Effect of Modifications on the Performance of Helical Gears

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Abstract Helical gears will remain an essential element in mechanical engineering world. They work efficiently during their working lifetime. During this time wear progresses affecting the efficiency of functioning. Even sudden failure may result at any time. So, immediate replacement is a must in all cases. Although, helical gears are standard and being machined with standard cutters having standard modules, but nowadays all the profiles of the gears are being modified during machining for multi reasons. Some modifications are needed to avoid tip or root interferences. Some are needed to adjust the center distance of the mating gears to meet the pre-designed value in the assembly box. Others may be to re-strengthen the tooth to stand heavier loads. Some of the parameter needed for manufacturing can be obtained directly through the use of metrological equipment but modification parameters can’t be measured. So, it has to be deduced by trial-and-error procedure. The procedure results in providing several alternatives, which requires further work to decide on the optimal solution. This paper works on determining the optimal value of the addendum modification. It is done by studying the stress variation along the tooth, the deflection of the tooth under load and the resulting strain due to the change in the addendum modification. Model for presenting the tooth profile with modification is given.

Keywords: helical gears, addendum modifications, Modified tooth profile


1. Introduction

Helical gears are in continuous contact with the mating unit, continuous rotation and subjected to varying static and dynamic loads. Such cases must result in progressive wear reducing its quality performance and may result in sudden failure. Such cases require immediate replacement using a pre-stored spare (rarely is the case) or re-produced one. However, in manufacturing a replacement geometrical parameter as well as modification parameters must be available. Some of those parameters can be obtained through counting or using metrological equipment, but others can, only, be estimated through trial-and-error techniques. The later provides several alternative solutions and to settle on the optimal solution, further analysis is required. The analysis involves the study of the effect of the addendum modifications on the stress distribution over the contacting teeth, the deflection of the tooth under the applied loads and the resulting strain. This paper will focus on such effects to end with the optimal values for the addendum corrections.

2. Literature Review

V Atanasiu1 et al [1], studied the effect of addendum modification on the characteristics of the contact profiles of spur gear. They built a mathematical model to study the effect on the sliding between the mating gears. The work concentrated on gears with small number of pinion teeth. They considered the design limitation for the correction between minimum correction value to avoid undercutting and maximum value to avoid tooth sharpening. They emphasized on the importance of proper distribution of the correction values between the mating gears.

Sándor Bodzás [2], studied the effect of the addendum modification on the normal stress and deformation in case of helical gears. Finite element technique was used on 5 sets of gears having variable modifications maintaining all other parameters constant. A mathematical model was developed to calculate the geometrical parameters and solid work was used to simulate the meshing. The deformation was found to illustrate the importance of knowing the effect of the modification on the gears to optimize the designed values.

Christoph Lohmann et al [3], focused on the effects of tip modification and achieved that it affects tooth wear and the smoothness of running. They also found that pressure peaks could be avoided by proper choice of tip modification value.

Ognyan Alipiev [4] summarized the geometrical equations for helical gears taking the correction into consideration. The equations are listed in two ways. The first is the normal procedure of determining the parameters if the basic ones are known. The second is a
reverse procedure if the center distance is known and the main parameters are required. Through this second case the transverse pressure angle was obtained, and the correction was determined.

Gonzalo González Rey et al [5] presented a reverse procedure to deduce the correction for re-produce malfunctioning gears. The solution gave several possible values for the correction, and which is the optimal is not given.

Omar M. Koura [6], investigated the effect of addendum modifications on the various parameter in case of spur gears. Analysis was carried out using Ansys packages. Results showed that the correction factor is important parameter when considering designing of gears.

Omar M. Koura [7], presented a paper giving full procedure to manufacture gears needed to replace mal-functioning used gears. The procedure used the technique of reverse engineering. The results showed that few number of gears with different correction factors satisfy the geometrical requirement. It still needed to determine which is the optimal solution to be used.

As seen, addendum correction is essential to gears and has effects on its performance. So, this paper assists in highlighting the changes that result in the stress distribution and the displacement of the teeth as the addendum correction changes aiming at helping the designer to decide on the values chosen for the correction.

