ANUSANDHAN- AISECT University Journal
Vol. 06, Issue No. 12, September-2017, P-ISSN 2278-4187

Spiral Bevel Gear Design and Development - Generation and Simulation of Meshing and Tooth Contact Analysis (TCA) for Improved Performance

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Abstract – Computer-based design analysis is nowadays a common activity in most development projects. When new software and manufacturing processes are introduced, traditional empirical knowledge is unavailable and considerable effort is required to find starting design concepts. This forces gear designers to go beyond the traditional standards-based design methods. The transformation has had a vast influence on gear manufacturing as well, providing process improvements that lead to higher gear quality and lower manufacturing costs. However, in the case of the gear industry, the critical process of Generation and Simulation of Meshing and Tooth Contact Analysis (TCA) of Spiral bevel gears for improved performance remains relatively unchanged.

Keywords: Spiral Bevel Gear, Design, Development, Generation, Simulation, Meshing Tooth Contact Analysis (TCA).

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I. INTRODUCTION

The purpose of gear is to transmit motion and torque from one shaft to another. That transmission normally has to occur with a constant ratio, the lowest possible disturbances and the highest possible efficiency. Tooth profile, length and shape are derived from those requirements.

Gearing is one of the most critical components in a mechanical power transmission system, and in most industrial rotating machinery. A gear is a mechanical part often used for transmission systems which allows rotational motion to be transferred to another gear or device. The gear teeth allow motion to be fully transmitted slippage less and depending as per their configuration, can transmit forces at different speeds, torques, and even in a different direction. Generation of spiral bevel gear teeth depends upon the theory of derivation of gear and pinion tooth surface. The accurate geometrical representation of gear tooth surface is the first step to design a successful gear drive.

Generation of spiral bevel gears depends upon the theory of derivation of gear and pinion tooth surface. The accurate geometrical representation of gear tooth surface is the first step to design a successful gear drive.

Spiral bevel gears are crucial to power transmission systems, power generation machines and automobiles. However, the design and manufacturing of spiral bevel gears are quite difficult. Currently, the major parameters of spiral bevel gears are calculated, but the geometries of the gears are not fully defined.

The procedures needed to develop spiral bevel gear sets for a new product can require months of trial-and-error work and thousands of dollars. In view of increasing global competition for lower priced products, spiral bevel gears are a prime target for the next generation of computerization. Answering this challenge, it has realized a new modified method through a shift in the way spiral bevel gear development is performed.

