>
<tr>
<td>( i_t, j_t, k_t )</td>
<td>unit direction vectors of coordinate system ( t )</td>
</tr>
<tr>
<td>( L_{ij} )</td>
<td>line of tangency of surfaces ( \Sigma_i ) and ( \Sigma_j )</td>
</tr>
<tr>
<td>([L_{ij}])</td>
<td>projection transformation matrix (from ( S_j ) to ( S_i ))</td>
</tr>
<tr>
<td>( m_{1p} = \frac{d\phi}{ds} )</td>
<td>kinematic ratio</td>
</tr>
<tr>
<td>( m'<em>{1p} = \frac{dm</em>{1p}}{ds} )</td>
<td>derivative of kinematic ratio of gear and rack cutter</td>
</tr>
</tbody>
</table>
\[ m_{21} = \frac{d\phi}{2} = \frac{\omega_2}{\omega_1} \]

Kinematic ratio of gears

\[ m'_{21} = \frac{d\bar{m}_{21}}{d\phi} \]

Derivative of kinematic ratio of gears

\[ [M_{ij}] \]

Coordinate transformation matrix (from \( S_j \) to \( S_i \))

\[ n_r \]

Velocity of end point of unit normal corresponding a point moving over a surface

\[ n_i(j) \]

Unit normal vector of surface \( \Sigma_j \) in coordinate system \( S_i \) [sometimes (i) is omitted if it is unnecessary to specify coordinate system]

\[ N_1 \]

Number of pinion teeth

\[ N_2 \]

Number of gear teeth

\[ O_i \]

Origin of coordinate system \( i \)

\[ P_n \]

Diametral pitch

\[ r_1 \]

Radius of pitch circle for pinion

\[ r_2 \]

Radius of pitch circle for gear

\[ R \]

Radius of arc of generating surface

\[ r_i(j)(u, \theta) \]

Position vector describing surface \( \Sigma_j \) with surface coordinate \( (u, \theta) \) in coordinate system \( S_i \) [sometimes (j) is omitted]

\[ S \]

Parameter of cutting motion

\[ S_i(X_i, Y_i, Z_i) \]

Coordinate system \( i \)

\[ t_p, t_G \]

Surface coordinates of pinion and gear

\[ u_i \]

Generating surface coordinate

\[ u^* \]

Auxiliary variable

\[ v_r \]

Velocity of a point moving over a surface

\[ v_j(i) \]

Velocity of surface \( \Sigma_i \) in coordinate system \( j \) (j is omitted sometimes)

\[ v_{ij} = v_j(i) - v_{ij}(j) \]

Relative velocity between surface \( \Sigma_i \) and \( \Sigma_j \) at contact point in coordinate system \( f \) (f is omitted sometimes).

\[ v_{ij}, v_{ij} \]

Projection of \( v_{ij} \) in the principal direction of surface

\[ x_i(j), y_i(j), z_i(j) \]

Coordinates of vector in \( S_i \) [sometimes (j) is omitted]
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>half of cone angle or coordinate of generating surface</td>
</tr>
<tr>
<td>$\beta$</td>
<td>generating surface coordinate</td>
</tr>
<tr>
<td>$\beta_p$</td>
<td>helical angle</td>
</tr>
<tr>
<td>$\Delta \gamma$</td>
<td>crossing angle between axes of pinion and gear</td>
</tr>
<tr>
<td>$\Delta \delta$</td>
<td>intersecting angle between axes of pinion and gear</td>
</tr>
<tr>
<td>$\Delta \phi_2$</td>
<td>kinematic error (transmission error)</td>
</tr>
<tr>
<td>$\Delta \phi'_2$</td>
<td>derivative of kinematic error with respect to $\phi_1$</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>elastic deformation of the contacting point</td>
</tr>
<tr>
<td>$\theta_i$</td>
<td>generating surface coordinate</td>
</tr>
<tr>
<td>$\kappa_i$, $\kappa''_i$</td>
<td>principal curvatures of surface $\Sigma_i$</td>
</tr>
<tr>
<td>$\kappa_i = \kappa'_i + \kappa''_i$</td>
<td>auxiliary function</td>
</tr>
<tr>
<td>$\lambda_i$</td>
<td>rotation of certain section of gear shaft</td>
</tr>
<tr>
<td>$\rho$</td>
<td>radius of genetrix arc for revolute surface</td>
</tr>
<tr>
<td>$\sigma(ij)$</td>
<td>angle between $\sigma_i$ and $\sigma_j$</td>
</tr>
<tr>
<td>$\Sigma_i$</td>
<td>pinion tooth surface</td>
</tr>
<tr>
<td>$\Sigma_2$</td>
<td>gear tooth surface (or shape)</td>
</tr>
<tr>
<td>$\Sigma_P$</td>
<td>gear generating surface</td>
</tr>
<tr>
<td>$\phi_P$</td>
<td>pinion generating surface</td>
</tr>
<tr>
<td>$\phi_G$</td>
<td>angle of rotation for pinion being generated</td>
</tr>
<tr>
<td>$\phi_1$</td>
<td>angle of rotation for gear being generated</td>
</tr>
<tr>
<td>$\phi_2$</td>
<td>angle of pinion rotation in meshing with gear</td>
</tr>
<tr>
<td>$\phi_{20}$</td>
<td>angle of gear rotation in meshing with pinion</td>
</tr>
<tr>
<td>$\psi_1, \psi_2$</td>
<td>theoretical angle of gear rotation in meshing with pinion</td>
</tr>
<tr>
<td>$\psi_c, \psi_n$</td>
<td>new coordinates to describe parabolic function</td>
</tr>
<tr>
<td>$\omega_1$</td>
<td>angular velocity of pinion</td>
</tr>
<tr>
<td>$\omega_2$</td>
<td>angular velocity of gear</td>
</tr>
<tr>
<td>$\omega_P$</td>
<td>angular velocity of pinion being generated</td>
</tr>
<tr>
<td>$\omega_G$</td>
<td>angular velocity of gear being generated</td>
</tr>
</tbody>
</table>
\( \omega (12) = \omega (1) - \omega (2) \) relative angular velocity

\( \mu \) angle for installment of pinion cutting tool

\( \nu_i \) deflection of certain point of gear shaft
SUMMARY

The topology of several types of modified surfaces for helical gears are proposed. The modified surfaces allow absorption of linear or almost linear function of transmission errors caused by gear misalignment and deflection of shaft. These surfaces result in the improved contact of gear tooth surfaces. The principles and corresponding programs for computer aided simulation of meshing and contact of gears have been developed. The results of this investigation are illustrated with numerical examples.

1. INTRODUCTION

Traditional methods for generation of involute helical gears with parallel axes provide developed ruled tooth surfaces for the gear teeth (Fig. 1.1). The tooth surfaces contact each other at every instant along a line, L, that is the tangent to the helix on the base cylinder. The surface normals along L do not change their orientation. The disadvantage of regular helical gears is that they are very sensitive to misalignments such as the crossing or intersection of gear axes. The misaligned gears transform rotation with a linear function of transmission errors (a main source of noise) and the bearing contact is shifted to the edge of the teeth. The frequency of transmission errors coincides with the frequency of tooth meshing. The actual contact ratio (the average number of teeth being in mesh at every instant) is close to one and is far from the expected value.
These are the reasons why we have to reconsider the canonical ideas on involute helical gears and modify their tooth surfaces. Crowning of the gear surfaces is needed to negate the effects of transmission errors and the shift of contact between the gear tooth surfaces. Deviations of screw involute gear tooth surfaces to provide a new topology that can reduce the gear sensitivity to misalignment will be developed. Theoretically, the modified tooth surfaces will be in contact at every instant at a point instead of a line. Actually, due to the load applied between meshing teeth, the contact will be spread over an elliptical area whose dimensions may be controlled. Methods for gear tooth surface generation that provide the desirable surface deviation are proposed. For economical reasons only the pinion tooth surface is modified while the gear surface is kept as a regular screw involute surface.

2. BASIC CONCEPTS AND CONSIDERATIONS

2.1 Simulation of Meshing

The investigation of influence of gear misalignment requires a numerical solution for the simulation of meshing and contact of gear tooth surfaces. The basic ideas of this method (Litvin, 1968) are as follows:

(1) The meshing of gear tooth surfaces is considered in a fixed coordinate system, $S_f$. Usually, the generated gear tooth surfaces may be represented in a three parametric form with an additional relation between these parameters - Gaussian
coordinates. Such a parametric form is the result of representation of a gear tooth surface as an envelope of the family of the tool surface (the generating surface) and two from the three Gaussian coordinates are inherited from the tool surface.

The continuous tangency of gear tooth surfaces is represented by the following equations

\[ \vec{r}_{1}^{(1)}(u_1, \theta_1, \psi_1, \phi_1) = \vec{r}_{2}^{(2)}(u_2, \theta_2, \psi_2, \phi_2) \]  
\[ \vec{n}_{1}^{(1)}(u_1, \theta_1, \psi_1, \phi_1) = \vec{n}_{2}^{(2)}(u_2, \theta_2, \psi_2, \phi_2), \quad |\vec{n}_{1}^{(1)}| = |\vec{n}_{2}^{(2)}| \]  
\[ f_6(u_1, \theta_1, \psi_1) = 0 \]  
\[ f_7(u_2, \theta_2, \psi_2) = 0 \]

Here: \( u_i \) and \( \theta_i \) are the tool surface curvilinear coordinates, \( \psi_i \) is the parameter of motion in the process of generation of the gear tooth surface, \( \phi_i \) is the angle of rotation of the gear being in mesh with the mating gear.

Equations (2.1.1) to (2.1.4) provide that the position vectors \( \vec{r}_{1}^{(1)} \) and \( \vec{r}_{2}^{(2)} \) and surface unit normals \( \vec{n}_{1}^{(1)} \) and \( \vec{n}_{2}^{(2)} \) are equal for the gear tooth surfaces in contact (Fig. 2.1). Vector equations (2.1.1) and (2.1.2) yield five independent equations and the total equation system is
An instantaneous point contact instead of a line contact is guaranteed if the Jacobian differs from zero, i.e. if

\[ \frac{\partial (f_1, f_2, f_3, f_4, f_5, f_6, f_7)}{\partial (u_1, \theta_1, \psi_1, u_2, \theta_2, \psi_2, \phi_2)} \neq 0 \]  \hspace{1cm} (2.1.6)

If the inequality equation (2.1.6) is observed, then the system of equations (2.1.5) may be solved in the neighborhood of the contact point by functions

\[ u_1(\phi_1), u_2(\phi_1), \psi_1(\phi_1), \ldots, \phi_2(\phi_1) \]  \hspace{1cm} (2.1.7)

These functions are of class \( C^1 \) (at least they have continuous derivatives of the first order). Functions (2.1.7) and equations (2.1.5) enable calculation of the transmission errors (deviation of \( \phi_2(\phi_1) \) from the prescribed linear function) and the path of the contact point over the gear tooth surface.

For the case when the gear tooth surface is a regular screw involute surface, it may be directly represented in a two-parametric form and the number of equations in system (2.1.5) may be reduced to six.
2.2 Simulation of Contact

Due to the elastic approach of the gear tooth surfaces their contact is spread over an elliptical area. It is assumed that the magnitude of the elastic approach is known from experiments or may be predicted. Knowing in addition the principal curvatures and directions for two contacting surfaces at their point of contact we may determine the dimensions and orientation of the contact ellipse (Litvin, 1968).

The determination of principal curvature and directions for a surface represented in a three-parametric form is a complicated computational problem. A substantial simplification of this problem may be achieved using the relations between principal curvatures and directions, and the parameters of motion for two surfaces being in contact at a line. One of the contacting surfaces is the tool surface and the other is the generated surface.

Helical gears with modified gear tooth surfaces will be designed as surfaces being in point contact at every instant. The point of contact traces out on the surface a spatial curve (the path of contact) whose location must be controlled. The tangent to the path of contact and the derivative of the gear ratio \( \frac{d}{d\phi_1} (m_{21}(\phi_1)) \) may be controlled by using the relationship between principal curvatures and directions for two surfaces that are in point contact (ref. 2). Here:

\[
m_{21} = \frac{\omega_2}{\omega_1} = f(\phi_1)
\]
is the gear ratio.

2.3 Partial Compensation of Transmission Errors

Aligned gears transform rotation with a constant gear ratio $m_{21}$ and

$$\phi_{20}(\phi_1) = \frac{N_1}{N_2}\phi_1$$  \hspace{1cm} (2.3.1)

is a linear function. Here: $N_1$ and $N_2$ are the numbers of gear teeth. An investigation of the effect of helical gear rotational axis intersection or crossing indicates that $\phi_2(\phi_1)$ becomes a piece-wise function which is nearly linear for each cycle of meshing (Fig. 2.2(a)). The transmission errors are determined by

$$\Delta\phi_2(\phi_1) = \phi_2(\phi_1) - \phi_1 \frac{N_1}{N_2}$$  \hspace{1cm} (2.3.2)

and they are also represented by a piece-wise linear function (Fig. 2.2(b)). Transmission errors of this type cause a discontinuity of the gear angular velocity at transfer points and vibration becomes inevitable. The new topology of gear tooth surfaces proposed in this report allows the absorption of a linear function of transmission errors that results in a reduced level of vibration. This is based on the possibility to absorb a linear function by a parabolic function.

Consider the interaction of a parabolic function given by

$$\Delta\phi_2^{(1)} = -a\phi_1^2$$  \hspace{1cm} (2.3.3)
with a linear function represented by

$$\Delta \phi^{(2)}_2 = b\phi_1$$  \hfill (2.3.4)

The resulting function

$$\Delta \phi_2 = b\phi_1 - a\phi_1^2$$  \hfill (2.3.5)

may be represented in a new coordinate system (Fig. 2.3):

$$\psi_2 = -a\phi_1^2$$  \hfill (2.3.6)

where

$$\psi_2 = \Delta \phi_2 - \frac{b^2}{4a^2}, \quad \psi_1 = \phi_1 - \frac{b}{2a}$$  \hfill (2.3.7)

We consider that $\Delta \phi^{(1)}_2 = -a\phi_1^2$ is a predesigned function that exists even if misalignments do not appear. The absorption of function $\Delta \phi^{(2)}_2 = b\phi_1$ by the parabolic function $\Delta \phi^{(1)}_2 = -a\phi_1^2$ means that gear misalignment does not change the predesigned parabolic function of transmission errors. Thus the resulting function of transmission errors $\Delta \phi_2 = \Delta \phi^{(1)}_2 + \Delta \phi^{(2)}_2$ will keep its shape as a parabolic function although the gears are misaligned. The resulting function of transmission errors $\psi_2(\phi_1)$ may be obtained by translation of the parabolic function $\Delta \phi^{(1)}_2$.

The absorption of a linear function of transmission errors by a parabolic function is accompanied by the change of transfer
points. The transfer points determine the positions of the gears where one pair of teeth is rotating out of mesh and the next pair is coming into mesh. The change of transfer points is determined with \( \Delta \phi_1 = \left| \frac{b}{2a} \right| \) and \( \Delta \phi_2 = \frac{b^2}{4a^2} \), the cycle of meshing of one pair of teeth is \( \phi_1 = \frac{2\pi}{N_1} \). It may happen that the absorption of a linear function by a parabolic function is accompanied with a change that is too large. If this occurs the transfer points and the resulting parabolic function of transmission errors, \( \psi_2(\psi_1) \), will be represented as a discontinuous function for one cycle of meshing (Fig. 2.4). To avoid this, it is necessary to limit the tolerances for gear misalignment.

### 2.4 Misalignment of Regular Helical Gears

Regular helical pinion and gear can be represented by their surface position vectors and normal vectors in coordinate systems \( S_1 \) and \( S_2 \) as:

\[
[r_1] = \begin{bmatrix}
x_1 \\
y_1 \\
z_1 \\
1
\end{bmatrix} = \begin{bmatrix}
\cos^2 \psi_n \cos(\phi_p - \psi_c)[t_p \sin \phi_p + r_1 \phi_p] + r_1 \sin \phi_p \\
-\frac{\cos \psi_n}{\cos \psi_c} \cos(\phi_p - \psi_c)[t_p \sin \phi_p + r_1 \phi_p] + r_1 \sin \phi_p \\
\frac{\cos \psi_n}{\cos \psi_c} \sin(\phi_p - \psi_c)[t_p \sin \phi_p + r_1 \phi_p] + r_1 \cos \phi_p \\
\frac{\sin^2 \phi_p}{\cos \phi_p} + r_1 \phi_p \sin^2 \psi n \cos^2 \phi_p \end{bmatrix}
\]

(2.4.1)

\[
[n_1] = \begin{bmatrix}
n_{1x} \\
n_{1y} \\
n_{1z}
\end{bmatrix} = \begin{bmatrix}
\cos \psi \cos \phi n \cos \phi_p + \sin \psi \sin \phi_p \\
-\cos \psi \cos \phi n \sin \phi_p + \sin \psi \cos \phi_p \\
+ \cos \psi \sin \phi_p
\end{bmatrix}
\]

(2.4.2)
\[ r_2 = \begin{bmatrix} x_2 \\ y_2 \\ z_2 \\ 1 \end{bmatrix} = \begin{bmatrix} \frac{\cos^2 \psi_n}{\cos \psi_c} \sin(\phi_G - \phi_c) [-t_G \sin \beta_p + r_2 \phi_G] + r_2 \sin \phi_G \\ \frac{\cos^2 \psi_n}{\cos \psi_c} \sin(\phi_G - \phi_c) [-t_G \sin \beta_p + r_2 \phi_G] + r_2 \cos \phi_G \\ t_G (\cos \beta_p + \sin^2 \psi_n \frac{\sin \beta_p}{\cos \beta_p}) - r_2 \phi_G \sin^2 \psi_n \tan \beta_p \\ 1 \end{bmatrix} \]  

(2.4.3)

\[ n_2 = \begin{bmatrix} n_{2x} \\ n_{2y} \\ n_{2z} \end{bmatrix} = \begin{bmatrix} \cos \psi_n \cos \phi_G + \sin \psi_n \sin \phi_G \\ -\cos \psi_n \cos \phi_G + \sin \psi_n \cos \phi_G \\ -\cos \psi_n \sin \beta_p \end{bmatrix} \]  

(2.4.4)

where \( \psi_n \) and \( \psi_c \) are the pressure angles in gear tooth normal section and transverse section respectively; \( \beta_p \) is the helical angle at the pitch cylinder of the pinion and the gear; \( r_1 \) and \( r_2 \) are the radii pitch cylinder of the pinion and the gear respectively; \( \phi_p \), and \( t_p \) are the surface parameters of the pinion tooth surface; \( \phi_G \) and \( t_G \) are the surface parameters of the gear tooth surface.

When the helical pinion and gear are in mesh, with their axes misaligned, their position vectors and normal vectors can be transformed to the fixed coordinate system \( S_f \). The basic ideas have already been discussed in the Section 2.1. And the real approach of transformation and the matrices to describe the misalignment and gear rotation will be given in Section 3.8.

It is found that when the misalignment occurs the regular
pinion and gear surface cannot contact in tangency. That is, in $S_f$, their normals can not be equal in all circumstances. In this case, only the gear tooth edge contacts pinion tooth surface in tangency. Therefore, in the fixed coordinate system, there are four equations to describe the contact, that is, the equalities of three position vectors describing gear tooth edge and pinion tooth surface as well as the zero product of gear tooth edge tangency and pinion tooth normal.

The computer aided simulation of meshing of misaligned helical gears with regular tooth surfaces shows that the transformation of rotation is accompanied with large transmission errors. There are two sub-cycles of meshing during the complete meshing cycle for one pair of teeth. These sub-cycles correspond to the meshing of (1) a curve with a surface, and (2) a point with the surface. The curve is the involute curve at the edge of the tooth of the gear and the point is the tip of the gear tooth edge. The transmission errors for the period of a cycle are represented by two linear functions (Fig. 2.5). The transformation of rotation will be accompanied with a jump of the angular velocity of the driven gear and therefore vibrations are inevitable.

The results of computation are presented for the following case. Given: number of teeth $N_1 = 20$, $N_2 = 40$, diametral pitch in normal section $P_n = 10$ in$^{-1}$, gear tooth length $L = 10/P_n$ the helical angle $\beta_p = 15^\circ$, the normal pressure angle $\psi_n = 20^\circ$. The gear axes are crossed and form an angle $\Delta \gamma = 5$ arc minutes. The computed transmission errors are represented in table 2.4.1.
### TABLE 2.4.1 - TRANSMISSION ERRORS OF REGULAR HELICAL GEARS WITH CROSSED AXES

<table>
<thead>
<tr>
<th>deg $\phi_1'$</th>
<th>-8</th>
<th>-5</th>
<th>-2</th>
<th>1</th>
<th>4</th>
<th>7</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \phi_2'$ sec</td>
<td>4.90</td>
<td>3.06</td>
<td>1.22</td>
<td>-0.61</td>
<td>-2.45</td>
<td>-4.29</td>
<td>-6.12</td>
</tr>
</tbody>
</table>

2.5 Surface Deviation by the Change of Pinion Lead

Helical gears in this case are designed as helical gears with crossed axes. The crossing angle is chosen with respect to the expected tolerances of the gear misalignment ($\Delta \gamma$ is in the range of 10 to 15 arc minutes). The gear ratio for helical gears with crossed axes may be represented (Litvin, 1968) as

$$M_{12} = \frac{\omega_1}{\omega_2} = \frac{r_{b2} \sin \lambda_{b2}}{r_{b1} \sin \lambda_{b1}}$$

(2.5.1)

where $r_{bi}$ and $\lambda_{bi}$ are the radius of the base cylinder and the lead angle on this cylinder, $i \in 1, 2. \left| \lambda_{p2} - \lambda_{p1} \right| = \Delta \gamma$. Here, $\lambda_{pi}$ is the lead angle on the pitch cylinder. The advantage of application of crossed helical gears is that the gear ratio is not changed by the misalignment (by the change of $\Delta \gamma$). The tooth surfaces contact each other at a point during meshing. The disadvantage of this type of surface deviation is that location of the bearing contact of the gears is very sensitive to gear misalignment. A slight change of the crossing angle causes shifting of the contact to the edge of the tooth (Fig. 2.6).

The discussed type of surface deviation is reasonable to apply for manufacturing of expensive reducers of large dimensions.
when the lead of the pinion can be adjusted by regrinding. While changing by regrinding the parameters $r_{b1}$ and $\gamma_{b1}$, the requirement that the product $r_{b1} \sin \lambda_{b1}$ must be kept constant. Then, the gear ratio $M_{21}$ will be of the prescribed value and transmission errors caused by the crossing of axes will be zero.

Theoretically, transmission errors are inevitable if the axes of crossed helical gears become intersected. Actually, if gear misalignment is of the range of 5 to 10 arc minutes, the transmission errors are very small and may be neglected. The main problem for this type of misalignment is again the shift of the bearing contact to the edge (Fig. 2.6).

3. GENERATION OF PINION TOOTH SURFACE BY A SURFACE OF REVOLUTION

3.1 Basic Consideration

The purpose of this method for deviation of the pinion tooth surface is to reduce the sensitivity of the gears to misalignment. Also the transmission error must be kept to a low level and stabilize the bearing contact. This investigation shows that this goal may be achieved by the proposed method of crowning but the bearing contact cannot cover the whole surface. The reason for this is that the instantaneous contact ellipse moves across but not along the surface (Fig. 3.1).

The proposed method for generation is based on the following considerations. It is well known that the generation of a helical gear may be performed by an imaginary rack-cutter with skew teeth whose normal section represents a regular rack-cutter
for spur gears (Fig. 3.2(a)). We may imagine that two generating surfaces, $\Sigma_G$ and $\Sigma_P'$, are applied to generate the gear tooth surface and the pinion tooth surface, respectively (Fig. 3.2(b)). Surface $\Sigma_G$ is a plane (a regular rack-cutter surface), and $\Sigma_P$ is a cone surface. Surfaces $\Sigma_G$ and $\Sigma_P$ are rigidly connected and perform translational motion, while the pinion and the gear rotate about their axes (Fig. 3.3). The generated pinion and gear will be in point contact and transform rotation with the prescribed linear function $\phi_2(\phi_1)$. However, due to gear misalignment, function $\phi_2(\phi_1)$ becomes a piecewise linear function (Fig. 2.2(a)) that is not acceptable. To absorb a linear function of transmission errors (Fig. 2.2(b)), a predesigned parabolic function of transmission errors is used. For this reason a surface of revolution that slightly deviates from the cone surface is proposed (Fig. 3.2(c)). The radius of the surface of revolution in its axial section determines the level of the predesigned parabolic function. The pinion crowning process may be accomplished by grinding, shaving or lapping.

3.2 Principle of Generation and Used Coordinate Systems

Consider two rigid connecting surfaces $\Sigma_G$ and $\Sigma_P$. The generating surface $\Sigma_G$ is a plane and generates the helical gear tooth surface that is an involute screw surface. Surface $\Sigma_P$ is a surface of revolution. Initially, we consider that $\Sigma_P$ is a cone surface and $\Sigma_P$ and $\Sigma_G$ contact each other along a straight line that is the generatrix of the cone.
Fig. 3.4 shows the generating surfaces $\Sigma_G$ and $\Sigma_P$. Fig. 3.5 illustrates the process for generation. While the rigidly connected generating surfaces perform a translational motion, the pinion and gear rotate about their axes $O_1$ and $O_2$, respectively. The parameter of motion of the cutter, $S$, and the angles of rotation of the pinion and the gear, $\phi_1$ and $\phi_2$, are related as follows:

$$S = r_1\phi_p = r_2\phi_G$$  \hspace{1cm} (3.2.1)

where $r_1$ and $r_2$ are the great centrodes radii, the cutter centrode is the straight line that is tangent to the gear centrodes. Point $I$ is the instantaneous center of rotation. Coordinate systems $S_1$ and $S_2$ are rigidly connected to the helical pinion and the helical gear, whereas coordinate systems $S_c$ and $S_f$ are rigidly connected to the tool surface and fixed frame. The generating surface $\Sigma_G$ (a plane) and $\Sigma_P$ are covered with a set of contact lines $L_{G2}$ and $L_{P1}$ respectively—the instantaneous lines of tangency of surfaces $\Sigma_G$ and $\Sigma_2$ and $\Sigma_P$ and $\Sigma_1$ (Fig. 2.3, a,b). The location of these lines depends on the value of parametric $\phi_G$ and $\phi_P$ ($\phi_P$ and $\phi_G$ are related). Line $L_{GP}$ is the line of tangency of generating surfaces $\Sigma_G$ and $\Sigma_P$. When $\Sigma_1$ and $\Sigma_2$ are generated, at any moment, one point $M_i$ on line $L_{PG}$ are generating corresponding point $M_{P1}$ and $M_{G1}$ on the helical gear surface $\Sigma_1$ and $\Sigma_2$. When the $\Sigma_1$ and $\Sigma_2$ are meshing without misalignment $M_{P1}$ and $M_{G1}$ contact each other in turn. Now it is clear why $L_{PG}$ is not parallel with the edge of $\Sigma_G$. The reason is
that in this way, the contact ratio of crowned helical pinion and regular helical gear will be higher.

