Abstract:
The demand for quick prototyping of gears has highly increased than ever. With NVH targets on the other hand, compromises if any, on such prototype gears have to be predicted before testing. To add another constraint, cost of prototyping comes in. This paper demonstrates a way that uses an existing hob cutter of different module followed by profile grinding to make prototype gears. Method to predict possible deviations and the consequences are discussed. An experiment of such gear pair is demonstrated.

1. INTRODUCTION

Gears have become inevitable components of almost all industries, in particular mechanical products. Stringent NVH and packaging targets drive the design towards optimum point and hence testing becomes mandatory of every design iteration. Tests are done on different grounds like fatigue strength, impact strength, NVH etc. It is a well-known fact that manufacturing these gears take a lead time of an average of 30 days. Such a long lead results in reduction in of no. of iterations and increase in design cost. Plus, the cutters designed for one proposal may not suit the second one.

Mahindra, like any other OEM, has been looking out for a way to use existing cutters for making gears of different geometry. Cutter versatility was decided to be explored. However, any literature on using same hob for gears of different geometry is not found. Robert Endoy (Ref. 1) and Keith Liston (Ref. 2) discuss to a great depth on cutters (hob and shave) design, life prediction of those and cycle time estimation. But versatility of a hob is seldom discussed.

2. BASIC MECHANISM OF HOBBING

A continuously meshing rack with defined relative rotation of a blank generates an involute tooth. The theoretical concept of “continuously meshing rack” is transformed to a practical form by the longitudinal section of helix. This tool is called a hob (Fig. 1).

The rack formed by a standard hob conventionally is made of the same module and pressure angle as of the gear to be hobbed. With this setup, the intersection of normal plane of hob axis and line of action between hob & gear happens exactly at a point in pitch circle. Naturally, the Line Of Action (LOA) is tangential to the base circle of gear (Fig. 2).

3. HOBBING WITH NON-STANDARD HOB

As the further discussions of the article will explain, hobbing can be done with a hob which is of different module and pressure angle than that of the gear. In this case, the intersection of normal plane of hob axis and LOA is not at pitch circle. However, the LOA still is tangential to the base circle of the gear (Fig. 3).

From Fig. 2,

\[ D_B = D \times \cos \alpha \]
\[ D_B = m_t \times z \times \cos \alpha \quad ---- \quad (Eq. 1) \]
Where,

\( D \) = PCD of gear

\( \alpha \) = Pressure angle of the gear

\( \propto \) = Pressure angle of standard rack

\( m_t \) = Transverse module of gear

\( z \) = No. of teeth of gear

From Fig. 3,

\[ D_B = D' \times \cos \propto' \]  ---- (Eq. 2)

Where,

\( D' \) = Diameter at the point of intersection of normal plane of hob and LOA of hob and gear

\( \propto' \) = Pressure angle of non-standard standard rack

For the hob to cut equi-spaced teeth on the gear, pitch of hob and pitch of gear have to be equal

\[ \frac{\pi \times D'}{z} = m_{t'} \times \pi \]

\[ \therefore D' = m_{t'} \times z \]

\[ D_B = m_{t'} \times \cos \propto' \times z \]  ---- (Eq. 3)

Where,

\( m_{t'} \) = Module of the hob at transverse section of gear while hobbing

Equating Eq. 1 and Eq. 3,

\[ m_t \times z \times \cos \alpha = m_{t'} \times \cos \propto' \times z \]

\[ \frac{m}{\cos \beta} \times \cos \propto = \frac{m_{t'}}{\cos \beta'} \times \cos \propto' \]

\[ \therefore \frac{m}{\cos \beta} \times \cos \propto = \frac{m}{\cos \beta} \times \cos \propto \]

Where,

\( m \) = Normal module of gear

\( m' \) = Normal module of tool at normal plane of gear while hobbing

\( \beta \) = Helix angle of gear

\( \beta' \) = Helix angle of hob teeth while hobbing

Since the gear tooth trace and the hob tooth trace will be at same helix angle during hobbing,

\[ \cos \beta = \cos \beta' \]

\[ m \times \cos \alpha = m' \times \cos \alpha' \]  --- (Eq. 4)