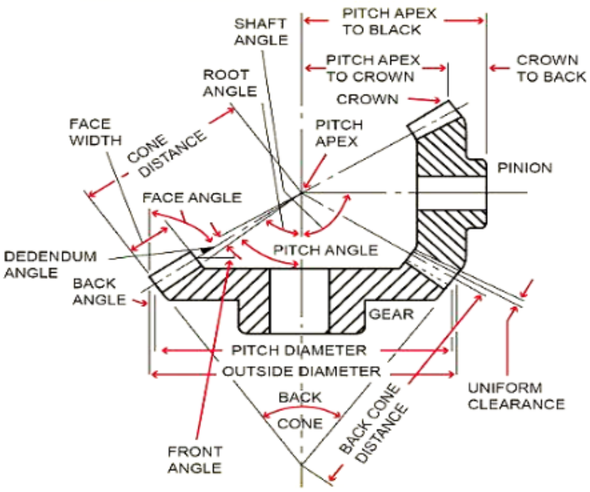

Fig 1.1 Bevel Gear Terminologies

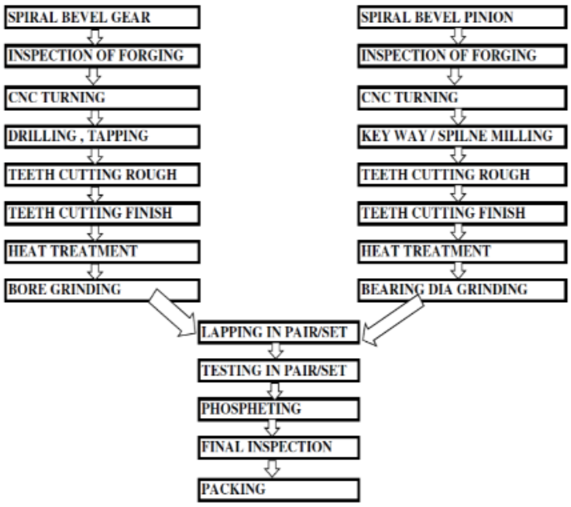

Fig 1.2 Spiral Bevel Gear Manufacturing Process

II. TEETH GENERATION PROCESS

$$\frac{\omega_t}{\omega_c} = \frac{N_c}{N_t}$$

In the spiral bevel gear generation process, two sets of related motions are generally defined. The first set of related motion is the rotation of the tool (cutter head) and rotation of the work piece, namely,

$$\frac{\omega_t}{\omega_c} = \frac{N_c}{N_t}$$

Eq. 2.1

Here *ωt* and *ωc* denote the angular velocities of the tool and the work piece; *Nc* and *Nt* denote the number of the blade groups and the number of teeth of the work piece, respectively. This related motion provides the continuous indexing between the tool and the work for the face hobbing process. The indexing relationship also exists between the rotation of the tool and the generating gear as,

$$\frac{\omega_t}{\omega_c} = \frac{N_c}{N_t}$$

Eq. 2.2

Where *ωc* and *Nc* denote the angular velocity and the number of teeth of the generating gear respectively. In the face hobbing process, the indexing motion between the tool and the generating gear kinematically forms the tooth surface of the generating gear with an extended-epicycloid lengthwise tooth curve.

$$\frac{\omega_w}{\omega_c} = \frac{N_c}{N_w} = R_a$$

The second set of related motions is the rotation of the generating gear and rotation of the work piece. Such a related motion is called rolling or generating motion and is represented as

$$\frac{\omega_w}{\omega_c} = \frac{N_c}{N_w} = R_a$$

Eq 2.3

Where *Ra* is called the ratio of roll the generating motion is provided for both face milling and face hobbing processes when the gear or pinion is cut in the generating method. In the non-generating (FORMATE) process, which is usually applied to the gear, both the generating gear and the work piece are held at rest, and only the cutter rotation is provided. Therefore, the gear tooth surfaces are actually the complementary copy of the generating tooth surfaces, which are formed by the cutter motion described here.

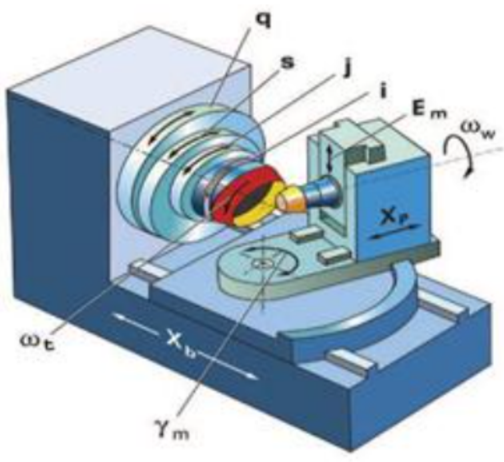

Fig 2.1 Kinematical model of a spiral bevel generator

III. MOTIVATION AND OBJECTIVES

Motivation

The fundamental motives for doing this research were following:

(i) To get a robust and computerized tooth generation approach along with the tooth contact analysis to provide a better way to reduce the wear, noise and vibration problems related to spiral bevel gears.

(ii) Using the proposed mathematical model, the tooth surface sensitivity matrix to the variations in machine–tool settings is investigated.

(iii) To investigate surface deviations of a real cut pinion and gear with respect to the theoretical tooth surfaces.

(iv) An optimization procedure for finding corrective machine–tool settings to minimize surface deviations of real cut pinion and gear-tooth surfaces.

(v) Therefore, the proposed method for obtaining corrective machine–tool settings can improve the conventional development process and can also be applied to different manufacturing machines and methods for bevel gear generation.

(vi) To plan in cutting the noise. Experimental research centered on the investigation into the relation between the gear error and noise.