3.3 Tool Surface

The pinion generating surface is a cone and may be represented in an auxiliary coordinate system $S_d$ (Fig. 3.7) as follows:

$$
\mathbf{x}_d = \begin{bmatrix} x_d \\ y_d \\ z_d \\ 1 \end{bmatrix} = \begin{bmatrix} u \cos \theta \sin \alpha \\ \psi_0 - u \cos \alpha \\ -u \sin \theta \sin \alpha \\ 1 \end{bmatrix}
$$

(3.3.1)

where $0 < u < \frac{d}{\cos \alpha}$, $0 < \theta < 2\pi$. The surface normal is represented by

$$
\mathbf{n}_d = \frac{\partial \mathbf{x}_d}{\partial \alpha} \times \frac{\partial \mathbf{x}_d}{\partial \psi_0} = u \sin \alpha \begin{bmatrix} \cos \alpha \cos \theta \\ \sin \alpha \\ \cos \alpha \sin \theta \end{bmatrix}
$$

(3.3.2)

The unit surface normal is (provided $u \sin \alpha \neq 0$)

$$
\mathbf{n}_d = \begin{bmatrix} \cos \alpha \cos \theta \\ \sin \alpha \\ \cos \alpha \sin \theta \end{bmatrix}
$$

(3.3.3)

Figure 3.8 illustrates the installment of the conic tool in coordinate system $S_c$ step by step as follows:

(i) From coordinate system $S_d$ to $S_b'$, the cone is tangent to the plane $y_b'$, $o_b'$, $z_b'$ where the tangent line $L_{PG}$ (see Section 3.2) is coincident with $y_b'$ axis. Here, we have (Fig. 3.8a).
\[
[M_{b'd}] = \begin{bmatrix}
\cos \alpha & \sin \alpha & 0 & -d \sin \alpha \\
-\sin \alpha & \cos \alpha & 0 & d \tan \sin \alpha \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\] (3.3.4)

where the \( d \) is the height of cone.

(ii) From coordinate system \( S_b' \) to \( S_b' \) the tangent line of cone and plane \( y_b o_b z_b \) is declined with an angle \( \psi \) (see Fig. 3.4), also the origin \( o_b' \) and \( o_b \) are not coincident. Here we have (Fig. 3.8b).

\[
[M_{bb'}] = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & \cos \psi & -\sin \psi & -\frac{b}{\cos \psi_n} \\
0 & \sin \psi & \cos \psi & \frac{b}{\cos \psi_n} \tan \psi \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\] (3.3.5)

where \( b \) is the addendum height of the tool.

(iii) From coordinate system \( S_b \) to \( S_a \), the tool is declined with a pressure angle \( \psi_n \). For the helical gear, the \( \psi \) is measured at the normal cross section. Here, we have (Fig. 3.8c).

\[
[M_{ab}] = \begin{bmatrix}
\cos \psi_n & -\sin \psi_n & 0 & 0 \\
\sin \psi_n & \cos \psi_n & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\] (3.3.6)

(iv) From coordinate system \( S_a \) to \( S_c \), the helix angle \( \beta_p \) is considered. Here we have (Fig. 3.8d).

\[
[M_{ca}] = \begin{bmatrix}
\cos \beta_p & 0 & -\sin \beta_p & 0 \\
0 & 1 & 0 & 0 \\
\sin \beta_p & 0 & \cos \beta_p & 0 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\] (3.3.7)
In coordinate system $S_c$, the tool surface and its normal can be represented as:

$$[r_c^{(p)}] = [M_{ca}][M_{ab}][M_{bb}'][M_{bd}][r_d]$$  \hspace{1cm} (3.3.8)

$$[n_c^{(p)}] = [L_{ca}][L_{ab}][L_{bb}'][L_{bd}][n_d]$$

where 3 x 3 $L$ matrix is from corresponding 4 x 4 $M$ matrix, excluding the last row and last column. Substituting Eq. (3.3.1), (3.3.3), (3.3.4), (3.3.5), (3.3.6) and (3.3.7) into Eq. (3.3.8), finally we obtain the tool surface $r_p$ and its normal in coordinate system $S_c$ as

$$[r_c^{(p)}] = \begin{bmatrix} x_c^{(p)} \\ y_c^{(p)} \\ z_c^{(p)} \\ 1 \end{bmatrix}, \quad [n_c^{(p)}] = \begin{bmatrix} n_{cx}^{(p)} \\ n_{cy}^{(p)} \\ n_{cz}^{(p)} \end{bmatrix}$$  \hspace{1cm} (3.3.9)

where

$$x_c^{(p)} = u_p \cos \theta_p \sin \alpha (\cos \alpha \cos \psi_n \cos \beta_p + \sin \alpha \sin \psi_n \cos \mu \cos \beta_p)$$

$$+ \sin \alpha \sin \psi_n \sin \beta_p + u \sin \theta_p \sin \alpha (\sin \psi_n \sin \mu \cos \beta_p - \cos \psi_n \cos \beta_p)$$

$$+ u \cos \alpha (\cos \alpha \sin \psi_n \cos \beta_p - \sin \alpha \cos \psi_n \cos \mu \cos \beta_p + \cos \alpha \sin \psi_n \sin \beta_p)$$

$$- \left( \frac{d}{\cos \alpha} - \frac{b}{\cos \psi_n \cos \mu} \right) [\sin \psi_n \cos \mu \cos \beta_p + \sin \psi_n \sin \beta_p]$$

$$y_c^{(p)} = u_p \cos \theta_p \sin \alpha (\cos \alpha \sin \psi_n - \sin \psi_n \cos \mu)$$

$$- u \sin \theta_p \sin \alpha \cos \psi_n \sin \mu - u \cos \alpha (\sin \psi_n \sin \mu + \cos \psi_n \cos \mu)$$

$$+ \left( \frac{d}{\cos \alpha} - \frac{b}{\cos \psi_n \cos \mu} \right) \cos \psi_n \cos \alpha$$
The equation of meshing of the generating surface $E_p$ and the helical pinion tooth surface is represented by

$$\tilde{N}(P) \cdot \tilde{y}(P) = \tilde{N}(P) \cdot (\tilde{y}(P) - \tilde{y}(1)) = 0 \quad (3.4.1)$$

We can also use equation based on the fact that the contact normal of generating and generated surfaces must intersect the instantaneous axis of rotation I-I (Litvin, 1968). Thus, we obtain (Fig. 2.2).
where \((X_c, Y_c, Z_c)\) are the coordinates of a point that lies on axis I-I; \(x_c(P), y_c(P), z_c(P)\) are the coordinates of cone surface; \(n_{cx}, n_{cy}\) and \(n_{cz}\) are the projections of the surface unit normal. From Fig. 3.5, it is known that

\[
X_c = S = r_1 \phi_p, \quad Y_c = 0
\]

Equation (3.4.2), (3.4.3), and (3.3.9) yield

\[
f_1(u_p, \theta_p, \phi_p) = -u_p \left[ \cos \theta \left( \cos \psi \cos \alpha + \sin \psi \sin \theta \right) 
+ \sin \theta \left( \sin \psi \cos \alpha - \cos \psi \sin \theta \right) 
+ \frac{d}{\cos \alpha - \cos \psi \cos \theta} \left( \cos \phi \cos \alpha + \sin \alpha \right) \right] 
+ r_1 \phi_p \left[ \cos \theta \cos \alpha \left( \sin \psi \cos \phi - \sin \phi \cos \psi \right) 
+ \sin \alpha \left( \sin \psi \cos \phi - \sin \psi \cos \phi \right) \right] 
= 0
\]

(3.4.4)

The helical pinion tooth surface can be obtained by transforming the generating tool surface \(S_p\) to coordinate system \(S_f\), together with equation of meshing. The coordinate transformation in transition from \(S_c\) to \(S_f\) is represented by the matrix \(M_{fc}\) as (Fig. 3.5)

\[
[M_{fc}^{-1}] = \begin{bmatrix}
1 & 0 & 0 & -r_1 \phi_p \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\]

(3.4.5)
The coordinate transformation in transition from \( S_f \) to \( S_1 \) is represented by the matrix \( M_{1f} \) as (Fig. 3.5).

\[
[M_{1f}] = \begin{bmatrix}
\cos \phi_p & \sin \phi_p & 0 & 0 \\
-sin \phi_p & \cos \phi_p & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]  
(3.4.6)

Therefore, the helical pinion surface can be represented in coordinate system \( S_1 \) as:

\[
[r_1] = [M_{1c}][r_c^{(P)}] = [M_{1f}][M_{fc}'][r_c^{(P)}]
\]  
(3.4.7)

together with Eq. (3.4.4). Substituting Eq. (3.4.5), (3.4.6) and (3.3.9) into Eq. (3.4.7) we have

\[
[r_1] = \begin{bmatrix}
(x_c^{(P)} - r_1 \phi_p) \cos \phi_p + y_c^{(P)} \sin \phi_p \\
(y_c^{(P)} - r_1 \phi_p) \sin \phi_p + x_c^{(P)} \cos \phi_p \\
z_c^{(P)}
\end{bmatrix}
\]  
(3.4.8)

Eq. (3.4.8) and (3.4.4) represents the pinion tooth surface where \( x_c^{(P)} \), \( y_c^{(P)} \) and \( z_c^{(P)} \) are expressed in Eq. (3.3.9).

Using the same approach, the unit normal pinion tooth surface can be represented by Eq. (3.4.9) and (3.4.4) where \( n_{cx}^{(P)} \), \( n_{cy}^{(P)} \) and \( n_{cz}^{(P)} \) are expressed in Eq. (3.3.9)

\[
[n_1] = \begin{bmatrix}
n_{cx}^{(P)} \cos \phi_p + n_{cy}^{(P)} \sin \phi_p \\
n_{cx}^{(P)} \sin \phi_p + n_{cy}^{(P)} \cos \phi_p
\end{bmatrix}
\]  
(3.4.9)
It is clear that if we set \( \beta_p = 0 \), the pinion becomes spur pinion. Therefore, crowning spur pinion using conic tool is only a special case of crowning helical pinion.

### 3.5 Condition of Pinion Non-Undercutting

The problem of undercutting of the helical pinion tooth surface by crowning is related with the appearance on the pinion tooth surface of singular points. From differential geometry, it is known that the surface point is singular if the surface normal is equal to zero at such a point.

Litvin, proposed a method to determine a line on the tool surface whose points will generate singular points on the surface generated by the tool. This line designated by \( L \) (Fig. 3.9) must be out of the working part of the tool surface to avoid undercutting of the pinion by crowning.

The limiting line \( L \) of the tool surface is determined by the following equations

\[
\mathbf{r}_c^{(P)} = \mathbf{r}_c^{(P)}(u_p, \theta_p) \quad (3.5.1)
\]

\[
f_1(u_p, \theta_p, \phi_p) = 0 \quad (3.5.2)
\]

\[
F(u_p, \theta_p, \phi_p) = 0 \quad (3.5.3)
\]

Vector equation (3.5.1) represents the tool surface [see Eq. (3.3.9)]; equation (3.5.2) is the equation of meshing [see Eq. (3.4.4)] and equation (3.5.3) comes from the requirement of
limiting line $L$ as:

\[
\begin{vmatrix}
\frac{\partial x}{\partial u}^{(p)} & \frac{\partial x}{\partial \theta}^{(p)} & v^{(c1)} \\
\frac{\partial z}{\partial u}^{(p)} & \frac{\partial z}{\partial \theta}^{(p)} & v^{(c1)} \\
\frac{\partial f}{\partial u} & \frac{\partial f}{\partial \theta} & \frac{\partial f}{\partial \phi}
\end{vmatrix}
= 0
\]  

(3.5.4)

where $v^{(c1)}_{C}$ is the relative velocity of the tool and generated surface at generating point, represented in coordinate system $S_c$. Actually, we can write $v^{(c1)}_{C}$ as

\[
v^{(c1)}_{C} = v^{(c)}_{C} - v^{(1)}_{C}
\]

(3.5.5)

where $v^{(c)}_{C}$ is the velocity of the cutter and $v^{(1)}_{C}$ is the velocity of the pinion. From Fig. 2.2, we get

\[
v^{(c)}_{C} = \begin{bmatrix}
-\frac{da}{dt} \\
0 \\
0
\end{bmatrix} = \begin{bmatrix}
w_p \\
0 \\
0
\end{bmatrix}
\]

(3.5.6)

\[
v^{(1)}_{C} = w_p \times r^{(p)}_C + \frac{\partial \phi}{\partial C_1} \times \omega_p
\]

(3.5.7)

where

\[
\omega_p = \begin{bmatrix}
0 \\
0 \\
1
\end{bmatrix} \omega \quad \frac{\partial \phi}{\partial C_1} = \begin{bmatrix}
r_1 \phi_p \\
-r_1 \\
0
\end{bmatrix}
\]

(3.5.8)
Equations (3.5.6), (3.5.7) and (3.5.8) yield

\[
\begin{pmatrix}
  y_c^{(p)} \\
  -x_c^{(p)} + r_1 \phi_p \\
  0
\end{pmatrix} \omega = (3.5.9)
\]

where \( x_c^{(p)} \) and \( y_c^{(p)} \) are represented by equations 3.3.9.

Equation (3.5.9), (3.3.9), (3.4.3) and (3.5.4) yield

\[
u_p^2 YW + u_p (r_1 G^3 + u_p^* (WZ + XY)) + u_p^* xZ = 0 \quad (3.5.10)
\]

where

\[
W = (B^2 E + A^2 E) + (BD-AF) I + \sin^3 \theta_p (A^2 F - B^2 F + 2ABD) \\
- \cos^3 \theta_p (2AFB + B^2 D - A^2 D) - \sin \theta_p (2A^2 F + ABD - AEI) \\
+ \cos \theta_p [BEI + 2B^2 D + ABF]
\]

\[
X = [(A F \sin^2 \alpha - CE) \cos \theta_p + (A D \sin^2 \alpha - AE \cos^2 \alpha) \sin \theta_p \\
+ (A F \cos^2 \alpha - DC)] (B \cos \theta_p + A \sin \theta_p + I)
\]

\[
Y = D t g \alpha \cos \theta_p - F t g \alpha \sin \theta_p - E c t g \alpha
\]

\[
Z = \cos \mu \cos \psi_n
\]
\[ U_p^* = \left( \frac{d}{\cos \alpha} - \frac{b}{\cos \psi_n \cos \mu} \right) \]

\[ A = \cos \mu \cos \beta_p + \sin \psi_n \sin \mu \sin \beta_p \]

\[ B = \cos \alpha \cos \psi_n \sin \beta_p + \sin \alpha \sin \psi_n \cos \mu \sin \beta_p - \sin \alpha \sin \psi_n \cos \beta_p \]

\[ C = \cos \alpha \cos \psi_n \sin \beta_p \]

\[ D = (\cos \alpha \sin \psi_n - \sin \alpha \cos \psi_n \cos \mu) \cos \alpha \]

\[ E = (\sin \alpha \sin \psi_n + \cos \alpha \cos \psi_n \cos \mu) \sin \alpha \]

\[ F = \cos \alpha \cos \psi_n \sin \mu \]

\[ G = D \cos \theta + E - F \sin \theta \]

\[ I = \cot \alpha (\cos \alpha \sin \psi_n \cos \mu \sin \beta_p - \sin \alpha \sin \psi_n \sin \beta_p - \cos \alpha \sin \mu \cos \beta_p) \]

Using Eq. (3.5.10) and taking it into account that \( \frac{\partial F}{\partial \theta_p} \neq 0 \), we can represented the \( u_p \) as a function of \( \theta_p \). Undercutting will be avoided if

\[ u_p(\theta_p) > \frac{d}{\cos \alpha} \quad (3.5.11) \]

The analysis of Eq. (3.5.10) indicates that the inequality (3.5.11) is satisfied if the condition of helical pinion non-
undercutting by a regular rack cutter is satisfied.

3.6 Principal Directions and Curvatures of Tooth Surface

A simplified approach to determine principal directions and curvatures of helical pinion has been proposed by Litvin (Litvin, 1968). The main idea is representing the principal directions and curvatures of generated surface $\Sigma_1$ by the principal directions and curvatures of generating surface $\Sigma_p$.

Let us determine the principal directions of curvatures of tool surface $\Sigma_p$. The tool surface is a cone surface and its principal directions coincide with the direction of the cone generatrix and the direction that is perpendicular to the cone generatrix.

The Rodrigue's formula (Eq. 3.6.1) can be used to obtain the principal curvature and directions

$$\kappa_{I,II} \bar{v}_r = -\bar{\kappa}_r$$

(3.6.1)

where $\bar{v}_r$ is the velocity of a point that moves over a surface and $\bar{\kappa}_r$ is the derivative of the surface unit normal $\bar{n}$, when $\bar{n}$ changes its direction due to the motion over the surface.

Using Eq. 3.6.1, the principal directions and curvatures of cone surface $\Sigma_p$ can be expressed in coordinate system $S_d$ as:
The negative sign for $\kappa_I$ indicates that the curvature center is located on the negative direction of the surface normal. The principal curvatures are invariants with respect to the used coordinate system. Whereas the principal direction will be represented in coordinate system $S_f$ as

$$[\mathbf{e}^{(p)}]_{f} = [L_{fc}][L_{cd}][\mathbf{e}^{(p)}]_{d}$$

where $[L_{cd}] = [L_{ca}][L_{ab}][L_{ab}'][L_{b'd}], 3 \times 3 L$ matrices can be obtained from corresponding $4 \times 4 M$ matrices [see Eq. (3.3.4), (3.3.5), (3.3.6) and (3.3.7)], $L_{fc}$ is $3 \times 3$ unitary matrix (see Fig. 3.5).

The determination of principal curvatures and directions for the pinion tooth is based on the following equations (see Litvin, 1968)

$$\tan 2\sigma^{(p)} = \frac{2b_{13}b_{23}}{b_{23} - b_{13} - (\kappa^{(p)} - \kappa^{(p)})b_{33}}$$

$$\kappa^{(1)} - \kappa^{(1)} = \frac{b_{23} - b_{13} - (\kappa^{(p)} - \kappa^{(p)})b_{33}}{b_{33}\cos 2\sigma^{(p)}}$$

$$\kappa^{(p)} = -\frac{1}{u_p \cos \alpha}$$
\[ \kappa_{11}^{(1)} + \kappa_{1}^{(1)} = \kappa_{I}^{(p)} + \kappa_{II}^{(p)} + \frac{b_{13}^2 + b_{23}^2}{b_{33}} \quad (3.6.6) \]

where \( \kappa_{I}^{(p)}, \kappa_{II}^{(p)} \) and \( e_{I}^{(p)}, e_{II}^{(p)} \) are the principal curvatures and unit vector of principal directions of \( \Sigma_{p} \). \( \kappa_{I}^{(1)}, \kappa_{II}^{(2)} \) and \( e_{I}^{(1)}, e_{II}^{(1)} \) are the principal curvatures and unit vectors of principal directions of \( \Sigma_{p} \). Angle \( \sigma_{I}^{(p1)} \) is measured counterclockwise from \( e_{I}^{(p)} \) to \( e_{I}^{(1)} \) (Fig. 3.10). The coefficient \( b_{13}, b_{23}, \) and \( b_{33} \) have been derived as shown in (Litvin 1968) but modified for the case when a rack cutter generates a gear. The expressions for \( b_{13}, b_{23}, \) and \( b_{33} \) are as follows:

\[
\begin{bmatrix}
 b_{13} \\
 b_{23}
\end{bmatrix} = \begin{bmatrix}
 e_{II}^{(p)} \cdot \omega_{p} \\
 -e_{I}^{(p)} \cdot \omega_{p}
\end{bmatrix} - \begin{bmatrix}
 -\kappa_{I}^{(p)} & 0 \\
 0 & -\kappa_{II}^{(p)}
\end{bmatrix} \begin{bmatrix}
 y_{I}^{(p1)} \\
 y_{I}^{(p1)}\cdot e_{I}^{(p)}
\end{bmatrix}
\]

\[ (3.6.7) \]

\[ b_{33} = \begin{bmatrix}
 n & \omega_{p} & y_{I}^{(p1)}
\end{bmatrix} + \begin{bmatrix}
 n & \omega_{p} & y_{I}^{(p1)}
\end{bmatrix} - \kappa_{I}^{(p)} (y_{I}^{(p1)} \cdot e_{I}^{(p)})^2 \\
- \kappa_{II}^{(p)} (y_{I}^{(p1)} e_{II}^{(p)})^2 - \frac{\omega_{p}^2}{m_{l}} m_{l} [n \cdot e_{I}^{(p)}] k_{f}
\]

\[ (3.6.8) \]

where \( m_{l} = \frac{d_{p}}{ds}, \quad m_{l}' = \frac{dm_{l}}{ds} \).

The vectors used in Eq. (3.6.7) and (3.6.8) are represent in coordinate system \( S_{f} \) (Fig. 3.5) with \( i_{f}, j_{f}, k_{f} \) as its unit vectors of axes. The expressions of the vectors in Eq. (3.6.7)
and (3.6.8) are as follows (Fig. 3.5)

\[ \omega_p = \omega_k \kappa_f \]  
\[ (3.6.9) \]

is the angular velocity of the pinion being in meshing with the rack cutter.

\[ v^{(p)}_{tr} = -\omega r_1 i_f \]  
\[ (3.6.10) \]

is the transfer velocity of a point on the rack cutter that performs translational motion, \( r_1 \) is the radius of pinion centrode.

\[ v^{(1)}_{tr} = \omega_p \times \kappa_f^{(p)} = \omega \begin{bmatrix} -y_f \\ x_f \\ 0 \end{bmatrix} = \omega \begin{bmatrix} - (y_c + r_1) \\ x_c - r_1 \psi_p \\ 0 \end{bmatrix} \]  
\[ (3.6.11) \]

is the transfer velocity of the pinion

\[ \gamma^{(p)}_{tr} = \gamma^{(p)} - \gamma^{(1)} = \omega \begin{bmatrix} y_c \\ -x_c + r_1 \phi_p \\ 0 \end{bmatrix} \]  
\[ (3.6.12) \]

is the "sliding" velocity - the velocity of a point of rack cutter with respect to the same point of pinion.

Substituting Eq. (3.6.9), (3.6.10), (3.6.11), (3.6.12), (3.6.2) and (3.3.9) into Eq. (3.6.7) and (3.6.8), then substituting Eq. (3.6.7) and (3.6.8) into (3.6.4), (3.6.5) and
(3.6.6), finally we can obtain the principal directions and curvatures from Eq. (3.6.4), (3.6.5), (3.6.6) and (3.6.2). Since the expressions of tool surface and its principal direction are complicated and tedious. It is difficult for us to write down the expression of $\kappa_I^{(1)}$, $\kappa_I^{(1)}$, $\sigma_I^{(1)}$ and $\sigma_{II}^{(2)}$. However, a corresponding computer program is developed for determining the principal directions and curvatures of any point of the pinion surface using the algorithm discussed above.

The same approach can be used to determine the principal directions and curvatures of regular helical gear. However, in this case, the generating surface is a plane, and the problem becomes simpler.

3.7 Contact Ellipse and Bearing Contact

The dimensions and orientation of the instantaneous contact ellipse can be determined based on the equations proposed by Litvin. (Litvin 1968). The input data for computation is: $\kappa_{I,II}^{(i)}$ $(i = 1, 2)$, $e_I^{(1)}$, $\sigma^{(12)}$ and $\epsilon$, where $\kappa_{I,II}^{(i)}$ are the principal curvature of pinion tooth surface $\Sigma_1$ and gear tooth surface $\Sigma_2$. $e_I^{(1)}$ is the unit vector of the first principal direction of $\Sigma_1$. $\sigma^{(12)}$ is the angle formed by the unit vectors of principal directions $\sigma_1^{(1)}$ and $\sigma_{II}^{(2)}$ (Fig. 3.11) and $\epsilon$ is the elastic approach of the contacting surfaces. The bearing contact is formed by a set of instantaneous contact ellipses that move over the gear tooth surface in the process of meshing.

The axes of the contact ellipse are directed along the $\eta$ axis and $\xi$ axis, respectively. The orientation of contact
ellipse is determined by the angle $\alpha$, which is angle between $\eta$ and $e_{I}^{(1)}$. (Fig. 3.11) The dimensions of ellipse are determined by $a^*$ and $b^*$ which are the half lengths of major and minor axis of the ellipse respectively. The following equations are used to determine $a$, $a^*$ and $b^*$.

\[
A = \frac{1}{4} \left[ \kappa_e^{(1)} - \kappa_e^{(2)} - |g_1 - g_2| \right] \\
B = \frac{1}{4} \left[ \kappa_e^{(1)} - \kappa_e^{(2)} + |g_1 + g_2| \right] \\
w \tan(2\alpha) = \frac{g_1 \sin2\sigma^{(12)}}{g_1 - g_2 \cos2\sigma^{(12)}}
\]

where

\[
\kappa_e^{(1)} = \kappa_I^{(1)} + \kappa_{II}^{(1)}, \quad \kappa_e^{(2)} = \kappa_I^{(2)} + \kappa_{II}^{(2)} \\
g_1 = \kappa_I^{(1)} - \kappa_{II}^{(1)}, \quad g_2 = \kappa_I^{(2)} - \kappa_{II}^{(2)}
\]

and

\[
a^* = \left| \frac{\varepsilon}{A} \right|^{1/2} \quad b^* = \left| \frac{\varepsilon}{B} \right|^{1/2}
\]
regular involute helical gear with misaligned axis, we will use
the following coordinate system, as shown in Fig. 3.11 and Fig.
3.12: (i) $S_f$ is rigidly connected to the frame (ii) an
auxiliary coordinate system $S_h$ that is also rigidly connected to
the frame (iii) $S_1$ and $S_2$ are rigidly connected to the pinion and
the gear respectively. The relations between $S_1$ and $S_f$ and
between $S_2$ and $S_h$ are shown in Fig. 3.12 and expressed by $M_{f1}$ and
$M_{h2}$ as

$$M_{f1} = \begin{bmatrix}
\cos\phi_1 & \sin\phi_1 & 0 & 0 \\
-sin\phi_1 & \cos\phi_1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}$$

(3.8.1)

$$M_{h2} = \begin{bmatrix}
\cos\phi_2 & -\sin\phi_2 & 0 & 0 \\
\sin\phi_2 & \cos\phi_2 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}$$

(3.8.2)

It is obvious that the rotation axis of the pinion and gear are
$Z_f(Z_1)$ and $Z_h(Z_2)$ respectively. Therefore, the error of assembly
of gears can be simulated with orientation and location of
coordinate system $S_h$ with respect to $S_f$. Figure 3.13 shows the
orientation of $S_h$ and $S_f$. When the pinion and gear axes are
crossed (Fig. 3.13a) and intersected (Fig 3.13b) with operating
center distance $C = O_fO_h$. It must be emphasized that $C$ can be
different from the nominal center distance given by $C_0 = r_1 + r_2$,
where $r_1$ and $r_2$ are the radii of the pinion and gear pitch
circles. The coordinate transformation from $S_h$ to $S_f$ is
represented by $[M_{fh}]$ as follows (Fig. 3.13)
where the gear axes are crossed as shown in Fig. 3.13a.

\[
[M_{fh}] = \begin{bmatrix}
-\cos\Delta \gamma & 0 & \sin\Delta \gamma & 0 \\
0 & -1 & 0 & C \\
\sin\Delta \gamma & 0 & \cos\Delta \gamma & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (3.8.3)

where the gear axes are intersected as shown in Fig. 3.13b.