Eq. 4 serves as governing equation to use a hob of different module to make a gear.
4. TOOTH FORM IN KISSSOFT

A separate tab “tooth form” in KISSsoft has the capability of accepting hob of different module and pressure angle to give possible output of gear tooth form. Also, the software comes programmed to satisfy the governing equation (Eq. 4) as an option to the user. In other words, the user is given a flexibility to check the outputs of any hob that obeys or does not obey Eq. 4 (Fig. 4).

If Eq. 4 is not met, the resulting hobbed profile will have a pressure angle different from the targeted. This effect can be observed easily using KISSsoft (Fig. 5).

5. APPLICATION OF ‘TOOTH FORM’ IN PROTOTYPE MANUFACTURE:

The detailed understanding of tooth form option gives the confidence of attempting existing hobs for new gear designs. Primarily, a data base of all existing hobs with details like module, pressure angle, semi topping, root fillet radius, protuberance and very importantly “m’xcos(α’)” was prepared. Fig. 6 shows such a data base. Some detailed technical content such as protuberance, semi topping etc. are not shown.

With exactly same m’xcos(α’), the generated profile will coincide precisely with the targeted. Root fillet shape is still a compromise though. If the m’xcos(α’) is lower than that of the targeted profile, the output profile produced has a higher pressure angle. This ends up producing a step at shaving / grinding process (Fig. 7).

Whereas, the learning is that greater m’xcos(α’) produces a profile of lower pressure angle. This, when grinding, removes higher amount of material at tip and approaches no-material removal condition at root fillet. Analogically, it provides the effect of protuberance of a standard hob cutter. Hence, this is a favourable condition. The activity explained in this paper has therefore used a cutter with greater m’xcos(α’) than the expected mxcos(α).

If the cutter is not tailor-made, three parameters may change from the targeted. Prototype gear has to be designed, understanding the intent so that the compromise can be wisely negotiated. Tab. 1 shows such parameters that may change and the predicted limitations for testing because of those on testing:

<table>
<thead>
<tr>
<th>Expected change</th>
<th>Tests not suitable with this change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root diameter</td>
<td>If the gear is hobbed in a shaft, the shaft strength will change. Hence with this compromise, strength tests are better not carried out. (Ref. 3)</td>
</tr>
<tr>
<td></td>
<td>Any test related to tip clearance.</td>
</tr>
<tr>
<td>DOB</td>
<td>Rattle behaviour tests will be unreliable because of change in backlash. (Ref. 4 &amp; 5)</td>
</tr>
<tr>
<td>Tip chamfer</td>
<td>Gear whine tests may give false results as contact ratio changes. (Ref. 6)</td>
</tr>
<tr>
<td></td>
<td>With huge deviation in tip chamfer, strength testing is not liable.</td>
</tr>
</tbody>
</table>

Tab. 1 – Predictable change in parameters and consequences

Simply put, to achieve one of the parameters of the above, the other two might have to be compromised. The comfort of having a software like KISSsoft is that those compromises can be quantitatively found and their consequences can be analysed in seconds. The test planned with the prototype decides the one parameter to be matched with designed value. Since it is beyond the scope of the article to study the consequential changes of each parameter in detail, only one case is demonstrated. DOB as per the final design has been targeted and the effects are discussed.
6. PROTO-MANUFACTURE OF GEARS