(b) Objectives

If the gears were perfectly rigid and no geometrical errors or modifications were present, the gears would transmit the rotational motion perfectly, which means that a constant speed at the input shaft would result in a constant speed at the output shaft. The assumption of no friction – leads, that the gears would transmit the torque perfectly, which means that a constant torque at the input shaft would result in a constant torque at the output shaft. No force variations would exist and hence no vibrations and no sound (noise) could be created. Of course, in reality, there are geometrical errors, deflections and friction present, and accordingly, gears sometimes create noise to such an extent that it becomes a problem.

The overall research objectives:

(i) To develop an automated process for spiral bevel gear to reduce design and development time and to improve tooth contact analysis (TCA) by computer programs for the analysis of meshing and tooth bearing contact.

(ii) To develop a framework flexible to interfaces, fast and accurate, with integration and automation capability by improving understanding of optimization techniques for spiral bevel gear design and development.

(iii) To formulate a mathematical model of universal spiral bevel gear tooth surfaces generator based on Gleason's approach by taking into account all the kinematic motions of common Gleason CNC machine tools dedicated to spiral bevel gears machining.

(iv) To create Spiral Bevel Gear Gleason Dimension in MASTA by entering the details from the Gleason Dimension Sheet by comparing the geometry in MASTA with that in the Dimension Sheet. Based upon the developed theory, an advanced tooth surface generation and TCA program is to be developed and integrated into Gleason.

IV. DESIGNING AND MACHINE SETTING

Design Considerations accuracy of the output of a gear depends on the accuracy of its design and manufacturing. The correct manufacturing of a gear requires a number of prerequisite calculations and design considerations. The design considerations are taken into account before manufacturing of gears.

Smart Manufacturing Technology's premier full-system transmission design and analysis software MASTA is used to address within the context of the full system from an integrated workflow that fully considers the design geometry of bevel tooth flanks via the manufacturing machine settings.

Modern design practices provide a new design-to-manufacture solution for spiral bevel gears with significant performance advantages and cost savings over current processes.

This improved virtual analysis and testing helps avoid the costs associated with repeated manufacturing and testing of prototype gears, saving customers both time and money.

There are following benefits of using MASTA.

(i) Accurately and rapidly design transmission systems from scratch or imported concepts,

(ii) Rapidly predict key performance characteristics at the design stage,

(iii) Easily explore changes in transmission layout, component selection and/or design, materials and manufacturing processes in the convenience of a virtual environment,

(iv) Perform full system simulations for any transmission or driveline configuration,

(v) Incorporate manufacturing simulation at the design stage to reduce process development time & cost,

(vi) Design entire transmission and driveline systems using a comprehensive selection of components and design databases,

(vii) Gear tooth geometry optimization.

(viii) Enhanced Computer Program for Simulation of Meshing and Contact

Dimension Sheet is created in MASTA by entering the details from the following Gleason Dimension Sheet and compared the resulting geometry in MASTA with that in the Dimension Sheet.

Table 4.1

Gleason Dimension Sheet

Note: When entering data from a Gleason Dimension Sheet care should be taken with units. It is common to see Gleason Dimension Sheets where the gear properties are in mm while the cutter properties are in inches. In the below sheet all length dimensions are in mm.