The helical pinion tooth surface and its normal can be expressed in coordinate system \( S_f \) as:

\[
[r_{f(1)}] = [M_{f1}][r_1]
\] (3.8.5)

\[
[n_{f(1)}] = [L_{f1}][n_1]
\]

where \( L_{f1} \) is \( 3 \times 3 \) matrix from \( M_{f1} \). The helical gear tooth surface and its normal can be expressed in coordinate system \( S_f \) as

\[
[r_{f(2)}] = [M_{fh}][M_{h2}][r_2]
\] (3.8.6)

\[
[n_{f(2)}] = [L_{fh}][L_{h2}][r_2]
\]

where \( L_{fh} \) and \( L_{h2} \) is \( 3 \times 3 \) matrices from \( M_{fh} \) and \( M_{h2} \).

For a helical gear (lefthand), \( [r_2] \) and \( [n_2] \) can be represented as:
\[
[r_2] = \begin{bmatrix}
\cos^2 \psi_n 
/ \cos \psi_c \cos (\phi_G - \psi_n) [-t_G \sin \beta + r_2 \phi_G] + r_2 \sin \phi_G \\
\cos^2 \psi_c \sin (\phi_G - \psi_c) [-t_G \sin \beta + r_2 \phi_G] + r_2 \cos \phi_G \\
t_G (\cos \beta + \sin^2 \psi_n \cos \psi_c) - r_2 \phi_G \sin^2 \psi_n \tan \beta
\end{bmatrix}
\] (3.8.7)

\[
[n_2] = \begin{bmatrix}
-(\cos \psi_n \cos \beta \cos \phi_G + \sin \psi_n \sin \phi_G) \\
\cos \psi_n \cos \beta \sin \phi_G - \sin \psi_n \cos \phi_G \\
\cos \psi_n \sin \beta
\end{bmatrix}
\]

where \( t_G \) and \( \phi_G \) are the surface parameters and \( \psi_c = \arctan (\tan \psi_n / \cos \beta) \) is the pressure angle in the transverse section of the gear tooth.

From Eq. (3.3.9), (3.4.4), (3.4.8), (3.8.5), (3.8.6), and (3.8.7), it is known that: [substituting Eq.(3.4.4) into (3.3.9) to eliminate \( \theta_p \)]:

\[
\xi_f^{(1)} = \xi_f^{(1)} (\phi_p, \theta_p, \psi_1)
\]

\[
n_f^{(1)} = n_f^{(1)} (\phi_p, \theta_p, \psi_1)
\]

\[
\xi_f^{(2)} = \xi_f^{(2)} (\phi_G, t_G, \phi_2)
\]

\[
n_f^{(2)} = n_f^{(2)} (\phi_G, t_G, \phi_2)
\] (3.8.8)

The contact of gear tooth surface is simulated in the TCA program by the following equations
Vector equation (3.8.9) comes from the equality of the position vectors at the contact point and provide three independent equations whereas vector equation (3.8.10) comes from the equality of surface unit normals and provide only two independent equations. Therefore, Eq. (3.8.9) and (3.8.10) yield five independent scalar equations as follows:

\[ f_i(\phi_1, \theta_p, \phi_p, \phi_2; t_G, \phi_G) = 0 \quad (i = 1, 2, \ldots, 5) \quad (3.8.11) \]

Equation system 3.8.11 is the expression in implicit form of functions of one variable, i.e. \( \phi_1 \). Using theorem of implicit function, we can obtain

\[ \phi_2 = \phi_2(\phi_1) \quad (3.8.12) \]

considering at the neighborhood of \( P^O = (\phi_1, \theta_p, \phi_p, \phi_2; t_G, \phi_G) \) where \( P^O \) satisfy Eq. (3.8.11) and

\[ J = \frac{D(f_1, f_2, f_3, f_4, f_5)}{D(\phi_p, \theta_p, \phi_2; t_G, \phi_G)} \neq 0 \quad (3.8.13) \]

The function of transmission error can be determined by
3.9 Modification of Generating Surface $\Gamma_p$

Using cone as a tool surface to generate the helical pinion is a good way to localize bearing contact. By using the TCA program, it can be shown that the transmission errors caused by gear misalignment are on a very low level. However, the shape of the function of transmission errors is unfavorable as shown in Fig. 3.14(a). This shape of the function of transmission errors will result in interruption and interference with change of meshing gear teeth. A more favorable shape of the function of transmission errors is shown in Fig. 3.14(b). To obtain this shape of transmission error function, we need to modify generating surface $\Gamma_p$ into a revolute surface. The reason for using revolute surface is similar to the case for crowning a spur pinion (see Litvin and Zhang, 1987).

The surface of revolution is generated by an arc circle with radius $\rho$. The arc has a common normal with the cone generatrix line at the point $M$ (Fig. 3.15(a)). The circular arc and its normal are expressed in an auxiliary coordinate system $S_e$ as follows

$$
X_e = \rho [\cos(\alpha + \beta) - \cos \alpha] + \left( \frac{d}{\cos \alpha} - \frac{b}{\cos \psi_n \cos \mu} \right) \sin \alpha
$$

$$
= \left( \frac{d}{\cos \alpha} - \frac{b}{\cos \psi_n \cos \mu} \right) \sin \alpha - 2\rho \sin \frac{\beta}{2} \sin(\alpha + \frac{\beta}{2})
$$

$$
Y_e = \rho [\sin(\alpha + \beta) - \sin \alpha] + \frac{b}{\cos \psi_n \cos \mu} \cos \alpha
$$

(3.9.1)
\[
\frac{b}{\cos \psi_n \cos \psi} \cos \alpha + 2 \rho \sin \frac{\beta}{2} \cos (\alpha + \frac{\beta}{2})
\]

\[z_e = 0\]

\[
\begin{bmatrix}
\cos (\alpha + \beta) \\
\sin (\alpha + \beta) \\
0
\end{bmatrix}
\]

The surface of revolution is generated by rotation of the circular arc about the \(y_e\) axis and can be represented in coordinate system \(S_d\) as follows

\[
[r_d] = [L_{de}][r_e], \quad [n_d] = [L_{de}][r_e]
\]

where (Fig. 9.2(b))

\[
[L_{de}] = \begin{bmatrix}
\cos \theta_p & 0 & \sin \theta_p \\
0 & 1 & 0 \\
-\sin \theta_p & 0 & \cos \theta_p
\end{bmatrix}
\]

Then we obtain

\[
x_d = \left[\left(\frac{d}{\cos \alpha} - \frac{b}{\cos \psi_n \cos \psi}\right) \sin \alpha - 2 \rho \sin \frac{\beta}{2} \sin (\alpha + \frac{\beta}{2})\right] \cos \theta_p
\]

\[
y_d = \frac{b}{\cos \psi_n \cos \psi} + 2 \rho \sin \frac{\beta}{2} \cos (\alpha + \frac{\beta}{2})
\]

\[
z_d = \left[\left(\frac{d}{\cos \alpha} - \frac{b}{\cos \psi_n \cos \psi}\right) \sin \alpha - 2 \rho \sin \frac{\beta}{2} \sin (\alpha + \frac{\beta}{2})\right] \sin \theta_p
\]
The installment of the generating surface in coordinate system is the same as described in Section 3.3. The generated crowning pinion tooth surface can be obtained using the same approach as that described in section 3.4.

The meshing of gears using the crowning method described in this section has been simulated by numerical methods. The results of the investigation are illustrated with the following example.

Given: number of pinion teeth \( N_1 = 20 \), number of gear teeth \( N_2 = 40 \), diametral pitch in normal section \( P_n = 10 \) in\(^{-1} \), pressure angle in normal section \( \psi_n = 20^\circ \), helical angle \( \beta = 15^\circ \). The pinion tooth is crowned by revolute surface with generatrix arc \( \phi = 30 \) in. The revolute surface is deviated from a cone (comparing \( \xi \) in figure 3.2(b) and (c)). The cone has half apex angle \( \alpha = 20^\circ \) and bottom radius \( R = 10.6 \) in.

The topology of the pinion tooth surface provides a parabolic type of predesigned transmission errors with \( d = 6 \) arc seconds (Fig. 2.3 (a)) and a path contact that is directed across the tooth surface (Fig. 3.1).

The influence of gear misalignment has been investigated with the developed computer program and the results of computation are represented in table 3.9.1 and 3.9.2 for crossed and intersected gear axes, respectively. The misalignment of gear axes is 5 arc minutes.
The results of computation show that the resulting function of transmission errors is a parabolic one. Thus the linear function of transmission errors that was caused by gear misalignment has been absorbed by the predesigned parabolic function. Fig. 3.14 show the results of transmissions errors for crossed helical gears with (Table 3.9.1) and without (Table 3.4.1) crowning of the pinion.

**TABLE 3.9.1 - TRANSMISSION ERRORS OF CROSSED HELICAL GEARS**

<table>
<thead>
<tr>
<th>$\Phi_1$ (deg)</th>
<th>-14</th>
<th>-11</th>
<th>-8</th>
<th>-5</th>
<th>-2</th>
<th>1</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi_2$ (sec)</td>
<td>-4.99</td>
<td>-1.51</td>
<td>0.65</td>
<td>1.51</td>
<td>1.05</td>
<td>-0.75</td>
<td>-3.87</td>
</tr>
</tbody>
</table>

**TABLE 3.9.2 - TRANSMISSION ERRORS OF INTERSECTED HELICAL GEARS**

<table>
<thead>
<tr>
<th>$\Phi_1$ (deg)</th>
<th>-11</th>
<th>-8</th>
<th>-5</th>
<th>-2</th>
<th>1</th>
<th>4</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi_2$ (sec)</td>
<td>-6.15</td>
<td>-2.72</td>
<td>-0.60</td>
<td>0.20</td>
<td>-0.32</td>
<td>-21.9</td>
<td>-5.40</td>
</tr>
</tbody>
</table>

4. CROWNED HELICAL PINION WITH LONGITUDINAL PATH CONTACT

4.1 Basic Concepts and Considerations

A longitudinal path of contact means that the gear tooth surfaces are in contact at a point at every instant and the instantaneous contact ellipse moves along but not across the surface (Fig. 4.1(a)). It can be expected that this type of contact provides improved conditions of lubrication. Until now
only the Novikov-Wildhaber's gears could provide a longitudinal path of contact. A disadvantage of this type of gearing is their sensitivity to the change of the center distance and the axes misalignment. The sensitivity to non-ideal orientation of the meshing gears cause a higher level of gear noise in comparison with regular involute helical gears. Litvin et al. (Litvin, 1985) proposed a compromising type of non-conformal helical gears that may be placed between regular helical gears and Novikov-Wildhaber helical gears. The gears of the proposed gear train are the combination of a regular involute helical gear and a specially crowned helical pinion. The investigation of transmission errors for helical gears with a longitudinal path of contact shows that their good bearing contact is accompanied with an undesirable increased level of linear transmission errors. The authors propose to compensate this disadvantage by a predesigned parabolic function of transmission errors, that will absorb the linear function of transmission errors (see section 2.3). The two following methods for derivation of the pinion tooth surface will the modified topology will now be considered.

4.2 Method 1

Consider that two rigidly connected generating surfaces, $\Sigma_G$ and $\Sigma_P$, are used for the generation of the gear and the pinion, respectively (Fig. 4.1(b)). Surface $\Sigma_G$ is a plane and represents the surface of a regular rack-cutter; surface $\Sigma_P$ is a cylindrical surface whose cross-section is a circular arc. We may imagine that while surfaces $\Sigma_G$ and $\Sigma_P$
translate, as the pinion and the gear rotate about their axes. To provide the predesigned parabolic function of transmission errors it is necessary to observe the following transmission functions by generation

\[
\frac{V}{\omega_G} = r_2 = \text{const}, \quad \frac{V}{\omega_p} = r_2 \left( \frac{N_1}{N_2} - 2a_p \right) = f(\phi_p) \tag{4.2.1}
\]

Here: \( \omega_G \) and \( \omega_p \) are the angular velocities of pinion and gear by cutting; \( V \) is the velocity of the rack-cutter in translational motion; \( N_1 \) and \( N_2 \) are the gear and pinion tooth numbers; \( \phi_p \) is the angle of rotation of the pinion by cutting. The generated gears will be in point contact at every instant and transform rotation with the function

\[
\phi_2(\phi_1) = \frac{N_1}{N_2} \phi_1 - a_1^2 \phi_1^2 \quad 0 < \phi_1 < \frac{2\pi}{N_1} \tag{4.2.2}
\]

This function relates the angles of rotation of the pinion and the gear, \( \phi_1 \) and \( \phi_2 \), respectively, for one cycle of meshing. The predesigned function of transmission errors is

\[
\Delta \phi_2 = -a_1^2 \phi_1 \tag{4.2.3}
\]

It is evident that after differentiation of function (4.2.2) we obtain that the gear ratio \( \omega_2/\omega_1 \) satisfies equation (4.2.1), if \( \phi_1 \) and \( \phi_2 \) are used instead of \( \phi_p \) and \( \phi_G \).

To apply this method of generation in practice it is necessary to vary the angular velocity of the pinion in the
process of its generation that may be accomplished by a computer controlled machine for cutting.

It is obvious that in this method the gear tooth surface is kept as regular skew involute surface as shown in Eq.(2.4.1) and (2.4.2) since its generating surface $r_G$ is a plane and generating motion is $V = \omega_G \cdot r_2$. Now, let us derive the pinion tooth surface equations.

The pinion generating surface $r_p$ is a cylindrical surface with circular arc as its cross section and can be represented in an auxiliary coordinate system $S_a$ as follows: (see Fig. 4.2)

$$\begin{align*}
\mathbf{r}_a &= \begin{bmatrix} x_a \\ y_a \\ z_a \\ 1 \end{bmatrix} = \begin{bmatrix} R[\cos(\psi_n + \alpha) - \cos\phi_n] \\ R[\sin(\psi_n + \alpha) - \sin\phi_n] \\ t_p \\ 1 \end{bmatrix} \\
\end{align*}$$

(4.2.4)

The unit surface normal is represented by

$$\begin{align*}
\mathbf{n}_a &= \begin{bmatrix} n_{ax} \\ n_{ay} \\ n_{az} \end{bmatrix} = \begin{bmatrix} \cos(\psi_n + \alpha) \\ \sin(\psi_n + \alpha) \\ 0 \end{bmatrix} \\
\end{align*}$$

(4.2.5)

From coordinate system $S_a$ to $S_c$ the helical angle $\beta_p$ is introduced. Based on Fig. 3.8(d) and $[M_{ca}]$ as shown in Eq. (3.3.7), we have

$$\begin{align*}
\mathbf{r}_c^{(p)} &= \begin{bmatrix} x_c^{(p)} \\ y_c^{(p)} \\ z_c^{(p)} \\ 1 \end{bmatrix} = [M_{ca}] \mathbf{r}_a = \begin{bmatrix} R[\cos(\psi_n + \alpha) - \cos\phi_n] - t_p \sin\beta_p \\ R[\sin(\psi_n + \alpha) - \sin\phi_n] \\ R[\cos(\psi_n + \alpha) - \cos\phi_n] + t_p \sin\beta_p \\ 1 \end{bmatrix} \\
\end{align*}$$

(4.2.6)
\[
\begin{bmatrix}
\frac{n_c(p)}{L_{ca} x} \\
\frac{n_c(p)}{L_{ca} y} \\
\frac{n_c(p)}{L_{ca} z}
\end{bmatrix} = \begin{bmatrix}
\cos(\psi_n + \alpha)\cos \beta_p \\
\sin(\psi_n + \alpha) \\
\cos(\psi_n + \alpha)\sin \beta_p
\end{bmatrix}
\]

The generating process is described in the Fig. 3.5 where

\[
S = r_2\phi_p \left( \frac{N_1}{N_2} - a\phi_p \right)
\]

The equation of meshing of the generating surface \( r_p \) and the helical pinion tooth surface is given by:

\[
\eta(p) \cdot \eta(p1) = \eta(p) \cdot (\eta(p) - \eta(1)) = 0
\]

In the system shown in Fig. 3.5, it can be found that

\[
y(p) = \begin{bmatrix}
-\frac{ds}{dt} \\
0 \\
0
\end{bmatrix}
\]

\[
y(1) = \begin{bmatrix}
-r_1 - y_c(p) \\
-S + x_c(p) \\
0
\end{bmatrix} \omega_p
\]

Taking into account that \( \frac{d\phi_p}{dt} = \omega_p \) and from Eq. (4.2.1) we have

\[
y(p1) = y(p) - y(1) = \omega_p \begin{bmatrix}
\frac{N_1}{N_2} - 2a\phi_p \\
-2x_c(p) + 2r_2\phi_p \left( \frac{N_1}{N_2} - a\phi_p \right)
\end{bmatrix}
\]
Substituting Eq. (4.2.6), (4.2.7) and (4.2.11) into Eq. (4.2.9), the equation of meshing can be obtained as:

\[
\cos(\psi_n + \alpha) \cos \beta_p \left\{ R [\sin(\psi_n + \alpha) - \sin \psi_n] + 2r_2 a \phi_p \right\} \\
+ \sin(\psi_n + \alpha) \left\{ -R [\cos(\psi_n + \alpha) - \cos \psi_n] - t \sin \beta_p \right\} + r_2 \phi_p \left( \frac{N_1}{N_2} - a \phi_p \right) = 0
\]  

(4.2.12)

Equation of meshing gives the relation among three variables, that is, \( t_p \), \( \alpha \) and \( \phi_p \). It is obvious that from Eq. 4.2.12, the equation of meshing can be rewritten as:

\[
t_p = \cotan(\psi_n + \alpha) \cotan(\beta_p) \left\{ R [\sin(\psi_n + \alpha) - \sin \psi_n] + 2r_2 a \phi_p \right\} \\
+ \frac{1}{\sin \beta_p} \left\{ -R [\cos(\psi_n + \alpha) - \cos \psi_n] + r_2 \phi_p \left( \frac{N_1}{N_2} - a \phi_p \right) \right\}
\]

(4.2.13)

The pinion tooth surface can be determined with the same approach.
as that described in the section 3.4 and represented by Eq. (3.4.8) and (3.4.9) together with Eq. (4.2.6), (4.2.7) and (4.2.13).

4.3 Method 2

The derivation of the crowned pinion tooth surface is based on two stages of synthesis. On the first stage it is assumed the pinion tooth surface $C_1$ is exact conjugate surface to the gear tooth surface which is regular skew involute surface under the condition that the rotation transformed by the pinion and the gear is described in Eq. (4.2.2) with predesigned parabolic function of transmission errors.

On the second stage of synthesis it is necessary to localize the bearing contact and substitute the instantaneous line contact by a point contact. This becomes possible if the pinion tooth surface will be deviated as it is shown in Fig. 4.1(c). Only a narrow strip, $L$, will be kept while $C_1$ will be changed into $C_1^1$. The deviation of $C_1^1$ with respect to $C_1$ may be accomplished in various ways, for instance, in such a way, that the cross-section of $C_1^1$ is only a circular arc. The generation of $C_1^1$ requires a computer controlled machine to relate the motions of the tool surface and the being generated pinion surface $C_1^1$. The tool surface (it may be only a plane) and $C_1^1$ will be in point contact in the process of generation.

Now, let us derive the pinion tooth surface equations based on the two stages discussed above. First, we can derive the intermediate pinion tooth surface $C_1$ as that generated by gear
tooth surface ξ₁. The relation of rotation for the pinion and
the gear is shown in Eq.(4.2.2). The gear tooth surface ξ₂ and
its unit normal are shown in Eq.(2.4.3) and (2.4.4).

To represent the gear tooth surface ξ₂ in the fixed
coordinate system S_f in Fig. 4.3, it is necessary to transform
[r₂] and [n₂] into [r₉] and [n₉] as:

\[
[r₉] = [M₂][r₂]
\]

\[
[n₉] = [L₂][n₂]
\]

(4.3.1)

where \[M₂ = \begin{bmatrix} -\cos θ₂ & \sin θ₂ & 0 & 0 \\ -\sin θ₂ & -\cos θ₂ & 0 & 0 \\ 0 & 0 & 1 & C \\ 0 & 0 & 0 & 1 \end{bmatrix} \]

Substituting Eq.(2.4.3) and(2.4.4) into Eq.(4.3.1) we obtain:

\[
[r₉] = \begin{bmatrix} x₉^{(2)} \\ y₉^{(2)} \\ z₉^{(2)} \\ 1 \end{bmatrix} = \begin{bmatrix} \cos^2 ψ_n \cos(ϕ_G-ψ_C-θ₂)[-t_G\sin β_p+r₂ϕ_G]-r₂\sin(ϕ_G-θ₂) \\ -\frac{\cos^2 ψ_n}{\cos ψ_c} \cos(ϕ_G-ψ_C-θ₂)[-t_G\sin β_p+r₂ϕ_G]-r₂\sin(ϕ_G-θ₂) \\ t_G^2\cos^2(1+\sin ψ_n+\sin β_p)-r₂ϕ_G\sin ψ_n t\psi_p \\ 1 \end{bmatrix}
\]

(4.3.2)

\[
[n₉] = \begin{bmatrix} nₓ₉^{(2)} \\ nᵧ₉^{(2)} \\ nᶻ₉^{(2)} \end{bmatrix} = \begin{bmatrix} \cos ψ_n \cos β_p \cos(ϕ_G-θ₂)+\sin ψ_n \sin(ϕ_G-θ₂) \\ -\cos ψ_n \cos β_p \sin(ϕ_G-θ₂)+\sin ψ_n \cos(ϕ_G-θ₂) \\ \cos ψ_n \sin β_p \end{bmatrix}
\]

(4.3.3)
The generating process is shown in Fig. 4.3 where $\phi_1$ and $\phi_2$ is given by Eq. (4.2.2). The equation of meshing of the generating surface $\Sigma_2$ and generated surface $\Sigma_1$ is described as:

$$\dot{N}^{(2)}_2 \cdot \dot{Y}^{(21)} = N^{(2)}_2 (\dot{Y}^{(2)} - \dot{Y}^{(1)}) = 0 \quad (4.3.4)$$

The relative velocity $\dot{Y}^{(21)}$ can be expressed as

$$\dot{Y}^{(21)} = \dot{Y}^{(2)} - \dot{Y}^{(1)} = \omega_2 \times (\overrightarrow{O_2O_1} + \zeta_f) - \omega_1 \times \zeta_f \quad (4.3.5)$$

where

$$\omega^{(1)} = \begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix} \omega_1; \quad \omega^{(2)} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \omega_2 = \begin{bmatrix} 0 \\ 0 \\ \omega_1 \frac{N_1}{N_2} - 2a\phi_1 \end{bmatrix}$$

and the relation between $\omega_1$ and $\omega_2$ is obtained by taking derivative of Eq. (4.2.2). By rearranging and simplifying Eq. (4.3.5), we obtain

$$\dot{Y}^{(21)} = \begin{bmatrix} -y_f^{(2)} \\ x_f^{(2)} \\ 0 \end{bmatrix} \omega_1 \left[ \frac{N_2}{N_1} + 1 - 2a\phi \right] + \begin{bmatrix} C \\ 0 \\ 0 \end{bmatrix} \omega_1 \left[ \frac{N_1}{N_2} - 2a\phi \right] \quad (4.3.6)$$

Substituting Eq. (4.3.6) (4.3.2) and (4.3.3) into Eq. (4.3.4) and
simplifying it, we can obtain:

\[
\cos(\phi_G - \phi_2 - \psi_c) = \cos \psi_c \left[ 1 - \frac{2a \phi_1}{N_2} \right] \tag{4.3.7}
\]

where \( \psi_c \) is the pressure angle in transverse section of helical gear. Equation 4.3.7 is the equation of meshing which describes the relation between \( \phi_G \) and \( \phi_2 \). We can rearrange Eq. 4.3.7 as:

\[
\phi_G = \phi_2 + \lambda(\phi_1) = \frac{N_1}{N_2} \phi_1 - a \phi_1^2 + \lambda(\phi_1) \tag{4.3.8}
\]

where \( \lambda(\phi_1) = \psi_c - \arccos \cos \psi_c \left[ 1 - \frac{2a \phi_1}{1 + N_1/N_2} \right] \)

The pinion tooth surface \( \xi_1 \) and its normal can be determined by transforming \( \xi^{(2)}_f \) into coordinate system \( S_1 \) as

\[
[r_1] = [M_{1f}] [\xi^{(2)}_f] \tag{4.3.9}
\]

\[
[n_1] = [L_{1f}] [n^{(2)}_f]
\]

where \([M_{1f}] = \begin{bmatrix} \cos \phi_1 & -\sin \phi_1 & 0 & 0 \\ \sin \phi_1 & \cos \phi_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}\)

Substituting (4.3.2) (4.3.3) into Eq.(4.3.9), we can get

\[
[r_1] = \begin{bmatrix} x_1 \\ y_1 \\ z_1 \\ 1 \end{bmatrix}
\]

\[
[n_1] = \begin{bmatrix} n_{1x} \\ n_{1y} \\ n_{1z} \end{bmatrix}
\]

47
where

\begin{align*}
  x_1 &= \frac{\cos^2 \psi n}{\cos \psi_c} \cos(\phi_1 + \psi_c - \lambda(\phi_1))[-t_G \sin \beta_p + r_2 \phi_G] \\
  &\quad + r_2 \sin(\phi_1 - \lambda(\phi_1)) - C \sin \phi_1 \\
  y_1 &= \frac{\cos^2 \psi n}{\cos \psi_c} \sin(\phi_1 + \psi_c - \lambda(\phi_1))[-t_G \sin \beta_p + r_2 \phi_G] \\
  &\quad - r_2 \cos(\phi_1 - \lambda(\phi_1)) + C \cos \phi_1 \\
  z_1 &= t_G \cos \beta_p (1 + \sin^2 \psi_n + g^2 \beta_p) - r_2 \phi_G \sin^2 \psi_n t \beta_p
\end{align*}

\begin{align*}
  n_{1x} &= \frac{\cos \psi n \cos \beta_p}{\cos \psi_c} \cos(\phi_1 - \lambda(\phi_1) + \psi_c) \\
  n_{1y} &= \frac{\cos \psi n \cos \beta_p}{\cos \psi_c} \sin(\phi_1 - \lambda(\phi_1) + \psi_c) \\
  n_{1z} &= \cos \psi n \sin \beta_p
\end{align*}

Equations (4.3.10), (4.3.8) and (4.2.2) represent pinion tooth surface \( \Sigma_1 \) in coordinate system \( S_1 \). But \( \Sigma_1 \) is only an intermediate surface. Now we come to the second stage, that is, to deviate \( \Sigma_1 \) into \( \Sigma^{1}_{1} \). The surface \( \Sigma^{1}_{1} \) must satisfy such condition that when it is in mesh with gear tooth surface \( \Sigma_2 \) without misalignment, the contact path will be in longitudinal direction. The surface \( \Sigma^{1}_{1} \) will be formed in two steps: (i) the contact path curve in \( \Sigma_1 \) is chosen and kept. (ii) the profile of surface \( \Sigma_1 \) in transverse section is replaced
by a smaller circular arc attached on the L in such a way that
the original normal of $\Sigma_1$ along L is kept.

