

Development of MATLAB Based Software for Simple Spur Gear Design and its Validation for Stress Simulations

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Abstract

From the tiny things like watches to the automobiles, gears have huge application. The designing portion and selection of gears has been the difficult part for the engineers. The spur gear designing software created by using MATLAB is a great tool to design simple external spur gears in efficient manner. This software asks for the input parameters to the users and performs the calculations and provides the output in the form the calculated value along with the model of designed spur gear. It also checks whether the designed gear is satisfactory or not. The currently available software are expensive and are not specific to gears thus the spur gear designing software will be very useful in local manufacturing workshop and also cost effective for the specific use of designing gears. The software also incorporates fem stress analysis carried out on the gear tooth. The result of the stress analysis done from the software is to be validated by comparing it to the results of stress analysis of the gear in Solidworks. The program is user friendly by the help of Graphical User Interface and can be used to development of any kind of spur gear needed for various projects and systems.

Keywords

Spur Gear, Gear Design, MATLAB, Stress Simulation, FEM

1. Introduction

Gears are one of the modest creations of humankind. A gear can be defined as the mechanical element used for transmitting power and motion from one shaft to another shaft by the progressive engagement of projections known as teeth [1]. The two bodies have either a rolling or a sliding motion along the tangent at the point of contact [2]. Spur gears are gears having straight teeth cut on the rim, parallel to the axis of rotation. It is designed to transmit motion and power between the parallel shafts, which rotates in opposite direction and is the most common and cost effective type of gear. Steel, aluminum and plastic are the materials that are generally used for manufacturing spur gears [3].



Figure 1: A Simple Spur Gear Mesh [4]

1.1 Origin of the Idea and Problem Statement

Gear design requires an iterative process to determine parameters that satisfy kinematic, performance and strength requirement [5]. Engineers face problems of extracting information from data books, calculating the forces and then solving for module to design gear. The process is inefficient, time consuming and does not allow engineers to view variations in parameters at a glance. With computer aided engineering tools the knowledge of the experts has been captured in the form of design rules which is then be embedded into software systems in the form of constraint equations [6]. A software has been developed using design standards and programming practices. The packages like Solidworks and ANSYS are highly expensive, not specific for gear designs and do not focus on calculation of parameters for design but to develop CAD model and stress analysis after the parameters have been obtained using complex calculations. Thus a new package that features an ergonomic graphical user interface (GUI) and automatically generates model of the gear pair and a logically complete parameters of the spur gear has been developed [3].

2. Gear Design Concept and Software Framework

The American Gear Manufacturers Association (AGMA) methods and recommendations as defined in standards will be used in this study. Basic dimensions (such as addendum, dedendum, thickness etc.) are used for teeth having pressure angles of 14.5° and 20°. In the design of a gear, the following data are usually the input: the power to be transmitted, the speed of the driving gear, the speed of the driven gear or the velocity ratio and the centre distance [4]. Following requirements must be met in the design of a gear [4]:

1. The gear teeth should have sufficient strength so that they will not fail under static loading or dynamic loading during normal running conditions.
2. The gear teeth should have wear characteristics so that their life is satisfactory.
3. The use of space and material should be economical.

2.1 Design Procedure for Spur Gears [4]

1. The design Tangential Tooth Load (W_T) is obtained from the Power Transmitted (P), Service factor (C_S) and the Pitch Line Velocity (v) by using:

$$W_T = \frac{P}{v} \times C_S \quad (1)$$

2. Apply the Lewis equation on the weaker gear with Allowable static stress (σ_o) and face width (b) to solve for module (m):

$$W_T = (\sigma_o \cdot C_V) \cdot b \cdot \pi \cdot m \cdot y \quad (2)$$

3. Calculate the dynamic load (W_D) on the tooth by using Buckingham equation:

$$W_D = W_T + \frac{21v(b \cdot C + W_T)}{21v + \sqrt{b \cdot C + W_T}} \quad (3)$$

4. Find the Static Tooth Load (W_S) from Flexural Endurance Limit (σ_e):

$$W_S = \sigma_e \cdot b \cdot \pi \cdot m \cdot y \quad (4)$$

For safety against breakage, W_S should be greater than W_D .

