Fillet Profile Optimization for Maximum Bending Strength using Direct Gear Design Approach

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Abstract - Traditional standard gear design is based on a basic (or generating) gear rack. Parameters of this basic gear such as profile angle, addendum, and whole depth and fillet radius proportions were standardized. This made gear design indirect. Traditional gear design does not provide the best possible performance for any particular gear application because it is constrained by tooling parameter. Today we are forced to increase load carrying capacity, reduce transmission weight and fulfil noise requirements without increasing manufacturing cost High performance gears – aerospace and automotive, for example – do not use standard basic rack for design. Instead, they rely on custom racks which provide higher pressure angles or contact ratio. Direct gear design method introduces an alternative gear design approach to maximize gear drive performance in custom gear applications. It does not use tooling rack parameters. Instead, it defines gear shape based on required performance and operating conditions. It allows for the separation of the active involute flank and tooth fillet design. In this paper, gear pair for automotive gear box application was designed based on direct gear approach. The flank profiles were designed first to satisfy primary performance requirements. The tooth fillet design is based on completely defined involutes flank parameters. The initial fillet profile is a trajectory of the mating gear tooth tips in the tight mesh condition (zero backlashes). Fillet profile was optimized based on finite element analysis (FEA) and random search method so that to reduce the bending stress values in the fillet profile to obtain maximum load carrying capacity.

Keywords: Traditional gear design, Direct gear design, Fillet profile, FEA, Bending stress

1,. INDRODUCTION

Gears are the most important part of transmitting power in the power transmission world. They vary from a small size used in watches to the large gears used in industrial applications and speed reducers. They plays major role of main and ancillary mechanisms in most of machines such as automobiles, tractors, cutting machine tools etc. Toothed gears are used to change the speed and power ratio as well as direction between input and output. Gear analysis is done analytical methods, which required a number of assumptions and simplifications.

Gear design is a highly complicated art. The constant pressure to build less expensive, quieter running, light weight, low cost and more powerful machinery has resulted in a steady change in gear design. The extensive ongoing research deals with the analysis of gear stresses, transmission errors, dynamic loads, noise, and failure of gear tooth, which are very useful for optimal design of gear set.

In gear analysis, form input parameters which influence the output parameters viz. bending stress, compressive stress, tangential force, dynamic tooth load, wear tooth load, beam strength, are of interest to researchers and manufacturers. A method for the determination of load and stress distribution along the contact lines of the instantaneously engaged teeth of spur and helical gears was reported. This method includes the tooth profile modification and crowning, manufacturing and alignment error of gears, tooth deflections, local contact deformations of the teeth. It also covers the influence of gear parameters on the load and stress distributions.

An alternative method of analysis and design of spur and helical involute gears (Alexander et al. 2002) was investigated. They considered the direct gear design method, which separates gear geometry definition from tool selection, to achieve the best possible performance for a particular product and application. The direct design approach that is commonly used for most parts of mechanisms and machines, determines their profiles according to the operating conditions and desired performance.

II DIRECT GEAR DESIGN

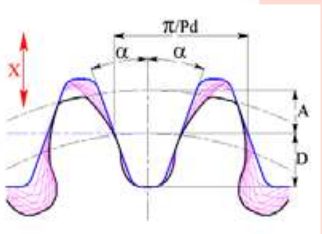
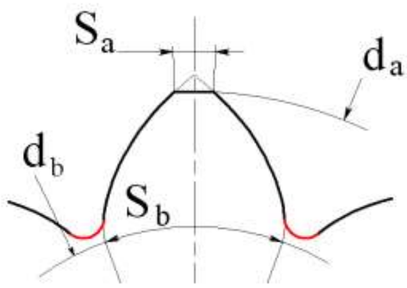
Over the last several decades, gearing development has focused on improvements in materials, manufacturing technology and tooling, thermal treatment, and coatings and lubricants. In contrast, gear design methods have remained frozen in time, as the vast majority of gears are designed with standard tooth proportions. This over-standardization significantly limits the potential performance of custom gear drives, especially in demanding aerospace or automotive applications.

Direct Gear Design introduces an alternate gear design approach to maximize gear drive performance in custom gear applications. It is not constrained by predefined tooling parameters. It allows for the analysis of a wide range of parameters for all possible gear combinations in order to find the most suitable solution for a particular custom application. It is a modern description of how gear should be defined today when we have computer tools that allow us to optimize our gear designs far

