INTEGRATED KBE APPROACH FOR DESIGN AND ANALYSIS OF GEARS

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THEME

CAE Methods

SUMMARY

Gears are widely used to transmit power and rotary motion with or without change of speed or direction. Automotive, aerospace, ship and other industries uses spur and helical gears. The need for efficient power transmission in machines has increased the demand for gear systems. Traditionally, gears are designed using popular AGMA standards followed by CAD modelling and manufacturing. FEA is also used to analyse, optimize and validate gear design and has become one of the important steps in gear design cycle. Currently, gear design and analysis steps (AGMA, CAD, and FEA) are done independently and are loosely coupled. This uncoupled traditional process requires 150 to 200 man-hours to complete new optimized design of a typical gear. Excel automations are used to perform AGMA calculations. Parametric design is used to reduce the cycle time in CAD modelling of gears. However, an integrated gear design and analysis tool is necessary to reduce the design cycle time, to realize optimal designs and for quick validation. This reduces the need for physical testing. Hence, the present work aims to develop an integrated tool using VB.Net while integrating AGMA, CAD and FEA processes. This integrated tool uses Knowledge-Based Engineering (KBE) approach to embed AGMA rules in initial calculations and parametric modelling in CAD as well as FEA. CATIA customization is carried out to produce 3D CAD models of spur and helical gears based on AGMA calculations embedded into the tool. Nastran is used as solver and Patran-PCL code is integrated. This tool also generates complete design and analysis reports in company specific templates. The integrated tool helps in realizing becomes faster, simpler and standard gear designs.

KEYWORDS

KBE, Gear Design, AGMA, CATIA-VB, PATRAN-PCL, Nastran
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1. INTRODUCTION

Gear is one of the most important machine elements used in machinery which translates power, motion and torque with great (up to 98%) efficiency [1]. Automotive, aerospace, ship and other industries use spur and helical gears. The crucial requirement of efficient power transmission across components of these machines has increased the demand for gear systems. In spite of number of investigations devoted to gear research and analysis, there is still a need to develop an integrated approach for designing gears. There is voluminous published research and literature [2-4] on gear design using analytical models. Traditionally, American Gear Manufacturers Association (AGMA) or International Organization for Standardization (ISO) methods are commonly used for gear design [5]. Literature review indicates that computer-aided design became important in late 70’s. Recently, commercial Computer Aided Design (CAD) and Finite Element Analysis (FEA) tools are widely used to analyse, optimize and validate gear designs.

Accurate CAD modelling is not only important for gear manufacturing using CNC machines but also for FE analysis. Most types of gears can be modelled using a variety of CAD software, but most gear geometries are complex, repetitive and are difficult to generate. Hence, parametric modelling is important. Parametric modelling allows the designer to let the characteristic parameters of a product drive the design of that product. During the gear design, main parameters that would describe the designed gear are module, pressure angle, root radius, tooth thickness and number of teeth. Recently, various researchers [6-11] attempted to create parametric model of gears using commercial CAD tool such as CATIA, PRO/E, etc. Apart from using CAD tool excel based parametric model is also developed [12]. Such efforts of parametric modelling have reduced repetitive gear modelling tasks drastically. Aziz and Chassapis [13] developed a knowledge based system for integrated engineering design process from the initial concept to production using the feature based modelling and design for CAD and FE analysis. The system utilizes manufacturing and design knowledge base. Thus, parametric design has been playing an important role in CAD modelling of gears [14]. This has reduced design cycle time to some extent but there is growing need for quicker and optimized designs in short period of time before the production processes and expensive experimental testing. So the development of integrated gear design and analysis tool is essential.