SPIRAL BEVEL GEAR DIMENSIONS NO. M Input a Name VERSION:1.0.4.7 2/20/2013 17:12

Input a Customer ID

	PINION	GEAR
NUMBER OF TEETH.	14	39
PART NUMBER.		
MODULE		4.536
FACE WIDTH	25.40	25.40
PRESSURE ANGLE - PIN CONCAVE	20D 0M	
PRESSURE ANGLE - PIN CONVEX.	20D 0M	
SHAFT ANGLE.	90D 0M	
TRANSVERSE CONTACT RATIO . .		1.181
FACE CONTACT RATIO		1.454
MODIFIED CONTACT RATIO . . .		1.873
OUTER CONE DISTANCE.		93.98
MEAN CONE DISTANCE		81.28
PITCH DIAMETER	53.50	176.90
CIRCULAR PITCH	14.25	
WORKING DEPTH.	7.71	
WHOLE DEPTH.	8.56	8.56
CLEARANCE.	0.85	0.85
ADDENDUM	5.40	2.31
DEDENDUM	3.17	6.25
OUTSIDE DIAMETER	73.66	178.47
THEORETICAL CUTTER RADIUS. *	76.93	
CUTTER RADIUS.	114.30	
CALC. GEAR FINISH. PT. WIDTH		2.10
GEAR FINISHING POINT WIDTH .		2.10
ROUGHING POINT WIDTH	1.60	2.10
OUTER SLOT WIDTH	2.58	2.10
MEAN SLOT WIDTH.	2.19	2.10
INNER SLOT WIDTH	1.63	2.10
FINISHING CUTTER BLADE POINT	1.60	1.25
STOCK ALLOWANCE.	0.03	0.00
MAX. RADIUS - CUTTER BLADES.	1.16	1.49
MAX. RADIUS - MUTILATION . .	0.33	1.88
MAX. RADIUS - INTERFERENCE .	1.04	2.23
CUTTER EDGE RADIUS	0.30	1.40
CALC. CUTTER NUMBER.	6	13
MAX. NO. OF BLADES IN CUTTER		19.732
CUTTER BLADES REQUIRED . . .	STD DEPTH	STD DEPTH
*CUTTER SPECIFICATIONS ARE IN METRIC UNITS		
GEAR ANGULAR FACE - CONCAVE.		16D 7M
GEAR ANGULAR FACE - CONVEX .		16D 3M
GEAR ANGULAR FACE - TOTAL. .		18D 15M

ALL DIMENSIONS ARE METRIC UNLESS OTHERWISE SPECIFIED
RELEASED BY - Eng1

		PINION		GEAR
PITCH APEX TO CROWN.		86.63		23.57
FACE ANG JUNCT TO PITCH APEX				
MEAN CIRCULAR THICKNESS. . .		7.16		4.96
OUTER NORMAL TOPLAND		1.51		3.00
MEAN NORMAL TOPLAND.		1.72		2.67
INNER NORMAL TOPLAND		1.96		2.09
PITCH ANGLE.		19D 45M		70D 15M
FACE ANGLE OF BLANK.		23D 33M		72D 11M
INNER FACE ANGLE OF BLANK. .				
ROOT ANGLE		17D 49M		66D 27M
DEDENDUM ANGLE		1D 56M		3D 48M
OUTER SPIRAL ANGLE				36D 51M
MEAN SPIRAL ANGLE.				35D 0M
INNER SPIRAL ANGLE				33D 57M
HAND OF SPIRAL		LH		RH
DRIVING MEMBER		PIN		
DIRECTION OF ROTATION-DRIVER		REV		
OUTER NORMAL BACKLASH. . . .	MIN	0.13	MAX	0.18
DEPTHWISE TOOTH TAPER. . . .		STD		
GEAR TYPE.				GENERATED
FACE WIDTH IN PCT CONE DIST.				27.027
DEPTH FACTOR - K				
ADDENDUM FACTOR - C1				
GEOMETRY FACTOR-STRENGTH-J .		0.2295		0.2736
STRENGTH FACTOR - Q.		12.688		3.82019
EDGE RADIUS USED IN STRENGTH		1.00		1.40
CUTTER RADIUS FACTOR - KX. .		1.000		
FACTOR	KI	1.0676		
STRENGTH BALANCE DESIRED . .		GIVN		
STRENGTH BALANCE OBTAINED. .	GIVN		-	0.172
GEOMETRY FACTOR-DURABILITY-I		0.1134		
DURABILITY FACTOR - Z. . . .		4751.18		2846.64
GEOMETRY FACTOR-SCORING -G .		0.006230		
SCORING FACTOR - X		0.4579		
ROOT LINE FACE WIDTH		25.40		25.40
PROFILE SLIDING FACTOR . . .		0.00322		0.00463
RATIO OF INVOLUTE/OUTER CONE				1.581
RATIO OF INVOLUTE/MEAN CONE.				1.828
AXIAL FACTOR - DRIVER CW . .	OUT	0.748	OUT	0.060
AXIAL FACTOR - DRIVER CCW. .	IN	0.471	OUT	0.217
SEPARATING FACTOR-DRIVER CW.	SEP	0.168	SEP	0.269
SEPARATING FACTOR-DRIVER CCW	SEP	0.606	ATT	0.169
DUPLEX SUM OF DEDENDUM ANG .		8D 38M		
ROUGHING RADIAL.		3.728"		
INPUT DATA . . . . KTT		1		
INPUT DATA . . . . .CUTM				1
NUMBER OF BLADE GROUPS . . .				
EFFECTIVE CUTTER RADIUS. . .				
SLOT WIDTH PCT FOR BLADE PT.				

