A Finite Element Approach to Stress Analysis of Face Gears

Lokamanya Siva Manohar Rampilla
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A FINITE ELEMENT APPROACH TO STRESS ANALYSIS OF FACE GEARS

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Bachelor of Mechanical Engineering

Jawaharlal Nehru Technological University, India

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MASTER OF SCIENCE IN MECHANICAL ENGINEERING

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A FINITE ELEMENT APPROACH TO STRESS ANALYSIS OF FACE GEARS

LOKAMANYA SIVA MANOHAR RAMPILLA

ABSTRACT

Face Gears have alternative gear-teeth configuration compared to Bevel Gears. Face Gear have a standard spur pinion as opposed to a bevel Gear. This work concentrates on modeling of a Face-gear, Meshed with a spur gear, using CAD Software and Finite Elements Analysis. The bending stress developed at the gear teeth is determined. Numerical results are validated using the bending stress developed between two involute spur gears.
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CHAPTER I

INTRODUCTION

Face gears are the kinds of gears which can mesh with either spur or helical pinions having cylindrical base surfaces and the terminology of Face Gear set is shown in Figure 1. The axes of the gear and the pinion generally, but not necessarily, intersect at the right angles. When the axes intersect at right angles the gear set is called “On-Center” face gear or else the gear set is called “off-set” face gear as shown in Figure 2.

Figure 1:   Face gear set terminology
In this thesis we will be dealing with the On-center gear set, where the axes intersect and are perpendicular with each other.

Face Gear set consists of a spur or a helical pinion that is in mesh with a face gear. The pinions are really not any different from their parallel axis counterparts except for the fact that they are in mesh with a face gear and involute spur gear. Face gears have teeth cut into the blank such that the axis of the teeth lies in a plane that is perpendicular to the shaft axis. The mating pinion is either a spur or a helical gear. The pinion and face
gear axes most often form a $90^\circ$ are possible. In operation, this type of gear is similar to an equivalent set of straight gears.

The face gear tooth changes shape from one end of the tooth along the radius of the face of the gear as shown in Fig 3. The load capacity of face gear set, compared with that of bevel gears, is less, thus they are used mostly used as motion transmission gears rather than as power gears. Face gear sets are relatively easy to make and less expensive compared to the bevel gears. But the calculations involved in designing the face gear set are more complex in nature, because of the change in face width, undercutting and pointing. There were some initial works done in 1950's and 1960's in Russia [1] [2]. Also a major contribution was done by Dudley in 1960's giving the formulae which will be discussed in the section 1.1.

Figure 3: Face gear teeth
1.1 Previous Works

Face gears were used for centuries in wagons by Chinese and power generation by Romans [3, 4]. The invention if the modern type of face gear set was an invention of the Fellows Company. The importance of face gears was recognized when it is proposed to use in helicopter transmission because of its split torque and its less weight, which is a major advantage for the flying objects.

Fellows Company has invented the face gear drive and it is initially called “Cylkro Gear” by a Dutch company [4]. Darle W. Dudley[6][5], F.L.Litvin [2] [6] [7] [8] [4], Bloomfield B. [11] [12] has contributed a lot in the development of Face Gear in early stages. Which are followed by J.Chakraborty [13] [14], B.S Bhadoria [14] [13], David G. Lewicki [15], Aleksandar M. Egelja [10]. The advanced research on Face Gears was done by Crown Gear B.V. Company in Netherlands. The research was followed in United States, Germany and Japan.

Litvin has published many works on Face Gear including design of Face Gear cutters, theoretical study of face gears by dividing into elemental parts and also designed and performed stress analysis on symmetric and asymmetric face gear drives [9]. Litvin also designed computer programs to perform design and analysis on any kind of symmetric or asymmetric Face Gear drives.

Claudio Zanzi and Jose I. Pedrero [16] has also developed a modified geometry and performed tooth contact analysis and stress analysis on the Face Gear set with a double crowned pinion. These analyses are performed to find the bearing contact and stresses throughout meshing of the pinion with the Face Gear, but during the analyses the
tilt angle is ignored. And the main advantage of this kind of design is the position and orientation of the bearing contact can be modified or controlled using the parameters of the modified pinion.