A gear pair which is in one of Mahindra’s successful five speed transmission was taken for the study. Availability of holding fixtures, blanks, metrology facilities etc. were few important reasons. This is a helical gear pair with an \( m \times \cos(\alpha) \) of 2.077. A similar database to Fig. 6 was prepared and tools with higher \( m' \times \cos(\alpha') \) were filtered.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Drive gear</th>
<th>Driven gear</th>
<th>Hob</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal module (mm)</td>
<td>2.21</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>Normal pressure angle (°)</td>
<td>20</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>( m \times \cos(\alpha) ) (mm)</td>
<td>2.077</td>
<td>2.161</td>
<td></td>
</tr>
<tr>
<td>Helix angle</td>
<td>17</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Root dia. (mm)</td>
<td>33.304</td>
<td>60.204</td>
<td></td>
</tr>
<tr>
<td>DOB (mm)</td>
<td>44.124 / 44.042</td>
<td>70.744 / 70.659</td>
<td></td>
</tr>
<tr>
<td>Ball size (mm)</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Tip chamfer (mm)</td>
<td>0.3</td>
<td>0.3</td>
<td></td>
</tr>
</tbody>
</table>

Tab. 2 – Gear and hob parameters

Tab. 2 shows final parameters to be met. At hobbed condition a suitable stock was left for HT distortion and profile grinding. Thus a DOB at hobbed stage was arrived for each gear. In KISSsoft tooth form, all tool inputs were given (Fig. 8).

To find out the profile shift needed to achieve DOB values, a spreadsheet with complex trigonometric relationships was used. In the same way, information of profile grinding were also fed to KISSsoft. Through the tooth form graphic output, possible tip chamfer output, max. amount of material removal at grinding, and root form diameter were predicted.

7. RESULTS AND DISCUSSIONS

With the help of KISSsoft, it was predicted beforehand that the grinding stock is not uniform along the involute. The tooth form graphic show it ranging from 1.1 mm at EAP and 0 mm little below SAP diameters. After heat treatment (HT), removal of 1.1 mm at EAP will remove the case-hardened layer completely. Hence, a strategy of grinding before HT was taken. A consequence of reduction of gear quality to DIN 7–8 was accepted (Fig. 9). Profile and lead inspection at different stages of both the gears are shown.

KISSsoft predicted the achievable root diameter as 32.95 mm against a target of 33.304 mm. To know if this will lead to failure of gear, “Graphical method” option of form factor was used (Ref. 7). With this option both intended profile and achievable profile were compared. The effect in root factor of safety was approximately 7%. This was considered a worthy compromise.

The closeness to the KISSsoft-predicted profile at hob and grind can be seen at Fig. 10.

In parallel, the time taken since the blanks, hobs and fixtures were brought to the shop floor was measured. For the drive gear, an average of 2h and for the drive gear an average of 3h were noted. This involves machine and metrology. HT time is excluded.

A general rule of quick manufacture results in expensive decision is also found broken. A rough comparison with an involuted gear of similar size shows approx. 2.5 times the cost of the method explained in this paper.
8. CONCLUSION

Short lead time being the ultimate target is evidently achieved, moving gears from “Long lead items” list to “Short lead items” one. The uses of a tool like KISSsoft at different stages of calculation and decision making are quite remarkable. The scope can further be extended to detailed analysis of the compromises because of this method. With such studies, a perfect correlation between the tested results of prototype and to-be tested results of mass produced components can be made. This will make proto-making of gear using an existing hob and profile grinding much more reliable.

REFERENCES

FIGURES

Fig. 1 – Gear cutting mechanism of a hob

Fig. 2 – Hobbing using a standard cutter

Fig. 3 – Hobbing using a non-standard cutter
Fig. 4 – Tooth form option in KISSsoft and sizing buttons to calculate $m'$ and $\alpha'$

Fig. 5 – Output of using hobs of different $m' \times \cos(\alpha')$ – Graphic taken from KISSsoft

Fig. 6 – Sample data base preparation

Fig. 7 – Lower $m' \times \cos(\alpha')$ leading to a ground step at root -Graphics taken from KISSsoft
Fig. 8 – Hob data fed to KISSsoft tooth form

Fig. 9 – Achieved profile and lead forms

Fig. 10 – Profile prediction by KISSsoft (Blue) merging pretty close with the actual profile