5. Find the Wear Tooth Load (W_w) from Pitch Circle Diameter (D_p) by using the relation:

$$W_w = D_p \cdot b \cdot Q \cdot K \quad (5)$$

The wear load (W_w) should not be less than the dynamic load (W_D).

2.2 Secondary formula for design of gear [4]:

1. Tooth form factor (y):

$$\begin{aligned} y &= 0.124 - \frac{0.684}{T} : 14.5^\circ \text{ system} \\ &= 0.154 - \frac{0.912}{T} : 20^\circ \text{ fulldepth} \\ &= 0.175 - \frac{0.841}{T} : 20^\circ \text{ stub} \end{aligned}$$

2. Velocity factor (C_V):

$$\begin{aligned} C_V &= \frac{3}{3+v} \text{ (ordinary cut, upto 12.5m/s)} \\ &= \frac{4.5}{4.5+v} \text{ (careful cut, upto 12.5m/s)} \\ &= \frac{6}{6+v} \text{ (accurate cut, upto 12.5m/s)} \end{aligned}$$

3. Deformation factor (C) from Young's Modulus of Pinion (E_P) and Gear (E_G):

$$C = \frac{K \cdot e}{\frac{1}{E_P} + \frac{1}{E_G}} \quad (6)$$

4. Ratio factor (Q) from number of teeth in pinion (T_P) and gear (T_G):

$$Q = \frac{2T_G}{T_G - T_P} \quad (7)$$

5. Load Stress factor (K) from pressure angle (ϕ), Young's Modulus of Pinion (E_P) and Gear (E_G):

$$K = \frac{(\sigma_{es})^2 \sin \phi}{1.4} \left(\frac{1}{E_P} + \frac{1}{E_G} \right) \quad (8)$$

2.3 Software Interface

MATLAB based software for simple spur gear design consists of six different functions required for the six interfaces. The first interface is the main interface of the software which consists of the name of the software and logo of Thapathali Campus, Institute of Engineering. The first interface also consists of static texts asking for the procedure by which the gear is to be designed according to the input variables and is shown in figure 2. The four procedures for designing the gear available in the software are:

- Direct module input
- Module from power and number of teeth
- Module from power and center distance
- Module from number of teeth and diameter

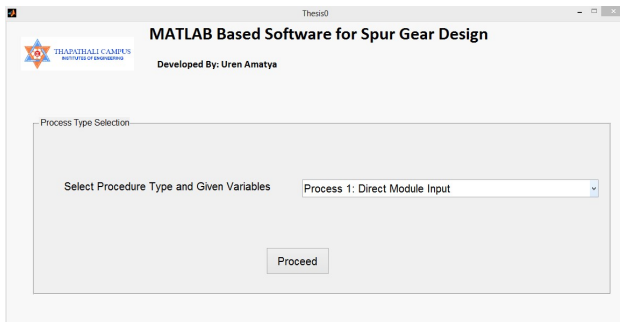


Figure 2: Starting Interface of the Software

The second interface shown in figure 3 is reached after ‘Process 1: Direct Module Input’ is selected in the pop-up menu. The process 1 is the direct module input type of gear designing process. Thus, the second interface consists of six input parameters: Pressure Angle, Number of Teeth, Module, Face width to module ratio, Force and Gear Material. In addition to the input panel it consists of a plot panel and an output panel. The plot panel consists of 5 checkboxes corresponding to the different figures on the plot. The checkboxes all have the function of activating and deactivating the plot parameters in the plot. The output panel consists of eight outputs: Module, addendum circle diameter, dedendum circle diameter, pitch circle diameter, base circle diameter, face width of the gear, allowable static stress and weakest element.