beyond what the standard allow us. This gear design method can exceed the limits of traditional rack generating methods of gear design.
Direct Gear Design is an alternative method of analysis and design of involute gears which separates gear geometry definition from tool selection to achieve the best possible performance for a particular product and application. This method has successfully been applied for a number of automotive applications.
The direct design approach, which uses the operating conditions and performance parameters as a foundation for the design process, is common for most parts of mechanisms and machines (for example, crankshafts, rods, etc.). It is important to note that the gear and tooth geometry were defined (or designed) first. The manufacturing process and tools then formed or cut this geometry in wood, stone, or metal. In other words, gear parameters were primary and the manufacturing process and tool parameters were secondary. This is the essence of Direct Gear Design. The theoretical foundation of modern Direct Gear Design was developed by Dr. E.B. Vulgakov in his Theory of Generalized Parameters . Practical engineering implementation of this theory was called Direct Gear Design . Direct Gear Design is an application driven gear development process with primary emphasis on performance maximization and cost efficiency without concern for any predefined tooling parameters.
Direct gear design defines the gear tooth details without using the generating rack parameters like module, addendum height and pressure angle. Tool characteristics and manufacturing operations are secondary. In general, the profile on one side of a gear tooth is functionally different from that of the other side. The work load on the profile of one side is significantly higher and is applied for a longer period than at the other side. The design intent is to improve the performance of the primary contacting profile by degrading the performance of the opposite side profile. The applications of asymmetric gears are wind mill, Helicopter main gearbox and turbo-prop engine drives.
The load carrying capacity of gear drive is enhanced by different methods such as heat treatment process (i.e. case hardening and shot peening), modification of gear geometry as asymmetric gears with high contact ratio and direct design procedures. Conventional gear design and direct gear design are the two major approaches used to design gears of which conventional gear design is based on standard rack cutter and the direct gear design is an application driven gear development process without concern for any predefined tooling parameters.

2.1 TRADITIONAL VS. DIRECT GEAR DESIGN

Table - 1 The differences in basic principles and application of Traditional and Direct Gear Design.

Traditional Gear Design	**Direct Gear Design**
	
Gear design is driven by manufacturing (cutting tool profile parameters).	Gear design is driven by application (performance parameters).
General Application Gears • Stock gears. • Gearboxes with interchangeable gear sets (like old machine tools) • Mechanical drive prototyping. • Low production machined gears.	**Custom Application Gears** • Plastic and metal molded, powder metal, die cast, and forged gears. • High production machined gears. • Gears with special requirements and for extreme applications.

III EXPERIMENTAL WORK

The Direct Gear Design method typically includes:

1 . Gear Mesh Synthesis
2. FEA Modeling
3.Efficiency Maximization
4.Bending Stress Balance
5.Fillet Profile Optimization

3.1 GEAR MESH SYNTHESIS

3.1.1 Gear Tooth

Direct Gear Design defines the gear tooth without using the generating rack parameters like diametral pitch, module, or pressure angle. The gear tooth (Fig.1) is defined by two involutes of the base circle db and the circular distance (base tooth thickness) Sb between them. The outer diameter da limits tooth height to avoid having a pointed tooth tip and provides a desired tooth tip thickness Sa. The non-involute portion of the tooth profile, the fillet, does not transmit torque, but is a critical element of the tooth profile. The fillet is the area with the maximum bending stress, which limits the strength and durability of the gear.

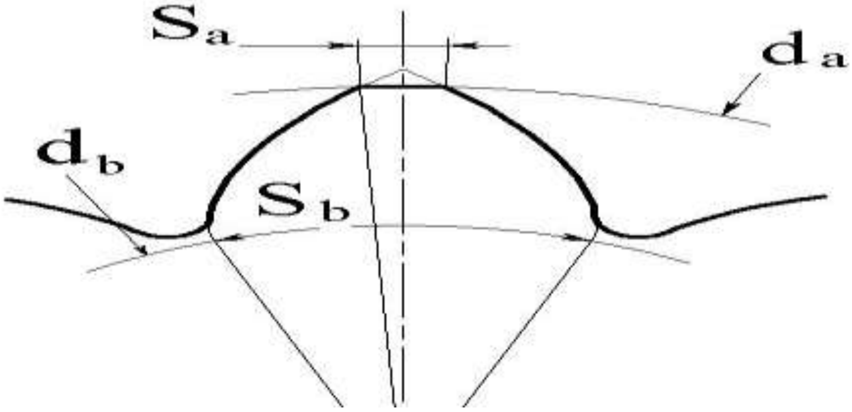


Figure - 1 Tooth parameters

3. 1.2 Gear Mesh

Two involute gears can mesh together (Fig.6) if they have the same base circle pitch. Other parameters of a gear mesh are:

- Center distance aw
- Operating pitch diameters dw1 and dw2 (diameters with pure rolling action and zero sliding)
- Tooth thicknesses on the operating pitch diameters Sw1 and Sw2
- Operating pressure angle αw (involute profile angle on the operating pitch diameters)
- Contact ratio ε_α