To choose curve L on $\Sigma_1$ we could define that the contact
path on the gear tooth surface is in the middle of the tooth,
that is

$$r = r_2$$

(4.3.11)

where $r = \sqrt{x_2^2 + y_2^2}$ is the distance of the surface point to gear
axis in transverse section. Substituting Eq. (2.4.3) into Eq.
(4.3.10) and simplifying it, we can obtain the relation of surface
parameter along the contact path as

$$r^2 G - t \sqrt{c} \sin \phi_p = 0$$

(4.3.12)

Applying Eq.(4.3.12) to Eq.(4.3.10), we can find the curve L on
pinion tooth surface $\Sigma_1$ as:

$$x_1 = r_2 \sin(\phi_1 - \lambda(\phi_1)) - C \sin \phi_1$$

$$y_1 = -r_2 \cos(\phi_1 - \lambda(\phi_1)) + C \cos \phi_1$$

$$z_1 = r_2 \cot \phi_p \left( \frac{N_1}{N_2} \phi_1 - a + \phi_2 + \lambda(\phi_1) \right)$$

(4.3.13)

where the $\phi_1$ is the curve parameter and $\lambda(\phi_1)$ is described in
Eq. (4.3.8).
Now we should attach the circular arc to the L described by Eq. (4.3.13) in the transverse section to form new surface $\Sigma_1^1$. Also the tangent of the arc at the point on the line L must be perpendicular to the normal of $\Sigma_1$ described in Eq. (4.3.10). As shown in Fig. 4.4, the equation of new surface $\Sigma_1^1$ are:

$$x_1' = x_1 + r[\cos(\mu+a) - \cos\mu]$$

$$y_1' = y_1 + R[\sin(\mu+a) - \sin\mu]$$

$$z_1' = z_1$$

(4.3.14)

where $\mu = \phi_1 - \lambda(\phi_1) + \psi_c$. Equation (4.3.14) describes the new pinion surface $\Sigma_1^1$. In Eq. (4.3.14) when $a = 0$, the designed contact path path L is obtained.

### 4.4 Discussion and Example

In section 4.2 and 4.3, two methods have been presented with derivation of the equations of pinion tooth surface. Comparing the two methods for the generation of the pinion tooth surface, it may be concluded that both provide a localized bearing contact, a longitudinal path of contact and predesigned parabolic function of transmission errors. The difference between these methods is that the tool and pinion tooth surfaces are in line contact by applying the first method for generation and in point contact by the second one. The disadvantage of both methods for crowning of the pinion is that the transmission errors caused by
gear misalignment are large and it is necessary to envision a high level of the predesigned parabolic function for the absorption of transmission errors. This is illustrated with the following example (the algorithms for simulation have been discussed in Section 3.8).

Given (the data is from ref. 3): pinion tooth number \( N_1 = 12 \), gear tooth number \( N_2 = 94 \); diametral pitch in normal section \( p_n = 2 \) in\(^{-1} \); pressure angle in normal section \( \phi_n = 30^0 \); helical angle \( \beta = 15^0 \).

The pinion tooth surface is a crowned surface whose cross-section is an arc of a circle of the radius 0.3584in. The predesigned parabolic function is of the level \( d = 25 \) arc seconds (Fig. 2.3(a)).

Consider now that the axes of the gear and the pinion are crossed and the crossing angle is 3 arc minutes. The computer program for the simulation of meshing provides the data of transmission errors that is given in Table 4.1. The data of Table 4.1 shows that the resulting function of transmission errors is a parabolic function. Thus, the linear function of transmission errors caused by misalignment of gear axes has been absorbed by the predesigned parabolic function.

Table 4.2 represents the transmission errors for the same helical gears for the case when the gear axes are intersected and form an angle of 3 arc minutes. The resulting function of transmission errors is again a parabolic function with the level \( d = 26.2 \) arc seconds. The relatively high level of transmission errors is the price that must be paid for the longitudinal path
of contact. However, the proposed topology of the pinion tooth surface provides a reduction of the level of gear noise since the linear function of transmission errors is substituted by a parabolic function.

TABLE 4.1 TRANSMISSION ERRORS FOR CROSSED HELICAL GEARS

<table>
<thead>
<tr>
<th>$\phi_1$ (deg)</th>
<th>-23</th>
<th>-18</th>
<th>-13</th>
<th>-8</th>
<th>-3</th>
<th>2</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \phi_2$ (sec)</td>
<td>-17.94</td>
<td>-3.06</td>
<td>5.64</td>
<td>8.23</td>
<td>4.84</td>
<td>-4.39</td>
<td>-19.37</td>
</tr>
</tbody>
</table>

TABLE 4.2 TRANSMISSION ERRORS OF INTERSECTED HELICAL GEARS

<table>
<thead>
<tr>
<th>$\phi_1$ (deg)</th>
<th>-20</th>
<th>-15</th>
<th>-10</th>
<th>-5</th>
<th>0</th>
<th>5</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \phi_2$ (sec)</td>
<td>-23.06</td>
<td>-8.50</td>
<td>0.15</td>
<td>2.96</td>
<td>0.00</td>
<td>-3.66</td>
<td>-22.95</td>
</tr>
</tbody>
</table>

5. DEFORMATION OF HELICAL GEAR SHAFT

5.1 Basic Concepts and Considerations

Deformation of gear shafts always exists when the gears are used to transmit power. This is because under the load the force applied on gear tooth surface is transferred to the gear shaft and the shaft is not rigid body. It can be proven that the deformation of gear shaft results in the same effects as misalignment induced by assembly. The misalignment from assembly could be reduced to as little as possible. But the shaft deformation is inevitable. Fortunately, all the transmission
errors and shift of bearing contact due to deformation of gear shaft can be compensated by crowning helical pinion tooth surface with the methods discussed in Chapters 3 and 4.

5.2 Force Applied on Gear Shaft

When the pinion and gear mesh a force, between their tooth surfaces, is applied on the contact point. The direction of the force is along the normal of the contact point. For the case of regular helical gears, in the fixed coordinate system \( S_f \) as described in section 3.8, the force direction is a constant since the normal of the contact point is a constant (Litvin, 1968) and can be expressed as:

\[
\hat{n}_C = \begin{bmatrix} 
\cos \psi_n & \cos \theta_p \\
\sin \psi_n & \\
\cos \psi_n & \sin \theta_p 
\end{bmatrix} \quad (5.2.1)
\]

As shown in Fig. 5.1, the force applied on the pinion tooth surface is:

\[
\tilde{F} = \tilde{F}_t + \tilde{F}_z = -F \begin{bmatrix} 
\cos \psi_n & \cos \theta_p \\
\sin \psi_n & \\
\cos \psi_n & \sin \theta_p 
\end{bmatrix} \quad (5.2.2)
\]

where \( \tilde{F}_t = -F \begin{bmatrix} 
\cos \psi_n & \cos \theta_p \\
\sin \psi_n & \\
0 & 
\end{bmatrix} \); \( \tilde{F}_z = -F \begin{bmatrix} 
0 & \\
\cos \psi_n & \sin \theta_p 
\end{bmatrix} \)
$F_t$ is called as transverse force since it is applied on the transverse section of the pinion and the gear and $F_z$ is called as axial force. Transverse force $F_t$ is always in tangency with the base circle in transverse section. Therefore, if the torque transferred by the gears is constant, the magnitude of transverse force is also constant. So is the magnitude of axial force since it has certain ratio with transverse force.

Both transverse force and axial force can be transferred to the axis of gear shaft with resultant torque (designated by $F^*_t$ and $F^*_z$). For the transverse force, the resultant torque is the torque transferred by the gear. For the axial force, the resultant torque is balanced by the support bearings. Assuming the force is applied on the middle section of the gear, after the force is decomposed and transferred to the axis of gear shaft as shown in Fig. 5.1 (b), both the transverse force and axial force will act on the origin of coordinate system $S_f$. Actually, both forces will cause deformation of the shaft. But since the axial force only cause very small tension or compression of the shaft, it can be neglected.

5.3 Modelling of Shaft Deformation

As shown in Fig. 5.2, the transverse force $F_t$ is applied on the point A which is the center of the shaft corresponding to the pinion or gear middle cross section. Under the force, the deformation of the shaft is composed of two parts, that is, deflection of shaft at the point A designated by $V_D$ and rotation of the shaft cross section with A as a center designated by
\( \lambda_p \). The value \( V_p \) and \( \lambda_p \) depend on the magnitude of transverse force, geometry and material of shaft and the way how the shaft is supported. (Timoshenko 1973).

Now, let us model the deformation of the helical pinion shaft. For convenience and consistency with the previous chapters, we establish our coordinate system as follows:

(1) As shown in Fig. 5.3a \( S_f \) is a fixed coordinate system and rigidly connected to the frame. \( S_a \) is an auxiliary coordinate system with the \( Y_a \) axis coincident with the direction of transverse force. The angle \( \psi_c \) is the pressure angle in the transverse section of helical gear. The matrix \( [M_{fa}] \) can transfer vector from \( S_a \) to \( S_f \) and is expressed as:

\[
[M_{fa}] = \begin{bmatrix}
\sin\psi_c & \cos\psi_c & 0 & 0 \\
-cos\psi_c & sin\psi_c & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]  
(5.3.1)

(2) Coordinate system \( S_{f1} \) and \( S_{a'} \) [Fig. 5.3(b)] are connected to the axis of pinion shaft. Without deformation, \( S_{f'} \) and \( S_{a'} \) are coincident with \( S_f \) and \( S_a \) respectively. The matrix \( [M_{a'f'}] \) can transfer vector from \( S_{f'} \) to \( S_{a'} \), and is expressed as:

\[
[M_{a'f'}] = \begin{bmatrix}
\sin\psi_c & -\cos\psi_c & 0 & 0 \\
\cos\psi_c & \sin\psi_c & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]  
(5.3.2)

(3) Coordinate systems \( S_a \) and \( S_{a'} \) are not coincident when shaft deformation occurs. As shown in Fig. 5.2, their relation can be
expressed as:

\[
M_{aa'} = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & \cos \lambda_p & -\sin \lambda_p & -v_p \\
0 & \sin \lambda_p & \cos \lambda_p & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (5.3.3)

(4) As described in previous chapter, pinion tooth surface can be expressed in coordinate systems \( S_1 \) as a position vector \( \xi_1 \) with its normal \( n_1 \). The relation of \( S_1 \) and \( S_{f'} \) is shown in Fig. 5.3(c) and expressed as:

\[
M_{f',1} = \begin{bmatrix}
\cos \phi_1 & \sin \phi_1 & 0 & 0 \\
-\sin \phi_1 & \cos \phi_1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (5.3.4)

After the coordinate systems are established, it is easy to find that the deformation of the pinion shaft can be modelled by matrix \( M_{ff'} \) as:

\[
[M_{ff'}] = [M_{fa}][M_{aa'}][M_{a'f'}]
\]

\[
= \begin{bmatrix}
1+\cos^2 \psi_c (\cos \lambda_p -1) & \sin \psi_c \cos \psi_c (\cos \lambda_p -1) & -\cos \psi_c \sin \lambda_p & -v_p \cos \psi_c \\
\sin \psi_c \cos \psi_c (\cos \lambda_p -1) & 1+\sin^2 \psi_c (\cos \lambda_p -1) & -\sin \psi_c \sin \lambda_p & -v_p \sin \psi_c \\
\sin \lambda_p \cos \psi_c & \sin \lambda_p \sin \psi_c & \cos \lambda & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (5.3.5)
Since $\lambda_p$ is very small angle, it is reasonable to use $\lambda_p$ instead of $\sin \lambda_p$ and one instead of $\cos \lambda_p$. Therefore, Eq. (5.3.5) can be written as:

$$
\begin{bmatrix}
1 & 0 & -\lambda_p \cos \psi_c & -V_p \cos \psi_c \\
0 & 1 & -\lambda_p \sin \psi_c & -V_p \sin \psi_c \\
\lambda_p \cos \psi_c & \lambda_p \sin \psi_c & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
$$

(5.3.6)

Also, for the gear shaft, the coordinate systems $S_G$, $S_G'$, $S_b$, and $S_b'$ are used instead of $S_f$, $S_f'$, $S_a$ and $S_a'$, and $\lambda_p$ and $V_p$ are used instead of $\lambda_p$ and $V_p$. Then, using the same ideas, the deformation of gear shaft can be modelled by matrix $[m_{aa'}]$ as:

$$
M_{GG'} = \begin{bmatrix}
1 + \cos^2 \psi_c (\cos \lambda_G - 1), \sin \psi_c \cos \psi_c (\cos \lambda_G - 1), \cos \psi_c \sin \lambda_G, V_G \cos \psi_c \\
\sin \psi_c \cos \psi_c (\cos \lambda_G - 1), 1 + \sin^2 \psi_c (\cos \lambda_G - 1), \cos \psi_c \sin \lambda_G, V_G \cos \psi_c \\
-\sin \lambda_G \cos \psi_c, -\sin \lambda_G \sin \psi_c, \cos \lambda_G, 0 \\
0, 0, 0, 1
\end{bmatrix}
$$

(5.3.7)

Or considering that $\lambda_G$ is very small angle:

$$
M_{GG'} = \begin{bmatrix}
1 & 0 & +\lambda_G \cos \psi_c & V_G \cos \psi_c \\
0 & 1 & +\lambda_G \sin \psi_c & V_G \sin \psi_c \\
-\lambda_G \cos \psi_c & -\lambda_G \sin \psi_c & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
$$

(5.3.8)

It must be emphasized that the gear tooth surfaces are expressed
in coordinate system $S_2$. The relation of $S_2$ and $S_f'$ is shown in Fig. 5.4 and expressed as:

$$
\begin{align*}
[M_{G', 2}] &= \begin{bmatrix}
-\cos\phi_2 & \sin\phi_2 & 0 & 0 \\
-sin\phi_2 & -\cos\phi_2 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\end{align*}
$$

(5.3.9)

Also as shown in Fig. 5.5, the coordinate system $S_f$ and $S_G$ are not coincident. There is a center distance $C$ between their origins. Therefore $M_{fG}$ is represented as:

$$
\begin{align*}
[M_{fG}] &= \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & C \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\end{align*}
$$

(5.3.10)

Now it is easy to simulate the performance of the gears with the deformation of their shafts. Assuming, there is a helical pinion in coordinate system $S_1$ represented by position vector $r_1$ and normal vector $n_1$ and a helical gear in coordinate system $S_2$ represented by $r_2$ and $n_2$, we can write the tooth contact equation as:

$$
\begin{align*}
[M_{ff'}] [r_{f', 1}] [r_1] &= [M_{fG}] [M_{GG'}] [M_{G', 2}] [r_2] \\
[L_{ff'}] [L_{f', 1}] [r_1] &= [L_{fG}] [L_{GG'}] [L_{G', 2}] [n_2]
\end{align*}
$$

(5.3.11)

where $L$ matrices are 3 x 3 matrices from corresponding 4 x 4 $M$ matrices, crossing 4th row and 4th column and $M$ matrices can be found in this section. Applying the same ideas discussed in Chapter 2 and used in section 3.8, we can find the transmission errors and the shift of the bearing contact by computer aided
It is interesting to mention that the deformation of the shaft can be expressed as a combination of misalignment with crossing axes, misalignment with intersecting axes, and change of the center distance. This is because, for example

\[
[M_{ff1}] = \begin{bmatrix}
1 & 0 & -\lambda_p \cos \psi_c & -V_p \cos \psi_c \\
0 & 1 & -\lambda_p \sin \psi_c & -V_p \sin \psi_c \\
\lambda_p \cos \psi_c & \lambda_p \sin \psi_c & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
\begin{bmatrix}
1 & 0 & -\lambda_p \cos \psi_c & 0 \\
0 & 1 & 0 & 0 \\
\lambda_p \cos \psi_c & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
\begin{bmatrix}
1 & 0 & 0 & -V_p \cos \psi_c \\
0 & 1 & 0 & -V_p \sin \psi_c \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

(5.3.12)

where the three decomposed matrices are represented by the matrix for crossing axis with small angle \( \lambda_p \cos \psi_c \), matrix for intersecting axis with small angle \( \lambda_p \sin \psi_c \), and matrix for axis displacement.

5.4 Example and Discussion

The results of investigation in this chapter are illustrated with the following example. Given: number of pinion tooth \( N_1 = 20 \), number of gear tooth \( N_2 = 40 \), diametral pitch in normal section \( P_n = 10 \) in\(^{-1} \), pressure angle in normal
section $\phi_n = 20^\circ$, helical angle $\beta = 15^\circ$, gear tooth length $L = 5/P_n$. Also assume deformation values $V_p = V_G = 0.0125$ in, $\lambda_p = \lambda_G = 2$ min. The computer program for simulation provides the data of transmission errors in Table 5.1.

From Table 5.1, it is known that the transmission errors due to gear shaft deformation is an approximately linear function for regular skew involute pinion and gear. Similar to the case of gear axis misalignment, the linear function of transmission errors can be absorbed by predesigned parabolic function of transmission errors that is obtained by crowning helical pinion tooth surface.

**TABLE 5.1 TRANSMISSION ERRORS FOR HELICAL GEAR WITH DEFORMED SHAFT**

<table>
<thead>
<tr>
<th>$\phi_1$ (deg)</th>
<th>3</th>
<th>6</th>
<th>9</th>
<th>12</th>
<th>15</th>
<th>8</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \phi_2$ (sec)</td>
<td>1.38</td>
<td>3.16</td>
<td>4.74</td>
<td>6.32</td>
<td>7.90</td>
<td>9.48</td>
<td>11.06</td>
</tr>
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</table>

6. CONCLUSION

Several methods of crowning helical pinion tooth surface have been developed. The modified pinion tooth surface can provide predesigned parabolic function of transmission errors that are able to absorb linear function of transmission errors induced by misalignment. Also, the modified pinion tooth surface can improve the bearing contact. Principles of computer aided simulation of meshing, contact, and respective computer programs have also been developed. The numerical results of examples of
crowned helical pinion in mesh with regular helical gear show that the ideas of crowning are useful to get favourable bearing contact and allowable transmission errors. But the synthesis of pinion tooth surface should be based on a compromise between the requirements of transmission errors and the patterns of the bearing contact.
REFERENCES


5. Maag Information 18, Topological Modification, Zurich.


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FIG. 2.1 Contacting Tooth Surfaces
FIG. 2.2 Transmission Error Caused by Gear Misalignment
FIG. 2.3 Interaction of Parabolic and Linear Functions
FIG. 2.4 Discontinued Parabolic Function of Transmission Errors
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\[ V = \omega \psi h = \omega^2 r_2 \]
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FIG. 4.3 Basic Coordinate Systems for Meshing Gears
FIG. 4.4 Derivation of Deviated Helical Pinion Tooth Surface
FIG. 5.1 Force Applied on Pinion and Its Shaft
FIG. 5.2 Shaft Deflection
FIG. 5.3 Coordinate Systems for Simulation of Shaft Deformation
FIG. 5.4 Coordinate Systems for Simulation of Shaft Deformation
FIG. 5.5 Coordinate Systems for Simulation of Shaft Deformation
FLOWCHART FOR PROGRAM I

START

INPUT GIVEN DATA

FIND AUXILIARY VALUES FOR CALCULATION

CALCULATE PROFILE OF PINION SURFACE CUT BY PLANE Z = CONST.

COMPARE THE PROFILE WITH INVOLUTE CURVE AT MIDDLE SECTION

STOP
PROGRAM I

SURFACE OF HELICAL PINION GENERATED BY CONE CUTTER

AUTHORS: FAYDOR LITVIN

JIAO ZHANG

PURPOSE

This program is used to calculate the surface of a helical pinion which is generated by cone cutter.

NOTE

This program is written in FORTRAN 77. It can be compiled by V compile in IBM mainframe or FORTRAN compiler in VAX system.

IMPLICIT REAL*8(A-H,O-Z)

DOUBLE PRECISION KSIN,MU,KSIC,MUO

DIMENSION X(100),Y(100),ERROR(100),FEEREC(100),UREC(100),
+THETAR(100)

DEFINE PARAMETERS USED BY PROGRAMS

(1) IN ANG LP ARE UNIT NUMBERS ASSIGNED TO THE INPUT AND OUTPUT DEVICES

IN=5

LP=6

(2) NDBUG IS USE TO CONTROL THE AUXILIARY OUTPUT FOR DEBUGGING

NDBUG=1

(3) NSOLVE IS THE UPPER LIMITATION OF REPEATATION FOR SOLVING NONLINEAR EQUATIONS;

EPSI IS THE CLEARANCE OF FUNCTION VALUES WHEN THE FUNCTIONS IS CONSIDERED AS SOLVED (ALL FUNCTION HAS FORMS OF F(X)=0); DELTA IS THE CLEARANCE OF VARIABLE INCREMENT WHEN FUNCTION IS SOLVED; NC, EPSI AND DELTA MAY BE CHANGED WHEN SOLUTIONS ARE DIVERGENT OR LESS ACCURATE

NSOLVE=100

DELTA=1.D-15

EPSI=1.D-15

(4) OTHER PARAMETERS (DON'T CHANGE)

DR=DATAN(1.D0)/45.D0

DEFINE INPUT PARAMETERS OF PROBLEM (USE INCH AS UNIT OF LENGTH)

(1) PINION AND GEAR: PN=DIAMETRAL PITCH; N1=PINOIN TOOTH NUMBER;

KSIN=PRESSURE ANGLE IN NORMAL SECTION (DEGREE);

BETAP=HELIX ANGLE (DEGREE);

HD=HEIGHT OF DEENDUM OF PINION;
HA=HEIGHT OF ADDENDUM OF PINION
ZCOE=COEFFICIENT OF PINION TOOTH LENGTH (THE LENGTH= ZCOE/PN)
PN=10.0D0
N1=20
KSIN=20.0D0*DR
BETAP=20.0D0*DR
HD=1.0D0/PN
HA=1.0D0/PN
ZCOE=10.

(2) TOOL: ALPHA=HALF OF CONE VERTEX ANGLE (DEGREE);
RC=RADIUS OF BOTTOM CIRCLE OF CONE;
MU= TILT ANGLE TO INSTALL PINION-CUTTING TOOL
ALP=80.0D0*DR
MUO=DATAN(DSIN(KSIN)*DTAN(BETAP))
MU=1.0*MUO
RC=1.0D0

(3) OUTPUT:
NZ=NO. OF CROSS SECTIONS WHERE PINION PROFILE IS SIMULATED;
NU=NO. OF MAXIMUM POINTS USED FOR SIMULATE PINION PROFILE
UIN=INCREMENT OF PINION TOOTH SURFACE COORDINATE U
NZ=21
NU=61
UIN=2.5D0*CH/(NU-1)

DESCRIPTION OF OUTPUT VARIABLES
Z1=DISTANCE BETWEEN CROSS SECTION CONSIDERED AND MIDDLE CROSS SECTION
NO=OUTPUT NO.
U=TOOL SURFACE COORDINATE
THETA=TOOL SURFACE COORDINATE
FEE=PINION TOOTH SURFACE GENERATION PARAMETER
X1=X COORDINATE OF PINION PROFILE
Y1=Y COORDINATE OF PINION PROFILE
R1=ADIUS OF PINION PROFILE
VSH=AVERAGE DEVIATION SHIFT OF CROSS SECTION PROFILE FROM PROFILE
OF GENERAL PINION (INVOLUTE CURVE)
VPE=MAXIMUM DEVIATION OF CROSS SECTION PROFILE FROM INVOLUTE CURVE
VSD=STANDARD DEVIATION OF CROSS SECTION PROFILE FROM INVOLUTE CURVE

THE PROGRAM IS WRITTEN BY JIAO ZHANG
SK=DSIN(KSIN)
CK=DCOS(KSIN)
SB=DSIN(BETAP)
CB=DCOS(BETAP)
SM=DSIN(MU)
CM=DCOS(MU)
SA=DSIN(ALPHA)
CA=DCOS(ALPHA)
KSIC=DATAN(SK/CK/CB)
CRC=DCOS(KSIC)
SKC=DSIN(KSIC)
PT=PN*CB
RP=N1/2./PT
RB = RP * DCOS (KSIC)
RA = RP + HA
CL = RC / SA
CH = HD / CK / CM

A1 = CA * CK * CB + SA * SK * CM * CB + SA * SM * SB
A2 = SK * SM * CB - CM * SB
A3 = CA * SK * CM * CB - SA * CK * CB + CA * SM * SB
A4 = SK * CM * CB + SM * SB
B1 = CA * SK - SA * CK * CM
B2 = CK * SM
B3 = SA * SK + CA * CK * CM
B4 = CK * CM

C1 = CA * CK * SB + SA * SK * CM * SB - SA * SM * CB
C2 = SK * SM * SB + CM * CB
C3 = CA * SK * CM * SB - SA * CK * SB - CA * SM * CB
C4 = -SK * CM * SB + SM * CB
D1 = CH * CB + SK * SM * SB
D2 = SA * SM * CB - SB * (CA * CK + SA * SK * CM)
D3 = CA * CK * SB
D4 = CA * (CA * SK - SA * CK * CM)
D5 = SA * (SA * SK + CA * CK * CM)
D6 = CA * CK * SM

DO 5 I = 1, NZ
Z1 = ZCOE / PN / 2. + ZCOE / PN * FLOAT (I - 1) / FLOAT (NZ - 1)

FEEO = Z1 * SB / CB / RP
CFO = DCOS (FEEO)

SFO = DSIN (FEEO)
R1 = RP
ERR = 0.