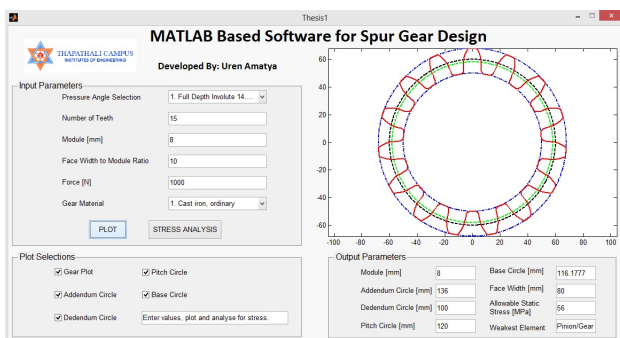


Figure 3: Interface for Direct Module Input

The third interface is reached after ‘Process 2: Module from Power and Number of Teeth’ of the process type is selected. Process 2 is the power and number of teeth input type of gear designing process. Thus, the third interface consists of nine input parameters: Pressure Angle, Pinion Material, Gear Material, Number of Teeth, and Face width to module ratio, Power, Speed of Pinion, Velocity Ratio and Service Factor as shown in figure 4. In addition to the input panel it consists of a plot panel and an output panel. The plot panel consists of 5 checkboxes

corresponding to the different figures on the plot similar to that of interface two. The output panel consists of eight outputs: Module, addendum circle diameter, dedendum circle diameter, pitch circle diameter, base circle diameter, face width of the gear, allowable static stress and weakest element. The dynamic load, surface endurance strength and wear load are calculated and analyzed to check for the conditions of design satisfaction.

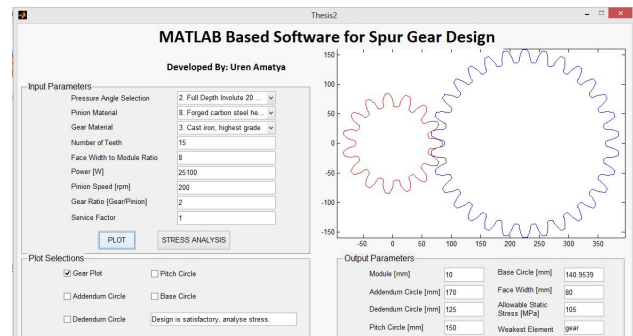


Figure 4: Interface for Number of Teeth and Power

The fourth interface is reached after ‘Process 3: Module from Power and Center Distance’ of the process type is selected. The fourth interface consists of nine input parameters: Pressure Angle, Pinion Material, Gear Material, Center Distance, Face width to module ratio, Power, Speed of Pinion, Velocity Ratio and Service Factor. In addition to the input panel it consists of a plot panel and an output panel. The dynamic load, surface endurance strength and wear load are calculated and analyzed to check for the conditions of design satisfaction as seen in figure 5.

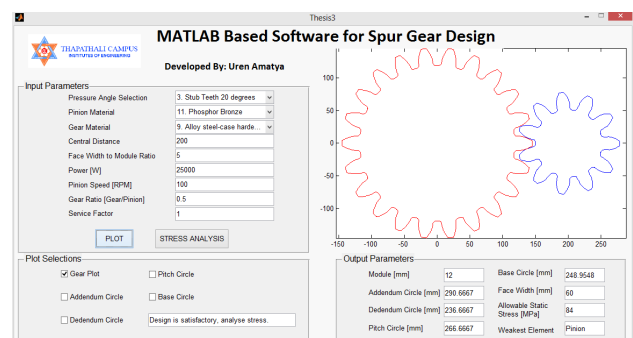


Figure 5: Interface for Central Distance and Power

The fifth interface is reached after ‘Process 4: Module from Number of Teeth and Diameter’ of the process type is selected and is shown in figure 6. The fifth interface consists of seven input parameters: Pressure Angle, Number of teeth, Diameter of gear or pinion, Face width to module ratio, Gear Ratio, Pinion or Gear Material and Force. In addition to the input

panel it consists of a plot panel and an output panel. The plot panel consists of check boxes corresponding to the different figures on the plot and have the function of activating and deactivating the plot parameters in the plot. The output panel consists of eight outputs: Module, addendum, dedendum, pitch, base circle diameter, face width, allowable static stress and weakest element.

