International Journal of Modern Science and Technology, 2018;3(4):83-89.
ISSN: 2456-0235.
www.ijmst.co

Research Article

Estimation and Validation of Highest Point Single Tooth Contact in Spur Gears using Spreadsheet Application

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Abstract

Gear is one of the most critical components widely used in the transmission of motion and power between two shafts. During motion, the gears are instantaneously loaded which develops bending stress at the root of the gear. The loading point is termed to be Highest Point Single Tooth Contact (HPSTC) and Lowest Point Single Tooth Contact (LPSTC). HPSTC is the most critical loading point in any gear. While a designer analyses a gear, it is essential to determine this instantaneous loading point (HPSTC, LPSTC) for the purpose of finding out the induced stress on the gear tooth. Moreover, this point is so important that it determines the bending stress at the root fillet portion of the gear. It is known fact that identification of these points involves many steps with huge ream of calculations. The present research work involves estimation of radius for Highest Point Single Tooth Contact using Spreadsheet application. This works for different range of input parameters like module, number of teeth, pressure angle etc., For this purpose, a customized spreadsheet is developed involving gear formula and all calculation steps. Two typical case studies were conducted using few specific parameters. The calculated outputs from the spreadsheets were compared with the available results of existing studies. It was noted that there were no variations notified in the calculated results, which indicates the validation of the current work. With addition of few formula and steps, this work can be extended to carryout bending stress analysis based on Lewis approach with AGMA standards. Further the study can be incorporated in ANSYS mechanical APDL.

Keywords: Highest Point Single Tooth Contact; Lowest Point Single Tooth Contact; Base root critical tooth thickness; Bending stress.

Introduction

Gears are known to be simplest and most efficient mechanical component in transmitting motion and power. Ever since the advancement of Gear technology there is an increasing demand for better design of gears. It is noteworthy that though extensive research has been conducted on this title, still some basics governing the gear theory has not been satisfactorily understood. Gear designer without proper knowledge will overdesign the system, which, always leads to a sacrifice in cost, material and compactness. Though this work is into the development of spreadsheet application for calculating the HPSTC radius, the fundamentals on gear and their relevant formula is depicted in this work. This serves the purpose of better understanding and deeper learning of gear design. AGMA 933-B03 [1], provides the details of basic gear geometry, which depicts that a clear and accurate understanding of the elements involved is indispensable to all who deals with the design, dimensioning, cutting and measurement of gear teeth. Gears are developed with several tooth forms and applied for gearing and other applications, which has its own uniqueness. Presently used are Involute, Cycloid, Hypocycloid, Epicycloid, Trochocentric, Beveloid, and Spiroid. Of these, the involute is the only tooth form that provides true conjugate action normal to the tangency of the tooth curves passing through the pitch point [2].

Researchers have described about the formation of involute tooth profile [3,4], though it has been described, it is still challenging to

Received: 08.04.2018; Received after Revision: 22.04.2018; Accepted: 22.04.2018; Published: 28.04.2018

construct the correct gear tooth profile in CAD and FEA code environment [5]. Researchers [6] have proposed an algorithm for describing the ideal spur gear profile using Visual basic macro in Excel. In a research work [7] has presented the method of Pro/E programs, relationship and parameters to conduct the parametric design for various types of gears. Researchers [8] in his work have explored the technique of generating the involute curve.

In a research work [9], researchers have presented the approximate and accurate method of generating the solid models of involute cylindrical gears using Autodesk inventor. In another research work, the author of the current work has implemented parametric technique using CATIA to develop template of spur gear [10]. Researchers [11] have discussed five characteristics of trochoids in their paper. The authors have introduced a concept-virtual involute and clearly determined the root fillet shapes generated by racks with a protuberance. The current author has developed a new method to calculate the gear parameters and HPSTC for non-symmetrical gear system through Matlab GUI [12].