V. CUTTING TOOL GEOMETRY AND RELATIVE MOTION

Fig 4.1 shows a typical FH blade with its geometry along its cutting edge is defined by the blade angle a_b, the rake angle τ, the hook angle μ the blade offset angle the cutter radius r_c, and the distance from the tip of blade to reference point *hf*.

The cutting edge is divided into four different sections as the *edge* (or tip radius), *toprem, profile* and *flankrem*that are all shown in Fig 4 (c). The edge and flankrem are usually circular arcs while toprem is usually a straight line at a slight angle from the profile section. Most of the cutting is done by the profile section of the blade that is usually a straight line or a circular arc. For a typical FM cutter, $\tau = \mu = \delta_b = 0$

Referring to Fig 4, an arbitrary point *A* on cutting edge is at position r=r(S) relative to the local coordinate system X*b* fixed to the cutter head (with its origin at reference point *M*) where *s* is the distance of point *A* to point *M* along the blade edge. With this, the unit tangent vector is $t=\frac{\partial r}{\partial s}$, and if the cutting edge is a line, it can be reduced to

$$t=[-\sin\alpha_b\ 0\ -\cos\alpha_b]^T$$

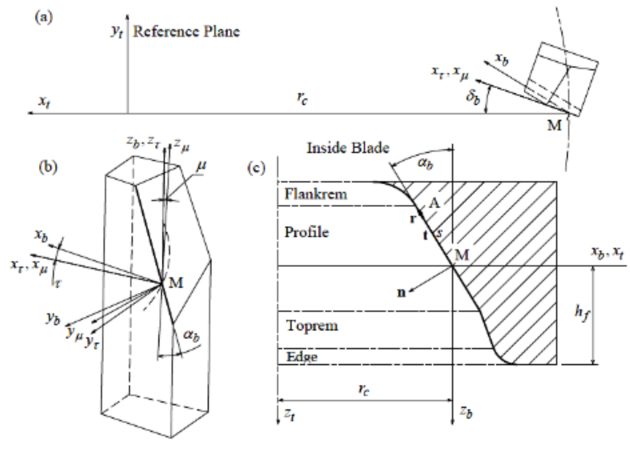

Fig 4.1: (a) Cutter head, (b) blade and (c) cutting edge geometry

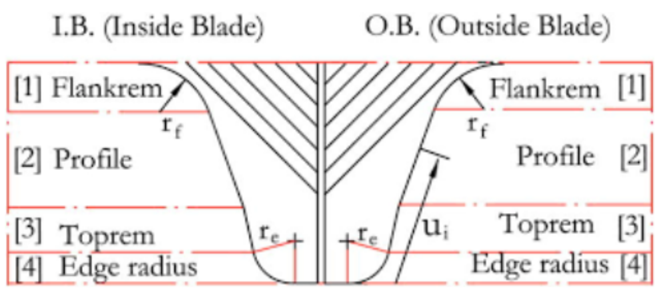

Fig 4.1: (d) Inside blade and Outside blade

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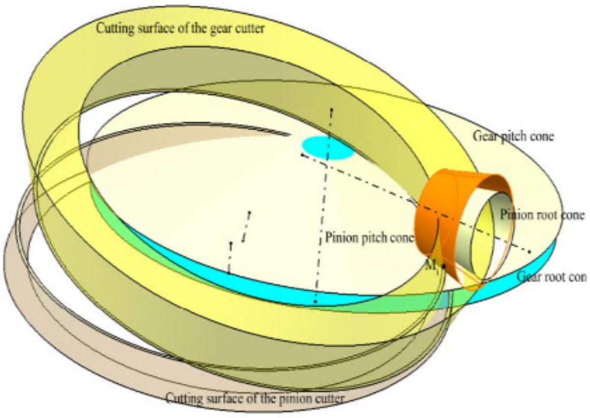


Fig 4.2 Local synthesis between gear cutting surface, gear, pinion and pinion cutting surface

VI. EXPERIMENTS EXECUTION

(a) Experiments Execution

The most conclusive test of spiral bevel gears is their operation under normal running conditions in their final mountings. Testing not only maintains quality and uniformity during manufacture, but also determines if the gears will be satisfactory for their intended applications.