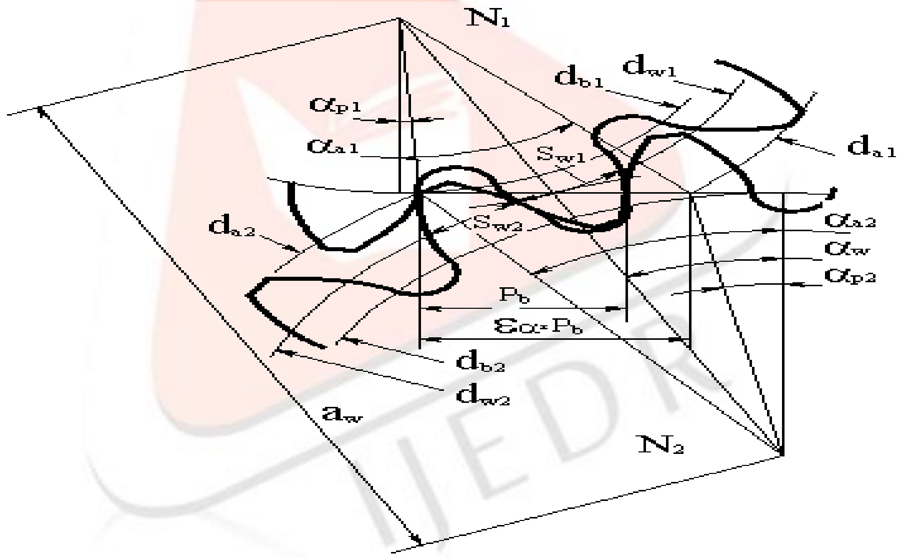


Figure - 2 Mesh parameters

In traditional gear design, the pressure angle is the tooling rack profile angle. In Direct Gear Design, the pressure angle is the mesh parameter. It does not belong to one gear. If the mesh condition (the center distance, for example) changes, the pressure angle changes as well.

Table - 2 Gear Mesh Synthesis Calculation Values

S.No	parameter	symbol	value
1	Number of teeth	Z_1 Z_2	14 28
2	Proportional top land thicknesses	m_{a1} m_{a2}	0.075 0.075
3	Center distance (mm)	a_w	76
4	Proportional base tooth thicknesses	m_{b1}	0.69

		m_{b2}	1.30
5	Profile angle in the involute intersection Point,deg.	V_1 V_2	41.03 40.36
6	Profile angles on outside diameters, deg	α_{a1} α_{a2}	40.02 38.84
7	Operating pressure angle, deg.	α_w	33
8	Transverse contact ratio	$\varepsilon_{a\ max}$	1.25
9	Profile angle in the bottom contact Points, deg	α_{p1} α_{p2}	18.67 29.00
10	Base diameters, (mm).	d_{b1} d_{b2}	42.60 85.22
11	Base pitch, (mm)	p_b	9.55
12	Operating pitch ,(mm)	P_w	11.4
13	Operating pitch dia, (mm)	d_{w1} d_{w2}	50.80 101.6
14	Operating tooth thicknesses, (mm)	s_{w1} s_{w2}	4.09 7.32
15	Outside diameters,(mm)	d_{a1} d_{a2}	55.63 109.40
16	Outside diameter tooth thicknesses, (mm)	s_{a1} s_{a2}	0.711 0.711
17	Sharp tip circle dia, (mm)	$d_{\Delta 1}$ $d_{\Delta 2}$	56.47 111.84

3.2 FEA Modelling

Based on the design parameters dimensions, computer models for pinion gear,Gear wheel , both Gear wheel and Pinion in the close mesh condition were generated using Pro E software. Version 2.0 was usedto generate these models.The close Mesh condition of the gear pair is such that no interference occurs between mesh gear and with zero backlash.

Table - 3 Material selection for Pinion and gear Wheel

Sl. No.	Component	Material selection for FEA model
1.	Pinion gear	C_{45} , Case Hardeed Steel
2.	Gear Wheel	C_{45} , Case Hardeed Steel

3.2.1 Direct Gear Design Input Data

Unlike in traditional gear design (where input data includes the pre-selected, typically standard cutting tool parameters), in Direct Gear Design all input data are related to the gears or the gear mesh at nominal operating conditions.

Data, describing physical size of the gears and their teeth are:

Number of Teeth for the Pinion and the Gear Nominal Operating Diametral Pitch

Material properties, friction condition and load parameters include:

Modulus of Elasticity and Poisson Ratio, Friction Coefficient, Pinion Torque

The dimensional tolerances include:

Minimum Backlash, Center Distance Tolerance, Tooth Thickness Tolerance for the Gear and the Pinion, Pitch Diameter, Runout for the Gear and the Pinion

The FEA setting parameters:

Number of Tooth Profile Nodes - This number does not include the constrained nodes and the nodes inside the area limited by the tooth profile and constrained nodes;

Compression coefficient - is the ratio of the density of the fillet nodes to the density of other profile nodes (excluding the fillet nodes);

Fillet Optimization Parameters – the parameters that define the iteration and random search processes

3.2.2 Direct Gear Design Output Data

The output data presents all nominal gear geometry parameters (diameters, profile angles, and tooth thicknesses, etc.), specific sliding velocities, gear efficiency, and geometrical and load data for the FEA.

The tolerance output file includes the minimum and maximum values of the gear drawing specification parameters. The fillet profile and root diameter are initially defined and will be finalized after the fillet profile optimization operation.

3. 3 EFFICIENCY MAXIMIZATION

Direct Gear Design maximizes gear efficiency by equalizing the maximum specific sliding velocities for both gears. Unlike in traditional gear design, it can be done without compromising gear strength or stress balance.