McDonnell Douglas Helicopter Company, NASA and U.S. Army Research Laboratory have done extensive research on the applications of Face Gear set in Aerospace Applications and have been successful. Mr Dudley and Mr. Drago in the early 1980’s came up with the use of Face Gear set in power transmission between two perpendicular axes. Its importance has been found in the Helicopter transmission because of its split torque and less weight compared to the bevel gears. So the bevel gears are replaced by face gears and other advantages will be discussed in Sec.1.1.2. Three different arrangements of Face Gear sets were arranged in the aerospace gearbox using ten pairs of gears. The Aim of this study is to find the functional ability and failure mode of the Face Gear set.

1.2 Advantages of Face Gears over Bevel Gears

- Bevel Gears can be replaced by face gears at high power and load transmissions in aerospace environment.
- The manufacturing of Face Gear is easy compared to the straight Bevel Gears. But the calculations are very complex in nature compared to other kinds of gear.
- The misalignment in the Face Gear set is very low and also reduces the stiffness in the bearing support. Litvin proposed a Face Gear set with less number of teeth in the pinion than the cutter.
• Due to less weight if the Face Gears over bevel gears, the use of Face Gear has been increased in the helicopter transmission.

1.3 My Contribution

As there are no standard formulae to obtain the Face Gear geometry named HyGears has been used to generate the geometry of the Face Gear set. Using these geometrical values from the HyGear, Face Gear tooth has been designed in Solidworks software. After designing the Face Gear tooth the load was applied to the tip of the tooth and bending stress was obtained using Solidworks simulation. The numerical results are validated according to AGMA standards.
CHAPTER II

VALIDATION OF RESULTS FOR BENDING STRESS OFFACE GEAR

2.1 Validation Of Bending Stress Results Using Lewis Formula And Solidworks Simulation As Per AGMA Standards

2.1.1 Calculating of bending stress using Lewis Formula

Bending Stress, \( \sigma = W^t K_o K_v K_s \frac{1}{F_m} \frac{K_m K_B}{F} \)

Tangential Load, \( W^t = 10000 \text{N} \)

Overload factors, \( K_o = 1 \), for uniform power source

Dynamic factor, \( K_v = \frac{A + \frac{200V}{A}}{B} \)

Where, \( A = 50 + 56(1-B) \); \( B = 0.25 \quad 12 - Q_v^{2/3} \)

\( Q_v = 8 \) for precision gearing

Pitch line velocity, \( V = \frac{\pi d_n}{60} = 15.7 \text{ m/sec} \)

Therefore \( K_v = 1.444 \)
Size factor, \( K_s = 1 \)

Face width, \( F = 0.06\,\text{m} \)

Module, \( m = \frac{D}{t} = \frac{60\times10^{-3}}{18} \)

Load distribution factor, \( K_m = 1 + C_{mc}(C_{pf}C_{pm} + C_{ma}C_e) \)

\( C_{mc} = 1 \) for uncrowned teeth

\( C_{pf} = \frac{F}{10\,d} - 0.0375 + 0.0125F = 0.06325 \)

\( C_{pm} = 1 \) for straddle mounted pinion

\( C_e = 1 \)

\( C_{ma} = A + BF + CF^2 = 0.06826 \)

For precision enclosed unit \( A = 0.0675; B = 0.0128; C = -0.9626\times10^{-4} \)

So, \( K_m = 1.13151 \)

Rim thickness factor, \( K_B = 1 \)

Bending strength geometry factor, \( J = 0.31 \)

Bending stress calculated, \( \sigma = 62\,\text{MPa} \)
2.1.2 Results from Solidworks Simulation

Maximum intensity stress from solidworks simulation = 66.6Mpa
2.1.3 Error percentage

Percentage error between the stress calculated from Lewis formula and Solidworks Simulation,

Error Percentage = 7.4%
CHAPTER III

HYGEARS

3.1 Introduction To HyGears

HyGears is the Gear Processor (The High Performance Software for Gear Engineering, Analysis and Production Control)

HyGears is an advanced and a 30 year old user friendly, 3D gear modeling software that has been extensively tested in industry. Developed by Claude Gosselin, Ph.D president of Involute Simulation Software Inc. and was initially developed in September 1982 on a text only display main frame. It was first released to public in 1994 in Japan.