DO 15 J = 1, NU
IF (R1 .GT. RA .AND. J .GT. 1) GOTO 55
U = CL - UIN * FLOAT (J - 1)

TEMP1 = (Z1 - (CL - CH) * C4 - U * CA * C3) / U / SA / DSQRT (C1 * C1 + C2 * C2)
TEMP2 = DARSIN (C1 / DSQRT (C1 * C1 + C2 * C2))
TEMP3 = DARSIN (TEMP1)
THETA = TEMP3 - TEMP2
CT = DCOS (THETA)
ST = DSIN (THETA)

XC = U * SA * (CT * A1 + ST * A2) + U * CA * A3 - (CL - CH) * A4
YC = U * SA * (CT * B1 - ST * B2) - U * CA * B3 + (CL - CH) * B4

FEE = (U * (CT * D1 + ST * D2) - (CL - CH) * ((CT * CA * SA + SA * SA) * D1 - ST * D3)) / RP +
(CT * D4 + D5 - ST * D6)
CF = DCOS (FEE)
SF = DSIN (FEE)

X1 = XC * CF + YC * SF - RP * FEE * CF + RP * SF
Y1 = -XC * SF + YC * CF + RP * FEE * SF + RP * CF
R1 = DSQRT (X1 * X1 + Y1 * Y1)

IF (R1 .LT. RB) GOTO 15

NP = NP + 1
X (NP) = X1
Y (NP) = Y1

FEERE (NP) = FEE
UREC (NP) = U
\[ \text{THETAR}(NP) = \text{THETA} \]
\[ XE = x1 \cdot C\Phi + y1 \cdot S\Phi \]
\[ YE = y1 \cdot S\Phi + y1 \cdot C\Phi \]
\[ YS = YE \]
\[ \text{FEET} = \text{FEE} + \text{FEEO} \]
\[ \text{DO 25 } K = 1, \text{NSOLVE} \]
\[ W = R\Phi \cdot \text{FEET} \cdot \text{C\Phi} \cdot \text{DSIN} (\text{FEET} - K\text{SIC}) + R\Phi \cdot \text{DCOS} (\text{FEET}) - YS \]
\[ \text{DWDF} = -R\Phi \cdot \text{SK\Phi} \cdot \text{DCOS} (\text{FEET} - K\text{SIC}) + R\Phi \cdot \text{FEET} \cdot \text{CK\Phi} \cdot \text{DCOS} (\text{FEET} - K\text{SIC}) \]
\[ D\Phi = W / DWDF \]
\[ \text{IF (DABS (W) .LT. EPSI.AND. DABS (DF).LT.DELTA) GOTO 65} \]
\[ \text{FEET} = \text{FEET} + D\Phi \]
\[ \text{CONTINUE} \]
\[ \text{CONTINUE} \]
\[ \text{ERROR (NP)} = XE - XS \]
\[ \text{WRITE (LP , 110) } K, W, D\Phi, \text{ERROR (NP)}, \text{FEET}, \text{FEE} + \text{FEEO} \]
\[ \text{C 110 FORMAT (1X, 'K=', I5, 5X, 'W=', D15.7, 5X, 'DF=', D15.7, D15.7, 2D25.17)} \]
\[ \text{ERR} = \text{ERR} + \text{ERROR (NP)} \]
\[ \text{CONTINUE} \]
\[ \text{VPE} = 0. \]
\[ \text{VSD} = 0. \]
\[ \text{DO 35 J = 1, NP} \]
\[ \text{ETEMP} = \text{ERROR (J)} + \text{VSH} \]
\[ \text{IF (DABS (ETEMP).GT.VPE) VPE = DABS (ETEMP)} \]
\[ \text{VSD} = \text{VSD} + \text{ETEMP**2} \]
\[ \text{DO 35 J = 1, NP} \]
\[ \text{R1} = \text{DSQRT (X(J)**2 + Y(J)**2)} \]
\[ \text{ETEMP} = \text{ERROR (J)} + \text{VSH} \]
\[ \text{WRITE (LP, 20) J, UREC(J), THETAR(J), FEEREC(J), X(J), Y(J), R1, ETEMP} \]
\[ \text{20 FORMAT (2X, 12, 2X, 7F15.7)} \]
\[ \text{CONTINUE} \]
\[ \text{STOP} \]
\[ \text{END} \]

\[ \text{ENTRY} \]
\[ \text{C FIND AUXILIARY VALUES FOR CALCULATION} \]
\[ \text{RP} = \text{FLOAT (N1) / 2.DO/PN} \]
\[ \text{CL} = \text{RC/DSIN (ALP)} \]
\[ \text{D} = \text{CL*DCOS (ALP)} \]
\[ \text{A1} = \text{CL-HDC/DCOS (RKS)} \]
\[ \text{RPU} = \text{RP+HAC} \]
\[ \text{DO 5 I = 1, NL} \]
\[ \text{Z} = \text{FLOAT (I-1)*ZI} \]
\[ \text{YY} = \text{D - Z/DTAN (ALP)} \]
\[ \text{WRITE (LP, 10) Z} \]
\[ \text{10 FORMAT (1H1, \'/1X, 'Z1=', ,F15.7/1X, 'NO=', 10X, 'Y1', 13X, 'XP', 13X, 'YP', +} \]
\[ 13X, 'R1', 13X, 'FEE')} \]

98
C  CALCULATE THE PROFILE OF THE SURFACE CUT BY PLANE Z=CONST

KKK=0

DO 15 J=1,N
Y1=YY*FLOAT(J-1)/FLOAT(N-1)
F=DSQRT(1.-(Z/(D-Y1)/DTAN(ALP))**2)
FEE=((D-Y1)*F/DCOS(ALP)-A1*(F*DCOS(ALP)*DCOS(ALP)+DSIN(ALP)*DSIN(ALP)))/RF/(DSIN(ALP)*DCOS(ALP-RKS)-F*DCOS(ALP)*DSIN(ALP-RKS))
XP(I,J)=(D-Y1)*(DTAN(ALP)*F*DCOS(ALP-RKS+FEE)-DSIN(ALP-RKS+FEE))
YP(I,J)=-(D-Y1)*(DTAN(ALP)*F*DSIN(ALP-RKS+FEE)+DCOS(ALP-RKS+FEE))
R1=DSQRT(XP(I,J)**2+YP(I,J)**2)
IF (R1.GT.RPU) THEN
JJ=J-1
XP(I,J)=XP(I,J)+XP(I,J)-XP(I,J))/((R1-R1TEMP)*(RPU-R1TEMP))
YP(I,J)=YP(I,J)+YP(I,J)-YP(I,J))/((R1-R1TEMP)*(RPU-R1TEMP))
FEE=FEETEM+(FEE-FEETEM)/(R1-R1TEMP)*(RPU-R1TEMP)
Y1=Y1TEM+(Y1-Y1TEM)/(R1-R1TEMP)*(RPU-R1TEMP)
R1=DSQRT(XP(I,J)**2+YP(I,J)**2)
KKK=1
END IF
WRITE (LP,20) J,Y1,XP(I,J),YP(I,J),R1,FEE
20 FORMAT (1X,I4,4F15.7,F15.7)
IF (KKK.GT.0) GO TO 30
FEETEM=FEE
Y1TEM=Y1
R1TEM=R1
15 CONTINUE
30 NS(I)=J-1
IF (I.NE.1) GO TO 55
NS2=NS(I)
GO TO 5

C  PREPARATION OF INTERPOLATION
55 NS2=NS(I)
DO 105 L=1,NS2
J=NS2+1-L
IF (YP(1,NS1).GT.YP(I,J)) GO TO 110
105 CONTINUE
110 NS2=J
NREC=2
XERS=0.DO
DO 115 L=1,NS2
J=NREC,NS1
IF (YP(1,J).GT.YP(I,L)) GO TO 120
115 CONTINUE
120 NREC=J
J1=J-1
XERROR(L)=XP(I,L)-XP(I,J1)-(YP(I,L)-YP(I,J1))*(XP(I,J)-XP(I,J1))
+ / (YP(I,J)-YP(I,J1))
XERS=XERS+XERROR(L)
115 CONTINUE
XERS=XERS/FLOAT(NS2)
XPE=0.DO
SDX=0.DO
IF (NDBUG.GT.2) WRITE (LP,80)
80 FORMAT (1H1,13X,'NO.',4X,'DIVIATION VALUE')
DO 45 L=1,NS2
XERROR(L)=XERROR(L)+XERS
IF (NDBUG.GT.2) WRITE (LP,50) L,XERROR(L)
50 FORMAT (13X,I3,2F15.7)
IF (DABS(XERROR(L)).GT.XPE) XPE=DABS(XERROR(L))
SDX=SDX+XERROR(L)**2
45 CONTINUE
SDX=DSQRT(SDX/FLOAT(NS2))
WRITE (LP,40) XERS,XPE,SDX
40 FORMAT (///1X,'XSH=',E15.7,5X,'XPE=',E15.7,5X,'SDX=',E15.7)
IF (NDBUG.GT.2) WRITE (LP,60) NS1,NS2
60 FORMAT (///5X,'NS1=',I6,6X,'NS2=',I6)
5 CONTINUE
STOP
END
FLOWCHART FOR PROGRAM II

START

INPUT GIVEN DATA

FIND AUXILIARY VALUES FOR CALCULATION

CHECK IF UNDERCUTTING OR FIND SOME DESIGNED PARAMETER TO AVOID UNDERCUTTING

STOP
**PROGRAM II**

**UDDERCUTTING CONDITION FOR HELICAL PINION GENERATED BY CONE CUTTER**

**AUTHOR:** FAYDOR LITVIN

**JIAO ZHANG**

---

**PURPOSE**

This program is used to find the uddercutting conditions for a helical pinion generated by cone cutter.

**NOTE**

This program is written in FORTRAN 77. It can be compiled by V compile in IBM mainframe or FORTRAN compiler in VAX system.

```
IMPLICIT REAL*8(A-H,0-Z)
DOUBLE PRECISION KSIN,MU
```

**DEFINE PARAMETERS USED BY PROGRAMS**

1. IN ANG LP are unit numbers assigned to the input and output devices
   - IN=5
   - LP=6

2. NDBUG is use to control the auxiliary output for debugging
   - NDBUG=2

3. Other parameters (Don’t change)
   - DR=DATAN(1.DO)/45.DO

**DEFINE INPUT PARAMETERS OF PROBLEM (USE INCH AS UNIT OF LENGTH)**

1. Pinion and gear: PN=diametral pitch; N1=pinion tooth number; KSIN=pressure angle; BETAP=helix angle of pinion; HD=height of dedendum of pinion
   - PN=10.DO
   - N1=20
   - KSIN=20.DO*DR
   - BETAP=30.DO*DR
   - HD=1.DO/PN

2. Tool: ALPHA=half of cone vertex angle (degree);
   - RC=radius of bottom circle of cone;
   - MU=tilt angle of mounting tool
   - ALPHA=20.DO*DR
   - RC=0.35DO
   - MU=DATAN(DSIN(KSIN)*DTAN(BETAP))
   - MU=0.*MUO

3. Problem: NPROB=ID no. of problem (-1=given N1 and HD, find if uddercutting occur; 0=given N1, find maximum HD without udder-
C CUTTING; l=GIVEN HD, FIND MINIMUM N1 WITHOUT UDDERCUTTING);
C N=NO. OF THETA VALUES USED CALCULATION;
C DELTHE=INCREMENT OF THETA(DEGREE)
NPROB= 1
N=21
DELTHE=1.DO*DR
C
C DESCRIPTION OF OUTPUT
C
C OUTPUT IS A STATEMENT BASED ON THE PROBLEM WITHOUT ANY LITERAL
C PARAMETER
C
C FIND AUXILIARY VALUES FOR CALCULATION
SK=DSIN(KSIN)
CK=DCOS(KSIN)
SB=DSIN(BETAP)
CB=DCOS(BETAP)
SM=DSIN(MU)
CM=DCOS(MU)
SA=DSIN(ALPHA)
CA=DCOS(ALPHA)
PT=PN*CB
RF=N1/2./PT
CL=RC/SA
CH=HD/CK/CM
UU=CL-CH
AA=CM*CB+SK*SM*SB
BB=CA*CK*SB+SA*SK*CM*SB-SA*SM*CB
CC=CA*CK*SB
DD=DD*CA
EE=SA*SK+CA*CK*CM
EE=EEI*SA
FF=FFI*CA
II=(CA*SK*CM*SB-SA*CK*SB-CA*SM*CB)*CA/SA
WRITE (LP,90)
90 FORMAT(1H1)
IF (NPROB) 5,15,25
C CHECK IF UNDERCUTTING OCCURS
5 WRITE (LP,10)
10 FORMAT (1H1/3X,'NO',7X,'THETA',12X,'A',13X,'B',14X,'C',10X,
+ 'B**2-4.*A*C',3X,'U1/(RC/SIN(ALPHA))')
UMIN=5.DO
DO 45 I=1,N
NN= (N+1)/2
THE=DBLE(FLOT(I-NN))*DELTHE
ST=DSIN(THE)
CT=DCOS(THE)
GG=DD*CT+EE-FF*ST
WW=(BB*BB+AA*AA)*EE+(BB*DD-AA*FF)*II+ST*ST*ST*(AA*AA*FF-BB*BB*FF
+ 2.*AA*BB*DD-CT*CT*CT*(BB*BB*DD-AA*AA*DD+2.*AA*BB*FF)
+ -ST*(2.*AA*AA*FF+AA*BB*DD-AA*EE*II)+CT*(2.*BB*BB*DD+AA*BB*FF
+ +BB*EE*II)

XX= ((AA*FF*SA*SA-CC*EE)*CT+ (AA*DD*SA*SA-AA*EE*CA*CA)*ST+ (AA*FF*CA +CA-CC*DD)) *(BB*CT+AA*ST+II)
YY=DD1*SA*ST-FF1*SA*ST-EE1*CA
ZZ=CM*CK
A=YY*WW
B=UU* (WW*ZZ+XX*YY) +RP*GG*GG*GG
C=UU*XX*ZZ
D=B*B-4.*A*C
IF (D.GE.0.) THEN
   U1= (-B+DSQRT (D))/2./A
   U2= (-B-DSQRT (D))/2./A
   U1=U1/CL
   U2=U2/CL
   THE=THE/DR
   IF (NDBUG.LT.1) WRITE (LP,100) I,THE,A,B,C,U1
100 FORMAT (1X,I4,8F 15.7)
   ELSE
   IF (NDBUG.LT.1) WRITE (LP,lOO) I,THE,A,B,C,DD
   END IF
45 CONTINUE
   IF (UMIN.LT.1.DO) WRITE (LP,110)
110 FORMAT (///lX,'UDDERCUTTING WILL OCCUR FOR YOUR DESIGN')
   IF (UMIN.GE.1.DO) WRITE (LP,120)
120 FORMAT (///lX,'UDDERCUTTING WILL NOT OCCUR FOR YOUR DESIGN')
   GO TO 35
C DETERMINE THE MAXIMUM ADDENDUM HEIGHT OF RACK CUTTER
15 WRITE (LP,20)
20 FORMAT (1H1/3X,'NO',7X,'THETA',12X,'A',13X,'B',14X,'C',15X,
   'B**2-4.*A*C',3X,'ALLOWED RATIO OF HD/(1/PN)'
   )
   UMIN=5.DO
   DO 55 I=1,N
      THE=DBLE (FLOAT(I-NN))*DELTHE
      ST=DSIN (THE)
      CT=DCOS (THE)
      GG=DD*CT+EE-FF*ST
      WW= (BB*BB+AA*AA)*EE+(BB*DD-AA*FF)*II+ST*ST*ST* (AA*AA*FF-BB*BB*FF
      +2.*AA*BB*DD)-CT*CT*CT*(BB*BB-DD-AA*DD+2.*AA*BB*FF)
      + -ST*(2.*AA*AA*FF+AA*BB*DD-AA*EE*II)+CT*(2.*BB*BB*DD+AA*BB*FF
      +BB*EE*III)
      XX= ((AA*FF*SA*SA-CC*EE)*CT+ (AA*DD*SA*SA-AA*EE*CA*CA)*ST+ (AA*FF*CA +CA-CC*DD)) *(BB*CT+AA*ST+II)
      YY=DD1*SA*CT-FF1*SA*ST-EE1*CA
      ZZ=CM*CK
      A=XX*ZZ
      B=CL* (WW*ZZ+XX*YY)
      C=CL*YY*WW+CL*RP*GG*GG*GG
      D=B*B-4.*A*C
      TEST=DABS (A/B)
      EPS=1.D-16
      THE=THE/DR
      IF (D.GE.0.) THEN
      IF (TEST.GT.EPS) THEN
         U1= (-B+DSQRT (D))/2./A
   104
U2=\(-B-\sqrt{D}\)/2./A
ELSE
U1=-C/B
U2=0.
END IF
U1=(CL-U1)*CK*PN
U2=(CL-U2)*CK*PN
IF (NDEBUG.LT.1) WRITE (LP,100) I;THE,A,B,C,D,U1,U2
ELSE
IF (NDEBUG.LT.1) WRITE (LP,100) I,THE,A,B,C,D
END IF
IF (UMIN.GT.U1) UMIN=U1
CONTINUE
WRITE (LP,200) UMIN
200 FORMAT (/*/*,'TO AVOID UDDERCUTTING, IT IS NECESSARY TO KEEP DEDE
+NDUM OF PINION <=',F10.7,'/PN')
GO TO 35
C DETERMINE THE MINIMUM NO. OF TEETH FOR UNUNDERCUTTING
25 WRITE (LP,30)
30 FORMAT (1H1/3X,'NO' ,7X, 'THETA' ,7X, 'NO. OF TEETH')
RNMAX=0.
DO 65 I=1,N
THE=DBLE (FLOAT (I-NN))*DELTHE
ST=DSIN (THE)
CT=DCOS (THE)
GG=DD*CT+EE-FF*ST
WW=BB*BB+AA*AA)*EE+(BB*DD-AA*FF)*II+ST*ST*ST*(AA*AA*FF-BB*BB*FF
+2.*AA*BB*DD-CT*CT*CT*(BB*BB*DD-AA*AA*DD+2.*AA*BB*FF)
XX=((AA*FF*SA*SA-CC*EE)*CT+(AA*DD*SA*SA-AA*EE*CA*CA)*ST+(AA*FF*CA
+CA-CC*DD)*(BB*CT+AA*ST+II)
YY=D1*SA*CT-FF1*SA*ST-EE1*CA
ZZ=CM*CK
RR=-CL*CL*YY*WW+CL*UU*(WW*ZZ+XX*YY)+UU*UU*XX*ZZ)/CL/GG**3
RN=2.*RR*PT
THE=THE/DR
IF (RNMAX.LT.RN) RNMAX=RN
IF (NDEBUG.LT.1) WRITE (LP,100) I,THE,RN
CONTINUE
WRITE (LP,300) RNMAX
300 FORMAT (///1X,'WITHOUT UDDERCUTTING, MINIMUM TOOTH NO. OF PINION
+IS: ',F11.7)
35 WRITE (LP,400)
400 FORMAT(1H1)
STOP
END
FLOWCHART FOR PROGRAM III

START

INPUT GIVEN DATA

FIND AUXILIARY VALUES FOR CALCULATION

FIND POSITION AND DIMENSION OF CONTACT ELLIPSE

STOP
PROGRAM III

CONTACT ELLIPSIS FOR HELICAL PINION GENERATED BY CONE CUTTER IN MESHING WITH REGULAR HELICAL GEAR

AUTHORS: FAYDOR LITVIN
JIAO ZHANG

PURPOSE

This program is used to find the shape and orientation of the contact ellipse when a helical pinion crowned by cone cutter is in meshing with a regular helical gear.

NOTE

This program is written in FORTRAN 77. It can be compiled by V compiler in IBM mainframe or FORTRAN compiler in VAX system.

IMPLICIT REAL*8(A-H,O-Z)
DOUBLE PRECISION KSIN,MU,MUO,MUT,KSIC,KF,KH,KSP,KQP,KSG,KQG
DIMENSION CMN(3,4),EFN(3),EHF(3),RND(3),RDI(4),EFF(3),EHF(3),
+ RNF(3),RC(3),RF(3),R1(3)

DEFINE PARAMETERS USED BY PROGRAMS

(1) IN ANG LP ARE UNIT NUMBERS ASSIGNED TO THE INPUT AND OUTPUT DEVICES

IN=5
LP=6

(2) NDBG IS USE TO CONTROL THE AUXILIARY OUTPUT FOR DEBUGGING
NDBG=2

(3) OTHER PARAMETERS (DON'T CHANGE)

DR=DATAN(1.00)/45.00

DEFINE INPUT PARAMETERS OF PROBLEM (USE INCH AS UNIT OF LENGTH)

(1) PINION AND GEAR: PN=DIAMETRAL PITCH; N1=PINION TOOTH NUMBER;
MPG=TOOTH NUMBER RATIO(GEAR TOOTH NO./N1);
KSIN=PRESSURE ANGLE IN NORMAL SECTION;
BETAP=HELIX ANGEL;
HD=HEIGHT OF DEEDENDUM OF PINION
PN=10.00
N1=20
MPG=2
KSIN=20.00*DR
BETAP=10.00*DR
HD=1./PN

(2) TOOL: ALPHA=HALF OF CONE VERTEX ANGLE(DEGREE);
RC=RADIUS OF BOTTOM CIRCLE OF CONE;
C MU= TILT ANGEL TO INSTALL PINION CUTTING TOOL
ALPHA= 80. DO* DR
MUO= D atan (DSIN (KSIN) * D atan (BETAP))
MU= 0.* MUO
RC= 1. DO
C (3) DEFORMATION: DEL=CONTACT DEFORMATION AT CONTACT POINT
DEL= 4. D-4
C (4) OUTPUT: NU= NUMBER OF CONTACT POINTS IN MATING SURFACES FOR US
C TO CALCULATE CONTACT ELLIPSES)
NU= 101
C
C DESCRIPTION OF OUTPUT PARAMETER
C
C R1= PINION RADIUS OF CONTACT POINT
C ALPHA= THE ROTATION ANGLE BETWEEN PRINCIPAL DIRECTION OF PINION
C TOOTH SURFACE AND AXES OF CONTACT ELLIPSE
C A= LENGTH OF HALF SHORT AXIS OF CONTACT ELLIPSE
C B= LENGTH OF HALF LONG AXIS OF CONTACT ELLIPSE (ALONG DIRECTION OF
C GEAR TOOTH LENGTH)
C RNF= UNIT NORMAL OF PINION TOOTH SURFACE AT CONTACT POINT
C EFF= PRINCIPAL DIRECTION OF PINION TOOTH SURFACE AT CONTACT POINT
C EHF= PRINCIPAL DIRECTION OF PINION TOOTH SURFACE AT CONTACT POINT
C
C FIND AUXILIARY VALUES FOR CALCULATION
SK= DSIN (KSIN)
CK= DCOS (KSIN)
SB= DSIN (BETAP)
CB= DCOS (BETAP)
SM= DSIN (MU)
CM= DCOS (MU)
SA= DSIN (ALPHA)
CA= DCOS (ALPHA)
KSIC= D atan (SK/CK/CB)
CKC= DCOS (KSIC)
SKC= DSIN (KSIC)
PT= PN* CB
RP= N1/2./ PT
RB= RP* DCOS (KSIC)
RA= RP+ 1./ PN
N2= N1* MPG
RG= RP* MPG
CL= RC/ SA
CH= HD/ CK/ CM
A= CL- CH
CMM (1, 1)= CA* CK* CB+ SA* SK* CH* CB+ SA* SM* SB
CMM (1, 2)= SA* CK* CB- CA* SK* CM* CB- CA* SM* SB
CMM (1, 3)= SK* SM* CB- CM* SB
CMM (1, 4)= -(SK* CH* CB+ SM* SB)
CMM (2, 1)= CA* SK- SA* CK* CM
CMM (2, 2)= SA* SK+ CA* CK* CM
CMM (2, 3)= - CK* SM
CMM (2, 4)= CK* CM
CMM (3, 1)= CA* CK* SB+ SA* SK* CM* SB- SA* SM* CB
CMM (3, 2)= SA* CK* SB- CA* SK* CM* SB+ CA* SM* CB

108
CMM(3,3) = SK*SM*SB + CM*CB
CMM(3,4) = -SK*CM*SB + SM*CB
D1 = CM*CB + SK*SM*SB
D2 = SA*SM*CB - SB*(CA*CK + SA*SK*CM)
D3 = CA*CK*SB
D4 = CA*(CA*SK - SA*CK*CM)
D5 = SA*(SA*SK + CA*CK*CM)
D6 = CA*CK*SM
UL = CL - 2.DO*CH
UU = CL
MUT = MUO/DR
WRITE (LP, 110) RP, RA, RB, MUT

110 FORMAT (///1X, 'RP=', F15.7, 5X, 'RA=', F15.7, 5X, 'RB=', F15.7, 5X,
+ 'MUO=', F15.7)

TH = 0.D0
ST = DSIN(TH*DR)
CT = DCOS(TH*DR)
EFD(1) = ST
EFD(2) = 0.D0
EFD(3) = -CT
EHD(1) = -CT*SA
EHD(2) = CA
EHD(3) = -ST*SA
RND(1) = CT*CA
RND(2) = SA
RND(3) = ST*CA
CALL MATMUL(CMM, EFD, EFF, 3, 3)
CALL MATMUL(CMM, EHD, EHF, 3, 3)
CALL MATMUL(CMM, RND, RNF, 3, 3)
WRITE (LP, 10) TH, (EFF(M), M=1,3), (EHF(M), M=1,3), (RNF(M), M=1,3)

10 FORMAT (1H1, //3X, 'THTEA:', F15.7, ' DEGREE' //1X, 'EFF:', 3F15.7/1X,
+ 'EHF:', 3F15.7/1X, 'NF :', 3F15.7)

DO 15 J = 1, NU
U = UU - (UU - UL) / FLOAT(NU - 1) * FLOAT(J - 1)
KF = -CA/SA/U
KH = 0.D0
RD(1) = U*CT*SA
RD(2) = -U*CA
RD(3) = U*ST*SA
RD(4) = A
CALL MATMUL(CMM, RD, RC, 3, 4)
FEE = (U*(CT*D1 + ST*D2) - A*((CT*CA*CA + SA*SA)*D1 - ST*D3)) / ((CT*D4 + D5 - ST*
+ D6)/RP)
RF(1) = RC(1) - RP*FEE
RF(2) = RC(2) + RP
RF(3) = RC(3)
RPP = DSQRT(RF(1)**2 + RF(2)**2)
CALL PROT(RF, R1, FEE)
TEMP = RC(2) * EFF(1) - RF(1) * EFF(2)
B13 = EHF(3) - KF*TEMP
B23 = -EFF(3)
B33 = - (RNF(1)*RF(1) + RNF(2)*RF(2) + KF*TEMP*TEMP)
SIGMA = 0.5D0*DATAN(2.*B13*B23/(B23*B23 - B13*B13 - (KF - KH)*B33))
COE1 = (B23*B23 - B13*B13 - (KF - KH)*B33)/B33/DCOS(2.*SIGMA)

109
COE2 = KF + (B13*B13 + B23*B23) / B33
KSP = (COE2 - COE1) / 2. DO
KQP = (COE2 + COE1) / 2. DO

IF (NDBUG.LT.1) WRITE (LP, 20) U, FEE, RPP, (R1(M), M=1,3), + B13, B23, B33, SIGMA, KSP, KQP


W = -(A - U)
KSG = 0.
KQG = 1. / (RG*SK*(CKC/CK/CB)**2 + W*CM*CK/SK)
G1 = KSP - KQP
G2 = KSG - KQG
S1 = KSP + KQP
S2 = KSG + KQG
SIGMGP = - SIGMA
ALPHA1 = 0.5D0 * DATAN (G2 * DSIN (2. * SIGMGP) / (G1 - G2 * DCOS (2. * SIGMGP)))
ALPHA2 = ALPHA1 + SIGMGP
AA = (S1 - S2 - DSQRT (G1 - G2 * DCOS (2. * SIGMGP) + G2 * G2)) / 4.
BB = (S1 - S2 + DSQRT (G1 - G2 * DCOS (2. * SIGMGP) + G2 * G2)) / 4.
AAA = 1. / DSQRT (DABS (AA))
BBB = 1. / DSQRT (DABS (BB))
RATIO = BBB / AAA
ALPHA1 = ALPHA1 / DR
ALPHA2 = ALPHA2 / DR

WRITE (LP, 130) G1, G2, S1, S2, ALPHA1

130 FORMAT (1X, 5F15.7)

WRITE (LP, 30) RPP, ALPHA2, AAA, BBB, RATIO


IF (RPP.GT.RA) GO TO 5

15 CONTINUE

5 STOP
END

C

SUBROUTINE MATMUL (CMM, A, B, N, M)
C
C THIS SUBROUTINE IS USED TO MULTIPLY THE MATRIX CMM(N*M) BY THE MATRIX
C A(M*1). THE RESULT IS STORED IN THE MATRIX B(N*1)
C
IMPLICIT REAL*8 (A-H, O-Z)
DIMENSION CMM(3, M), A(M), B(N)

DO 5 I = 1, N

5 B(I) = 0.

DO 15 I = 1, N

15 B(I) = B(I) + CMM(I, J) * A(J)

RETURN
END

C

SUBROUTINE PROT (A, B, FEE)
C
C THIS SUBROUTINE IS USED TO ROTATE COORDINATE SYSTEM PLANARLY IN XOY
C THROUGH ANGLE FEE

C

110
DOUBLE PRECISION A(3), B(3), FEE
B(1) = A(1) * DCOS(FEE) + A(2) * DSIN(FEE)
B(2) = A(2) * DCOS(FEE) - A(1) * DSIN(FEE)
B(3) = A(3)
RETURN
END
FLOWCHART FOR PROGRAM IV

START

INPUT GIVEN DATA

FIND AUXILIARY VALUES FOR CALCULATION

SIMULATE MESHING OF PINION AND GEAR

FIND WORKING RANGE OF TEETH AND MAXIMUM KINEMATIC ERROR

STOP
PROGRAM IV

TRANSMISSION ERRORS OF HELICAL PINION GENERATED
BY CUTTER WITH CONE OR REVOLUTE SURFACE
IN MESHING WITH REGULAR HELICAL GEAR

AUTHORS: FAYDOR LITVIN
JIAO ZHANG

PURPOSE

THIS PROGRAM IS USED TO CALCULATE THE TRANSMISSION ERRORS OF A
PINION GENERATED BY THE CUTTER WITH CONE OR REVOLUTE SURFACE
IN MESHING WITH A MISALIGNED REGULAR HELICAL GEAR

NOTE

THIS PROGRAM IS WRITTEN IN FORTRAN 77. IT CAN BE COMPILED BY V
COMPILER IN IBM MAINFRAME OR FORTRAN COMPILER IN VAX SYSTEM.

