DESIGN OPTIMISATION OF SPUR GEAR USING GENETIC ALGORITHM

Ajay Pillai K\textsuperscript{1}, Aritra Guha Ray\textsuperscript{2}, Shivam Kaul\textsuperscript{3},
Narendiranath Babu.T\textsuperscript{4}
\textsuperscript{1}Undergraduate Student, Mechanical, VIT Vellore, Tamil Nadu
\textsuperscript{2}Undergraduate Student, Mechanical, VIT Vellore, Tamil Nadu
\textsuperscript{3}Undergraduate Student, Mechanical, VIT Vellore, Tamil Nadu
\textsuperscript{4}Associate Professor, Mechanical, VIT Vellore, Tamil Nadu

Abstract. Gears are one of the most commonly used power transmission mechanisms in most types of machinery and. The design of gears is highly complicated involving the satisfaction of many constraints such as strength, pitting resistance, bending stress, scoring wear, and interference in involute gears. In addition, using conventional or traditional optimization techniques to solve this problem could not give optimum results. In this study, a spur gear pair was modelled and was subjected to static structural analyses for varying gear material. Stress analyses and deformation analyses were performed for each material and the optimum design for reduced weight structural stability was chosen. The design was then subjected to optimisation by Genetic Algorithm. A stochastic approach as a Genetic Algorithm (GA) is applied in this paper to find the optimal combination of design parameters for minimum weight of spur gears. The purpose of this study is minimizing the weight and the centre distance of one pair of spur gears. This objective was accomplished by the means of the GA under some constraint such as bending strength, a contact stress and each dimension conditions of gears, which must be satisfied. The results are calculated by using MATLAB tools of Genetic algorithm with three type of materials, which are alloy steel, cast iron, and epoxy glass composites. Keywords. Genetic Algorithm, MATLAB, epoxy glass composites.

1. INTRODUCTION

Spur gears are a type of cylindrical gear, with shafts that are parallel and coplanar, and teeth that are straight and oriented parallel to the shafts

A lot of research has been done in the past in the area of spur gear dimensioning and its characteristics, material used and stresses it is subjected to. But design optimisation requires further fine tuning in terms of weight reduction and several other parameters. Optimization design of gear reducer includes the continuous variables and discrete variables. Many studies indicate that the genetic algorithm has strong ability of general optimization, which is very effective in treating optimization problem containing continuous and discrete variables.

1.1 Literature Gap

It was observed that even though a thorough analysis was done on the material properties as well as the subsequent parameters that determine the life of the gear, such as stress and wear off rate, a final optimised design was never obtained.
2. OBJECTIVE FUNCTION

2.1 Centre Distance

Thus, the objective function for minimizing centre distance of spur gear train is expressed as:

\[ F_{1\text{-objective}} = F(Z_1, Z_2, m) \]  

(2)

Where \( a \) is the centre distance, \( m \) is the module, \( Z_1 \) and \( Z_2 \) is the number of teeth on pinion and on gear respectively.

2. Gear Weight

A weight reduction of gears improves performance of nonstationary systems and also it saves the material, which leads to cost reduction and easy assembling. The following is the equation of the weight of the gear set

\[ F_{2\text{-objective}} = F(Z_1, m, b) \]  

(4)

Where \( b \) represents the tooth width and \( \rho \) the density of the material.

2.2 Constraints

The geometry of gears train is very specific. Therefore, they are many constraints of assembly, dimension, contact stress, and bending stress must be satisfied and introduced in the objective function for the best selection of optimum results. All the constraints are formulated as shown belo
The maximum and minimum tooth width:

\[ g_1(x) = \frac{b}{m} - 12 \leq 0 \]  
\[ g_2(x) = 6 - \frac{b}{m} \leq 0 \]  

(5)  

(6)  

The maximum and minimum number of teeth:

\[ g_3(x) = z_1 - 30 \leq 0 \]  
\[ g_4(x) = 18 - z_1 \leq 0 \]  

(7)  

(8)  

The constraint of design bending stress:

\[ g_5(x) = \frac{i+1}{a_{miny}} [M_t] - [\sigma_b] \leq 0 \]  

(9)  

The constraint of design contact stress:

\[ g_6(x) = \frac{i+1}{\pi} \sqrt{\frac{i+1}{ib} E[M_t] - [\sigma_c]} \leq 0 \]  

(10)  

3. METHODOLOGY

3.1 Methodology

This project attempts to achieve the most suitable design in terms of functioning and weight reduction, following the genetic algorithm.

A spur gear prototype was designed with the help of **SolidWorks** software. Its properties would be compared by assigning three different materials to it. Upon analysis of these properties, the material that shows the least static stress shall be chosen as the best among the given lot of materials. After this, the spur gear shall be subjected to design optimisation in terms of weight reduction using the Genetic Algorithm and the obtained result shall be compared with that of the gear before it was subjected to the algorithm.
3.2 Modelling

The modelling of the gear parts was done on SolidWorks™ 2016. Gear Parameters were chosen for the design considering the power requirements of a windmill. The gear parameters are shown in Table 2.

| Parameters          | Symbol | Unit | Value       |
|---------------------|--------|------|-------------|
| Power Output        | P      | kW   | 25          |
| Gear Ratio          | i      |      | 2.5         |
| Pinion Speed        | N1     | rpm  | 1100        |
| Working Life        | N      | cycles | 1.32×10⁹    |

| Calculated          |        |      |             |
|---------------------|--------|------|-------------|
| Centre Distance     | a      | mm   | 157.500     |
| Module              | m      | mm   | 5           |
| Pinion teeth        | Z1     |      | 18          |
| Face width          | b      | mm   | 47.250      |
| Revised Torque      | [Mt]   | kN-m | 312.960     |
| Design Bending Stress| σ_b  | N/mm² | 88.984    |
| Design Contact Stress| σ_c  | N/mm² | 855.855    |

![Figure 1. SolidWorks Model of Spur Gear](image-url)
Table 2: Mass properties of Gear assembly as measured in SolidWorks (Configuration: Default)

|     |                  |
|-----|-----------------|
| Mass | 1969.06 grams   |
| Volume | 1969062.01 cubic millimetres |

3.3 Static Structural Analysis

The spur gear assembly was subjected to structural analysis in Ansys™ 2016, Static Structural Software. The pinion and the gear wheel were subjected to a frictionless support on the interior surface of the hole where the shafts sit. The pinion was then applied with a turning moment (Figure 2).