MASTA is an automated designing soft-ware that creates an optimized model of the gear tooth profile just by inputting the basic parameters. A mathematical model of an ideal spiral bevel gear-tooth surfaces based on the Gleason gear generator mechanism is used.

Using this mathematical model, the tooth surface sensitivity matrix to the variations in machine–tool settings is investigated. Surface deviations of a real cut pinion and gear with respect to the theoretical tooth surfaces are also investigated. An optimization procedure for finding corrective machine–tool settings is then proposed to minimize surface deviations of real cut pinion and gear-tooth surfaces.

The results are revealed that surface deviations of real cut gear-tooth surfaces with respect to the ideal ones are reduced. Therefore, the proposed method for obtaining corrective machine–tool settings improves the conventional development process and can also be applied to different manufacturing machines and methods for spiral bevel gear generation.

First of all, to get the relative position of contact pattern and tooth profile of the boundary, we need to locate tooth profile and contact pattern as well as their respective centric. In the meanwhile, it requires the guide, which can help to check whether the tooth profile on which the spiral bevel gear meets with the contact pattern is on its right position.

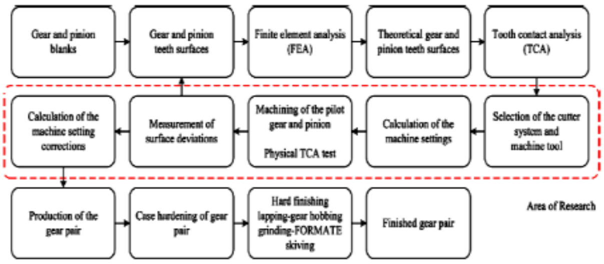


Fig 5.1 Analysis and machining cycle of spiral bevel bevel gears

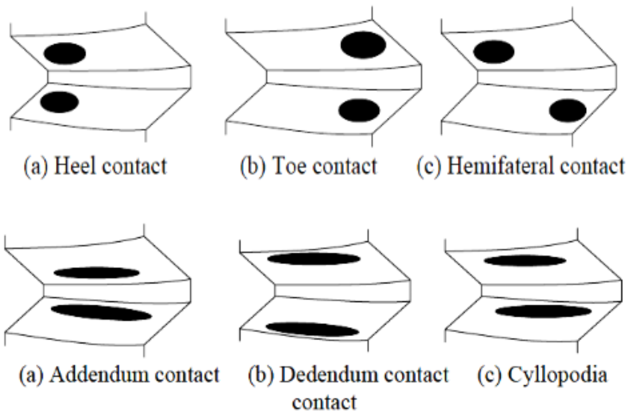


Fig 5.2 Various Contact Positions

VII. SIMULATIONS, RESULT AND ANALYSIS

A sound system design techniques developed based on literature survey and research done in the area of spiral bevel gear design and development, on the basis of following design framework.