Spur gears are categorized under two families, the involute and non-involute. The involute gears have distinguished advantages. When two curved surfaces act against each other, the line of action between them will be along the common normal to the two curves at that point of tangency. Some of the important angles like Pressure angle (ϕ), Roll angle (ψ), and the Involute angle (θ), as in AGMA 933-B03 [1], is represented in the Fig. 1, which defines the involute curve. The involute curve is generated by the end of a string which is unwound from a circle, as illustrated in Fig. 1. The circle from which the string is unwound is the base circle. AC represents the string, while AB represents the involute curve, which is the locus generated by the free end point A of the string. The equations and relations are found in many handbooks and manufacturing books like [13,14]. To find the coordinates of standard spur gear involute, the authors have implemented MATLAB GUI. Later these points were imported in Solidworks to create gear tooth spacing, gear profile and 3D Gear [15]. The equation and mathematical description of the involute curve are developed below and referred from [16]. Excel Spreadsheet has been successfully used by the author [17] to promote the conceptual change in mechanical system design and analysis. In Excel Spreadsheet students can perform alternative design and analysis.

In the fig. 1, an involute profile is formed from point A on the base circle of a gear with radius r_P. The tangent to the involute profile at start point A is AX. When the string is taut unwound to reach point B tracing an involute profile with length of string as BC. The line BC is tangent to the base circle as well as normal to the involute profile at B and indicates the direction of force or line of action. Also the length of the string BC will be equal to the length of arc AC.

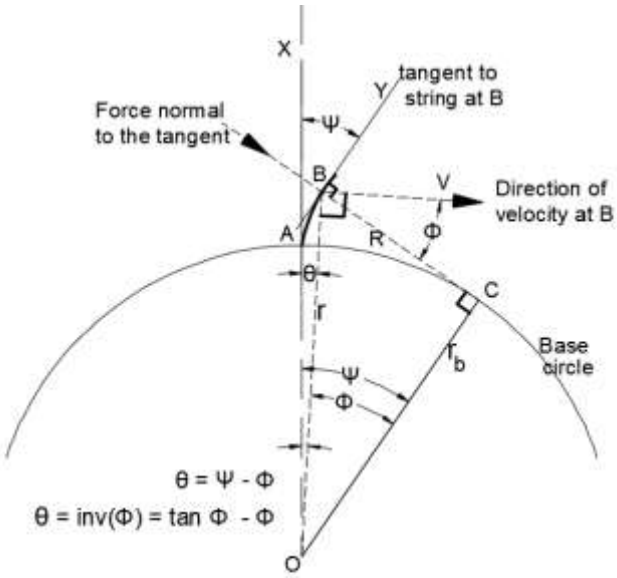

Fig. 1. Involute profile

The tangent to the involute profile at point B be BY. So, the tangent line AX has rolled to BY along the involute profile making an angle ψ is called roll angle. The radial line joining C to O makes 90° to BC and so tangent line BY and OC are parallel to each other which denotes that the angle subtended by the arc AC will also be equal to roll angle ψ. Let OB, the radius at point B be r and the line BV (perpendicular to OB) represents the direction of the velocity vector at B. The angle formed between the normal to involute BC and direction of velocity BV gives the involute pressure angle ϕ at point B. By geometry, angle between BO and OC will also be ϕ. From the $\Delta\, BOC$,

$$R = \left(\sqrt{r^2 - {r_b}^2}\right) \quad (1)$$

$$r_b = r\cos\phi \quad (2)$$

$$\tan\phi = \frac{R}{r_b} = \frac{\sqrt{r^2 - {r_b}^2}}{r_b} \quad (3)$$

Or

$$R = r_b \tan\phi \tag{3a}$$

From the length of the arc AC is equal to string length R

$$R = r_b * \psi \tag{4}$$

Comparing these equations 3a and 4 leads to

$$\psi = \tan\phi \tag{5}$$

The angle subtended by the involute at O from A to B is called involute angle, θ

$$\theta = \psi - \phi$$

Substituting for ψ

$$\theta = \tan\phi - \phi$$

This angle θ is written as involute function of pressure angle ϕ and is represented by inv (ϕ)

$$\theta = inv(\phi) = \tan\phi - \phi \tag{6}$$

If ϕ is the pressure angle of a gear at pitch point, then the involute angle θ for the tooth profile at the pitch circle can be calculated from eq. (6).

The length of arc at the pitch circle between the corresponding points on adjacent teeth gives the circular pitch. Circular thickness of a tooth is the length of arc measured between the two sides of the tooth along pitch circle. Circular tooth thickness t_c along the pitch circle is half the circular pitch p.

$$t_c = \frac{p}{2} = \frac{\pi m}{2} \tag{7}$$

The circular tooth thickness along the gear tooth can be determined with reference to the parameters at pitch circle of the gear.