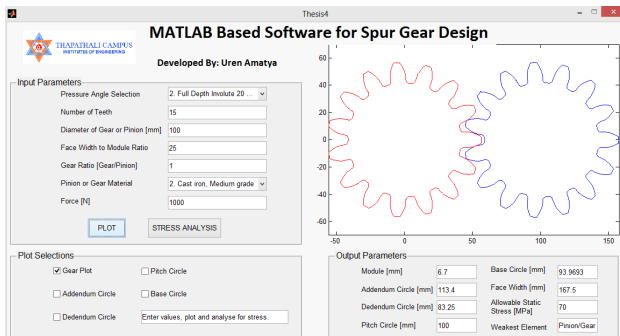


Figure 6: Interface for Diameter and Pinion Teeth

The samples of gear designing with input and output from all the procedures of the software are shown in table 1 and 2.

Table 1: Sample Input and Output of Software

Process	Input Parameters	Output Parameters
Number of teeth and power input	ϕ : Full depth 20° Number of teeth: 15 Power: 25100 W Face width to module ratio: 8 Pinion Material: Forged Carbon steel Gear Material: High grade cast iron Pinion Speed: 200 Gear Ratio: 2 Service Factor: 1	Module: 10 mm Circle Diameters: Pitch: 150 Addendum: 170 Dedendum: 125 Base: 140.95 Weakest: Gear Allowable Static Stress: 105 Mpa Face Width: 80
Center distance and power input	ϕ : Stub Teeth 20° Central Distance: 200 Power: 25000 W Face width to module ratio: 5 Pinion Material: Phosphor Bronze Gear Material: Alloy steel hardened Pinion Speed: 100 Gear Ratio: 0.5 Service Factor: 1	Module: 12 mm Circle Diameters: Pitch: 266.67 Addendum: 290 Dedendum: 237 Base: 248.95 Weakest: Pinion Allowable Static Stress: 84 Mpa Face Width: 60

Table 2: Sample Input and Output of Software

Process	Input Parameters	Output Parameters
Direct module input	ϕ : Full depth 14.5° Number of teeth: 15 Module: 8 mm Face width to module ratio: 10 Gear Material: Cast Iron, ordinary Force: 1000 N	Module: 8 mm Circle Diameters: Pitch: 150 Addendum: 136 Dedendum: 100 Base: 116.18 Weakest: Pinion/Gear Allowable Static Stress: 56 Mpa Face Width: 80
Diameter and number of teeth input	ϕ : Full Depth 20° Number of teeth: 15 Diameter: 100 mm Face width to module ratio: 25 Pinion Material: Case Iron, Medium Gear Ratio: 1 Force: 1000 N	Module: 6.7 mm Circle Diameters: Pitch: 100 Addendum: 113.4 Dedendum: 83.25 Base: 93.97 Weakest: Pinion/Gear Allowable Static Stress: 70 Mpa Face Width: 167.5

3. Stress Analysis Results and its Validation with Comparison to the Results from Solidworks

3.1 Stress Analysis of the designed gear within software

long with designing the gear from the input parameters, the user can proceed with the stress analysis of the gear tooth from the software. The stress analysis of the generated spur gear is done using Stress Analysis toolbox in MATLAB. The generated spur gear's tooth is modeled in the toolbox by graphically transferring the coordinates of the gear tooth profile. The user can select the type of mesh from coarse, medium and fine mesh according to the requirement of the user for precision as well as run time. The gear tooth profile is divided into finitely small elements and their respective nodes are built. The force transmitted by the mating gear is modeled to act at a certain node at the contact point. The stresses at the corresponding nodes are hence calculated using FEM. A contour plot is generated displaying different color bands for the different stress range at different nodes. The interface of the stress analysis toolbox is shown in figure 7.