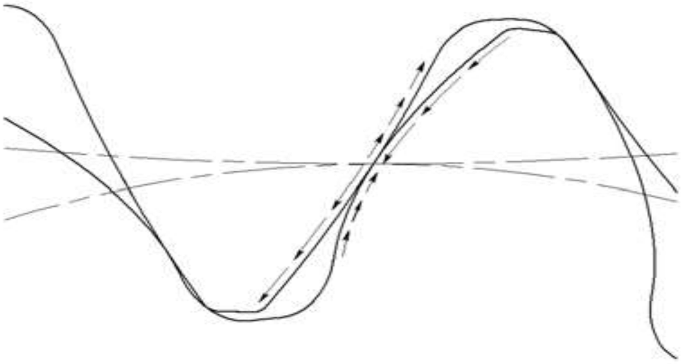


Figure - 3 Sliding velocities directions

3.4 . BENDING STRESS BALANCE

Mating gears should be equally strong. If the initially calculated bending stresses for the pinion and the gear are significantly different, the bending stresses should be balanced

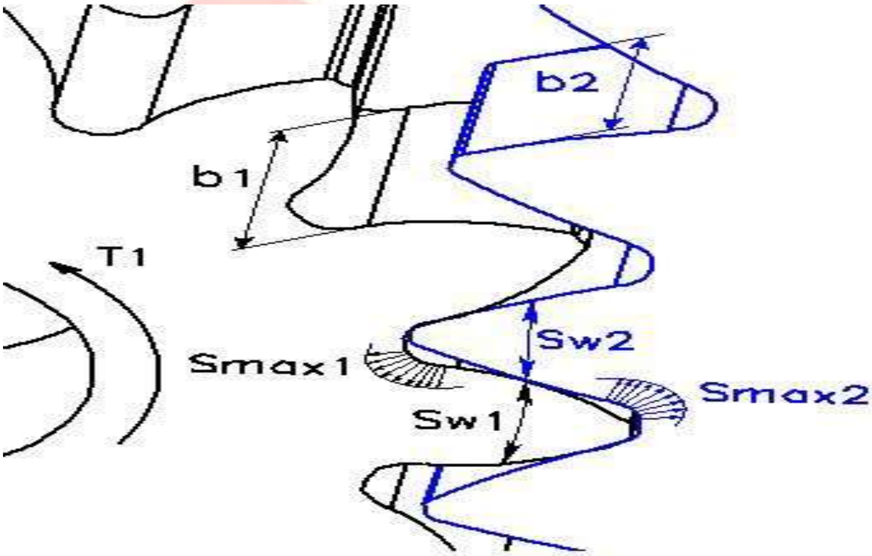


Figure - 4 Balance of the maximum bending stresses

Direct Gear Design defines the optimum tooth thickness ratio S_{p1}/S_{p2} , using FEA and an iterative method, providing a bending stress difference of less than 1%. If the gears are made out of different materials, the bending safety factors should be balanced.

3.5 FILLET PROFILE OPTIMIZATION

Traditional gear design is based on predefined cutting tool parameters; the fillet is defined by the trace of the cutting tool's edge. The cutting tool typically provides a fillet profile with an increased radial clearance in order to avoid root interference, resulting in high teeth with large radial clearance and small fillet radii in the area of maximum bending stress.

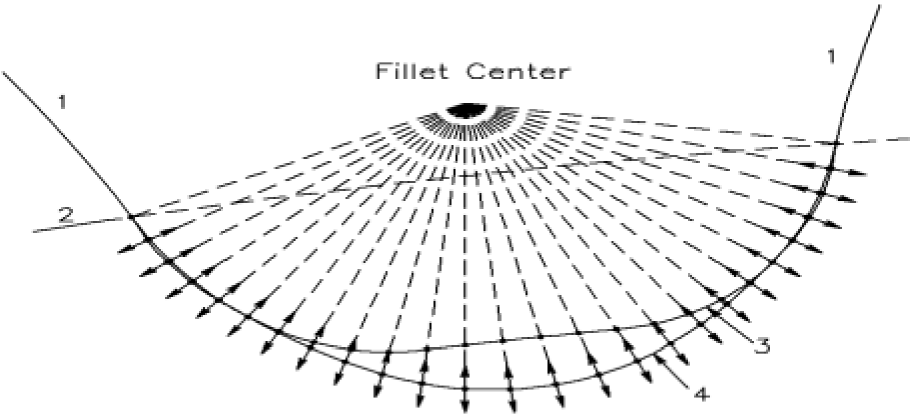


Figure - 5 Fillet profile optimization; 1. Involute profiles; 2. Form diameter; 3. Initial fillet profile; 4. Optimized fillet profile.

Direct Gear Design optimizes the fillet profile for any pair of gears in order to minimize the bending stress concentration. The initial fillet profile is a trace of the mating gear tooth tip. The optimization process is based on FEA and a random search method. The program analyzes successful and unsuccessful steps, altering the fillet profile to reduce the maximum bending stress. This process continues for a certain number of iterations, resulting in the optimized fillet profile.