In fig 2, consider O to be the center for all defining circles of gear. The involute profile starts from the base circle of the gear with radius r_b and B, a point along the involute profile on pitch circle of radius *r* with involute angle θ. D is the midpoint of tooth thickness and α be the angle formed by OA and OD and γ be the angle subtended by half of circular tooth thickness on the pitch circle from D to B. Then,

$$\alpha = \gamma + \theta \tag{8}$$

By geometry,

$$\gamma = \frac{t_c}{2r} = \frac{t_c}{d} \tag{8a}$$

$$\alpha = \frac{t_c}{d} + \theta \tag{9}$$

At any other point along the involute profile, say B', at any radius r_2 the parameters can be derived based on the parameters at pitch circle.

$$\alpha_2 = \gamma_2 + \theta_2 \tag{10}$$

Angle $\angle AOD = \alpha$ and angle $\angle A'OD' = \alpha_2$ are equal

Involute angle θ_2 at B' can be obtained from equation 6, given as

$$\theta_2 = \tan\emptyset_2 - \emptyset_2 \tag{11}$$

Where $\emptyset_2$ is the pressure angle at r_2 and is calculated as

$$r_b = r\cos\phi = r_2\cos\phi_2 \tag{12}$$

$$\emptyset_2 = \cos^{-1}\left(\frac{r_b}{r_2}\right) \tag{13}$$

Since, $\alpha_2 = \alpha$

$$\gamma_2 + \theta_2 = \gamma + \theta \tag{14}$$

From geometry;

$$\gamma_2 = \frac{t_{c2}}{2r_2} \text{ (in radians)} \tag{15}$$

Equation 15 becomes,

$$\frac{t_{c2}}{r_2} + \theta_2 = \frac{t_c}{r} + \theta$$

Circular tooth thickness at any point 2 with radius r_2 can be obtained from,

$$t_{c2} = r_2 * \left(\frac{t_c}{r} + \theta - \theta_2\right) \tag{16}$$

Where θ and θ_2 can be determined by eq. (6) and (11).

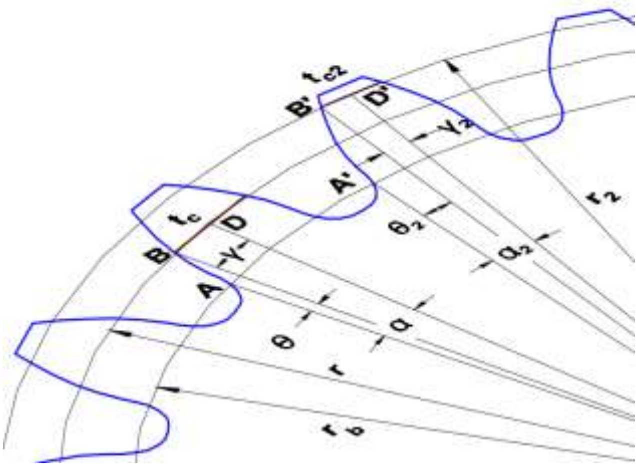

Fig. 2. Tooth thickness calculation

Methodology

The real power of excel spreadsheet lies within the manipulation of formulas, which uses the mathematical symbols to operate on a cell. Every formula begins with (=) symbol. Without this symbol, excel cell treats the entry as a simple text. Refer table S1 (Appendix) for the development of formulas which are coded in the excel cell, relevant to the gear calculations. The numeric precision of 15 digits is stored in the memory, but rounded and displayed. In fig. 3, the input parameters of the Pinion / Gear are provided in the respective cells, here it is D5 to D8. The input considered are number of teeth on Pinion (N_p), number of teeth on Gear (N_g), Pressure angle (Ø) and module (m). A systematic and progressive procedure is adopted which comprise seven steps were created in the excel spreadsheet. The calculations at each step is carried out or used in next cell elsewhere and finally the spreadsheet completes and displays the calculated value for the LPSTC and HPSTC.

