Study of Tooth Wear on Spur Gear Performance Parameters Using Reverse Engineering

Atul Kumar, P. K. Jain, and P. M. Pathak

Abstract— During power transfer, wear can occur on the gear tooth surface due to excessive service load, inappropriate operating conditions, owing to rubbing action between the meshed gears, foreign elements like dust particle or by metal debris. After certain number of hours, meshed gears geometry is not completely the same due to wear out on outer surface of the spur gear. An actual spur gear tooth profile is different from its corresponding tattered one. The influences of gear teeth wear can be considered on gear performance parameters like; backlash, center distance, pressure angle etc. Precision measurement of gears plays a vital role and this may be capable of measuring and inspecting of some spur gear performance parameters with an appropriate accuracy. In the present work a spur gear is selected for study and it has been scanned before and after wear using PICZA 3D laser scanner (Roland LPX60). The scanned data was obtained in the form of point cloud data, which was then used to remove the scanned noise. The data obtained in such a way is used to produce the curve geometry of gear tooth profile before and after wear. The generated curves have been taken for compression to identifying the worn-out portion on gear tooth surface. In this paper, reverse engineering approach has been proposed to tooth wear prediction and based on that, a study has been conduct for gear performance parameter after gear tooth wear.

Index Terms— Backlash, center distance, contact length, reverse engineering, spur gear.

I. INTRODUCTION

To advance technology innovation, assisted by computational manufacturing, the use of CAD/CAM technology is paramount. In a normal automated manufacturing environment, the operation sequence usually starts with a design concept via the geometric models created in CAD systems, while in reverse engineering a product is designed by capturing the shape of the object. Acquiring the shape of a physical part is an essential process in reverse engineering. The quality of digitization and reconstruction of surface model depends on accuracy of measured point data as well as the type of measuring device used. Now days, a CMM (coordinate measuring machine) and a three-dimensional (3D) laser scanner are frequently used in reverse engineering for quality inspection and redesign purpose. The scanning-type CMMs can be used for measuring freeform features however, they cannot measure a part made of soft materials and have relatively lower scanning speed compared to laser scanners [1, 2]. On the other hand non-contact techniques are obtaining large amount of point cloud data in a short time. Since the accuracy of the non-contact methods is getting improved, they are widely adopted for many applications in industry [3]. The scanning technology can also help in deciding the repair process for complex geometry parts, like cam shaft, impeller, ship hull water touching surface, gas turbine blades spur gear, etc. The use of 3D digitizing are being in targeted in the application of reverse engineering such as; quality control, differential inspection, direct replication, detection of inaccuracies, redesign of parts and manufacturing tools faster [4].

Gears are one of the most common mechanical element for transmitting power and motion. In, most of the modern industrial and transport applications, gears are important and are frequently used as fundamental mechanical components. Gear power transmissions systems under difficult work conditions may reduce their pitting resistance, bending strength and the period of exploitation of their transmissions. Wear is defined from a gear engineer’s perspective as that kind of tooth damage whereby layers of metal have been more or less uniformly removed from the surface. Surface wear is considered to be one of the major failure modes in gear systems rather than other being tooth bending fatigue, contact fatigue, scoring, cracking and over loading. Wear on gears teeth profile takes place because of dirty operation environment, in proper lubrication, higher gear operating speeds etc. The impact of wear on operational life of any gear system has far reaching consequences by affecting some gears performance parameters of almost every power transmission system. Apart from the direct material loss the surface wear causes the gear system to change its vibration behavior, speed ratio and noise characteristics significantly. Surface wear can also affect the patterns of gear contact affecting parameters such as backlash, center distance, tooth thickness, pressure angle etc. [5]. The determination of the teeth gear characteristics after a certain period of their use has vital role for the designing practice of the tooth gearing. For such a prognostic approach it is necessary to take into account the geometrical influence of spur gear tooth and effecting parameters of engaging the spur gear pair and the real shapes of the teeth. As result, the shape of the teeth is varying continuously due to teeth wear with respected to service time. This causes the change of the geometrical parameters of the gear and changes of the level of teeth wear [6]. This process is a continuous with a different degree of time intensity during the whole service life of gear train. Spur gears have the majority among all types of gears in use; therefore 3D measurement process of spur gears becomes a persisting target [7]. The current methods of gear measurement are either time consuming or expensive. In
addition, no single measurement method is available and capable of accurately measuring the wear out portion on gear tooth. The use of laser based system to measure the thickness, pitch, and tooth flank profile of spur gears was also investigated [8, 9].