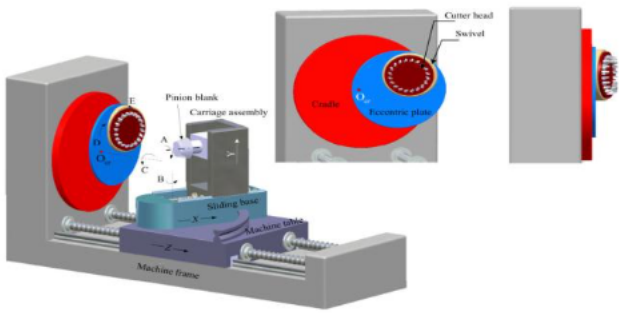


Fig 6.1 Structure of the multi-axis pinion generation machine

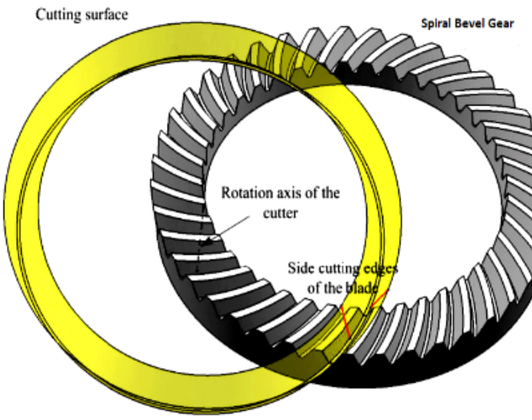


Fig 6.2 Gear tooth formed by non-generated machining process

VIII. INTRODUCTION TO MASTA

MASTA is capable of modelling a variety of gear types. Instructions for the creation spiral bevel gear pair models is found in the MASTA. This describes to use to input and design face milled spiral bevel gear sets.

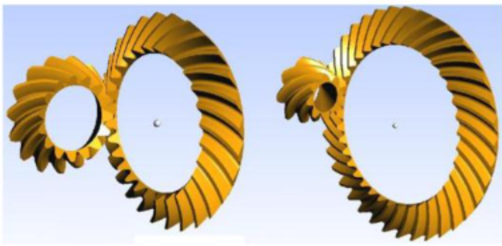
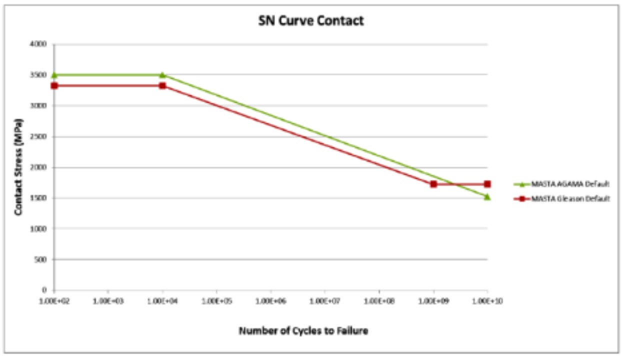


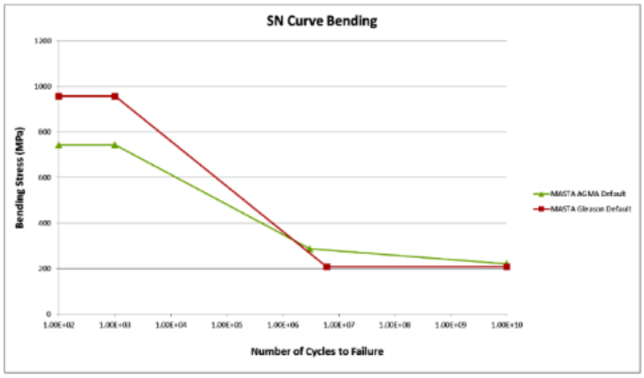
Fig 7.1 MASTA Spiral bevel gear pair models

Following MASTA modules functionality were used in this thesis.

- MC302 – AGMA/Gleason Spiral Bevel Gear Design and Rating
- MC303 – AGMA/Gleason Spiral Bevel Gear Macro Geometry Optimisation
- MC401 - AGMA / Gleason Spiral Gear Design and Rating
- MC402 - AGMA / Gleason Spiral Gear Macro Geometry Optimisation
- For AGMA the relevant life factor expressions can be found in, Figures 5 and 6 p 21 of ANSI/AGMA 2003-C10. Note that the corresponding AGMA Technical Report for Spiral Gears, AGMA 932-A05, also refers to the 2003-C10 graphs.
- This above process leads to the following default S/N curves for contact:



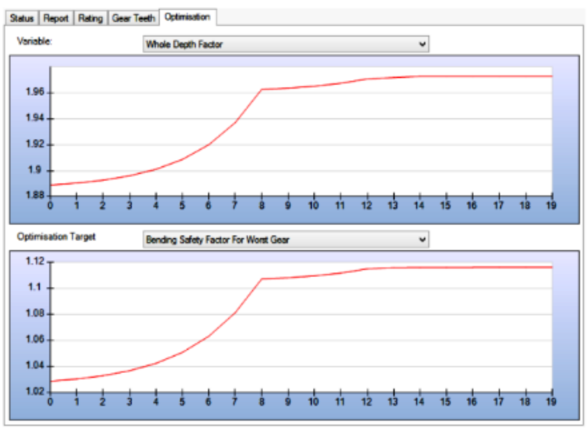
- and the following default S/N curves for bending:



(a) Notes:

- There is a significant difference between Gleason and AGMA S/N curves for Bending due to the significant differences in the Life Factor charts.
- Default materials cannot be edited or deleted but they can be duplicated.

