DESIGN OPTIMIZATION AND ANALYSIS OF AN AUTOMOTIVE MANUAL TRANSMISSION SHAFT USING TITANIUM ALLOY (Ti6Al4V)

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Abstract—Intent of this work is to design an automotive manual transmission shaft for its better performance. Therefore it must be strong enough to bear the needs, whilst avoiding too much additional weight as that would increase their inertia. So here the work deals with the design constraints such as natural frequency (resonant condition) and static strength which are subjected to torque. Sensitivity analysis and optimization on the best among material is done to optimize the constraint in the aim to get minimum weight and stress. Genetic Algorithm, one among the numerical methods, is used here. An effective techniques are carried out using finite element analysis software which are commercially available. Finally the weight and stress optimized for different materials are compared with the titanium alloy. Hence results revealed that the Ti6Al4V has the better result than other which are considered.

Keywords—Automotive manual transmission shaft, Design variables, Genetic algorithm, Ti6Al4V.

I. INTRODUCTION

In the era 1956, for the first time in automobile evaluation, the General Motor Corporation introduced its concept car firebird 2, with its skin made of titanium. So after some gap the automotive field industries has started to give importance to titanium but due to tremendous usage of other materials which are being used it get progressed high slowly. Race cars are more involved in titanium alloy parts for its better performance compared with other materials for specific parts only where it is needed. The first sports car which used titanium as a connecting rod is Honda NSX which is limited production car; with the usage of titanium alloy it eliminates the need of turbocharger.

Based on the United States Council for Automotive Research, the titanium alloy is used precisely to reduce the weight of the specific part in automobile industries. The most prevalent titanium alloy which is used in automobile field are Ti-6Al-4V and Ti-6Al-2Sn-4Zr-2Mo-0.1Si alloys. Though synchroniser is used to shift the gear smoothly, at some instance the commercial users may face problem due to time difference in the shifting time. So because of this fatigue failure and worn-outs, residual stress may occur and it leads to replacement of an input transmission shaft. These Problems will arise due to insufficient knowledge of commercial users about replacement the transmission shaft for normal vehicle and performance vehicle. Considering the above problems, Titanium alloy (Ti6Al4V) can be used to avoid such failures when compared with the other metal or alloys in use and also there will be an advantage of less weight in comparison with others. There are two main objectives that are concentrated. The first being natural frequency and following static torsional strength which are all based on input torque.

First, the natural frequency is one of the most powerful factor in any design whichever available today. Hence for safer side the natural frequency of the manual transmission shaft should be higher than the frequency of an engine by at least 10 times as a factor of safety. Second, the static strength of the manual transmission shaft based on torque. Hence these design variable are used here for the weight optimization.

For the manual transmission shaft used in automobile the majority of the work should be concentrated with the gear rattling sound produced during gear backlash and dry friction which may lead to many damages. However the transmission shaft should be designed in such a manner to reduce these as much as possible.

As far above, to find those design variable there are certain different approaches are available. To make the design variable favourable for our approach, one must choose the algorithm which suits the best. So here comes the optimization technique which are used commonly everywhere, since it will reduce the extra manufacturing cost of the particular component. There are different solution for optimization like graphical method, linear programming, and numerical method. So in response to this, we are choosing numerical method especially genetic algorithm is preferred which is more suitable for transmission shaft because of its simple solving procedure and also it provides more approximate solution for the transmission shaft, so it is chosen for our work.
II. MATERIAL SELECTION

Different materials are being used in manual transmission shaft from an earlier time. The torque transmitting capacity will vary depend upon the material and also on the corresponding design selection. At the same time the natural frequency will vary for different material. From this it is known that design variables play a major role in material selection.

This work mainly focus on titanium alloy (Ti6Al4V) material. Here Ti6Al4V is compared with other material which are being currently used in industries. Because titanium alloy has more advantage when compared with the other material and it also provides good result which will be compared below further.

Generally, most of the shaft material which in use are, Low carbon, cold drawn or hot rolled steels such as ANSI 1020-1050 steels. Carburizing grades of ANSI 1020, 4320, 4820 and 8620 are also used. Cold drawn steel is usually used for diameter under about 3 inches.

Here we use four materials for our intent to show the comparable results and they are as follows,

- Aluminium 7075-T6
- Titanium alloy Ti6Al4V
- AISI 18Ni maraging steel annealed and
- Magnesium alloy AZ80A-T6

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>Aluminium 7075-T6</th>
<th>Titanium alloy Ti6Al4V</th>
<th>AISI 18Ni maraging steel annealed</th>
<th>Magnesium alloy AZ80A-T6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>2.80</td>
<td>4.43</td>
<td>8.0</td>
<td>1.80</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.33</td>
<td>0.3-0.37</td>
<td>0.30</td>
<td>0.35</td>
</tr>
<tr>
<td>Tensile Strength(MPa)</td>
<td>510-572</td>
<td>862-1200</td>
<td>660-965</td>
<td>250-340</td>
</tr>
<tr>
<td>Young’s Modulus (GPa)</td>
<td>72</td>
<td>110-19</td>
<td>183</td>
<td>45</td>
</tr>
<tr>
<td>Shear Modulus (GPa)</td>
<td>26.9</td>
<td>40-45</td>
<td>70</td>
<td>17</td>
</tr>
<tr>
<td>Bulk Modulus (GPa)</td>
<td>70</td>
<td>96.8-153</td>
<td>140</td>
<td>45</td>
</tr>
</tbody>
</table>

Properties of different materials are shown in the table. From these material properties, analysis is performed using finite element analysis software. The results of varies material are shown using FEA software.