3. Methodology

The procedure and steps by which the study is performed follows the following steps.

i. Gear Material

The study is carried out on an Alloy steel gear with tensile strength of 723.82 MPa.

ii. Profile

The flow chart given in Figure 1, shows the algorithm suggested to calculate the modified tooth profile. Referring to Figure 2, The incremental values of Q1, Q2, Q3 and Q4 are obtained from:

\[
\text{Angle ocy} (e) = \pi / Z, \text{Angle ncy} (f) = S_b / D_b \]

and Angle \((n_1 + n_2)\) cy \((t) = S_i / D_o\)

\[
Q1 = (e - f) / n_1, Q2 = (f - t) / n_2, \]

\[
Q3 = t / n_1 \text{ and } Q4 = \left( (D_o - D_b) / (2 \times n_2) \right)
\]

Where: \(n_1\) and \(n_2\) are number of incremental steps at the circular zone and the involute zone respectively.

![Figure 1. Profile calculation](image)
iii. Stress, displacement, and strain
The analysis of the stress, displacement and strain are done using the solid work package. The load applied (P), the test design and the conditions used are given in Table 1.

Table 1. Test Conditions

<table>
<thead>
<tr>
<th>Tests From – to</th>
<th>Load (N)</th>
<th>Module (mm)</th>
<th>X step of 0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 9</td>
<td>100</td>
<td>3</td>
<td>-0.4, ... 0.4</td>
</tr>
<tr>
<td>10 to 18</td>
<td>100</td>
<td>5</td>
<td>-0.4, ... 0.4</td>
</tr>
<tr>
<td>19 to 27</td>
<td>100</td>
<td>10</td>
<td>-0.4, ... 0.4</td>
</tr>
<tr>
<td>28 to 30</td>
<td>1000</td>
<td>3, 5 &amp; 10</td>
<td>0.4</td>
</tr>
</tbody>
</table>

iv. Mesh information
The mesh information is shown in Figure 3. The number of elements, nodes and element size were determined by the solid work package. They varied within the range given in Table 2.

Table 2. Mesh information

<table>
<thead>
<tr>
<th>#</th>
<th>Number of elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of elements</td>
<td>From 6600 to 7850</td>
</tr>
<tr>
<td>Number of nodes</td>
<td>From 10000 to 12100</td>
</tr>
<tr>
<td>Element size</td>
<td>From 0.58 to 1.6</td>
</tr>
</tbody>
</table>

4. Results and Discussions

i. Effect of modification on stress
Figure 4 gives sample of the output of the solid work for correction factors – 0.4 and 0.4 for the three considered modules. The results are summarized in Figure 5. Over the considered range of the correction factor the change of the stress fluctuates is within ± 13% from the mean values. The results have a trend line that shows a continuous decrease in the stress as the correction factor increased from -0.4 to +0.4.
4(a). Effect on stress for M3, X0.4

4(b). Effect on stress for M3, X-0.4

4(c). Effect on stress for M5, X0.4
Figure 4. Stress variation as obtained from Solid Work
ii. Effect of modification on displacement

Figure 6 gives the effect of the modification factor on the displacement of the tooth. The maximum variation for M3 and M5 are within 11% based on the lowest value. However, it increased to about 21% in case of M10. This sound logical as the tooth height increased to about 22.5 mm giving more the tooth which is assumed to work as a cantilever to displace. Figure 7 shows the summarized results for the three modules.
<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement1</td>
<td>URES: Resultant Displacement</td>
<td>0.000e+00 mm, Node 1</td>
<td>1.34e-05 mm, Node 190</td>
</tr>
</tbody>
</table>

6(c) Effect on displacement for M5X0.4

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement1</td>
<td>URES: Resultant Displacement</td>
<td>0.000e+00 mm, Node 1</td>
<td>1.242e-05 mm, Node 10121</td>
</tr>
</tbody>
</table>

6(d) Effect on displacement for M5X-0.4

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement1</td>
<td>URES: Resultant Displacement</td>
<td>0.000e+00 mm, Node 1</td>
<td>1.342e-05 mm, Node 100</td>
</tr>
</tbody>
</table>

6(e) Effect on displacement for M10X0.4

M5X-0.4-Static 1-Displacement-Displacement1

M5X-0.4-Static 1-Displacement-Displacement1

M10X-0.4-Static 1-Displacement-Displacement1

M10X-0.4-Static 1-Displacement-Displacement1
iii. Effect of modification on strain