IV Results and Discussion

4.1 Stress Analysis of Pinion before Fillet Profile Optimization

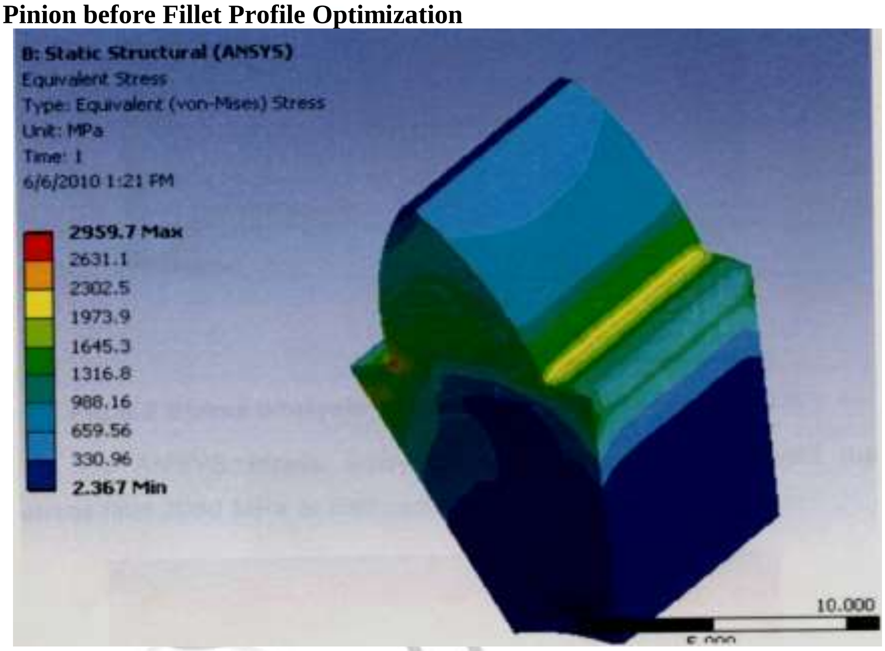


Figure - 6 Fillet profile of Pinion before optimization

Before fillet profile optimized, the stress analysis of pinion gear. The load is acting on operating pitch diameter where the gear teeth will contact. Maximum bending load will act on the mesh point of gears of operating pitch diameter. From the stress analysis it is observed that maximum bending stress is 2959 MPa.

4.2 Fillet Profile Optimization of Pinion

Random search method is adopted to obtain the maximum fillet radius. In the optimum fillet radius bending stress is minimum and it distributed evenly through the fillet area.

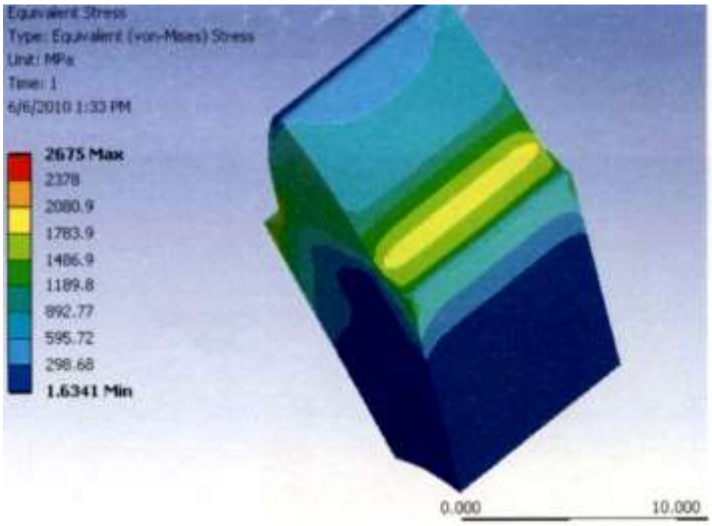


Figure - 7 Optimized fillet profile of pinion

By ANSYS stress analysis programme it is observed maximum bending stress value of 2080MPa at fillet radius 2.85 mm.

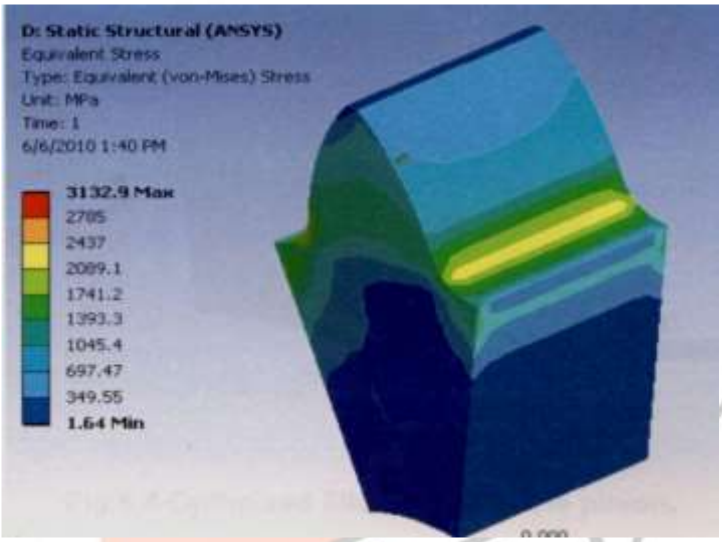


Figure - 8 Maximum bending stress at fillet radius of 2.85 mm

From the stress analysis using ANSYS programme, it is obtained at fillet radius 2.95 mm the maximum bending stress is 2437MPa. So random selection of fillet should be decreased around the initial one.

By several number of random search lead that optimum fillet radius of the fillet is 2.95 mm. at this radius the maximum bending stress is around 2000MPa. The optimized fillet profile generated using random search method for minimum bending stress at fillet area.