III. STRATAGEM FOR DESIGN

A. Primary CAD model

Here we are taking an initial model with specific dimension which is being used by the automotive industries now-a-days for the purpose of transmitting torque from engine to gear box with very less transmission loss.

Assumptions in primary design
- a) The Input torque to shaft is a constant torque without variations and the shaft rotates in constant speed.
- b) It has uniform annular cross section as hollow shaft has more Strength to weight ratio.
- c) The shaft is balanced and the Mass Center coincides with Geometric center of shaft.
- d) It obeys Hook’s Law.
- e) No fluid interaction like lubrication environment is not considered.
- f) No vertical forces, hence no bending moments.

The transmission shaft is checked for its Torque carrying capacity, torsional deflection, Torsional Buckling capacity & Natural frequency. If Torque carrying capacity, T of the shaft which is nothing but Load factor x Input torque (Assume Load factor=1) & S, is shear strength, t is the thickness of shaft, (d-di)/2

\[ T = S_n \frac{(d_i - d_f)^2}{16t} \]

B. Modified cad model design

An aspiration of this work is weight optimization to give better performance. After some thoughts on finalizing shaft diameters

\[ d = \left( \frac{16n}{\pi} \frac{1}{S_s} \left[ 4(K_1 M_m)^2 + 3(K_1 T_s)^2 \right]^{1/2} + \frac{1}{S_t} \left[ 4(K_1 M_m)^2 + 3(K_1 T_m)^2 \right]^{1/2} \right)^{1/3} \]

As per standard of ASME method of minimum diameter, B106.1M-1985 is

\[ d = \frac{3}{\pi} \sqrt[3]{\frac{32 \text{Safety Factor}}{\left( K_1 \frac{M_m}{S_m} \right)^2 + \frac{3}{4} \frac{T_m}{S_m}}^{1/2}} \]

Where,

M_m, M_m, T_s, and T_m are alternating and mean bending moment as well as torques.
S_f, S_e, S_y, S_ut are shaft material’s endurance, yield and ultimate strengths.

Since this work proceeds with four materials, now the CAD model is analysed using the FEA software to find the factor of safety, so that the optimization technique can be carried out. The necessary conditions for analysis are as follows:

The transmission shaft is used at maximum input torque of 230 Nm at 4500 rpm from the engine and the engine have a maximum rpm of 7000. The Von-misses stress of the shaft should be less than 75% yield strength with a safety factor of 1.25. The forcing frequency from engine which is 7000 /60 = 116.67 hertz. The natural frequency of transmission shaft should be at least 10 times higher than this.
Now comparing all the material factor of safety

Table II: factor of safety and natural frequency

<table>
<thead>
<tr>
<th>Material</th>
<th>Factor of safety</th>
<th>Frequency (hertz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti6Al4V</td>
<td>1.44</td>
<td>222400</td>
</tr>
<tr>
<td>AISI 28i steel maraging</td>
<td>1.55</td>
<td>209300</td>
</tr>
<tr>
<td>Aluminium 7075</td>
<td>0.922</td>
<td>221500</td>
</tr>
<tr>
<td>Magnesium AZ80</td>
<td>0.55</td>
<td>219500</td>
</tr>
</tbody>
</table>

Though AISI 28i steel maraging shows increase in factor of safety compared to all, AISI 28i maraging steel is 1.81 times weigh more than Ti6Al4V. From the values of frequency listed in above table for different material, the Natural frequencies of materials are very higher than the forcing frequency of engine, 116.67 Hz and the titanium alloy is having greater natural frequency than the other materials.

IV. SENSITIVITY ANALYSIS AND OPTIMIZATION

Sensitivity analysis & optimization on best among the materials is done in an aim to minimize weight and stress in transmission shaft. Sensitivity studies are used to determine whether a certain characteristic or property of the model is sensitive to a change in a design parameter. Specifically, the system calculates the changes in a model’s measures (such as stress and displacement) when a parameter varied over a specified range.

There are many optimization techniques available, but in that, numerical method is considered. One among the numerical method is, Genetic algorithm (GA).

Genetic algorithms (GA) belong to the class of stochastic search optimization methods, such as the simulated annealing method. These algorithms also belong to a class of methods known as evolutionary methods or nature-inspired methods. The algorithms are very general and can be applied to all kinds of problems—discrete, continuous, and non-differentiable. In addition, these methods determine global optimum solutions as opposed to the local solutions determined by a derivative-based optimization algorithm. The methods are easy to use since they do not require the use of gradients of cost or constraint functions.

Global sensitivity studies serve three primary purposes:

- To help understand how a measurable quantity is affected as a parameter varies through its range.
- To help eliminate unimportant parameters from an upcoming optimization.
- To determine a good initial value for a parameter in an optimization.

The Transmission shaft which uses Ti6Al4V is subjected to the following optimization analysis.

i. Design problem: Optimization of transmission shaft.
ii. Design objective: Minimize Von misses stress.
iii. Design constraint: Weight of the shaft.
iv. Design variables: Dimensions of Ball end groove and fillets in shaft.

So accordingly the optimization are carried out and the result from the excel sheet is provided below.
V. RESULTS

As we discussed above among the four materials the titanium alloy (Ti6Al4V) provides the better torque transmission. Though it’s very close to what the shaft had went before the optimization, we can select fourth combination of design variable which will give a weight of 4.83449 N against the existing weight of 4.83437781 N, which is slightly higher. The increase in weight provides an advantage of lower stress level with difference of 50 MPa.

REFERENCES


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