Currently, gear design and analysis steps like AGMA/ISO calculations, CAD modelling, and FEA analysis are done independently or loosely coupled. This uncoupled process requires about 150-200 man-hours to complete new optimized design of any gear. Hence, the present work aims to develop an integrated tool using VB.Net to tightly couple AGMA, CAD and FEA.
2. GEAR DESIGNER

Infosys developed *Gear Designer* tool provides an end to end solution. This tool integrates AGMA, CAD and FEA processes. Fig. 1 and 2 shows tool user interface developed using VB.Net. This integrated tool uses Knowledge-Based Engineering (KBE) approach to embed AGMA rules in calculations, parametric modelling in CAD and automated approach in FE analysis. Detailed CAD model is imported in Patran 2010 to carryout FE analysis using MSC.Nastran 2008 SOL600. CATIAV5R21 customization is carried out to produce 3D CAD models of spur and helical gears based on AGMA calculations embedded into the tool. Patran Command Language (PCL) is used to customize Patran. Finally, tool also generates complete design and analysis reports in company specific templates. Using this integrated tool, gear design solutions are quick and standardized. The user needs not to be an expert of CATIA or Patran/Nastran. The following inputs are required for the tool:

- Gear Type
- Transmitted Power
- Tooth System
- Width to Module Ratio
- Pressure Angle
- Gear Ratio
- Gear Material
- Quality of Gears
- Number of Tooth on Pinion
- Pinion Material
- Reliability
- Service factor
- Life
- Others

Fig. 3 shows overall process flow for the *Gear Designer*. This process flow gives insight into various steps involved in integrated tool. Initially, the user specifies power requirements along with other details. Gear dimensions are calculated using AGMA procedure to satisfy the strength requirements.

![Figure 1: First screen of Gear Designer](image-url)
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![User interface of Gear Designer](image1.png)

**Figure 2**: User interface of *Gear Designer*

![Gear Designer process flow](image2.png)

**Figure 3**: *Gear Designer* process flow
Three dimensional CAD model is created for gear and pinion assembly using parametric modelling approach. Present study assumes all tooth made of involute profile. Fig. 4 shows the construction geometry is used to create involute profile for tooth.

Figure 4: Involute profile for gear tooth

Using AGMA procedure safe module is calculated by tool. This module is used to produce CAD models in CATIA. According to AGMA the bending failure is avoided by considering the beam strength and the pitting failure (contact stress) is avoided by considering the wear strength. Gear design will be safe if equations 1 and 2 are satisfied.

Bending strength criteria:  \[ \sigma \leq \sigma_{\text{all}} \] (1)
Pitting strength criteria:  \[ \sigma_{c} \leq \sigma_{c\text{ all}} \] (2)

Where

\[
\sigma = W_t K_p K_v K_z \frac{1}{b m} \frac{K_K K_G}{Y_f} \\
\sigma_c = Z_E \sqrt{\frac{W_t K_p K_v K_z}{Y_f}} \frac{K_K}{b z_1} \\
\sigma_{\text{all}} = \frac{S_L}{S_p} Y_N Y_N \\
\sigma_{c\text{ all}} = \frac{S_c}{S_h} Z_N Z_W Y_Y Y_Z \\
W_t \quad \text{is the tangential transmitted load} \\
K_o \quad \text{is the overload factor}
\]
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\( K_v \) is the dynamic load factor
\( K_s \) is the size factor
\( K_H \) is the load distribution factor
\( K_B \) is the rim thickness factor
\( Y_J \) is the geometry factor for bending strength
\( Z_E \) is an elastic coefficient (N/mm²)
\( Z_R \) is the surface condition factor for pitting resistance
\( d_{W1} \) is the pitch diameter of the pinion
\( Z_I \) is the geometry factor for pitting resistance
\( b \) is the net face width of the narrower member
\( m \) is the module
\( S_i \) is allowable bending stress
\( Y_N \) is the stress cycle factor for bending
\( Y_\theta \) is temperature factor
\( Y_Z \) is reliability factor
\( S_F \) is the AGMA factor of safety
\( S_c \) is allowable contact stress
\( Z_N \) is stress life factor
\( Z_W \) is hardness ratio factor for pitting resistance
\( S_H \) is the AGMA factor of safety

Tool also integrates the material database for easy selection of users. After entering all input parameters tool calculates safe module. Safe module is standardized to the value which is available in general use using preferred number series as given in Table 1. Once module is known tooth dimensions are calculated using Table 2 and 3.