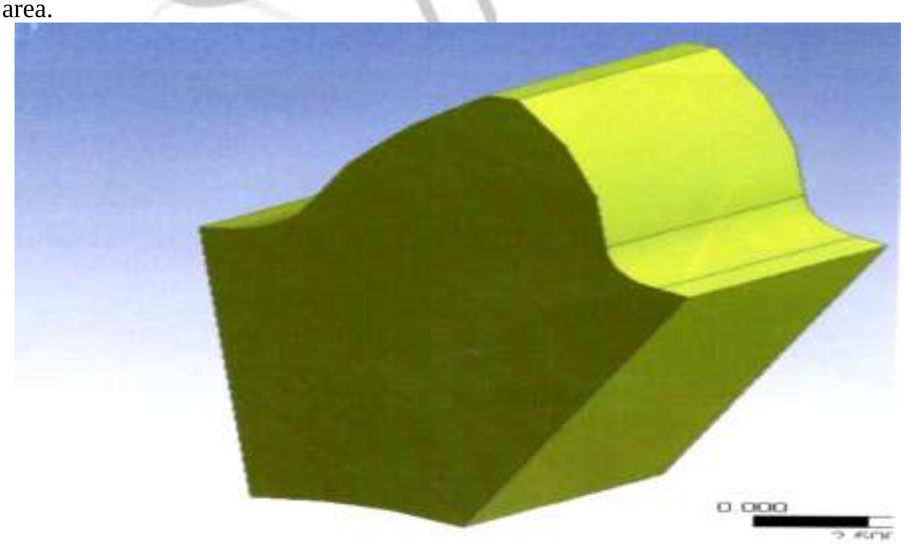


Figure- 9 Optimized fillet profile of pinion wheel

4.3 Stress Analysis of Gear before Fillet Optimization

Stress analysis of gear wheel before fillet profile is optimized. Maximum bending load will act on the mesh point of gears of operating pitch diameter. From the stress analysis, it is observed that maximum bending stress is 1317MPa.

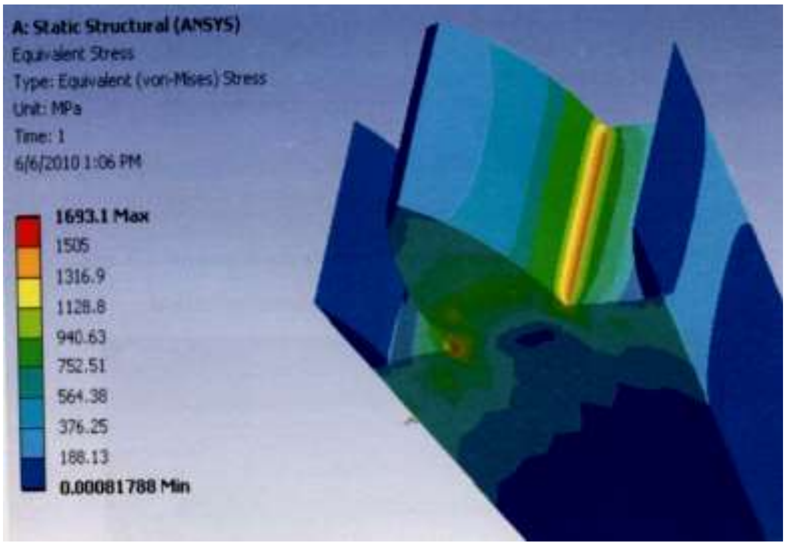


Figure – 10 Fillet profile of gear wheel before optimization

4.4 Fillet Profile Optimization of Gear Wheel

Random search method is adopted to obtain the optimum fillet radius. In the optimum fillet radius bending stress is maximum and it distributed evenly through the fillet area.

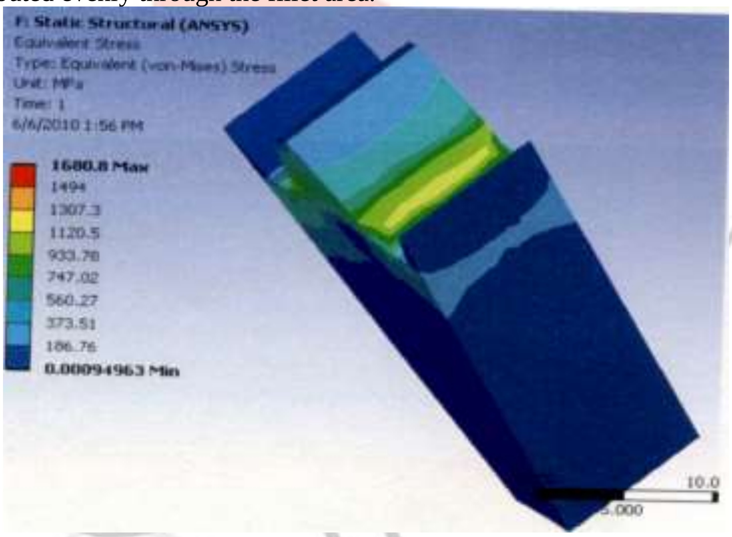


Figure – 11 Optimized fillet profile of gear wheel

Maximum bending stress at fillet area is 1307 MPa.