(b) Optimization: Displays the progress of optimization variables and targets in the form of line charts. Note that the x axis for these charts is not the number of iterations in the analysis but relates to the number of positive steps made during the optimization.



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IX. SUMMARY

(a) On the basis of un-modified roll and modified roll for traditional local synthesis, incomplete un-modified roll and incomplete modified roll are defined as new generation scopes of pinion.

(b) Tooth contact analysis (TCA) based on local synthesis is carried out to obtain contact pattern and transmission error function. The degrees of symmetry and agreement are defined as evaluation indexes of gear meshing performances. For symmetry and agreement degrees, two corresponding sub-objective functions are found and linear weighted combination method is applied to solve the dual objective optimization model.

(c) As for a pair of automobile spiral bevel gears, programs are studied to analyze meshing performances of gear pair for all typical generation scopes. Considering the stability and convergence of algorithm and optimization results, the optimal generation scope of pinion was determined among all.

(d) An optimization process able to design in an automated way the shape of spiral bevel gear flanks has been presented. It leads to a significant reduction of the development time, while allowing a strengthening of the quality of contact patterns by the reduction of the contact pressure. Its extension to the minimization of tooth contact errors made possible, in order to contribute to the reduction of noise and vibration levels and therefore a higher durability.

(d) Achieved in cutting the noise from an average 81-83 dB to 79-81 dB by both experimental and theoretical research. Experimental research was centered on the investigation into the relation between the gear error and noise. Theoretical research was centered on the geometry and kinematics of the meshing process of gears with geometric error.

X. CONCLUSION

(a) Developed an automated process for spiral bevel gear to reduce design and development time and improved tooth contact analysis (TCA) by MASTA program for the analysis of meshing and tooth bearing contact. Tooth contact analysis (TCA) based on local synthesis is carried out to obtain contact pattern and transmission error function. The degrees of symmetry and agreement are defined as evaluation indexes of gear meshing performances. For symmetry and agreement degrees, two corresponding sub-objective functions are found and linear weighted combination method is applied to solve the dual objective optimization model.

(b) Developed a framework flexible to interfaces, fast and accurate, with integration and automation capability improving optimization techniques for spiral bevel gear design and development. A method for tooth contact analysis in modified face-hobbed spiral bevel gears is presented.

(c) The method is applied to study the influence of tooth modifications on tooth contact in face-hobbed spiral bevel gears. On the basis of the obtained results the following conclusions can be made.

(d) A spiral bevel gear has been designed and analyzed using modern industry specifications combined with the implementation of known methodology through years of design and development experience and experiments results. Spiral bevel gears for a new model have been designed using the developed method and an appropriate tooth flank form has been designed and prototyped using the developed method.

(e) Formulated a mathematical model for spiral bevel gear tooth surfaces generator based on Gleason's approach taking into account all the kinematic motions of common Gleason CNC machine tools dedicated to spiral bevel gears machining such as Gl 116 / Gl 118 Pinion Generators. On the basis of un-modified roll and modified roll for traditional local synthesis, incomplete un-modified roll and incomplete modified roll are defined as new generation scopes of pinion. Tooth flank form measurement of spiral bevel gears and tooth contact technology promoted mainly by automotive manufacturers have been applied to large bevel gears and a gear design method based on the tooth flank form standard instead of the conventional tooth contact standard has been developed.

(f) Created Spiral Bevel Gear Gleason Dimension in MASTA by entering the details from the Gleason Dimension Sheet and compared the geometry in MASTA with that in the Dimension Sheet. Based upon the developed theory, an advanced tooth surface generation and TCA program developed and integrated into Gleason Gear Cutting System. As for a pair of automobile spiral bevel gears, programs are modified to analyze meshing performances of gear pair for all typical generation scopes. Considering the stability and convergence of algorithm and optimization results, the optimal generation scope of pinion can be determined among all.

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