SPREADSHEET FOR CALCULATING HPSTC, LPSTC OF PINION & GEAR					
Parameters	**Formula**	**Metric**		**Imperial**	
Input parameters					
Enter the number of teeth in pinion, N_P		23			
Enter the number of teeth in Gear, N_G		31			
Enter the Pressure angle, ø - degrees		20			
Enter the Module, m = 25.4/P - mm		2.54		2.54	
Diametral pitch, P = 25.4/m (if imperial)		10		10	
Output parameters		**Results**			
		Metric		**Imperial**	
Step 1: Calculation of basic parameters about Pitch Circle					
Circular Pitch,	p = π * m	7.9796	mm	0.3142	inches
Pitch circle diameter of pinion	d_P = m* N_P	58.42	mm	2.3	inches
Pitch circle radius of pinion,	r_P = d_P/2	29.21	mm	1.15	inches
Pitch circle diameter of Gear,	d_G = m* N_G	78.74	mm	3.1	inches
Pitch circle radius of Gear,	r_G = d_G/2	39.37	mm	1.55	inches
Step 2: Calculation of basic parameters about Addendum Circle					
Addendum	a = m	2.54	mm	0.1	inches
Dedendum,	b = 1.25*m	3.175	mm	0.125	inches
Addendum circle diameter of Pinion,	d_oP = d_P+2 a = d_P+2 m	63.5	mm	2.5	inches
Addendum circle radius of Pinion,	r_oP = d_oP/2	31.75	mm	1.25	inches
Addendum circle diameter of Gear	d_oG = d_G+2 a = d_G+2 m	83.82	mm	3.3	inches
Addendum circle radius of Gear,	r_oG = d_oG/2	41.91	mm	1.65	inches
Step 3: Calculation of basic parameters about Base Circle					
Drive side base circle diameter of Pinion	d_bP = d_P * cos(ø)	54.89684	mm	2.16129	inches
Drive side base circle radius of Pinion	r_bP = d_bP1/2	27.44842	mm	1.08065	inches
Drive side base circle diameter of Gear	d_bG = d_G cos(ø)	73.99140	mm	2.91305	inches
Drive side base circle radius of Gear	r_bG = d_bG1/2	36.99570	mm	1.45652	inches
Step 4: Calculation of Contact Ratio					
Angle, A	A = cos^(-1)(d_bG/d_oG)	28.02514	degrees	28.02514	degrees
Angle, β	β = tan^(-1){tan(ø) - [N_G/N_p *(tan(A)-tan(ø))]}	7.80818	degrees	7.80818	degrees
Angle, α	α = cos^(-1)(d_bP/d_oP)	30.17238	degrees	30.17238	degrees
Angle, B	B = tan^(-1){tan(ø)- [N_P/N_G * (tan(α)-tan(ø))]}	11.45721	degrees	11.45721	degrees
Contact ratio, m_f	m_f = N_G/(2 π) (tan(A)-tan(B))	1.62617	mm	1.62617	inches
Step 5: Calculation of Contact Diameters / Contact Radius					
Contact diameter in Pinion d_cP	d_cP = (d_P cos(ø))/cos(β)	55.41058	mm	2.18152	inches
Contact radius in Pinion r_cP	r_cP = d_cP /2	27.70529	mm	1.09076	inches
Contact diameter in Gear, d_cG	d_cG = (d_G cos(ø))/cos(B)	75.49578	mm	2.97227	inches
Contact radius in Gear, r_cG	r_cG = d_cG /2	37.74789	mm	1.48614	inches
Step 6: Calculation of LPSTC Diameters / LPSTC Radius					
Angle ε,	ε = tan^(-1){tan(α)- (2 π)/N_P]	17.12860	degrees	17.12860	degrees
LPSTC diameter in pinion, d_LP	d_LP = (d_P cos(ø))/cos(ε)	57.44474	mm	2.26160	inches
LPSTC radius in pinion, r_LP	r_LP = d_LP/2	28.72237	mm	1.13080	inches
Angle E,	E = tan^(-1){tan(A)- (2 π)/N_G]	18.24165	degrees	18.24165	degrees
LPSTC diameter in Gear, d_LG	d_LG = (d_G cos(ø))/cos(E)	77.90661	mm	3.06719	inches
LPSTC radius in Gear, r_LG	r_LG = d_LG/2	38.95331	mm	1.53359	inches
Step 7: Calculation of HPSTC Diameters / HPSTC Radius					