IMPLICIT REAL*8(A-H,O-Z)
DOUBLE PRECISION KSIN,MU,MUO,KSIC
DIMENSION Z(99),ANGLE(99),ERROR(99),ERR(99)
COMMON /BLOCK1/ X(11),Y(10),A(10,10),Y1(10),IPVT(10),WORK(10),
+ EPSI,DELTA,NC,NE,NDIM
+ COMMON /BLOCK2/ S(4,4),CMM(4,4),CMCD(4,4),C,R,RP,RG,A1,HD,RL,KSIC,
+ ALPHA,CK,SK,CB,SB,CM,SM,CA,SA,CKC,SKC,NTOOL

DEFINE PARAMETERS USED BY PROGRAMS

(1) IN ANG LP ARE UNIT NUMBERS ASSIGNED TO THE INPUT AND OUTPUT
DEVICES
IN=5
LP=6

(2) NDBUG IS USE TO CONTROL THE AUXILIARY OUTPUT FOR DEBUGGING
NDBUG=1

(3) NC IS THE UPPER LIMITATION OF REPEATATION FOR SOLVING NONLINEAR
EQUATIONS;
EPSI IS THE CLEARANCE OF FUNCTION VALUES WHEN THE FUNCTIONS
IS CONSIDERED AS SOLVED (ALL FUNCTIONS HAVE FORMS OF F(X)=0); 
DELTA IS THE RELATIVE DIFFERENCE FOR TAKING DERIVATIVES
NC, EPSI AND DELTA MAY BE CHANGED WHEN SOLUTIONS ARE DIVERGENT
OR LESS ACCURATE
NC=100
DELTA=1.D-3
EPSI=1.D-12

(4) OTHER PARAMETERS (DON'T CHANGE)
NDIM=10
NE=5
DEFINE INPUT PARAMETERS OF PROBLEM (USE INCH AS UNIT OF LENGTH)

(1) PINION AND GEAR: PN = DIAMETRAL PITCH; NP = PINION TOOTH NUMBER;
    RMPG = TOOTH NUMBER RATIO (GEAR TOOTH NO. / NP);
    KSIN = PRESSURE ANGLE IN NORMAL SECTION;
    BETAP = HELIX ANGLE OF PINION AND GEAR;
    HD = HEIGHT OF DEDENDUM OF PINION;
    COE = COEFF. OF CENTRAL DISTANCE (USUALLY COE = 1.)
    PN = 10. D0
    NP = 20
    RMPG = 2. D0
    KSIN = 20. D0 * DR
    BETAP = 15. D0 * DR
    HD = 1. D0 / PN
    COE = 1.000 D0

(2) TOOL: ALPHA = HALF OF CONE VERTEX ANGLE (DEGREE);
    RC = RADIUS OF BOTTOM CIRCLE OF CONE
    R = RADIUS OF ARC
    MU = TILT ANGLE OF MOUNTING TOOL
    NTOOL = TOOL ID NO. (1 = CONE SURFACE, 2 = REVOLUTE SURFACE)
    NTOOL = 2
    ALPHA = 20. D0 * DR
    RC = 10.3527 D0
    R = 3.0 D1
    MU = DATAN (DSIN (KSIN) * DTAN (BETAP))
    MU = 0.*MUO

(3) MISALIGNMENT: NMIS = ID NO. (1 = CROSSING AXES, 2 = INTERSECTING AXES);
    NG = NO. OF MISALIGNED ANGLES TO BE SIMULATED (FROM -(NG-1)/2 TO
        (NG-1)/2 TIMES GAMMA1 WITH ODD NG);
    GAMMA1 = INCREMENT OF MISALIGNED ANGLE (MINUTE);
    NMIS = 2
    NG = 2
    GAMMA1 = 5. D0

(4) OUTPUT: FEE1 = INCREMENT OF ROTATION ANGLE OF PINION (DEGREE)
    FEE1 = 1. D0 * DR

DESCRIPTION OF OUTPUT PARAMETERS

FEE1 = ROTATION ANGLE OF PINION
FEE2 = ROTATION ANGLE OF GEAR
RP = RADIUS OF PINION CONTACT POINT
RG = RADIUS OF GEAR CONTACT POINT

FIND AUXILIARY VALUES FOR CALCULATION

SK = DSIN (KSIN)
CK = DCOS (KSIN)
SB = DSIN (BETAP)
CB = DCOS (BETAP)
SM = DSIN (MU)
CM = DCOS (MU)
SA = DSIN (ALPHA)
CA = DCOS (ALPHA)
KSIC = DATAN(SK/CK/CB)
CKC = DCOS(KSIC)
SKC = DSIN(KSIC)
PT = PN*CB
RP = NP/2./PT
C RБ = RP * DCOS(KSIC)
C RA = RP + 1./PN
C NG = NP * RMPG
RG = RP * RMPG
RL = RC * CA/SA
W CH = HD/CK/CM
A1 = RL/CA-HD/CK/CM
C = (RP+RG) * COE
NCOEF = 360. DO*DR/FEEI/FLOAT(N1)+0.3
N = NCOEF*2+1
CALL INTMAT(CMCD,4,4)
AA = RL*SA*SA/CA-HD/CK/CM
CMCD(1,1) = CA*CK*CB+SA*SK*CM*CB+SA*SM*SB
CMCD(1,2) = SA*CK*CB-CA*SK*CM*CB-CA*SM*SB
CMCD(1,3) = SK*SM*CB-CH*SB
CMCD(1,4) = -RL*SA*CK*CB-CA*SK*(CM*CB+SM*SB)
CMCD(2,1) = CA*SK-SA*CK*CM
CMCD(2,2) = SA*SK+CA*CK*CM
CMCD(2,3) = -CK*SM
CMCD(2,4) = -RL*SA*SK+AA*CK*CM
CMCD(3,1) = CA*CK*SB-SA*SK*SB+SA*SM*CB
CMCD(3,2) = SA*CK*SB-CA*SK*SB-CA*SM*CB
CMCD(3,3) = SK*SM*SB+CM*CB
CMCD(3,4) = -RL*SA*CK*SB+AA*(-SK*CM*SB+SM*CB)
CALL INTMAT(S,4,4)
NGG = (NG-1)/2
DO 505 LL = 1,NG
GAMMA = GAMMAI*FLOAT(LL-NGG)/6O.DO*DR
CG = DCOS(GAMMA/60.*DR)
SG = DSIN(GAMMA/60.*DR)
IF (NMIS.EQ.1) THEN
WRITE (LP,500) COE,GAMMA
500 FORMAT (1H1,///,1X,'C=',F4.2,'*(RP+RG) CROSSING ANGLE=',
      'F5.1,'(M'))
S(1,1) = CG
S(1,3) = -SG
S(3,1) = SG
S(3,3) = CG
ELSE
WRITE (LP,501) COE,GAMMA
501 FORMAT (1H1,///,1X,'C=',F4.2,'*(RP+RG) INTERSECTING ANGLE=',
      'F5.1,'(M'))
S(2,2) = CG
S(2,3) = -SG
S(3,2) = SG
S(3,3) = CG
END IF
DO 205 L = 1,2
DO 5 I = 1,NE
5 X(I)=0.DO
IF (NTOOL.EQ.1) X(5)=RL/CA-HD/CK/CM
C WRITE (6,1100) (X(JK),JK=1,5),RL,CA,HD,CK,CM
C1100 FORMAT (1X, '###',5F15.7/7X,5F15.7)
DO 15 I=1,N
X(7)=FEEI*FLOAT(I-(N+1)/2)
IF (L.EQ.1) X(7)=0.DO
C X(5)=DARSIN(RP*X(7)/SK/R)
X(2)=X(7)/RMPG
CALL NONLIN
X(8)=X(2)+X(3)
IF (L.EQ.1) THEN
XIN=X(8)
WRITE (LP,10)
FORMAT (///8X, 'FEEl(D)',8X, 'FEE2(D)',8X, 'K-ERROR(S)',5X, +
    'RP',13X,'RG',F15.7/)
GO TO 205
END IF
X(8)=X(8)-XIN
X(7)=X(7)/DR
X(8)=X(8)/DR
X(9)=(X(8)-X(7)/RMPG)*3600.DO
Z(I)=X(8)
ERR(I)=X(9)
WRITE (LP,20) (X(J),J=7,11)
20 FORMAT (1X,5F15.7,F15.7)
C WRITE (LP,30) (X(J),J=1,6)
C 30 FORMAT (1X,'###',6F15.7)
C WRITE (LP,30) XP,YP,ZP,XG,YG
CONTINUE
NT=N-NCOEF
FII=FEEI/DR/2.DO*FLOAT(NCOEF)
WRITE (LP,80)
80 FORMAT (///,'Find the working range for one tooth:',F15.7/)
DO 55 I=1,NT
X(7)=FEEI*FLOAT(I-(N+1)/2)/DR/2.DO
X(8)=X(7)+FII
KK=I+NCOEF
ANGLE(I)=Z(KK)-Z(I)
ERROR(I)=(ANGLE(I)-FII)*3600.DO
WRITE (LP,60) X(7),X(8),ANGLE(I),ERROR(I)
60 FORMAT (1X,('','F7.2,','--','F7.2,''),F15.7,F15.7)
CONTINUE
DO 95 I=1,NT
ATEMP2=ERROR(I)
IF (I.NE.1) THEN
IF (ATEMP1*ATEMP2.LE.0.DO) GOTO 105
END IF
ATEMP1=ATEMP2
95 CONTINUE
WRITE (LP,160)
160 FORMAT (///, 'Meshing is discontinuous')
105 IF (DABS(ATEMP1).LT.DABS(ATEMP2)) I=I-1
EMAX=0.
EMIN=0.
DO 135 J=1,NCOEF
KS=I+J-1
ET=ERR(KS)
IF (ET.LT.EMIN) EMIN=ET
IF (ET.GT.EMAX) EMAX=ET
135 CONTINUE
ET=EMAX-EMIN
KK=I+NCOEF
WRITE (LP, 170) Z(I), Z(KK), ET
170 FORMAT (' ', 'WORKING RANGE FOR ONE TOOTH: ', F7.2, '----', F7.2/
+ ' ', 'THE MAXIMUM KINEMATIC ERROR: ', F15.7, ' (S)', I2)
205 CONTINUE
505 CONTINUE
STOP
END

SUBROUTINE FUNC
IMPLICIT REAL*8(A-H,O-Z)
DOUBLE PRECISION KSIN, MU, MUO, KSIC
COMMON /BLOCK1/ X(11), Y(10), A(10,10), Y1(10), IPVT(10), WORK(10), + EPSI, DELTA, NC, NE, NDIM
COMMON /BLOCK2/ S(4,4), CMM(4,4), CMCD(4,4), C, R, RP, RG, AI, HD, RL, KSIC,
+ ALPHA, CK, SK, CB, SB, CM, SM, CA, SA, CKC, SKC, NTOOL
DIMENSION RD(4), RND(4), RC(4), RNC(4), RF(4)
C
CFEE=DCOS(X(3))
SFEE=DSIN(X(3))
CT=DCOS(X(4))
ST=DSIN(X(4))
CP=DCOS(X(7))
SF=DSIN(X(7))
IF (NTOOL.EQ.1) THEN
RD(1)=X(5)*CT*SA
RD(2)=RL-X(5)*CA
RD(3)=X(5)*ST*SA
RND(1)=CT*CA
RND(2)=SA
RND(3)=ST*CA
ELSE
CAL=DCOS(ALPHA+X(5))
SAL=DSIN(ALPHA+X(5))
SL2=DSIN(X(5)/2.)
CAL2=DCOS(ALPHA+X(5)/2.)
SAL2=DSIN(ALPHA+X(5)/2.)
RD(1)=(A1*SA-2.*R*SL2*SAL2)*CT
RD(2)=HD/CK/CM*CA+2.*R*SL2*CAL2
RD(3)=(A1*SA-2.*R*SL2*SAL2)*ST
RND(1)=CAL*CT
RND(2)=SAL
RND(3)=CAL*ST
END IF
RD(4)=1.
CALL MATMUL(CMCD, RD, RC, 4, 4)
CALL MATMUL(CMCD, RND, RNC, 3, 3)
X(6) = (RC(1) - RC(2) * RNC(1) / RNC(2)) / RP
RF(1) = RC(1) - RP * X(6)
RF(2) = RC(2) + RP
RF(3) = RC(3)
RF(4) = 1.
CFPF1 = DCOS(X(6) + X(7))
SFPF1 = DSIN(X(6) + X(7))
XPF = RF(1) * CFPF1 + RF(2) * SFPF1
YPF = RF(2) * CFPF1 - RF(1) * SFPF1
ZPF = RF(3)
XNPF = RNC(1) * CFPF1 + RNC(2) * SFPF1
YNPF = RNC(2) * CFPF1 - RNC(1) * SFPF1
ZNPF = RNC(3)
CF2FG = DCOS(X(3))
SF2FG = DSIN(X(3))
A2 = -X(1) * SB + RGS2
RFG1 = CK * CK / CKC * DCOS(X(1) + KSI) * A2 + RGS2 * CF2FG
RFG2 = CK * CK / CKC * DSIN(X(1) + KSI) * A2 - RGS2 * SF2FG
RFG3 = X(1) * (CB + SK * SK * SB / CB) - RGS2 * SK * CF2FG
RNF1 = CK * CB * CF2FG - SK * SF2FG
RNF2 = CK * CB * SF2FG + SK * CF2FG
RNF3 = CK * SB
XGF = RFG1 * S(1,1) + RFG2 * S(1,2) + RFG3 * S(1,3)
YGF = RFG1 * S(2,1) + RFG2 * S(2,2) + RFG3 * S(2,3)
ZGF = RFG1 * S(3,1) + RFG2 * S(3,2) + RFG3 * S(3,3)
XNFG = RNF1 * S(1,1) + RNF2 * S(1,2) + RNF3 * S(1,3)
YNFG = RNF1 * S(2,1) + RNF2 * S(2,2) + RNF3 * S(2,3)
ZNFG = RNF1 * S(3,1) + RNF2 * S(3,2) + RNF3 * S(3,3)
C WRITE (6,100) X(1), X(2), X(3), X(4), X(5)
C WRITE (6,100) XPF, YPF, ZPF, XGF, YGF, ZGF
C 100 FORMAT (1X, 'ZZZZ', 8F15.7)
C WRITE (6,100) XNPF, YNPF, ZNPF, XNFG, YNFG, ZNFG
C Y(I) = XPF + YPF
C Y(2) = YPF - YGF - C
C Y(3) = ZPF - ZGF
C Y(4) = YNPF - YGF
C Y(5) = ZNPF - ZNGF
C X(10) = DSQRT(XPF * YPF + YPF * YPF)
C X(11) = DSQRT(XGF * XGF + YGF * YGF)
C WRITE (6, 20) (Y(I), I=1, 5)
C 20 FORMAT (1X, 'SSSS', 6F15.7)
RETURN
END

SUBROUTINE INTMAT(A, N, M)
C THIS SUBROUTINE IS USED TO INITIATE THE MATRIX, WITH UNIT DIAGONAL
C ELEMENTS AND NULL OTHER ELEMENTS
IMPLICIT REAL*8 (A-H, O-Z)
DIMENSION A(4,4)
DO 5 I=1,N
DO 5 J=1,M
A(I, J) = 0.
SUBROUTINE MATMUL(CMM, A, B, N, M)
C THIS SUBROUTINE IS USED TO MULTIPLY THE MATRIX CMM(N*M) BY THE MATRIX A(M*1). THE RESULT IS STORED IN THE MATRIX B(N*1)
IMPLICIT REAL*8(A-H,O-Z)
DIMENSION CMM(4,4),A(4),B(4)
DO 5 I=1,N
  5 B(I)=0.
  DO 15 I=1,N
  DO 15 J=1,M
  15 B(I)=B(I)+CMM(I,J)*A(J)
RETURN
END

SUBROUTINE NONLIN
IMPLICIT REAL*8(A-H,O-Z)
COMMON /BLOCK1/ X(11),Y(10),A(10,10),Y1(10),IPVT(10),WORK(10),
             EPS1,DELTA,NC,NE,NDIM

DO 5 I=1,NC
  CALL FUNC
  WRITE (6,10) I,(X(J),Y(J),J=1,5)
  DO 15 J=1,NE
  IF (DABS(Y(J)).GT.EPSI) GO TO 25
  15 CONTINUE
  GO TO 105

  25 CONTINUE
  DO 35 J=1,NE
  35 Y1(J)=Y(J)
  DO 45 J=1,NE
  DIFF=DABS(X(J))*DELTA
  IF (X(J).EQ.0.0) DIFF=DELTA
  XMAM=X(J)
  X(J)=X(J)-DIFF
  CALL FUNC
  X(J)=XMAM
  DO 55 K=1,NE
  55 A(K,J)=(Y1(K)-Y(K))/DIFF
  CONTINUE
  DO 65 J=1,NE
  65 Y(J)=-Y1(J)
  CALL DECOMP (NDIM,NE,A,COND,IPVT,WORK)
  CALL SOLVE (NDIM,NE,A,Y,IPVT)
  DO 75 J=1,NE
  75 X(J)=X(J)+Y(J)
  CONTINUE
  RETURN
END
SUBROUTINE DECOMP (NDIM,N,A,COND,IPVT,WORK)

IMPLICIT REAL*8(A-H,O-Z)
DIMENSION A(NDIM,N),WORK(N),IPVT(N)

DECOMPOSES AREAL MATRIX BY GAUSSIAN ELIMINATION,
AND ESTIMATES THE CONDITION OF THE MATRIX.

-COMPUTER METHODS FOR MATHEMATICAL COMPUTATIONS-, BY G. E. FORSYTHE,
M. A. MALCOLM, AND C. B. MOLER (PRENTICE-HALL, 1977)

USE SUBROUTINE SOLVE TO COMPUTE SOLUTIONS TO LINEAR SYSTEM.

INPUT..

NDIM = DECLARED ROW DIMENSION OF THE ARRAY CONTAINING A
N = ORDER OF THE MATRIX
A = MATRIX TO BE TRIANGULARIZED

OUTPUT..

A CONTAINS AN UPPER TRIANGULAR MATRIX U AND A PREMUTED
VERSION OF A LOWER TRIANGULAR MATRIX I-L SO THAT
(PERMUTATION MATRIX)*A=L*U

COND = AN ESTIMATE OF THE CONDITION OF A.
FOR THE LINEAR SYSTEM A*X = B, CHANGES IN A AND B
MAY CAUSE CHANGES COND TIMES AS LARGE IN X.
IF COND+1.0.EQ. COND, A IS SINGULAR TO WORKING
PRECISION. COND IS SET TO 1.0D+32 IF EXACT
SINGULARITY IS DETECTED.

IPVT = THE PIVOT VECTOR
IPVT(K) = THE INDEX OF THE K-TH PIVOT ROW
IPVT(N) = (-1)**(NUMBER OF INTERCHANGES)

WORK SPACE.. THE VECTOR WORK MUST BE DECLARED AND INCLUDED
IN THE CALL. ITS INPUT CONTENTS ARE IGNORED.
ITS OUTPUT CONTENTS ARE USUALLY UNIMPORTANT.

THE DETERMINANT OF A CAN BE OBTAINED ON OUTPUT BY
DET(A) = IPVT(N) * A(1,1) * A(2,2) * ... * A(N,N).

IPVT(N)=1
IF (N.EQ.1) GO TO 150
NM1=N-1

ANORM=0.DO
DO 20 J=1,N
T=0.DO
DO 10 I=1,N
10 T=T+DABS(A(I,J))
IF (T.GT.ANORM) ANORM=T

CONTINUE

C DO GAUSSIAN ELIMINATION WITH PARTIAL
C PIVOTING.

DO 70 K=1,NM1
KP1=K+1

C FIND THE PIVOT.

M=K
DO 30 I=KP1,N
   IF (DABS(A(I,K)).GT.DABS(A(M,K))) M=I
30 CONTINUE

IPVT(K)=M
IF (M.NE.K) IPVT(N)=-IPVT(N)
T=A(M,K)
A(M,K)=A(K,K)
A(K,K)=T

C SKIP THE ELIMINATION STEP IF PIVOT IS ZERO.

IF (T.EQ.0.DO) GO TO 70

C COMPUTE THE MULTIPLIERS.

DO 40 I=KP1,N
   A(I,K)=-A(I,K)/T
40 CONTINUE

C INTERCHANGE AND ELIMINATE BY COLUMNS.

DO 60 J=KP1,N
   T=A(M,J)
   A(M,J)=A(K,J)
   A(K,J)=T
   IF (T.EQ.0.DO) GO TO 60
   DO 50 I=KP1,N
50 A(I,J)=A(I,J)+A(I,K)*T
60 CONTINUE
70 CONTINUE

C COND = (1-NORM OF A)*(AN ESTIMATE OF THE 1-NORM OF A-INV)
C THE ESTIMATE IS OBTAINED BY ONE STEP OF INVERSE ITERATION FOR THE
C SMALL SINGULAR VECTOR. THIS INVOLVES SOLVING TWO SYSTEMS
C OF EQUATIONS, (A-TRANSPOSE)*Y = E AND A*Z = Y WHERE E
C IS A VECTOR OF +1 OR -1 COMPONENTS CHOSEN TO CAUSS GROWTH IN Y.
C ESTIMATE = (1-NORM OF Z)/(1-NORM OF Y)
C
DO 100 K=1,N
   T=0.DO
   IF (K.EQ.1) GO TO 90
   KM1=K-1
   DO 80 I=1,KM1
80   T=T+A(I,K)*WORK(I)
90   EK=1.DO
   IF (T.LT.0.DO) EK=-1.DO
   IF (A(K,K).EQ.0.DO) GO TO 160
100   WORK(K)=-(EK+T)/A(K,K)
   DO 120 KB=1,NM1
      K=N-KB
      T=0.DO
   120 CONTINUE
KP1=K+1
DO 110 I=KP1,N
110 T=T+A(I,K)*WORK(K)
   WORK(K)=T
   M=IPVT(K)
   IF (M.EQ.K) GO TO 120
   T=WORK(M)
   WORK(M)=WORK(K)
   WORK(K)=T
120 CONTINUE

YNORM=0.DO
DO 130 I=1,N
130 YNORM=YNORM+DABS(WORK(I))

CALL SOLVE (NDIM,N,A,WORK,IPVT)

ZNORM=0.DO
DO 140 I=1,N
140 ZNORM=ZNORM+DABS(WORK(I))

ESTIMATE THE CONDITION.

COND=ANORM*ZNORM/YNORM
IF (COND.LT.1.DO) COND=1.DO
RETURN

1-BY-1 CASE..
150 COND=1.DO
IF (A(1,1).NE.0.DO) RETURN

EXACT SINGULARITY
160 COND=1.0D32
RETURN
END

SOLVES A LINEAR SYSTEM, A*X = B
DO NOT SOLVE THE SYSTEM IF DECOMP HAS DETECTED SINGULARITY.

- COMPUTER METHODS FOR MATHEMATICAL COMPUTATIONS-, BY G. E. FORSYTHE,
M. A. MALCOLM, AND C. B. MOLER (PRENTICE-HALL, 1977)

INPUT..

NDIM = DECLARED ROW DIMENSION OF ARRAY CONTAINING A
N = ORDER OF MATRIX
A = TRIANGULARIZED MATRIX OBTAINED FROM SUBROUTINE DECOMP
B = RIGHT HAND SIDE VECTOR
IPVT = PIVOT VECTOR OBTAINED FROM DECOMP

OUTPUT..
DO THE FORWARD ELIMINATION.

IF (N.EQ.1) GO TO 50

NM1=N-1
DO 20 K=1,NM1
   KP1=K+1
   M=IPVT(K)
   T=B(M)
   B(M)=B(K)
   B(K)=T
   DO 10 I=KP1,N
      B(I)=B(I)+A(I,K)*T
10    CONTINUE
20    CONTINUE

NOW DO THE BACK SUBSTITUTION.