For closer control over the accuracy of gearing, precision measurement of gears plays a vital role. The deviation of worn-out tooth profile from the design profile, the profile error, can be measured in a number of ways. The simplest way is to use the 3D laser scanner and scanned the gear teeth profile before wear and after wear. After that generate the teeth surface profile using scanned data with suitable file formats like; point cloud, STL, etc [10]. This profile can be utilized to identifying the wear-out portion on the tooth surface and further, worn-out portion has been used to study the geometrical performance parameters of spur gear pair. Therefore, the measurement and inspection of spur gears has been emphasized by many researchers.

This paper presents an approach where gear tooth wear is measured through reverse engineering approach. This measured value is used in evaluating the required change of center distance due to presence of backlash due to wear, change of pressure angle required and change in contact length.

II. REVERSE ENGINEERING OF SPUR GEAR

Reverse engineering is the process of scanning an object and then generating curve profiles or CAD model. The spur gear has been designed according to AGMA standard for present study using gear design handbook [11]. The design has been done for commercial enclosed gear units. The specifications used to design the spur gear are presented in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pinion</th>
<th>Gear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of teeth</td>
<td>12</td>
<td>24</td>
</tr>
<tr>
<td>Module</td>
<td>6.35</td>
<td>6.35</td>
</tr>
<tr>
<td>Pressure Angle</td>
<td>20°</td>
<td>20°</td>
</tr>
<tr>
<td>Diameter of pitch circle (mm)</td>
<td>76.2</td>
<td>152.4</td>
</tr>
<tr>
<td>Diameter of base circle (mm)</td>
<td>71.60</td>
<td>143.2</td>
</tr>
<tr>
<td>Diameter of Addendum circle (mm)</td>
<td>89</td>
<td>165.1</td>
</tr>
<tr>
<td>Diameter of Dedendum circle (mm)</td>
<td>60.325</td>
<td>136.525</td>
</tr>
<tr>
<td>Face width (mm)</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

Necessitates of application of reverse engineering method is to generate point cloud data, data analysis, pre-processing and accurate 3D CAD virtual models. In reverse engineering, some step process are used to manipulate data collected from sources into the final model, i.e., creation of wire frame geometry from parametric or non-parametric curves, shapes recognition, feature recognition and geometry reconstruction. A logical structured approach has been taken to convert the scanned data points into desired features.

A. Data Acquisition and Preprocessing

The point cloud data is acquired by scanning the form of x, y and z co-ordinates of the multiple point of the object surface. Using the 3D laser scanner the dark or shiny surface objects are difficult to digitize and they need to be sprayed with white coating. Then the object has to be set properly on the rotating table using reference features on the part, such as marking on scanning object and on a rotary table. The scanned data from each orientation need to be combined and represented in a common coordinate system. This is called as registration. Gear has been scanned at once for five different face angles such as 10°, 40°, 70°, 80°, and 90° and the best result is found with 80° face angle as shown in Fig. 1.

The scan data is collected with the help scanning software (Roland LPXEZ studio) and data is saved as a .GSF file format. The scanned data usually contain some noise because of this scanned data cannot be directly used for surface modeling operation. Some pre-processing such as overlapped point data, filtering etc. are to be carried out for reducing the scanned data noise. The pre-processed image of scanned gear surface profile has been shown in Fig. 2. Point cloud file format is used as output of scanned data.

In this work after complete scanning by laser, scanned data has been saved in the point cloud format. The number of scanned data for original gear is 453645. Number of points representing x and y co-ordinate respectively out of them comprise of 505 data for a single tooth. Also, the number of scanned data for wear out gear is 452742 out of them 504 data are for a single tooth.

B. Profile Recreation of Spur Gear Teeth

Noise less data has been saved as a point cloud data in ASCII file format at different values of z. The reason for dividing the surface into these surface patches was to avoid
the occluded region around the jutting surface section. Recreation of model by scanned data is done with the help of Microcal (TM) Origin working model (version 6.0) software. The recreated model before wear is shown in Fig. 3 (a). Fig. 3 (b) shows the model after wear in three teeth of the gear marked as A, B and C. By comparing Fig. 3(a) and (b) one can estimate the amount of wear at the gear tooth B.