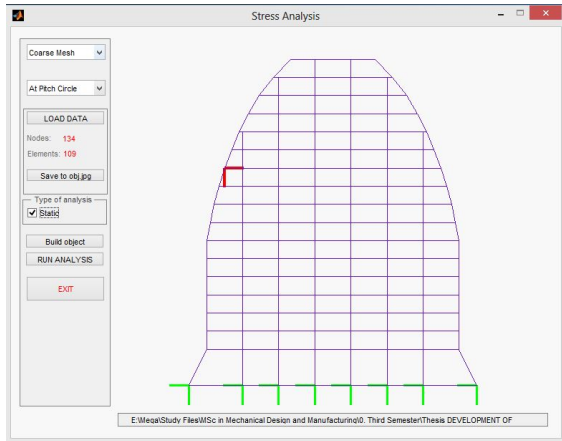


Figure 7: Stress Analysis Toolbox with Gear Tooth

The software runs the static simulation of the gear tooth with the loads and auto assumes the base nodes of the tooth to be fixed. The analysis is performed after the clicks of buttons Build Object and Run Analysis. The stress analysis result as shown in figure 8 is obtained. The stress on the elements near the applied force is very high that which decreases as the element is further from the applied force location.

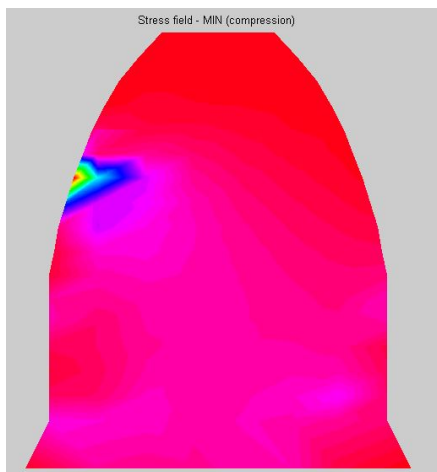


Figure 8: Stress Analysis Plot of the Gear Tooth

3.2 Stress Analysis of the designed gear in Solidworks

In order to verify and validate the stress analysis results from the Matlab based spur gear design software, four gears each from one design process with the same parameters were extracted in Solidworks. As in the software, the gear tooth of each gear were taken for analysis. The load was loaded into the tooth, fixtures and materials were specified and three different meshes for each gear were created resulting in approximately similar number of elements and nodes as from the

matlab based software. A sample of the mesh created is shown in figure 9

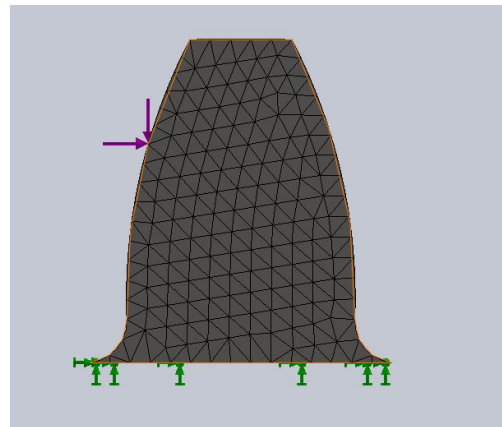


Figure 9: Gear Tooth Mesh in Solidworks

The simulation was run in solidworks and the results of the simulation were obtained as in figure 10. The static stress simulation plot from the MATLAB based software and Solidworks were similar in nature. The stress analysis data were probed and extracted in form of excel sheet for further verification and hypothesis testing.