The equivalent stress and total deformation were then observed for three different materials viz. Alloy Steel, Cast Iron, Epoxy Glass Composites. Results of stress analysis on Alloy Steel is shown in Figure 3.
Figure 3. Equivalent Stress in Alloy Steel

Total deformation analysis on Alloy Steel is shown in Figure 4.

Figure 4. Total Deformation in Alloy Steel

3.4 Genetic Algorithm Implementation

The Optimization of weight and centre distance is carried out by using GA with help of a program developed on MATLAB platform. Many Factors are considered in this optimization as such as torque, material, width of tooth, gear ratio and input power as defined in the table below (Table 3).
**Table 3. Design Variables and Parameters**

| Parameters                  | Symbol | Unit      | Value  |
|-----------------------------|--------|-----------|--------|
| Material Density            | $\rho$ | kg/m$^3$  | 7850   |
| Alloy Steel                 | $\rho$ | kg/m$^3$  | 7200   |
| Cast Iron                   | $\rho$ | kg/m$^3$  | 7850   |
| Epoxy Glass Composite       | $\rho$ | kg/m$^3$  | 7200   |
| Young’s Modulus             | $E$    | MPa       | 2.1x10^5 |
| Alloy Steel                 | $E$    | MPa       | 1.4x10^5 |
| Cast Iron                   | $E$    | MPa       | 0.72x10^5 |
| Epoxy Glass Composite       | $E$    | MPa       | 0.72x10^5 |
| Number of Pinion Teeth      | $Z_1$  |           | [18 30] |
| Module                      | $m$    | mm        | [1.25 6] |
| Face width                  | $b$    | mm        | [9 72]  |

B. Constraints:

The geometry of gears train is very specific. Therefore, they are many constraints of assembly, dimension, contact stress, and bending stress must be satisfied and introduced in the objective function for the best selection of optimum results. All the constraints are formulated as shown below:

4. RESULTS AND DISCUSSION

4.1 Structural Analysis Results:

**Table 4. Structural Analysis Results**

| Material              | Equivalent Stress (MPa) | Total Deformation (mm) | Mass (kg)  |
|-----------------------|-------------------------|------------------------|------------|
| Alloy Steel           | 23.991                  | 0.002599               | 15.457     |
| Cast Iron             | 24.077                  | 0.004605               | 14.177     |
| Epoxy Glass Composite | 28.86                   | 0.029556               | 3.741      |

The analysis of the given materials shows that the stress developed and also the deformation was least in alloy steel. However, the mass of the gear made with this material was more as compared with cast iron and glass composite.
4.2 Genetic Algorithm Results:

Figure 5. Optimization of Cast Iron

Figure 6. Optimization of Alloy Steel
Figure 7. optimization of Epoxy Glass Composite

Table 5. Genetic Algorithm optimization Results

| Materials            | Gen | Z1 | m (mm) | b (mm) | Centre Distance (mm) | Weight (kg) |
|----------------------|-----|----|--------|--------|-----------------------|-------------|
| Cast Iron            | 218 | 18 | 4.682  | 52.591 | 147.49                | 15.315      |
| Alloy Steel          | 122 | 20 | 3.418  | 35.625 | 119.66                | 7.445       |
| Epoxy Glass Composite| 329 | 27.24 | 5.822  | 68.668 | 277.563               | 18.689      |

The table shows that alloy steel presents the best fitness of the weight of assembly and centre distance with a value of 7.445 kg and 119.66 mm respectively. The model of gears train with the epoxy glass composite represent the high weight and centre distance with an average in the tooth width value. This is because of the low design bending tress and design contact stress values for epoxy material. Thus, for the safety of design and to meet all the constraints the epoxy assembly needs to be much larger and bulkier in size compared to the metallic assemblies. The optimal result of the module was found to be equal to 3.418 mm with the Alloy Steel material. The variation of the best fitness of the weight and centre distance are presented in the figures 8 to 9.
Figure 8. Weight vs Material

Figure 9. Centre Distance vs Material
In figure 10, the optimal value of the number of teeth is presented in the case of cast iron. For the module and the tooth width, the alloy steel gives the best value. Therefore, the choice of materials is an exercise considering both the Genetic Algorithm results as well as the stress and deformation values obtained from the Structural Analysis. It gives us a vision on the concentrations of stress, allowable deformation, design modification possibilities and to estimate the lifecycle of the system.

5. CONCLUSION

Design optimization was performed on the spur gears as designed on SOLIDWORKS. Initially, three different materials viz. Alloy Steel, Cast Iron and Epoxy Glass Composite, were analyzed in terms of their equivalent stress and mass. Based on the acquired result, Alloy Steel was chosen as a suitable material in comparison with the others. Upon doing so, Genetic algorithm was incorporated to further enhance the design of the Alloy Steel spur gear. It was seen that alloy steel presents the best fitness of the weight of assembly and center distance with a value of 7.445 kg and 119.66 mm respectively. The optimal result of the module was found to be equal to 3.418 mm with the Alloy Steel material.

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