III. IDENTIFICATION OF GEAR TOOTH WORN-OUT PORTION

The pre-processed data is analyzed to extract the point cloud data for different values of z (z = 0, 0.2, 0.4…12.8). The free-form scanned surface section of the spur gear was divided into 12 individual tooth surface patches. The occluded region could be divided into an adequate number of surface patches which could be recreated the tooth curve profile using the ASCII file format. Some minor error may occur during the profile comparison because of scanning process variables like change in voltage, misplacement of gear and variation in rpm while table rotation. The wear out portion has been indicated in Fig. 4. The reduction in tooth thickness along the pitch circle can be evaluated from Fig. 4 as:

At point A the coordinate values for X and Y axis are: -36.2, -18.20
At point B the Coordinate values for X and Y axis are: -35.6, -20.1.
Then reduction in tooth thickness will be given as

$$B' = \sqrt{(x_A - x_B)^2 + (y_A - y_B)^2}$$

$$B' = \sqrt{(-36.20 + 35.60)^2 + (-18.20 + 20.10)^2}$$

$$B' = 1.992 \text{ mm}$$

IV. STUDY OF GEAR PERFORMANCE PARAMETERS

The investigation of the effect of tooth deformation and wear on the geometrical performance parameters have been carried out. The investigation has been carried out with the help of gear tooth worn out portion as shown in Fig. 4. The study founds the change in center distance required due to backlash generated due to wear. The effect on pressure angle and contact length has also been investigated. The effect of these geometrical parameters due to wear has been described as follows:

A. Effect on Backlash and Center Distance

Calculations for gears are usually made of assumption that operation will occur in metal to metal contact. Backlash for involute gear can also be obtained by appropriate increase in the center distance. On some occasions a set of gear must operate on a center distance which is not one half the sums of the standard pitch diameters of the meshing gears. There are several kinds of backlash: circumferential backlash, normal backlash, radial backlash and angular backlash. The designer is confronted with nonstandard center distance in several situations the more important of which are:

- Gear trains in which the teeth are made to standard tooth thickness and backlash is introduce by increasing the standard center distance slightly.
- Tooth strength, wear, or scoring may be affected in gear train, in which the sum of the tooth thickness of pinion and gear is not equal to the circular pitch due to some reasons.
- Gear train in which a minor changes in ratio has been
made without a change in center distance.

The approximate degree of backlash is to be set an amount of \( e_1 \) deeper into the blank with circular pitch \( p \), pressure angle \( \theta \) and as shown in Fig. 5 (a), then for a good approximation, arc PQ or one half of the theoretical pitch is reduced by \( e_1\tan\theta \) at both ends. Then one can relate the actual tooth thickness \((t_i)\) with pitch using (1) as

\[
t_i + 2e_1\tan\theta = \frac{1}{2}p 
\]

(1)

\[
e_1' = \frac{1}{2}\frac{p-t_i}{\tan\theta}
\]

(2)

For pinion circular pitch \( p \) can be calculated by (3) as:

\[
p = \frac{\pi \times \text{Pitch diameter}}{\text{Number of teeth}} = \frac{3.14 \times 76.2}{12} = 19.949 \text{ mm}
\]

(3)

The gears are to operate with a backlash \((B)\), the center distance must be increased by \( B/2\tan\theta \) as shown in Fig. 5 (b) the actual center distance \( C' \) is then equal to:

\[
C' = C - \frac{p - t_1 - t_2 - B}{2\tan\theta}
\]

(6)

If \( \Delta C = C - C' \), the above equation reducts to:

\[
\Delta C = \frac{p - t_1 - t_2 - B}{2\tan\theta}
\]

(7)

Assuming \( t_1 = t_2 = p/2 \). The backlash value was evaluated in section III as \( B = 1.992 \text{ mm} \) from the tooth profile comparison as shwon in Fig. 4 and the recomnded backlash for pinion is 0.2286 mm [11], then the actual backlash \( B \) is 1.7634 mm. Then \( \Delta C \) can be evaluated as -2.422 mm.