Table 1: Preferred series for module

<table>
<thead>
<tr>
<th>Modules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preferred</td>
</tr>
<tr>
<td>Next Choice</td>
</tr>
</tbody>
</table>

Table 2: Spur gear dimensions

<table>
<thead>
<tr>
<th>Quantity Desired</th>
<th>Formula</th>
<th>Equation No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch Diameter</td>
<td>( D = m.N )</td>
<td>(7)</td>
</tr>
<tr>
<td>Circular Pitch</td>
<td>( p = \pi.m )</td>
<td>(8)</td>
</tr>
<tr>
<td>Root Diameter</td>
<td>( Dr = D - d - c )</td>
<td>(9)</td>
</tr>
<tr>
<td>Dedendum Diameter</td>
<td>( Dd = D - d )</td>
<td>(10)</td>
</tr>
<tr>
<td>Addendum Diameter</td>
<td>( Da = D + a )</td>
<td>(11)</td>
</tr>
<tr>
<td>Tooth Thickness</td>
<td>( t = \frac{p}{2} )</td>
<td>(12)</td>
</tr>
<tr>
<td>Clearance</td>
<td>( c = d = a )</td>
<td>(13)</td>
</tr>
</tbody>
</table>
Table 3: Tooth system for spur gears

<table>
<thead>
<tr>
<th>Tooth System</th>
<th>Pressure Angle (Degrees)</th>
<th>Addendum (a)</th>
<th>Dedendum (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Tooth</td>
<td>20</td>
<td>1 m</td>
<td>1.25 m</td>
</tr>
<tr>
<td></td>
<td>22.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stub</td>
<td>20</td>
<td>0.8 m</td>
<td>1 m</td>
</tr>
</tbody>
</table>

Parametric modelling uses parameters to control the dimensions and shape of CAD model. Generally, it is useful to explore design spaces by modifying parametric relations and to create multiple instantiations of designs. In present work different parameters are created in design tree (see Fig. 5). This is one of the useful features of tool. For some reason, if user wants to change estimated module by tool then this feature of tool can be used and accordingly CAD models are automatically updated.

![Parameters used in parametric gear design](image)

After successful creation of assembly, CAD model is exported in IGES format. This IGES file is imported in MSC.Patran 2010 for pre-processing. Once user hits Analysis button on the tool, Patran is invoked automatically. It executes following statement using shell command of Vb.Net within tool:

> patran.exe -sfp <session file containing PCL scripts>
Patran-PCL scripts are integrated in tool to perform meshing using HEX elements. HEX elements are generated by sweeping QUAD elements along face width of the tooth. Loads ($W'$) are applied on tooth tip and gears fixed at shaft holes. Load is calculated using Eq. 14. Appropriate tooth contacts are defined to perform FE analysis using Nastran.

$$W' = \frac{60000H}{\pi Dn}$$

(14)

Where,
- $H$ is power in KW
- $n$ is speed in RPM

SOL 600 is used as problem involves contact nonlinearity. Once successful BDF is generated MSC.Nastran is invoked automatically by tool. It executes following statement using shell command of Vb.Net:

```
>nastranw.exe <BDF name> scr=yes
```

To run Patran and Nastran user should specify home directory and working directory. Home directory is a place where Patran and Nastran installed whereas working directory is a place where all files are generated.

Using F06 file, tool gives message of success or failure of solution. In case of successful solution XDB results are attached automatically to Patran database to post process results using Patran-PCL script. Finally, tool generates report in company template. Report contains input information in table format and output images of various stages such as CAD model, FE model, Stress plots, etc. CATIA-VB and Patran-PCL scripts within tool generate various images and tables to be used in report generation.