HyGears supports:

- Spiral and hypoid gears for the Face Milling - Fixed Setting, Duplex Helical, Modified Roll, Spread Blade, Formate and Helixform - cutting processes (all, The Gleason Works)
- It can also model the Face Hobbing process (Klingelnberg and Gleason)
- Straight bevel gears (external and internal); straight bevels which can be ‘forged’ and thus used to create forging dies
- Spur and helical gears, external and internal, in planetary or offset arrangements
- Involute splines and face gears

Figure 4: Planet gear developed using Hygears

Figure 5: Helical Bevel Gear
3.2 Gear Design

HyGEARS allows the design, analysis and optimization of gear sets through functions such as Tooth Contact Analysis (TCA) and Loaded Tooth Contact Analysis (LTCA).

The initial design of a gear set requires very few data input as numerous default values can be computed as a starting point; these default values can easily be modified later during the design process. The gear set is generated and displayed in WYSIWYG (What You See Is What You Get) format as shown below.
Figure 6: Bevel gear compared to the real manufactured gear with the gear generated using hygear

TCA ANALYSIS

The Transmission Error (TE) and the actual extent of the Bearing Pattern (BP), unloaded and loaded, are readily accessed in graphic form, as shown below. E, P, G, runout, alignment and shaft angle values may also be changed to see how a gear pair will behave in different operating positions as imposed by manufacturing tolerances or housing deformation under load.

In addition, E, P, G, alignment and shaft angle values may be modified in pairs to produce a “map” of the expected behavior of a given gear pair over, say, a given tolerance range.

Shown below is such a grid where E and P are modified in combinations. Obviously, the E-P combinations along the diagonal from top-left to bottom-right are not a problem; however, the E-P combinations along the top-right to bottom-left diagonal are to be avoided.
LTCA ANALYSIS

The load and torque transmitted by neighbouring tooth pairs in mesh can be established through the LTCA optional module. The associated bending and contact stresses, bearing reactions, thermal-EHD oil film thickness, temperature increase and scoring factor can be calculated and assessed in real time to ensure a sound design.

The axial and radial positions of meshing gear pairs, their alignment and shaft angle can be modified to analyze “worst case” conditions, or to automatically produce grid-like projections of the loaded behavior of a gear pair.

For example, in the figure below, the E and P values of a gear pair are modified to produce E-P combinations allowing prediction of the Hertz contact stresses as the pinion and gear relative position, because of gearbox deflection, manufacturing tolerances, or else, displaces the contact pattern.

This Grid-like output can be applied to several combinations of relative positions for gear pairs under load (LTCA). Support bearings and gearbox housing stiffness can be accounted for in the LTCA such that the TE, BP, contact and fillet stresses are calculated at the actual location under load.

CMM, CORRECTIVE MACHINE SETTINGS AND REVERSE ENGINEERING

Target files for Coordinate Measurement Machines (CMM) can be defined and outputted in Zeiss Ram/Rfd, Gear Bevel, Hoeffler and Klinglenberg-P formats (other formats can easily be added).

When the diameter of the CMM probing sphere is given, the sphere (white ball in the figure below) can be displayed and animated along the target CMM grid to visually
detect possible interference with the opposite tooth flank, or the root, as measurement proceeds.

HyGEARS can import any text based CMM output file to calculate Corrective Machine Settings, or to Reverse Engineer existing gearsets. CMM results can also be used to estimate the TCA and LTCA behaviour of a real gear pair, and thus allows the troubleshooting and improvement of problematic gear sets.

**FEA PRE-PROCESSING AND FINITE STRIPS**

HyGEARS offers advanced functions such as Finite Element Analysis pre-processing (meshing and load application, left figure below), or the analysis of the gears under load using the integrated Finite Strips (right figure below), a subset of the FEA.
CONTACT ELEMENT

An advanced Contact Element is integrated into HyGEARS to allow the precise evaluation of the contact stresses at any point on the tooth surface. Tooth surface irregularities obtained from CMM measurements can be accounted for in the analysis.

UNIVERSAL 5 AXIS CNC MACHINE OUTPUT

Any (face milled) spiral-bevel gear design that is targeted for cutting on a conventional generator can be converted to a Universal 5 Axis CnC machine, given the sign convention of the axes on the CnC machine is known.