Figure 8 is given for the effect on strain for module 10 at modifications of -0.4 and 0.4. The most effective strain is clear at the root of the tooth. It shows higher strain as the correction factor moves to be negative. Similarly, Figure 9 summarizes the effects of modification on all three modules. Same trends as in stress cases the trend is that the strain decreases as the correction factor moves to the positive side.
<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain1</td>
<td>Equivalent</td>
<td>4.556e-07,</td>
<td>1.111e-06,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Element: 4785</td>
<td>Element: 2222</td>
</tr>
</tbody>
</table>

8(b) Effect on Strain for M3-X0.4

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain1</td>
<td>Equivalent</td>
<td>8.247e-07,</td>
<td>1.832e-06,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Element: 5128</td>
<td>Element: 6526</td>
</tr>
</tbody>
</table>

8(c) Effect on Strain for M5-X0.4

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain1</td>
<td>Equivalent</td>
<td>8.909e-07,</td>
<td>2.566e-06,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Element: 4624</td>
<td>Element: 5360</td>
</tr>
</tbody>
</table>

8(d) Effect on Strain for M5-X-0.4

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain1</td>
<td>Equivalent</td>
<td>4.283e-07,</td>
<td>8.665e-07,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Element: 1912</td>
<td>Element: 5579</td>
</tr>
</tbody>
</table>

8(e) Effect on Strain for M10-X0.4
<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain1</td>
<td>ESTRN: Equivalent Strain</td>
<td>4.553e-07, Element 4491</td>
<td>1.131e-06, Element 2327</td>
</tr>
</tbody>
</table>

Figure 8. Displacement variation as obtained from Solid Work

Figure 9. Effect of modification on strain

Figure 10. Effect of load at X = 0.4
iv. Effects of load at different modules

The results of increasing the load applied from 100 N to 1000 N at modification factor of 0.4 is given in Figure 10. All show continues decrease is the effects on stress, displacement, and strain. Figure 11 gives the displacement at applied load of 1000N for the modules 3, 5 and 10 mm.

**Figure 11.** Displacement at X = 0.4
5. Conclusion

1. The model used for the determination of the modified profile of the tooth for helical gear is successful and it is recommended strongly that it should be included in the libraries of the solid work, Ansys, … and other packages, so real modified profile are used when studying gears.

2. The effect of correction factor within the range -0.4 to 0.4 shows a tendency to decrease the values of the stresses and strain resulted due to loads.

3. The effect of addendum modification is more critical on the displacement factor with increasing effect as the correction factor is chosen to be more positive.

4. If gears are subjected to higher loads, it is preferable to go for higher module which has less rate of effect of correction on the three response factors.

5. In general, in designing gears and several gears with different correction factors were found to satisfy the requirement, it is preferable to choose the higher correction value.

Appendix

Geometrical relationships for modified helical gears.
The equations of the gear geometry are given in several literatures [4,8] and not deduced in this paper.

Reference circle diameter:

\[
D_{ref} = (M * Z) / \cos \beta
\]

Tip circle diameter:

\[
D_b = D_{ref} + 2 * M * (1 - Y + X)
\]

Transverse pressure angle

\[
\alpha_t = \tan^{-1}(\tan \alpha / \cos \beta)
\]

Base circle diameter:

\[
D_h = (M * Z * \cos \alpha_t) / \cos \beta
\]

\[
S_t = D_h \left[ \left( \frac{\pi}{2 * Z} \right) + \left( \frac{2 * X * \tan \alpha + CT}{Z} \right) \right] + \text{inv} \alpha_t - \text{inv} \alpha_o
\]

Where:
- \( M \): Module
- \( Z \): number of teeth
- \( \alpha \): pressure angle
- \( \beta \): helix angle
- \( \alpha_t \): Pressure angle at tip circle in the transverse plane
- \( \alpha_c \): Pressure angle at tooth circle in the transverse plane
- \( X \): Addendum correction
- \( Y \): Coefficient for center distance modification
- \( CT \): Circumferential backlash
- \( D_c \): Tip circle diameter
- \( D_{ref} \): Reference circle diameter
- \( D_b \): Base circle diameter
- \( S_t \): Tooth thickness at tip circle in the transverse plane
- \( S_o \): Tooth thickness at base circle in the transverse plane

References