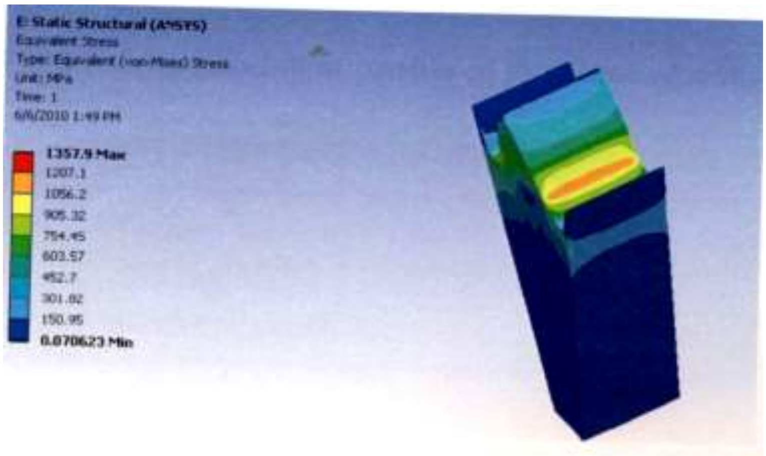


Figure – 12 Maximum bending stress value at the fillet radius of 2.87 mm

By stress analysis using ANSYS programme at the fillet radius 2.87 mm the maximum bending stress is 1056MPa.

By several number of random search lead that optimum fillet radius of the fillet is 2.87 mm. at this radius the maximum bending stress is around 1050MPa.

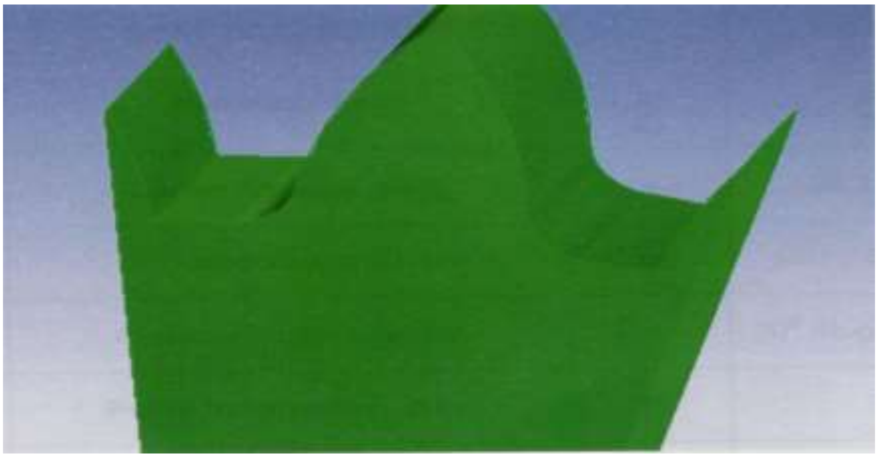


Figure – 13 Optimized fillet profile of gear wheel

4.5 Bending Stress values for Traditional Gear

Table – 4 Bending stress values for traditional gear

	Pinion (MPa)	Wheel (MPa)
Maximum bending stress	2852	1295

4.6 Bending Stress Analysis

Bending stress analysis of direct gear design and traditional gear design is done as follows

4.6.1 Bending Stress pattern for Traditional Gear Design

The traditionally designed gear where the fillet profile is the trajectory of the cutting tooth profile.

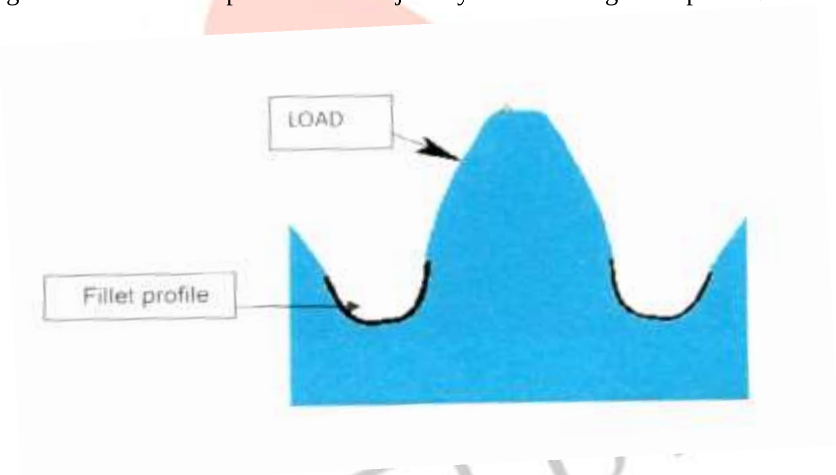


Figure – 14 Traditional gear – Bending stress pattern

Bending concentration is not uniformly distributed in traditionally designed gear. Bending stress sharply concentrated to some of the fillet portion.