For example, below, a partial output for a Universal 5 Axis CnC machine is given for a spiral-bevel pinion manufactured with cutter tilt. In this output, Q and Roll are respectively the cradle and work-piece roll angles on the conventional generator; the X, Y
and Z axis are conventional, i.e. X is horizontal and + towards the right when facing the machine, Z is vertical and + upwards, and Y is perpendicular to X and Z and + going into the machine; the B axis supports the turntable, and the C axis is the turntable holding the work piece, and thus provides the roll angle of the work-piece on the CnC machine.

“STEP” OUTPUT

HyGEARS can directly export the topography of the pinion and gear teeth to any STEP capable CAD/CAM system.

Thus, molds for plastic gears, electrodes for sintered gears, or simply CAD models, can conveniently be obtained using the exact tooth topography.

For example, the left figure below shows a spiral-bevel pinion tooth in the HyGEARS display; the topography of this tooth was exported in STEP format to a CAD system, which is displayed in the right figure below.
CHAPTER IV
RESULTS

CASE 1
INPUT DATA:
Number Of Teeth, Pinion = 17
Number Of Teeth, Gear = 94
Pressure Angle = 20°
Pitch Diameter, Pinion = 76.5mm
Face Width, Gear = 43.09mm
Face Width, Pinion = 43.09mm
Module = 4.5

OUTPUT FROM HYGEARS
General Data
Pinion
Minor Diameter = 63.3290
Outside Diameter = 85.5000
Diameter Over Ball = 92.2654
Roller-Ball Diameter = 9.5250
Addendum Factor = 1.0000
Dedendum Factor = 1.1500
Fillet Factor = 0.2500
Addendum = 4.5000
Dedendum = 6.5856

Gear
Number Of Teeth = 94
Face Width = 43.0931
Inner Diameter = 398.04
Pitch Diameter = 423.0000
Outside Diameter = 498.2230
Addendum Factor = 1.0000
Dedendum Factor = 1.2500
Fillet Factor = 0.2500
Addendum = 4.4998
Dedendum = 6.3506
Blank Data

Pinion
Mean Helix Angle (Right) = 0.00.00
Mean Helix Angle (Left) = 0.00.00
Mean Press Angle (Right) = 19.59.28
Mean Press Angle (Left) = 19.59.27

Gear
Mean Helix Angle (Right) = 1.18.30
Mean Helix Angle (Left) = 1.18.29
Mean Press Angle (Right) = 29.07.19
Mean Press Angle (Left) = 29.07.19

Tooth Data

Pinion
Calculated Tooth Depths (Chordal):
Form Depth (Mid-F) = 7.0142
Whole Depth (Mid-F) = 11.6541

Calculated Tooth Depths (Circular):
Form Depth (Mid-F) = 6.8362
Whole Depth (Mid-F) = 11.0856
Fillet Radius @ Mid-Face:

Drive – Root Diameter = 4.6138
Coast = 4.6160

Drive – Form Diameter = 12.4105
Coast = 12.4161

Fillet Radius Pressure Angle @ Mid-Face:

Drive – Root Diameter = 75.94
Coast = 76.02

Drive – Form Diameter = 0.07
Coast = 0.07

Calculated Blank Diameters:

Root Diam. (Toe) = 63.3290
Tip Diam. (Toe) = 85.5000

Calculated Chordal Tooth Thickness @Mid-Face:

Theo. Finish Thickness = 7.0592
Normal Thick. @ Mean Point = 7.5168
Trans. Thick @ Mean Point = 7.5192
Tooth Topland (Toe) = 2.9261
Tooth Topland (Heel) = 2.9261
Gear

Calculated Tooth Depths (Chordal):

Form Depth (Mid-F) = 11.6627
Whole Depth (Mid-F) = 12.6810

Calculated Tooth Depths (Circular):

Form Depth (Mid-F) = 11.6620
Whole Depth (Mid-F) = 12.6799

Fillet Radius @ Mid-Face:

Drive – Root Diameter = 1.7199
Cost = 1.7199

Drive – Form Diameter = 9.7158
Cost = 9.7150

Fillet Radius Pressure Angle @ Mid-Face:

Drive – Root Diameter = 72.84
Cost = 72.84

Drive – Form Diameter = 29.11
Cost = 29.11

Calculated Chordal Tooth Thickness @Mid-Face:

Tooth Finish Thickness = 14.0902
Normal Thick  @ Mean Point = 8.4709
Trans. Thick  @ Mean Point = 8.4684
Tooth Topland (Toe) = 4.2355
Tooth Topland (Hoel) = 0.4490

**Operating Data**

**Pinion**
Backlash (Min) = 0.1016
Backlash (Max) = 0.1524
Backlash (Cals @ M.Point) = 0.1295
Bottom Clearance (Toe) = 2.0856
Bottom Clearance (Heel) = 2.0856

**Gear**
Bottom Clearance (Toe) : 1.9956
Bottom Clearance (Heel) : 1.9956

**Pinion Cutter Specifications**

**Left and Right**
Helix Angle = 0.00.00
Cutter Type = Normal Shaper
Blade Angle = 20.00.00
Blade Edge Radius = 0.0443
Blade Thickness = 0.3105
Addendum = 0.3100
Dedendum = 0.1772

Machine Settings
Left and Right
X Factor = 0.0000
Generating Pitch Dia. = 76.50000
Roll Rate = 0.664052
Tooth Crowning = 0.0450
Crowning Order = 2
Distance To Edge = 10.7733

Gear Cutter Specifications:
Left and Right
Helix Angle = 0.00.00
Cutter Type = Normal Shaper
Blade Angle = 20.00.00
Blade Edge Radius = 0.0443
Blade Thickness = 0.3055
Addendum = 0.7042
Dedendum = 0.1772
Machine Settings:

X Factor = 0.0000

Generating Pitch Dia. = 455.1299

Roll Rate = 0.111617

Tooth Crowning = 0.0000

Crowning Order = 1

Distance To Edge = 0.0000
Using the above values from the HyGears, the FaceGear has been developed in the SolidWorks 2011 and performed Finite Element Analysis using SolidWorks Simulation.

The load has been applied on the tip of the tooth at an angle of 20°.

The results are:

**Meshing of Face Gear teeth**
Stress Intensity results:

A load of 1200N of force is applied on the tip of the Face gear
Displacement results:

In the figure above 1:400 scale has been taken to have a clear understanding of the Teeth Deformation
CASE 2

INPUT DATA:
Number Of Teeth, Pinion = 17
Number Of Teeth, Gear = 94
Pressure Angle = 25°
Pitch Diameter, Pinion = 76.5mm
Face Width, Gear = 43.09mm
Face Width, Pinion = 43.09mm
Module = 4.5

OUTPUT DATA FROM HYGEARS:

Pinion
Minor Diameter = 64.8907
Pitch Diameter = 76.5000
Out Side Diameter = 85.5000
Diameter Over Ball = 92.6465
Roller-Ball Diameter = 9.7790
Addendum Factor = 1.0000
Dedendum Factor = 1.1500
Fillet Factor = 0.2500
Addendum = 4.5000
Dedendum = 5.8048

Gear

Inside Diameter = 398.04
Pitch Diameter = 423.0000
Outside Diameter = 484.2216
Addendum Factor = 1.0000
Dedendum Factor = 1.2500
Fillet Factor = 0.2500
Addendum = 4.5001
Dedendum = 5.4498

Blank Data

Pinion

Mean Helix Angle (Right) = 0.00.00
Mean Helix Angle (Left) = 0.00.00
Mean Helix Angle (Right) = 24.59.32
Mean Press Angle (Left) = 24.59.31

Gear

Mean Helix Angle (Right) = 0.44.48
Mean Helix Angle (Left) = 0.44.49
Mean Helix Angle (Right) = 29.38.29
Mean Press Angle (Left) = 29.38.29

**Tooth Data**

**Pinion**

Calculated Tooth Depths (Chordal):

Form Depth (Mid - F) = 7.8586
Whole Depth (Mid - F) = 10.8479

Calculated Tooth Depths (Circular):

Form Depth (Mid – F) = 7.6189
Whole Depth (Mid – F) = 10.3048

Fillet Radius & Mid – Face:

Drive – Root Diameter = 3.7126
Coast = 3.7096

Drive – Form Diameter = 9.8940
Coast = 9.8953

Fillet Radius Pressure Angle & Mid – Face:

Drive – Root Diameter = 71.87
Coast = 71.80

Drive – Form Diameter = 9.47
Coast = 9.47
Calculated Blank Diameters:

Root Diam. (Toe) = 64.8907
Tip Diam. (Toe) = 85.5000

Calculated Chordal Tooth Thickness & Mid – Face:

Theo. Finish Thickness = 7.0588
Normal Thick . &Mean Point = 7.5092
Trans. Thick. & Mean Point = 7.5110
Tooth Topland (Toe) = 2.1006
Tooth Topland (Heel) = 2.1006

Gear

Calculated Tooth Depths (Chordal):
Form Depth (Mid - F) = 10.6913
Whole Depth (Mid - F) = 11.7642

Calculated Tooth Depths (Circular):
Form Depth (Mid – F) = 10.6908
Whole Depth (Mid – F) = 11.7632

Fillet Radius & Mid – Face:
Drive – Root Diameter =1.8584
Coast =1.8584
Drive – Form Diameter = 10.1929
Coast = 10.1950

Fillet Radius Pressure Angle & Mid – Face:
Drive – Root Diameter =72.23
Coast = 72.23
Drive – Form Diameter = 29.60
Coast =29.60
Calculated Chordal Tooth Thickness & Mid – Face:
Theo. Finish Thickness =13.8215
Normal Thick. & Mean Point = 7.5528
Trans. Thick. & Mean Point = 7.5502
Tooth Topland (Toe) = 3.6221
Tooth Topland (Heel) = 0.1341

Operating Data
Pinion
Backlash (Min) = 0.1016
Backlash (Max) = 0.1524
Backlash (Calc&M.Point) = 0.1337
Bottom Clearence (Toe) = 1.3046
Bottom Clearance (Heel) = 1.3046
Gear

Bottom Clearence (Toe) = 1.0961
Bottom Clearance (Heel) = 1.0961

Pinion Cutter Specifications

Left and Right

Helix Angle = 0.00.00
Cutter Type = Normal Shaper
Blade Angle = 25.00.00
Blade Edge Radius = 0.0443
Blade Thickness = 0.3196
Addendum = 0.3100
Dedendum = 0.1772

Machine Settings

X Factor = 0.0000
Generating Pitch Dia. = 76.5000
Roll Rate = 0.664052
Tooth Crowning = 0.0450
Crowning Order = 2
Distance To Edge = 10.7733
**Gear Cutter Specifications**

Left and Right

Helix Angle = 0.00.00

Cutter Type = Normal Shaper

Blade Angle = 25.00.00

Blade Edge Radius = 0.0443

Blade Thickness = 0.3146

Addendum = 0.7042

Dedendum = 0.1772

**Machine Settings**

X Factor = 0.0000

Generating Pitch Dia. = 441.1284

Roll Rate = 0.115159

Tooth Crowning = 0.0000

Crowning Order = 1

Distance To Edge = 0.0000
Gear [Finishing] Right [NoEr] E=0.00 P=0.00 G=0.00 [mm] B:0.134 [mm]

Gear [Finishing] Left [NoEr] E=0.00 P=0.00 G=0.00 [mm] B:0.134 [mm]
Using the above values from the HyGears, the FaceGear has been developed in the SolidWorks and performed Finite Element Analysis using SolidWorks Simulation.

The load has been applied on the tip of the tooth at an angle of 25°.

The results are:

After Meshing:
A load of 1200N of force is applied on the tip of the Face gear
Displacement Results:

In the figure above 1:400 scale has been taken to have a clear understanding of the Teeth Deformation
5.1 Conclusion

1. Finite Element method can be successfully used to predict bending stress of a typical Face Gear set

2. The percentage error between AGMA formula and from solidworks for an involute spur gear about 7.4%

3. The geometry can be generated with one face(inner face) of a regular involute spur gear and a point edge on the other face(outer face)

4. The bending stress has been obtained from Solidworks Simulation for two different gears of 20° and 25° pressure angle.

5. The result of this study can be used to size a face gear set for a given operating condition (transmitted power at a given speed) and the bending stress on the tooth can be determined
5.2 Future Scope

1. Contact stress can also be determined for the Facegear.

2. Experimental validation of the results predicted by AGMA formula and the Finite element analysis presented in this work.

3. Because of the high torque and high loads during operation, considerable amounts of heat is also dissipated. So the heat transfer condition can also be considered in the future analysis of the Facegear.
BIBLIOGRAPHY