DO 40 KB=1,NM1
   KM1=N-KB
   K=KM1+1
   B(K)=B(K)/A(K,K)
   T=-B(K)
   DO 30 I=1,KM1
      B(I)=B(I)+A(I,K)*T
30    CONTINUE
40    CONTINUE
50    B(1)=B(1)/A(1,1)
RETURN
END
FLOWCHART FOR PROGRAM V

START

INPUT GIVEN DATA

FIND AUXILIARY VALUES FOR CALCULATION

SIMULATE MESHING OF PINION AND GEAR

FIND WORKING RANGE OF TEETH AND MAXIMUM KINEMATIC ERROR

STOP
PROGRAM V

TRANSMISSION ERRORS OF CROWNED HELICAL PINION IN MESHING WITH REGULAR HELICAL GEAR WITH PREDESIGNED TRANSMISSION ERRORS AND CONTACT PATH

AUTHORS: FAYDOR LITVIN, JIAO ZHANG

Purpose

This program is used to calculate the transmission errors of a crowned helical pinion and a helical gear when their axes are mounted with some errors. The magnitude of transmission errors and contact path are pre-designed.

Note

This program is written in FORTRAN 77. It can be compiled by V compiler in IBM mainframe or FORTRAN compiler in VAX system.

Define parameters used by programs

1. In ANG LP are unit numbers assigned to the input and output devices
   IN=5
   LP=6

2. NDBUG is use to control the auxiliary output for debugging
   NDBUG=1

3. NC is the upper limitation of repetition for solving nonlinear equations;
   EPSI is the clearance of function values when the functions is considered as solved (all functions have forms of f(x)=0);
   DELTA is the relative difference for taking derivatives
   NC, EPSI and DELTA may be changed when solutions are divergent
   NC=100
   DELTA=1.D-3
   EPSI=1.D-10
C (4) OTHER PARAMETERS (DON'T CHANGE)
   NDIM=10
   NE=5
   DR=DATAN(1.DO)/45.DO
C DEFINE INPUT PARAMETERS OF PROBLEM (USE INCH AS UNIT OF LENGTH)
C (1) PINION AND GEAR: PN=DIAMETRAL PITCH; NP=PINION TOOTH NUMBER;
   RMPG=TOOTH NUMBER RATIO (GEAR TOOTH NO./NP);
   KSIN=PRESSURE ANGLE IN NORMAL SECTION;
   BETAP=HELIX ANGLE OF PINION AND GEAR;
   COE=COEFF. OF CENTRAL DISTANCE (USUALLY COE=1.)
   PN=2.DO
   NP=12
   RMPG=94./12.
   KSIN=30.DO*DR
   BETAP=15.DO*DR
   COE=1.0000DO
C (2) PREDESIGN TRANSMISSION ERRORS AND CONTACT PATH:
   AA=LEVEL OF PREDESIGNED PARABOLIC TRANSMISSION ERRORS IN SECOND
   KK=COEFFICIENT OF CONTACT PATH DIRECTION (1.D-3=CROSS TOOTH
   SURFACE; 5.D6=ALONG TOOTH SURFACE)
   R=RADIUS OF ARC ATTACHED TO CHOSEN CONTACT PATH
   AA=25.DO
   KK=5.D6
   R=0.3584DO
C (3) MISALIGNMENT: NMIS=ID NO. (1=CROSSING AXES, 2=INTERSECTING AXES);
   NG=NO. OF MISALIGNED ANGLES TO BE SIMULATED (FROM -(NG-1)/2 TO
   (NG-1)/2 TIMES GAMMAI WITH ODD NG);
   GAMMAI=INCREMENT OF MISALIGNED ANGLE (MINUTE);
   NMIS=1
   NG=3
   GAMMAI=3.DO
C (4) OUTPUT: FEE1=INCREMENT OF ROTATION ANGLE OF PINION (DEGREE)
   FEE1=1.00DO*DR
C
C DESCRIPTION OF OUTPUT PARAMETERS
C
C FEE1=ROTATION ANGLE OF PINION
C FEE2=ROTATION ANGLE OF GEAR
C RP=RADIUS OF PINION CONTACT POINT
C RG=RADIUS OF GEAR CONTACT POINT
C ZP=LENGTH OF PINION CONTACT POINT FROM MIDDLE SECTION
C ZG=LENGTH OF GEAR CONTACT POINT FROM MIDDLE SECTION
C
C FIND AUXILIARY VALUES FOR CALCULATION
C
C DEFINE USEFUL CONSTANTS AND PARAMETERS FOR PINION AND GEAR
   RMGP=1./RMPG
   NG=NP*RMPG+0.5
   AA=AA/(2/3600. *DR*(NP/DR/180.)*2)
   SK=DSIN(KSIN)
   CK=DCOS(KSIN)
   SB=DSIN(BETAP)
   CB=DCOS(BETAP)
   TB=SB/CB

126
KSIC=DATAN(SK/CK/CB)
CKC=DCOS(KSIC)
SKC=DSIN(KSIC)
PT=PN*CB
RP=NP/2./PT
RPB=RP*CKC
RPA=RP+1.0/PT
RG=NG/2./PT
RGB=RG*CKC
RGA=RG+1./PN
WRITE (LP,56) RP,RPB,RPA,RG,RGB,RGA,AA
56 FORMAT (1X,'&&&&&&','RP=',F15.7,5X,'RPB=',F15.7,5X,'RPA=',F15.7/
        + 1X,'&&&&&&','RG=',F15.7,5X,'RGB=',F15.7,5X,'RGA=',F15.7)
CON1=(1.+SK*SK*TB*TB)
AT (1)=(CK**4/CKC**2*KK**2-SK**4*TB**2)*RG
AT (2)=(2.*SK*SK*SB*CON1-2.*KK**2*SB*CK**2/CKC**2)*RG
AT (3)=(-2.*CK*CK/CKC*SKC*KK**2-2.*KK*SB*CON1)*RG
AT (4)=(2.*SB*CK/CKC*SKC*KK**2+2.*KK*CB*CON1)*RG
AT (5)=CK**4/CKC**2*SB**2*KK**2-CB**2*CON1*CON1
C=(RP+RG)*COE
CALL INTMAT(S,4,4)
NGG=(NG-1)/2
DO 505 LL=1,NG
    CG=DCOS(GAMMA/60.*DR)
    SG=DSIN(GAMMA/60.*DR)
    IF (NMIS.EQ.1) THEN
        WRITE (LP,500) COE,GAMMA
    500 FORMAT (1H1,///,1X,'C=',F9.4,'*(RP+RG) CROSSING ANGLE=',
                  + F8.4,'(M) ')
        S(1,1)=CG
        S(1,3)=-SG
        S(3,1)=SG
        S(3,3)=CG
    ELSE
        WRITE (LP,501) COE,GAMMA
    501 FORMAT (1H1,///,1X,'C=',F4.2,'*(RP+RG) INTERSECTING ANGLE=',
                  + F5.1,'(M) ')
        S(2,2)=CG
        S(2,3)=-SG
        S(3,2)=SG
        S(3,3)=CG
    END IF
NCOEF=IDINT(360.*DR/FEEI/FLOAT(NP)+0.5)
N=2*NCOEF
NHALF=(N+1)/2
XIN=0.
DO 205 L=1,2
    LSGN=(-1)**L
    DO 15 I=1,NHALF
        LI=NHALF+LSGN*(I-1)
        IF (L.EQ.1) NMIN=LI
        IF (L.EQ.2) NMAX=LI
        X(7)=LSGN*FEEI*FLOAT(I-1)
\( X(4) = X(7) \)
\( X(2) = X(7)/RMPG \)
\( X(3) = 0. \)
\( X(5) = (- (AT(2) \cdot X(2) + AT(4)) + DSQRT((AT(2) \cdot X(2) + AT(4))^2 - 4 \cdot AT(5) \cdot \cdot X(3)))/2. \cdot AT(5) \)
\( X(1) = 0. \)

CALL NONLIN
\( X(8) = X(1) + X(2) \)

**C** FIND INITIAL VALUE OF X(8)

IF (L.EQ.1 .AND. I.EQ.1) THEN
\( XIN = X(8) \)
WRITE (LP,51) XIN
GO TO 15
END IF

\( X(8) = X(8) - XIN \)
\( W(LI) = X(7) \cdot DR \)
\( Z(LI) = X(8)/DR \)
\( ERR(LI) = (X(8) - X(7)/RMPG) \cdot 3600.D0/DR \)
\( RPR(LI) = X(10) \)
\( RGR(LI) = X(11) \)
\( ZP(LI) = X(12) \)
\( ZG(LI) = X(13) \)

**C** WRITE (LP,20) W(L1),Z(LI),ERR(LI),RPR(LI),RGR(LI),ZG(LI)

GO TO 15

15 CONTINUE

205 CONTINUE

WRITE (LP,10)

10 FORMAT (8X,'FEE1(D)',8X,'FEE2(D)',8X,'K-ERROR(S)',5X,
+ 'RP',13X,'ZP',13X,'RG',13X,'ZG',F15.7/)

DO 25 I=NMIN,NMAX
WRITE (LP,20) W(I),Z(I),ERR(I),RPR(I),ZP(I),RGR(I),ZG(I)
20 FORMAT (1X,15.7,12.4,4F15.7)
25 CONTINUE

NT=NMAX-NCOEF
\( FII = \text{FEE}/\text{DR}/\text{RMPG*FLOAT(NCOEF)} \)
WRITE (LP,80)

80 FORMAT (8X,'FIND THE WORKING RANGE FOR ONE TOOTH: ',F15.7/)

DO 55 I=NMIN,NT
\( X(7) = \text{FEE} \cdot \text{FLOAT(I-(N+1)/2)} / \text{RMPG/DR} \)
\( X(8) = X(7)+FII \)
\( KK = I+NCOEF \)
\( ANGLE(I) = Z(KK)-Z(I) \)
\( ERROR(I) = (ANGLE(I)-FII)*3600.D0 \)

C WRITE (LP,60) X(7),X(8),ANGLE(I),ERROR(I)

C 60 FORMAT (1X,'(',F7.2,':','---',F7.2,'):',F15.7,F15.7)

CONTINUE

DO 95 I=NMIN,NT
\( ATEMP2 = \text{ERROR}(I) \)
IF (I.NE.NMIN) THEN
IF (ATEMP1*ATEMP2.LE.0.D0) GOTO 105
END IF
\( ATEMP1 = ATEMP2 \)
95 CONTINUE

128
WRITE (LP, 160)
160 FORMAT (/1X, 'MESHING IS DISCONTINUOUS')
GO TO 505
105 IF (DABS(ATEMP1).LT.DABS(ATEMP2)) I=I-1
EMAX=0.
EMIN=0.
NTEMP=NCOEF+1
DO 135 J=1,NTEMP
KS=I+J-1
ET=ERR(KS)
IF (ET.LT.EMIN) EMIN=ET
IF (ET.GT.EMAX) EMAX=ET
135 CONTINUE
ET=EMAX-EMIN
KK=I+NCOEF
WRITE (LP, 170) Z(1),Z(KK),ET
170 FORMAT (/1X,'WORKING RANGE FOR ONE TOOTH: ',F7.2,'----',F7.2/
+1X,'THE MAXIMUM KINEMATIC ERROR: ',F12.4,' (S)'),12
505 CONTINUE
STOP
END
SUBROUTINE FUNC
IMPLICIT REAL*8(A-H,O-Z)
DOUBLE PRECISION KSIN,MU,KK,KSIC
COMMON /BLOCK1/ X(13),Y(10),A(10,10),Y1(10),IPVT(10),WORK(10),
+EPSI,DELTA,NC,NE,NDIM
COMMON /BLOCK2/ S(4,4),AT(5),C,RP,RG,CK,SK,CB,SB,CKC,KSIC,TB,
+COEG1,COEG2,RMGP,AA,DR,KK,R
C
C
20 TEMP=CKC*(1.-AA*X(4))/(RMGP+1.)
IF (DABS(TEMP).GT.1.D0) THEN
X(4)=X(7)
GOTO 20
END IF
C
WRITE (6, 220) TEMP,X(4),AA
C
220 FORMAT(1X,'TEMP=',E15.7,'X(4)=',E15.7,'AA=',F15.7)
RLAM=KSIC-DARCOS(TEMP)
DLAMDF=-CKC*AA/(RMGP+1.)/DSQRT(1.-TEMP*TEMP)
FEEGP=X(4)*RMGP-AA/2.*X(4)*X(4)+RLAM
DFGDPF=RMGP-AA*X(4)+DLAMDF
CONA=AT(5)
CONB=AT(2)*FEEGP+AT(4)
CONC=AT(3)*FEEGP+AT(1)*FEEGP+FEEGP
COND=CONB*CONB-4.*CONA*CONC
IF (COND.LT.0.) THEN
X(4)=X(7)
GOTO 20
END IF
COND=DSORT(COND)
TP=(-CONB+COND)/2./CONA
IF (COND.EQ.0.0) THEN
DTPDFG=-AT(2)/2./CONA
ELSE
DTPDFG=(-AT(2)-(AT(2)*CONB-2.*CONA*(AT(3)+2.*AT(1)*FEEGP))/COND)
+ /2.*CONA

END IF

C

*** X(4)=FEEP; X(7)=FEE1 
AP1=X(4)-X(7) 
AP2=AP1-RLAM 
AP3=AP2+KSIC 
AP4=(X(4)-RLAM+KSIC 
DAP4DF=1.-DLAMDF 
CAP4=D(DAP4) 
CAP4=D(DAP4)AP 
AP1=R*(DSIN(MU+X(3))-DSIN(MU)) 
AP2=R*(DCOS(MU+X(3))=DCOS(MU)) 
XPF=CK*C2*DCOS(AP3)*AP+RG*DSIN(AP2)-(RP+RG)*DSIN(AP1)+ALP2 
YPF=CK*C2*DSIN(AP3)*AP-RC*DCOS(AP2)+(RP+RG)*DCOS(AP1)+ALP1 
ZPF=TP*CB*C2*CK/C2-SK*TB*RG*FEEGP 

C

DXDA=-DSIN(MU+X(3)) 
DYDA=DCOS(MU+X(3)) 
DXDF=CK*CK/C2*(CAP4*DAPDF-SAP4*AP*(DAP4DF)+RG*DCOS(X(4)-RLAM) 
+ *(1.-DLAMDF)-(RP+RG)*DCOS(X(4))-ALP1*DMUDFP 
DYDF=CK*CK/C2*(SAP4*DAPDF+CAP4*AP*(DAP4DF)+RG*DSIN(X(4)-RLAM) 
+ *(1.-DLAMDF)-(RP+RG)*DSIN(X(4)+ALP2*DMUDFP 
DZDF=CB*CK/C2/DTPDFG*DFGDFP-SK*TB*RG*DFGDFP 
XNP=DYDA*DZDF 
YNP=-DXDA*DZDF 
ZNP=DXDA*DYDF-DYDA*DXDF 
RMN=DSQRT(XNP*YNP+YNP*ZNP+ZNP*ZNP) 

C

WRITE(6,130) DXDA,DXDF,DYDF,DZDF,XNP,YNP,ZNP,RMN,TP,AP 
C 130 FORMAT(1X,S9.1,5F15.7/4X,5F15.7) 

C

CFZFG=DCOS(X(1)) 
SF2FG=DSIN(X(1)) 
CF2FGK=DCOS(X(1)+KSIC) 
SF2FG=DSIN(X(1)+KSIC) 
AG=-X(5)*SB+RG*X(2) 
RFG1=CK*C2*C2*SF2FG*AG+RG*SF2FG 
RFG2=CK*C2*C2*SF2FG*AG-RG*SF2FG 
RFG3=X(5)*CB-AG*SK*TB 
RNFG1=CK*CB*CF2FG-SK*SF2FG 
RNFG2=CK*CB*SF2FG+SK*CF2FG 
RNFG3=CK*SB
XGF = RFG1*S(1,1) + RFG2*S(1,2) + RFG3*S(1,3)
YGF = RFG1*S(2,1) + RFG2*S(2,2) + RFG3*S(2,3)
ZGF = RFG1*S(3,1) + RFG2*S(3,2) + RFG3*S(3,3)
XNGF = RNFG1*S(1,1) + RNFG2*S(1,2) + RNFG3*S(1,3)
YNGF = RNFG1*S(2,1) + RNFG2*S(2,2) + RNFG3*S(2,3)
ZNGF = RNFG1*S(3,1) + RNFG2*S(3,2) + RNFG3*S(3,3)

C WRITE (6,100) X(1), X(2), X(3), X(4), X(5)
C WRITE (6,100) XPF, YPF, ZPF, XGF, YGF, ZGF
C 100 FORMAT (1X, '%%%%%', 8E15.7)
C WRITE (6,100) XNPF, YNPF, ZNPF, XNGF, YNGF, ZNGF
Y(1) = XPF - XGF
Y(2) = YPF - YGF - C
Y(3) = ZPF - ZGF
Y(5) = XNPF - XNGF
Y(4) = ZNPF - ZNGF
X(10) = DSQRT(XPF*XPF + YPF*YPF)
X(11) = DSQRT(XGF*XGF + YGF*YGF)
X(12) = ZPF
X(13) = ZGF

C WRITE (6,20) Y(II), II = 1, 5
C 20 FORMAT (1X, '$$$$', 6F15.7)
RETURN

END

SUBROUTINE INTMAT (A, N, M)
C
C THIS SUBROUTINE IS USED TO INITIATE THE MATRIX, WITH UNIT DIAGONAL
C ELEMENTS AND NULL OTHER ELEMENTS
C IMPLICIT REAL*8 (A-H, 0-Z)
DIMENSION A(4,4)
DO 5 I = 1, N
   DO 5 J = 1, M
      A(I,J) = 0.
  5 CONTINUE
RETURN
END

SUBROUTINE NONLIN
C
C IMPLICIT REAL*8 (A-H, 0-Z)
COMMON /BLOCK1/ X(13), Y(10), A(10,10), Y1(10), IPVT(10), WORK(10),
                 EPSI, DELTA, NC, NE, NDIM

C
DO 5 I = 1, NC
   CALL FUNC
C WRITE (6,10) I, (X(J), Y(J), J = 1, 5)
C 10 FORMAT (1X, '***', 15/5(1X, 2D15.7/))
C DO 15 J = 1, NE
   IF (DABS(Y(J)) .GT. EPSI) GO TO 25
  15 CONTINUE
   GO TO 105
C DO 35 J = 1, NE
C 35 Y1(J) = Y(J)
DO 45 J=1,NE
DIFF=DABS(X(J))*DELTA
IF (DABS(X(J)).LT.1.D-12) DIFF=DELTA
XMAM=X(J)
X(J)=X(J)-DIFF
CALL FUNC
X(J)=XMAM
DO 55 K=1,NE
55 A(K,J)=(Y1(K)-Y(K))/DIFF
45 CONTINUE
DO 65 J=1,NE
65 Y(J)=-Y1(J)
DO 205 K=1,NE
WRITE (6,245) (A@, J),J=1,NE)
245 FORMAT (1X,'-(-(-',5D15.7)
CALL DECOMP (NDIM,NE,A,COND,IPVT,WORK)
CALL SOLVE (NDIM,NE,A,Y,IPVT)
DO 75 J=1,NE
75 X(J)=X(J)+Y(J)
5 CONTINUE
DO 105 J=1,NE
105 RETURN
END

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FOR THE LINEAR SYSTEM A*X = B, CHANGES IN  A AND B
MAY CAUSE CHANGES COND TIMES AS LARGE IN X.

IF COND+1.0 .EQ. COND, A IS SINGULAR TO WORKING PRECISION. COND IS SET TO 1.0D+32 IF EXACT SINGULARITY IS DETECTED.

IPVT = THE PIVOT VECTOR
IPVT(K) = THE INDEX OF THE K-TH PIVOT ROW
IPVT(N) = (-1)**(NUMBER OF INTERCHANGES)

WORK SPACE. THE VECTOR WORK MUST BE DECLARED AND INCLUDED IN THE CALL. ITS INPUT CONTENTS ARE IGNORED. ITS OUTPUT CONTENTS ARE USUALLY UNIMPORTANT.

THE DETERMINANT OF A CAN BE OBTAINED ON OUTPUT BY

\[ \det(A) = IPVT(N) \times A(1,1) \times A(2,2) \times \ldots \times A(N,N). \]

IPVT(N)=1
IF (N.EQ.1) GO TO 150
NM1=N-1

\[ \text{ANORM}=0.0 \]
DO 20 J=1,N
T=0.0
DO 10 I=1,N
10 T=T+DABS(A(I,J))
IF (T.GT.ANORM) ANORM=T
20 CONTINUE

DO GAUSSIAN ELIMINATION WITH PARTIAL PIVOTING.

DO 70 K=1,NM1
KP1=K+1

FIND THE PIVOT.

M=K
DO 30 I=KP1,N
30 CONTINUE
IF (DABS(A(I,K)).GT.DABS(A(M,K))) M=I

IPVT(K)=M
IF (M.NE.K) IPVT(N)=--IPVT(N)
T=A(M,K)
A(M,K)=A(K,K)
A(K,K)=T

SKIP THE ELIMINATION STEP IF PIVOT IS ZERO.

IF (T.EQ.0.0) GO TO 70

COMPUTE THE MULTIPLIERS.

DO 40 I=KP1,N
40 A(I,K)=-A(I,K)/T

INTERCHANGE AND ELIMINATE BY COLUMNS.

DO 60 J=KP1,N
T=A(M,J)
A(M,J)=A(K,J)
A(K,J)=T
IF (T.EQ.0.0) GO TO 60
DO 50 I=KP1,N
C A(I,J)=A(I,J)+A(I,K)*T
60  CONTINUE
70  CONTINUE
C
C COND = (1-NORM OF A)*(AN ESTIMATE OF THE 1-NORM OF A-INVERSE)
C THE ESTIMATE IS OBTAINED BY ONE STEP OF INVERSE ITERATION FOR THE
C SMALL SINGULAR VECTOR. THIS INVOLVES SOLVING TWO SYSTEMS
C OF EQUATIONS, (A-TRANSPOSE)*Y = E AND A*Z = Y WHERE E
C IS A VECTOR OF +1 OR -1 COMPONENTS CHOOSEN TO CAUSS GROWTH IN Y.
C ESTIMATE = (1-NORM OF Z)/(1-NORM OF Y)
C
C
SOLVE (A-TRANSPOSE)*Y = E .

DO 100 K=1,N
   T=0.DO
   IF (K.EQ.1) GO TO 90
   KM1=K-1
   DO 80 I=1,KM1
      T=T+A(I,K)*WORK(I)
   80   CONTINUE
   DO 90 EK=1.DO
      IF (T.LT.0.DO) EK=-1.DO
      IF (A(K,K).EQ.0.DO) GO TO 160
   90    WORK(K)=-(EK+T)/A(K,K)
   WORK(K)=T
   DO 110 KB=1,NM1
      K=N-KB
      T=0.DO
      KP1=K+1
      DO 110 I=KP1,N
         T=T+A(I,K)*WORK(K)
      110    WORK(K)=T
      WORK(M)=WORK(K)
      WORK(K)=T
   120 CONTINUE
C
YNORM=0.DO
DO 130 I=1,N
   YNORM=YNORM+DABS(WORK(I))
  130 CONTINUE
C
SOLVE A*Z = Y
CALL SOLVE (NDIM,N,A,WORK,IPVT)
C
ZNORM=0.DO
DO 140 I=1,N
   ZNORM=ZNORM+DABS(WORK(I))
  140 CONTINUE
C
ESTIMATE THE CONDITION.
COND=ANORM*ZNORM/YNORM
IF (COND.LT.1.DO) COND=1.DO
RETURN
C
1-BY-1 CASE..
150 COND=1.DO
   IF (A(1,1).NE.0.DO) RETURN
SUBROUTINE SOLVE (NDIM,N,A,B,IPVT)
IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION A(NDIM,N),B(N),IPVT(N)

SOLVES A LINEAR SYSTEM, A*X = B
DO NOT SOLVE THE SYSTEM IF DECOMP HAS DETECTED SINGULARITY.


INPUT..
NDIM = DECLARED ROW DIMENSION OF ARRAY CONTAINING A
N = ORDER OF MATRIX
A = TRIANGULARIZED MATRIX OBTAINED FROM SUBROUTINE DECOMP
B = RIGHT HAND SIDE VECTOR
IPVT = PIVOT VECTOR OBTAINED FROM DECOMP

OUTPUT..
B = SOLUTION VECTOR, X

DO THE FORWARD ELIMINATION.
IF (N.EQ.1) GO TO 50
NM1=N-1
DO 20 K=1,NM1
   KP1=K+1
   M=IPVT(K)
   T=B(M)
   B(M)=B(K)
   B(K)=T
   DO 10 I=KP1,N
      B(I)=B(I)+A(I,K)*T
   10 CONTINUE
20 CONTINUE

NOW DO THE BACK SUBSTITUTION.
DO 40 KB=1,NM1
   KM1=N-KB
   K=KM1+1
   B(K)=B(K)/A(K,K)
   T=-B(K)
   DO 30 I=1,KM1
      B(I)=B(I)+A(I,K)*T
   30 CONTINUE
40 CONTINUE
50 B(1)=B(1)/A(1,1)
RETURN
END

135
FLOWCHART FOR PROGRAM VI

START

INPUT GIVEN DATA

FIND AUXILIARY VALUES FOR CALCULATION

SIMULATE MESHING OF PINION AND GEAR

FIND WORKING RANGE OF TEETH AND MAXIMUM KINEMATIC ERROR

STOP
TRANSMISSION ERRORS OF HELICAL GEARS WITH THEIR AXES DEFORMED BY INTERACTING FORCE

AUTHORS: FAYDOR LITVIN
JIAO ZHANG

PURPOSE

THIS PROGRAM IS USED TO CALCULATE THE TRANSMISSION ERRORS OF A HELICAL PINION AND A HELICAL GEAR IN MESHING WHEN THEIR AXES ARE DEFORMED BY INTERACTING FORCE (BOTH PINION AND GEAR ARE NOT CROWNED)

NOTE

THIS PROGRAM IS WRITTEN IN FORTRAN 77. IT CAN BE COMPILED BY V COMPILER IN IBM MAINFRAME OR FORTRAN COMPILER IN VAX SYSTEM.