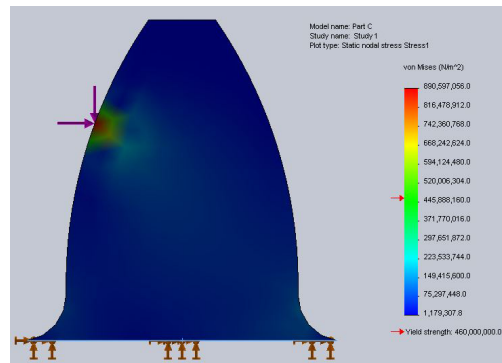


Figure 10: Solidworks Stress Analysis Gear Tooth

3.3 T-test for Comparison of Results and Validation [7]

The developed software was used to design a set of gear from each procedure on the software. Each set of the designed gear were developed on Solidworks with the output parameters as obtained from the software. The designed gear were subjected to static stress simulations in the software as well as Solidworks. Each gear were modelled with coarse, fine and medium grade meshes in both the softwares as seen on figures 7 and 9 and thus obtaining 12 different sets of results. A total of 1000 randomly selected sets of data of stress value along the nodes of the simulated

gear tooth were taken from the simulations obtained from the software and listed in excel sheet along with their coordinate position. The stress values obtained at the same coordinate position of the nodes were obtained from the simulations in Solidworks and listed in the excel sheet. A T-test was setup for the data of stress analysis to be compared and the software validated. A hypothesis was setup to perform the two tailed T-test as follows:

Total Number of Data (n) = 1001

Confidence Level = 95%

Degree of freedom = 1000

$A_i = i^{\text{th}}$ stress value from Matlab software

$B_i = i^{\text{th}}$ stress value from Solidworks

$d_i = B_i - A_i$
Null Hypothesis(H_0) : $\mu_d = 0$

Alternate Hypothesis(H_A) : $\mu_d \neq 0$

The null hypothesis states there is no significant difference in the stress values obtained from the two softwares and the alternative hypothesis states that there is a significant difference in the stress values obtained from the two softwares. If the null hypothesis is accepted we can say that the results from Matlab based software are significantly similar to the results obtained from Solidworks thus validating the results from the software.

The data obtained on process of the hypothesis are as follows:

$$\text{Mean Difference in data } (\bar{X}) = \frac{\sum d_i}{n} = 19.82 \times 10^6$$

$$\text{Standard Deviation of Data } (\sigma) = \frac{\sum (d_i - \bar{X})^2}{n} = 392.7$$

$$\text{Standard Error of Data } (S.E.) = \frac{\sigma}{\sqrt{n}} = 12.41$$

$$\text{Test Statistic of Hypothesis } (t) = \frac{(\bar{X})}{S.E.} = 1.6$$

The critical value for 95% confidence interval and 1000 degree of freedom two tailed T-tests can be obtained from the T-tests data table. The corresponding value is ± 1.962 . Since our test statistic (t) lies in between the critical values, we can accept the Null hypothesis. Thus, we can be 95% significant that the results of the stress analysis from the Matlab based software is similar to that of the results of stress analysis from an approved software Solidworks.

4. Limitations and Future Enhancements

4.1 Limitations of the Software

The limitations of the project are:

- The software is limited to design of external spur gears and incorporates static load, dynamic load and wear load in AGMA standard and method only.
- The velocity/gear ratio incorporated only works if the number of teeth is a whole number when calculated.
- The stress analysis done on the software has fixed numbers of elements for all three grades of meshes and are not user specific.
- Materials available in the software are limited to common materials used for gear manufacturing.
- At least the MATLAB compiler needs to be installed in order to run the software.

4.2 Possible Future Enhancements

The MATLAB based software for spur gear design has a vast potential for future enhancements. The software can be enhanced in the stress analysis model to be more dynamic and user specific. The software can be enhanced by incorporating full gear in the stress simulation instead of a tooth. The stress simulation can be developed to incorporate dynamic simulations as well. The software may also be enhanced by adding features of designing other types of gears like helical gears, worm gears and bevel gears in multiple standard and methods.

5. Conclusion

The MATLAB based software for spur gear design is a cost effective, efficient and interactive alternative application and can be used in local workshops and projects to design spur gears as required. The engineer can expel the process of requiring the data handbooks and standard manuals to extract information and iteratively design the gear with the help of the software. It consists of a simple graphical user interface that can be used by local workers, supervisors or handyman with basic knowledge of gear parameters. The gear plot designed in the

software can be converted to Scalable vector Graphics (SVG) file and can be used directly in CNC machines to manufacture the required gear.

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