Center distance \( C \) can be calculated by equation (8), where, \( d_p \) and \( d_g \) are the pitch circle diameter for pinion and gear respectively.

\[
C = \frac{d_p + d_g}{2}
\]

(8)

\[
= \frac{76.2 + 152.4}{2} = 114.3 \text{ mm}
\]

Then, the modified center distance will be given as:

\[
C' = C - \Delta C = 114.3 - (-2.422) = 116.722 \text{ mm}
\]

B. Effect on Pressure Angle

The pressure angle of involute gear tooth is determined by the size ratio between the base circle and pitch circle. Due to increase in center distance between the two gears now the pressure angle also changes. Let the old pitch circle radius of pinion and gear is \( r_p \) and \( r_g \), new pitch circle radius of gear and pinion is \( r'_p \) and \( r'_g \), then if base circle radius of pinion and gear are \( r_{bp} \) and \( r_{bg} \), and new pressure angle is \( \theta' \) then,

\[
r_{bp} = r_p \cos \theta = r'_p \cos \theta'
\]

(9)

\[
r_{bg} = r_g \cos \theta = r'_g \cos \theta'
\]

(10)

Using equation (9) and (10) one gets

\[
(r_p + r_g)\cos \theta = (r'_p + r'_g)\cos \theta'
\]

(11)

\[
\cos \theta' = \frac{C'}{C'}
\]

\[
\cos \theta' = \frac{114.3}{116.722} \times \cos 20
\]

\[
\theta' = 23.04^\circ
\]

C. Determination of New Pitch Circle Diameter

Using equation (9) and (10) one gets

\[
\frac{r_p}{r'_p} = \frac{r_g}{r'_g} = \cos \theta'
\]

(12)

Also from (11)

\[
\frac{\cos \theta'}{\cos \theta} = \frac{C}{C'}
\]

(13)

Using equations (12) and (13) one can write
\[ r_p = r_p - \frac{C}{C'} \]

Substituting the values in equation (14), one gets
\[ r_p = 38.90 \text{ mm} \quad \text{and} \quad r_p = 77.81 \text{ mm} \]

D. Effect on Contact Length

Tooth wear influences the dynamic response of gears due to increasing tooth deviation. Different wear depths along the tooth profile occur due to varying contact conditions (sliding velocity). Because of this the contact length may vary with respect to change in pressure angle correspondingly. This case causes the transmission errors during the meshing period. The original contact length can be given as

\[ l = \left[ r_{ap}^2 - r_{g}^2 \cos^2 \theta \right] + \left[ r_{ap}^2 - r_{p}^2 \cos^2 \theta \right] - (r_g + r_p) \sin \theta \]

Where \( r_{ap} \) is the addendum circle radius of gear and \( r_{ap} \) is the addendum circle radius of pinion. The new contact length can be given as

\[ l' = \left[ r_{ap}^2 - r_{g}^2 \cos^2 \theta' \right] + \left[ r_{ap}^2 - r_{p}^2 \cos^2 \theta' \right] - (r_g + r_p) \sin \theta' \]

After substituting the values one gets \( l = 28.51 \text{ mm} \) and \( l' = 21.92 \text{ mm} \)

V. CONCLUSION

In present work steps involved in reverse engineering of gear teeth have been explained using steps such as, data acquisition, data pre-processing, and teeth profile generation. Wear has been found by comparison of teeth profile after and before wear. The wear out portion is identifying for a particular tooth and a fixed value of \( z \) (i.e. \( z = 1 \)). This difference in pitch circle is the backlash due to wear of gear tooth. Thus using reverse engineering one can assess the gear tooth wear and in turn study the surface wear effect on gear’s geometrical parameters such as backlash, center distance clearance and pressure angle. It has been found that if the surface wear is increased, substantial backlash, center distance clearance and pressure angle also increases and as a result power loss increases. Accordingly operating condition of the gear train can be modified and improved to get more remaining life as well as to improve the performance of the gear train.

REFERENCES


Atul Kumar is pursuing PhD from Indian Institute of Technology Roorkee in the Department of Mechanical and Industrial Engineering. His research interest includes Design, reverse engineering (RE), CAD/CAE/CAI and FE simulation of statics elements. His research areas include reverse engineering, CAD, design, finite element analysis and bending fracture analysis. He has few papers published in national and international journals and conferences proceedings.

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