IMPLICIT REAL*8(A-H,O-Z)
DOUBLE PRECISION KSIN,MU,MUO,KSIC
DIMENSION Z(99),ANGLE(99),ERROR(99),ERR(99),W(99),RPR(99),RGR(99),
+ S1(4,4),S2(4,4),ZP(99)
COMMON /BLOCK1/ X(12),Y(10),A(10,10),Y1(10),IPVT(10),WORK(10),
+ EPSI,DELTA,NC,NE,NDIM,NCTL,CX2
COMMON /BLOCK2/ S(4,4),C,RP,RG,CK,SK,CB,SB,CKC,KSIC,ZG,TB,ZNP,F,
+ COEG1,COEG2,CB1,SB1,TB1

DEFINE PARAMETERS USED BY PROGRAMS

(1) IN ANG LP ARE UNIT NUMBERS ASSIGNED TO THE INPUT AND OUTPUT DEVICES

IN=5
LP=6

(2) NDBUG IS USE TO CONTROL THE AUXILIARY OUTPUT FOR DEBUGGING
NDBUG=1

(3) NC IS THE UPPER LIMITATION OF REPEATATION FOR SOLVING NONLINEAR EQUATIONS;
EPSI IS THE CLEARANCE OF FUNCTION VALUES WHEN THE FUNCTIONS IS CONSIDERED AS SOLVED (ALL FUNCIONS HAVE FORMS OF F(X)=0); DELTA IS THE RELATIVE DIFFERENCE FOR TAKING DERIVATIVES
NC, EPSI AND DELTA MAY BE CHANGED WHEN SOLUTIONS ARE DIVERGENT OR LESS ACCURATE
NC=100
DELTA=1.D-4
EPSI=1.D-13

(4) OTHER PARAMETERS (DON'T CHANGE)
NDIM=10
DR=DATAN(1.DO)/45.DO
DEFINE INPUT PARAMETERS OF PROBLEM (USE INCH AS UNIT OF LENGTH)

(1) PINION AND GEAR:
- \( P_N = \) DIAMETRAL PITCH; \( N_P = \) PINION TOOTH NUMBER;
- \( R_{MPG} = \) TOOTH NUMBER RATIO (GEAR TOOTH NO./\( N_P \));
- \( K_{sin} = \) PRESSURE ANGLE IN NORMAL SECTION;
- \( \beta_{p} = \) HELIX ANGLE OF PINION AND GEAR;
- \( P_{AD} = \) HEIGHT OF ADDENDUM OF PINION;
- \( G_{AD} = \) HEIGHT OF ADDENDUM OF GEAR;
- \( Z_G = \) GEAR TOOTH LENGTH (PINION TOOTH LENGTH IS LONGER)
- \( C_{OE} = \) COEFF. OF CENTRAL DISTANCE (USUALLY \( C_{OE} = 1.0 \))

\[
PN = 10.0 \quad NP = 20 \quad R_{MPG} = 2.0 \quad K_{sin} = 20.0 \quad \beta_{p} = 15.0 \quad P_{AD} = 1.0/PN \quad G_{AD} = 1.0/PN \quad Z_G = 5.0/PN \quad C_{OE} = 1.000000
\]

(2) SHAFT DEFORMATION:
- \( N_{SIM} = \) MODEL ID NO. (1 = SIMPLIFIED DEFORMATION MATRIX;
  2 = UNSIMPLIFIED DEFORMATION MATRIX)
- \( R_{LAMP} = \) PINION SHAFT ROTATION
- \( R_{LAMG} = \) GEAR SHAFT ROTATION
- \( R_{VP} = \) PINION SHAFT DEFLECTION
- \( R_{VG} = \) GEAR SHAFT DEFLECTION

\[
N_{SIM} = 1 \quad R_{LAMP} = 2.0/60. \quad R_{LAMG} = 2.0/60. \quad R_{VP} = 0.0125 \quad R_{VG} = 0.0125
\]

(3) OUTPUT:
- \( F_{EE1} = \) INCREMENT OF ROTATION ANGLE OF PINION (DEGREE)
  \( F_{EE1} = 1.000 \times DR \)

DESCRIPTION OF OUTPUT PARAMETERS

- \( F_{EE1} = \) ROTATION ANGLE OF PINION
- \( F_{EE2} = \) ROTATION ANGLE OF GEAR
- \( R_{P} = \) RADIUS OF PINION CONTACT POINT
- \( R_{G} = \) RADIUS OF GEAR CONTACT POINT

FIND AUXILIARY VALUES FOR CALCULATION

DEFINE USEFUL CONSTANTS AND PARAMETERS FOR PINION AND GEAR

\[
\Delta T = DR/60.0 \times 0.0 \quad \beta_{p1} = \beta_{p} + \Delta T
\]

\[
C_{LP} = \cos(R_{LAMP}) \quad S_{LP} = \sin(R_{LAMP})
\]

\[
C_{LG} = \cos(R_{LAMG}) \quad S_{LG} = \sin(R_{LAMG})
\]

WRITE (LP, 4) \( C_{LP}, S_{LP}, C_{LG}, S_{LG} \)

4 FORMAT (1X, 4F15.7)

\[
S_{K} = \sin(K_{sin})
\]

138
CK = DCOS(KSIN)
SB = DSIN(BETAP)
CB = DCOS(BETAP)
TB = SB/CB
SB1 = DSIN(BETAP1)
CB1 = DCOS(BETAP1)
TB1 = SB1/CB1
KSIC = DATAN(SK/CK/CB)
CKC = DCOS(KSIC)
SKC = DSIN(KSIC)
PT = PN*CB
RP = NP/2./PT
RPA = RP + PAD
RPATOL = RPA - 0.0005D0
RG = RP*RMPG
RGA = RG + GAD
RGATOL = RGA - 0.0005D0
WRITE (LP, 56) RPATOL, RGATOL

56 FORMAT (1X, '&&&&&&', 'RPA=', F15.7, 5X7, 'RGA=', F15.7)

COEG1 = 1. + SK*SK*TB*TB
COEG2 = RG/COEG1
ZNPF = CK*SB
C = (RP+RG)*COE
CALL INTMAT(S, 4, 4)
CALL INTMAT(S1, 4, 4)
CALL INTMAT(S2, 4, 4)
DO 505 LL = 1, 2
NSIM = LL
IF (NSIM.EQ.1) THEN
   WRITE (LP, 500)
500 FORMAT (1H1, ///, 1X, 'THE CASE OF SIMPLIFIED DEFORMATION MATRIX OF GEAR AXES')
   S(1, 3) = (RLAMP+RLAMG)*CKC
   S(2, 3) = (RLAMP+RLAMG)*SKC
   S(3, 1) = -S(1, 3)
   S(3, 2) = -S(2, 3)
   S(1, 4) = (RVP+RVG)*CKC
   S(2, 4) = (RVP+RVG)*SKC+C
   S(3, 4) = -C*RLAMP*SKC
ELSE
   WRITE (LP, 501)
501 FORMAT (1H1, ///, 1X, 'THE CASE OF UNSIMPLIFIED DEFORMATION MATRIX OF GEAR AXES')
   S1(1, 1) = 1. + CKC*CKC*(CLP-1.)
   S1(1, 2) = SKC*CKC*(CLP-1.)
   S1(1, 3) = CKC*SLP
   S1(2, 1) = S1(1, 2)
   S1(2, 2) = 1. + SKC*SKC*(CLP-1.)
   S1(2, 3) = SKC*SLP
   S1(3, 1) = -S1(1, 3)
   S1(3, 2) = -S1(2, 3)
   S1(3, 3) = CLP
   S1(1, 4) = RVP*CKC*CLP
   S1(2, 4) = RVP*SKC*CLP
\[ S_1(3,4) = -RVP*SLP \]
\[ S_2(1,1) = 1. + CKC*CKC*( CLG - 1 ) \]
\[ S_2(1,2) = SKC*CKC*( CLG - 1 ) \]
\[ S_2(1,3) = CKC*SLG \]
\[ S_2(2,1) = S_1(1,2) \]
\[ S_2(2,2) = 1. + SKC*SKC*( CLG - 1 ) \]
\[ S_2(2,3) = SKC*SLG \]
\[ S_2(3,1) = -S_1(1,3) \]
\[ S_2(3,2) = -S_1(2,3) \]
\[ S_2(3,3) = CLG \]
\[ S_2(1,4) = RVG*CKC \]
\[ S_2(2,4) = RVG*SKC + C \]
\[ S_2(3,4) = 0. \]
\[ \text{DO 12 MMI}=1,3 \]
\[ \text{DO 12 MMJ}=1,4 \]
\[ S(\text{MMI}, \text{MMJ})=0. \]
\[ \text{DO 12 MMK}=1,4 \]
\[ S(\text{MMI}, \text{MMJ}) = S(\text{MMI}, \text{MMJ}) + S_1(\text{MMI}, \text{MMK}) \times S_2(\text{MMK}, \text{MMJ}) \]
\[ 12 \text{ CONTINUE} \]
\[ \text{END IF} \]
\[ \text{NCoeff}=\text{IDInt}(360. * \text{DR}/\text{EEI}/\text{FLoat}(\text{NP}) + 0.5) \]
\[ N=3*\text{NCoeff} \]
\[ \text{NHalf}= (N+1)/2 \]
\[ XIN=0. \]
\[ \text{DO 205 L}=1,2 \]
\[ \text{LSGN} = (-1)**L \]
\[ \text{NCTL}=0 \]
\[ \text{NE}=4 \]
\[ \text{DO 5 I}=1, \text{NE} \]
\[ X(I)=0. \text{DO} \]
\[ X(10)=0. \]
\[ X(11)=0. \]
\[ \text{DO 15 I}=1, \text{NHalf} \]
\[ \text{IF (NCTL.EQ.2)} \text{GOTO 205} \]
\[ \text{LI}=\text{NHalf}+\text{LSGN}*(I-1) \]
\[ \text{IF (L.EQ.1)} \text{NNMin}=LI \]
\[ \text{IF (L.EQ.2)} \text{NNMax}=LI \]
\[ X(7)=\text{LSGN}*\text{EEI}/\text{FLOAT}(I-1) \]
\[ \text{IF (X(10).LE.RPATOL) THEN} \]
\[ X(4)=-X(7) \]
\[ \text{ELSE} \]
\[ \text{NE}=3 \]
\[ \text{NCTL}=\text{NCTL}+1 \]
\[ \text{END IF} \]
\[ \text{IF (X(11).LT.RGATOL) THEN} \]
\[ X(2)=X(7)/\text{RMPG} \]
\[ \text{ELSE} \]
\[ \text{NCTL}=\text{NCTL}+1 \]
\[ \text{CX2} = X(2) \]
\[ \text{END IF} \]
\[ X(3)=(ZG-RP*X(4)*SK*SK*TB)/CB/COEG1 \]
\[ \text{CALL NONLIN} \]
\[ X(8)=X(1)+X(2) \]
\[ \text{C FIND INITIAL VALUE OF X(8)} \]
IF (L.EQ.1.AND.I.EQ.1) THEN
XIN=X(8)
GO TO 15
END IF
C
X(8)=X(8)-XIN
W(LI)=X(7)/DR
Z(LI)=X(8)/DR
ERR(LI)=(X(8)-X(7)/RMPG)*3600.D0/DR
RPR(LI)=X(10)
RGR(LI)=X(11)
ZP(LI)=X(12)
C
WRITE (LP,21) ;I,W(LI),Z(LI),ERR(LI),RPR(LI),RGR(LI)
C
WRITE (LP,10)
10 FORMAT (1X,5F15.7,F15.7)

CONTINUE
205 CONTINUE
WRITE (LP,10)
10 FORMAT (1X,5F15.7)

CONTINUE
20 FORMAT (1X,5F15.7)
25 CONTINUE
NT=NMAX-NCOEF
FII=FEE1/DR/2.DO*FLOAT(NCOEF)
WRITE (LP,80)
80 FORMAT (1X,'FIND THE WORKING RANGE FOR ONE TOOTH:' ,F15.7)
DO 55 I=NMIN,NT
X(7)=FEE1*FLOAT(I- (N+1)/2)/DR/2.DO
X(8)=X(7)+FII
KK=I+NCOEF
ANGLE(I)=Z(KK)-Z(I)
ERROR(I)=(ANGLE(I)-FII)*3600.DO
WRITE (LP,60) X(7),X(8),ANGLE(I),ERROR(I)
60 FORMAT (1X,' (',F7.2, '-----',F7.2,') : ',F15.7,F15.7)

CONTINUE
55 DO 95 I=NMIN,NT
ATEMP2=ERROR(I)
IF (I.NE.NMIN) THEN
IF (ATEMP1*ATEMP2.LE.0.DO) GOTO 105
END IF
ATEMP1=ATEMP2
95 CONTINUE
WRITE (LP,160)
160 FORMAT (1X,'MESHING IS DISCONTINUOUS')
GO TO 505

IF (DABS(ATEMP1).LT.DABS(ATEMP2)) I=I-1
EMAX=0.
EMIN=0.
NTEMP=NCOEF+1
DO 135 J=1,NTEMP
KS=I+J-1
ET=ERR(KS)
IF (ET.LT.EMIN) EMIN=ET
135 CONTINUE
END
IF (ET.GT.EMAX) EMAX=ET
135 CONTINUE
ET=EMAX-EXMIN
KK=I+NCOEF
WRITE (LP,170) Z(I),Z(KK),ET
170 FORMAT (/1X,'WORKING RANGE FOR ONE TOOTH: ',F7.2,'-----',F7.2/
+ 1X,'THE MAXIMUM KINEMATIC ERROR: ',F15.7,'(s)',I2)
505 CONTINUE
STOP
END
SUBROUTINE FUNC
C
IMPLICIT REAL*8(A-H,O-Z)
DOUBLE PRECISION KSIN,MU,MUO,KSIC
COMMON /BLOCK1/ X(12),Y(10),A(10,10),Y1(10),IPVT(10),WORK(10),
+ EPSI,DELTAINC,NDIM,NCTL,CX2
COMMON /BLOCK2/
+ S(4,4),C,RP,RG,CK,SK,CB,SB,CKC,K2IC,ZG,TB,ZNPF,
+ COEG1,COEG2,CB1,SB1,TB1
C X(4)=FEEP; X(7)=FEE1
X(6)=X(4)+X(7)
CF1FP=DCOS(X(6))
SF1FP=DSIN(X(6))
AP=X(3)*SB1+RP*X(4)
XPF=CK*CK/CKC*DCOS(X(6)-KSIC)*AP+RP*SF1FP
YPF=CK*CK/CKC*DSIN(X(6)-KSIC)*AP+RP*CF1FP
ZPF=X(3)*CB1+AP*SK*SK*TB1
YNPF=-CK*CB1*SF1FP+SK*CF1FP
ZNPF=-CK*CB1*SF1FP+SK*CF1FP
C
ZNPF=CK*SB1
CF2FG=DCOS(X(1))
SF2FG=DSIN(X(1))
CF2FGK=DCOS(X(1)+KSIC)
SF2FGK=DSIN(X(1)+KSIC)
AG1=(-ZG*TB+RG*X(2))/COEG1
RFGL=CK*CK/CCK*CF2FG*KAG1+RG*SF2FG
RFG2=CK*CK/CCK*SF2FG*KAG1-RG*CF2FG
C
RFG3=ZG
RTFG1=CK*CK/CCK*(-AG1*SF2FG+COEG2*SF2FGK)-RG*CF2FG
RTFG2=CK*CK/CCK*(-AG1*CF2FG+COEG2*SF2FGK)-RG*SF2FG
C
RTFG3=0.
XGF=RFG1*S(1,1)+RFG2*S(1,2)+ZG*S(1,3)+S(1,4)
YGF=RFG1*S(2,1)+RFG2*S(2,2)+ZG*S(2,3)+S(2,4)
ZGF=RFG1*S(3,1)+RFG2*S(3,2)+ZG*S(3,3)+S(3,4)
XTGF=RTFG1*S(1,1)+RTFG2*S(1,2)
YTGF=RTFG1*S(2,1)+RTFG2*S(2,2)
ZTGF=RTFG1*S(3,1)+RTFG2*S(3,2)
C
WRITE (6,100) RTFG1,RTFG2,AG1,COEG2,COEG1,CF2FGK,SF2FGK
C
WRITE (6,100) X(1),X(2),X(3),X(4),X(5)
C
WRITE (6,100) XPF,YPF,ZPF,XGF,YGF,ZGF
100 FORMAT (1X,'%%%%%I',8E15.7)
C
WRITE (6,100) XNPF,YNPF,ZNPF,XTGF,YTGF,ZTGF
Y(1)=XPF-XGF
Y(2)=YPF-YGF

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Y(3)=ZPF-ZGF
IF (NCTL.NE.0) THEN
  Y(4)=X(2)-CX2
ELSE
  Y(4)=XNPF*XTGF+YNPF*YTGF+ZNPF*ZTGF
END IF
X(10)=DSQRT(XPF*XPF+YPF*YPF)
X(11)=DSQRT(RFG1*RFG1+RFG2*RFG2)
X(12)=ZPF
C WRITE (6,20) (Y(I1),I=1,4)
C 20 FORMAT (1X,'$$$$','6F15.7)
RETURN
END

SUBROUTINE INTMAT (A, N, M)
ELEMENTS AND NULL OTHER ELEMENTS
IMPLICIT REAL*8 (A-H, O-Z)
DIMENSION A(4,4)
DO 5 I=1,N
  DO 5 J=1,M
  5 CONTINUE
RETURN
END

THIS SUBROUTINE IS USED TO INITIATE THE MATRIX, WITH UNIT DIAGONAL
A(I, J)=0.

SUBROUTINE NONLIN
IMPLICIT REAL*8 (A-H, O-Z)
COMMON /BLOCK1/ X(12), Y(10), A(10,10), Y1(10), IPVT(10), WORK(10), + EPSI, DELTA, NC, NE, NDIM, NCTL, CX2
DO 5 I=1,NC
  CALL FUNC
WRITE (6,10) I, (X(J), Y(J), J=1,4)
10 FORMAT (1X, '***', 15/5(1X, 2D15.7/))
DO 15 J=1,NE
  IF (DABS(Y(J)).GT.EPSI) GO TO 25
  CONTINUE
15 CONTINUE
GO TO 105
25 DO 35 J=1,NE
  Y1(J)=Y(J)
35 DO 45 J=1,NE
  DIFF=DABS(X(J))*DELTA
  IF (DABS(X(J)).LT.1.D-12) DIFF=DELTA
  XMAM=X(J)
  X(J)=X(J)-DIFF
  CALL FUNC
  X(J)=XMAM
  DO 55 K=1,NE
  A(K, J)=(Y1(K)-Y(K))/DIFF
45 CONTINUE

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DO 65 J=1,NE
   65 Y(J)=-Y1(J)
C DO 85 K=1,NE
C 85 WRITE (6,104) (A(K,J),J=1,NE),Y(K)
C 104 FORMAT(1X,'A',2X,5E15.7)
   CALL DECOMP (NDIM,NE,A,COND,IPVT,WORK)
   CALL SOLVE (NDIM,NE,A,Y,IPVT)
   DO 75 J=1,NE
      75 X(J)=X(J)+Y(J)
   5 CONTINUE
105 RETURN
END

SUBROUTINE DECOMP (NDIM,N,A,COND,IPVT,WORK)
IMPLICIT REAL*8(A-H,O-Z)
DIMENSION A(NDIM,N),WORK(N),IPVT(N)

DECOMPOSES AREAL MATRIX BY GAUSSIAN ELIMINATION, AND ESTIMATES THE CONDITION OF THE MATRIX.

USE SUBROUTINE SOLVE TO COMPUTE SOLUTIONS TO LINEAR SYSTEM.

INPUT..
NDIM = DECLARED ROW DIMENSION OF THE ARRAY CONTAINING A
N   = ORDER OF THE MATRIX
A   = MATRIX TO BE TRIANGULARIZED

OUTPUT..
A CONTAINS AN UPPER TRIANGULAR MATRIX U AND A PREMUTED VERSION OF A LOWER TRIANGULAR MATRIX I-L SO THAT (PERMUTATION MATRIX)*A=L*U

COND = AN ESTIMATE OF THE CONDITION OF A.
FOR THE LINEAR SYSTEM A*X = B, CHANGES IN A AND B MAY CAUSE CHANGES COND TIMES AS LARGE IN X.
IF COND+1.0 .EQ. COND, A IS SINGULAR TO WORKING PRECISION. COND IS SET TO 1.0D+32 IF EXACT SINGULARITY IS DETECTED.

IPVT   = THE PIVOT VECTOR
IPVT(K) = THE INDEX OF THE K-TH PIVOT ROW
IPVT(N) = (-1)**(NUMBER OF INTERCHANGES)

WORK SPACE.. THE VECTOR WORK MUST BE DECLARED AND INCLUDED IN THE CALL. ITS INPUT CONTENTS ARE IGNORED.
ITS OUTPUT CONTENTS ARE USUALLY UNIMPORTANT.
THE DETERMINANT OF A CAN BE OBTAINED ON OUTPUT BY

\[
\text{DET}(A) = \text{IPVT}(N) \times A(1,1) \times A(2,2) \times \ldots \times A(N,N).
\]

IPVT(N)=1
IF (N.EQ.1) GO TO 150
NM1=N-1

COMPUTE THE 1-NORM OF A.

ANORM=0.DO
DO 20 J=1,N
T=0.DO
DO 10 I=1,N
10 T=T+DABS(A(I,J))
IF (T.GT.ANORM) ANORM=T
20 CONTINUE

DO GAUSSIAN ELIMINATION WITH PARTIAL PIVOTING.

DO 70 K=1,NM1
KP1=K+1

FIND THE PIVOT.

M=K
DO 30 I=KP1,N
   IF (DABS(A(I,K)).GT.DABS(A(M,K))) M=I
30 CONTINUE

IPVT(K)=M
IF (M.NE.K) IPVT(N)=-IPVT(N)
T=A(M,K)
A(M,K)=A(K,K)
A(K,K)=T

SKIP THE ELIMINATION STEP IF PIVOT IS ZERO.

IF (T.EQ.0.DO) GO TO 70

COMPUTE THE MULTIPLIERS.

DO 40 I=KP1,N
40 A(I,K)=-A(I,K)/T

INTERCHANGE AND ELIMINATE BY COLUMNS.

DO 60 J=KP1,N
   T=A(H,J)
   A(H,J)=A(K,J)
   A(K,J)=T
   IF (T.EQ.0.DO) GO TO 60
60 CONTINUE
DO 50 I=KP1,N
50 A(I,J)=A(I,J)+A(I,K)*T
50 CONTINUE
70 CONTINUE

COND = (1-NORM OF A)*(AN ESTIMATE OF THE 1-NORM OF A-INVERSE)
THE ESTIMATE IS OBTAINED BY ONE STEP OF INVERSE ITERATION FOR THE SMALL SINGULAR VECTOR. THIS INVOLVES SOLVING TWO SYSTEMS OF EQUATIONS, (A-TRANSPOSE)*Y = E AND A*Z = Y WHERE E IS A VECTOR OF +1 OR -1 COMPONENTS CHOSEN TO CAUSA GROWTH IN Y.
ESTIMATE = (1-NORM OF Z)/(1-NORM OF Y)

SOLVE (A-TRANSPOSE)*Y = E.
DO 100 K=1,N
  T=0.D0
  IF (K.EQ.1) GO TO 90
  KM1=K-1
  DO 80 I=1,KM1
  80  T=T+A(I,K)*WORK(I)
  90  EK=1.DO
       IF (T.LT.0.DO) EK=-1.DO
       IF (A(K,K).EQ.0.DO) GO TO 160
  WORK(K)=-(EK+T)/A(K,K)
  DO 120 KB=1,NM1
       K=N-KB
       T=0.DO
       KP1=K+1
       DO 110 I=KP1,N
       110  T=T+A(I,K)*WORK(K)
       WORK(K)=T
       M=IPVT(K)
       IF (M.EQ.K) GO TO 120
       T=WORK(M)
       WORK(K)=WORK(M)
       WORK(K)=T
       T=T+A(I,K)*WORK(K)
  120  CONTINUE
C  
C  YNORM=0.DO
DO 130 I=1,N
  130  YNORM=YNORM+DABS(WORK(I))
C  
C  CALL SOLVE (NDIM,N,A,WORK,IPVT)
C  
C  ZNORM=0.DO
DO 140 I=1,N
  140  ZNORM=ZNORM+DABS(WORK(I))
C  
C  ESTIMATE THE CONDITION.
C       COND=ANORM*ZNORM/YNORM
       IF (COND.LT.1.DO) COND=1.DO
RETURN
C  
C  1-BY-1 CASE..
C  
C  150 COND=1.DO
       IF (A(1,1).NE.0.DO) RETURN
C  
C  EXACT SINGULARITY
C  
C  160 COND=1.0D32
RETURN
END
SUBROUTINE SOLVE (NDIM,N,A,B,IPVT)
C  
IMPLICIT REAL*8(A-H,O-Z)
DIMENSION A(NDIM,N),B(N),IPVT(N)
C  
SOLVES A LINEAR SYSTEM,  A*X = B
C  DO NOT SOLVE THE SYSTEM IF DECOMP HAS DETECTED SINGULARITY.
C -COMPUTER METHODS FOR MATHEMATICAL COMPUTATIONS-, BY G. E. FORSYTHE,
M. A. MALCOLM, AND C. B. MOLER (PRENTICE-HALL, 1977)

INPUT..

NDIM = DECLARED ROW DIMENSION OF ARRAY CONTAINING A
N = ORDER OF MATRIX
A = TRIANGULARIZED MATRIX OBTAINED FROM SUBROUTINE DECOMP
B = RIGHT HAND SIDE VECTOR
IPVT = PIVOT VECTOR OBTAINED FROM DECOMP

OUTPUT..

B = SOLUTION VECTOR, X

DO THE FORWARD ELIMINATION.

IF (N.EQ.1) GO TO 50
NM1=N-1
DO 20 K=1,NM1
   KP1=K+1
   M=IPVT(K)
   T=B(M)
   B(M)=B(K)
   B(K)=T
   DO 10 I=KP1,N
      B(I)=B(I)+A(I,K)*T
10 CONTINUE
20 CONTINUE

NOW DO THE BACK SUBSTITUTION.

DO 40 KB=1,NM1
   KM1=N-KB
   K=KM1+1
   B(K)=B(K)/A(K,K)
   T=-B(K)
   DO 30 I=1,KM1
      B(I)=B(I)+A(I,K)*T
30 CONTINUE
40 CONTINUE
B(1)=B(1)/A(1,1)
RETURN
END
The contents of this report covers: (i) development of optimal geometry for crowned helical gears; (ii) method for their generation; (iii) tooth contact analysis (TCA) computer programs for the analysis of meshing and bearing contact of the crowned helical gears and (iv) modeling and simulation of gear shaft deflection. The developed method for synthesis is used for determination of optimal geometry for crowned helical pinion surface and is directed to localize the bearing contact and guarantee the favorable shape and low level of the transmission errors. Two new methods for generation of the crowned helical pinion surface have been proposed. One is based on application of the tool with a surface of revolution that slightly deviates from a regular cone surface. The tool can be used as a grinding wheel or as a shaver. The other is based on crowning pinion tooth surface with predesigned transmission errors. The pinion tooth surface can be generated by a computer controlled automatic grinding machine. The TCA program simulates the meshing and bearing contact of misaligned gears. The transmission errors are also determined. The gear shaft deformation has been modeled and investigated. It has been found that the deflection of gear shafts has the same effects as those of gear misalignment.