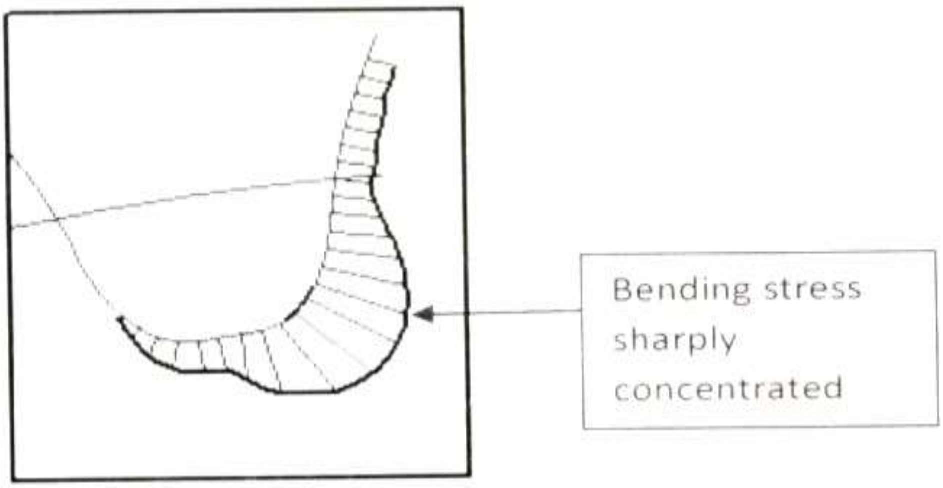


Figure – 15 Bending stress sharply concentrated on traditional gear

6.2 Bending Stress pattern for Direct Design Gear

Optimization procedure followed in direct gear design leads to generate best possible optimized fillet profile.

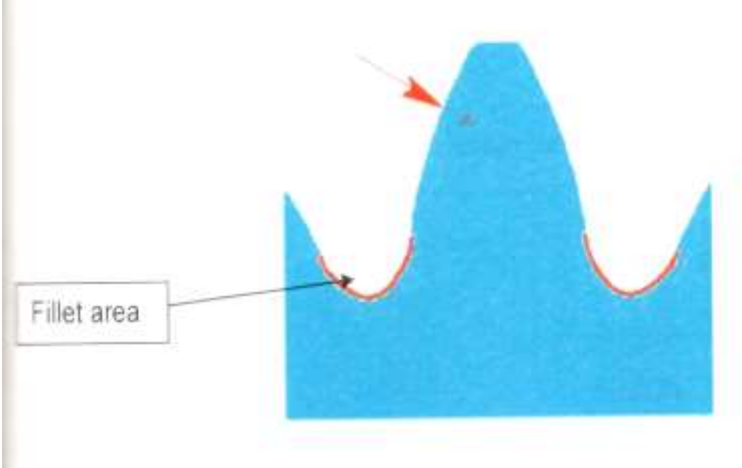


Figure – 16 Direct gear design gear – bending stress pattern

In direct gear design, bending concentration is uniform through the fillet profile. Also the bending stress in fillet profile is lesser in the fillet profile. This leads higher load carrying capacity.

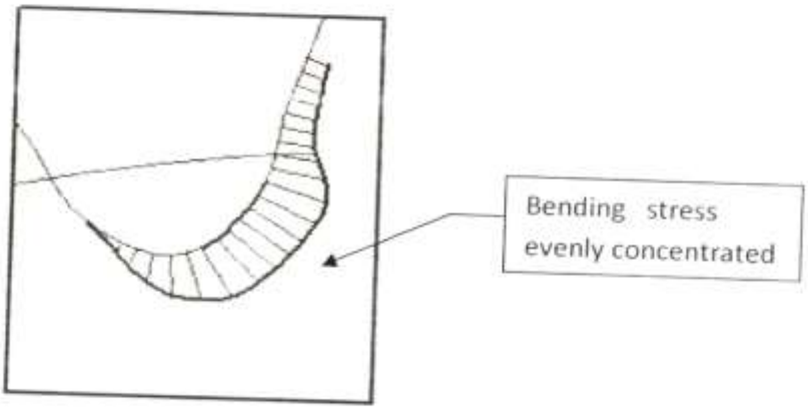


Figure – 17 Bending stress evenly concentrated on direct gear design gear

4.7 Comparison of Direct Gear Design with Traditional Gear Design

Table – 5 Direct gear design vs traditional gear design

	Bending Stress on Fillet Profile (M Pa)	
	Pinion wheel	**Gear Wheel**
Traditional gear design	2852	1295
Direct gear design	2000	1050
Reduction in bending stress	852	245
Percentage reduction	30	19

Data show clearly that the tooth fillet profile optimization using direct gear design provides significant (20-30%) bending stress reduction in bending stress values compared to traditional gear design. The bending stress reduction provide by the fillet optimization can be converted into other gear performance benefits, such as the contact stress reduction and increased gear mesh efficiency.

V Conclusion

Direct gear design, an alternative approach to traditional gear design, is not constrained by predefined tooling parameters. It allows for the analysis of a wide range of parameters for all possible gear combination in order to find the most suitable solution for a particular custom application. This gear design method can exceed the limits of traditional rack generating methods of gear design.

In this paper fillet profile optimization using finite element analysis and random search method have been used to find the optimum fillet radius. It allows reducing the maximum bending stress in the gear tooth root area by 20-30%. The load carrying capacity of the gears with conventional (Trochoidal or circular) fillet is limited by maximum bending stress. However load carrying capacity can be increased by reducing the bending stress using fillet profile optimization which in turn can reduce contact stress. The potential benefits of reducing the bending stress concentration optimization tooth fillet profile can be extended. This allows a gear with a greater number of teeth and finer module that generates less noise and vibration. It is likely possible to increase the hydrodynamic oil film thickness and reduce the flash temperature, because of the reduced profile sliding.

VI References

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