3. RESULTS AND DISCUSSION

In this work sample results are presented for end-to-end design of spur gear using Gear Designer. Table 4 shows sample inputs for typical applications of spur gear. Using this inputs tool generates CAD model of spur gears as shown in Fig. 6. IGES file of this tool is imported in Patran and performed all pre-processing activities to generate BDF automatically. Fig. 7 shows meshed model with materials, properties, contact and LBC’s defined. The model contains 12805 HEX elements. All elements passes quality test. Tangential load of 2757.33 N is applied on gear tooth.
Table 4: Sample inputs for spur gear

<table>
<thead>
<tr>
<th>Parameter</th>
<th>User Input</th>
<th>Parameter</th>
<th>User Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power to be Transmitted (KW)</td>
<td>20</td>
<td>Pressure Angle(Deg)</td>
<td>20</td>
</tr>
<tr>
<td>No. of Pinion Teeth</td>
<td>18</td>
<td>Helix Angle(Deg)</td>
<td>0</td>
</tr>
<tr>
<td>RPM of Pinion</td>
<td>700</td>
<td>Reduction Ratio</td>
<td>2</td>
</tr>
<tr>
<td>Quality of Gear</td>
<td>3</td>
<td>Width Ratio</td>
<td>5</td>
</tr>
<tr>
<td>Load Characteristics</td>
<td>Uniform</td>
<td>Tooth Systems</td>
<td>Full Depth</td>
</tr>
<tr>
<td>Gear Units Condition</td>
<td>Open Gearing</td>
<td>Gear Adjustment</td>
<td>At Assembly</td>
</tr>
<tr>
<td>Pinion Core Harness(HB)</td>
<td>300</td>
<td>Gear Core Hardness(HB)</td>
<td>300</td>
</tr>
<tr>
<td>Pinion Surface Hardness(HB)</td>
<td>300</td>
<td>Gear Surface Hardness(HB)</td>
<td>300</td>
</tr>
<tr>
<td>Pinion Teeth Type</td>
<td>Uncrowned</td>
<td>Pinion Material</td>
<td>Steel - Through Hardened Grade 1</td>
</tr>
<tr>
<td>Gear Teeth Type</td>
<td>Uncrowned</td>
<td>Gear Material</td>
<td>Steel - Through Hardened Grade 1</td>
</tr>
<tr>
<td>Reliability</td>
<td>0.9999</td>
<td>Life(Cycles)</td>
<td>10000000</td>
</tr>
<tr>
<td>Span</td>
<td>1000</td>
<td>Service Factor</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Figure 5: CAD model of (a) Gear (b) Pinion (c) Assembly
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Nastran is launched automatically to solve FE model using tool. After successful run of Nastran XDB results are attached to Patran database and results are post-processed. Fig. 7 shows stress plots within gear tooth. From FE results contact stress 380 MPa and bending stress is 30 MPa. These results are very close to AGMA results i.e. bending stress is 29.34 MPa and contact stress is 382.83 MPa. Finally tool generates sample report in PPT format.

Complete integrated process takes 6 to 8 hours depending on time taken by Nastran solver. There is tremendous turn-around time by using this tool. Normally it takes 150-200 man-hours to completed gear design process manually. This time come down to 50 man-hours if process is used without integration i.e. semi-automated process but using Infosys developed integrated Gear Designer tool it came down to maximum 8-10 man-hours.

4. CONCLUSIONS

The main conclusions of the current study are:

- Development of an integrated tool using KBE approach for design and analysis of gears.
• Results of integrated tool are satisfactory and FE results compares reasonably close to AGMA calculations validating accuracy of tool.
• The tool helped in reducing turn-around time automating the process by eliminating manual operations.
• This tool provides sophisticated functionality and easy user interface making it easy for infrequent or non-expert users.

5. ACKNOWLEDGEMENT

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