Angle f,	f = tan^(-1)[tan(β)+ (2 π)/N_p]	22.30885	degrees	22.30885	degrees
HPSTC diameter in pinion, d_HP	d_HP = (d_P cos(ø))/cos(f)	59.33824	mm	2.33615	inches
HPSTC radius in pinion, r_HP	r_HP = d_HP/2	29.66912	mm	1.16808	inches
Angle F,	F = tan^(-1){tanB+ (2 π)/N_G]	22.06557	degrees	22.06557	degrees
HPSTC diameter in Gear, d_HG	d_HG = (d_G cos(ø))/cos(F)	79.83926	mm	3.14328	inches
HPSTC radius in Gear, r_HG	r_HG = d_HG/2	39.91963	mm	1.57164	inches
Step 8: Circular tooth thickness at LPSTC					
Involute angle at pitch circle, θ	θ = tan (ø) - (ø)	0.01490	degrees	0.01490	degrees
Circular tooth thickness at pitch circle t_c	t_c = p / 2	3.98982	mm	0.15708	inches
Pressure angle at LPSTC in Pinion, ø_LP	ø_LP = cos^(-1)(d_bP/d_LP)	17.12860	degrees	17.12860	degrees
Involute angle at LPSTC in Pinion, θ_LP	θ_LP = tan (ø_LP) - (ø_LP)	0.00924	degrees	0.00924	degrees
Circular tooth thickness at LPSTC in Pinion, t_cLP	t_cLP = d_LP*[(t_c/d_P) + θ - θ_LP]	4.24882	mm	0.16728	inches
Pressure angle at LPSTC in Gear, ø_LG	ø_LG = cos^(-1)(d_bG/d_LG)	18.24165	degrees	18.24165	degrees
Involute angle at LPSTC in Gear, θ_LG	θ_LG = tan (ø_LG) - (ø_LG)	0.01121	degrees	0.01121	degrees
Circular tooth thickness at LPSTC in Gear, t_cLG	t_cLG = d_LG*[(t_c/d_G) + θ - θ_LG]	4.23525	mm	0.16674	inches
Step 9: Circular tooth thickness at HPSTC					
Pressure angle at HPSTC in Pinion, ø_HP	ø_HP = cos^(-1)(d_bP/d_HP)	22.30885	degrees	22.30885	degrees
Involute angle at HPSTC in Pinion, θ_HP	θ_HP = tan (ø_HP) - (ø_HP)	0.02095	degrees	0.02095	degrees
Circular tooth thickness at HPSTC in Pinion, t_cHP	t_cHP = d_HP*[(t_c/d_P) + θ - θ_HP]	3.69395	mm	0.14543	inches
Pressure angle at HPSTC in Gear, ø_HG	ø_HG = cos^(-1)(d_bG/d_HG)	22.06557	degrees	22.06557	degrees
Involute angle at HPSTC in Gear, θ_HG	θ_HG = tan (ø_HG) - (ø_HG)	0.02024	degrees	0.02024	degrees
Circular tooth thickness at HPSTC in Gear, t_cHG	t_cHG = d_HG*[(t_c/d_G) + θ - θ_HG]	3.61943	mm	0.14250	inches

Fig. 3. Excel spreadsheet development

Fig. 4 depicts the flow diagram of the stated methodology and the table S2 provides the details on the parameters, its relevant formula and excel coding. Step 1 to Step 3 calculates and displays the output for pitch circle, addendum circle and the base circle. Step 1: In this step the circular pitch and the pitch circle diameter and radius of pinion, gear is calculated. Step 2: The addendum circle and addendum radius are calculated and displayed in their appropriate cell. Step 3: Calculation of contact ratio, mf, determines the average number of teeth in contact while the teeth comes and goes out of contact with its mating gear. In other words, determining the ratio of the angle of action to the angular pitch. Step 4: Calculation of LPSTC of pinion; Step 5: Calculation of LPSTC of Gear; Step 6: Calculation of HPSTC of pinion; Step 7: Calculation of HPSTC of Gear, Finally, the calculated values are displayed in the appropriate cells. Step 8 and 9: Calculates the circular tooth thickness of pinion at LPSTC and HPSTC.

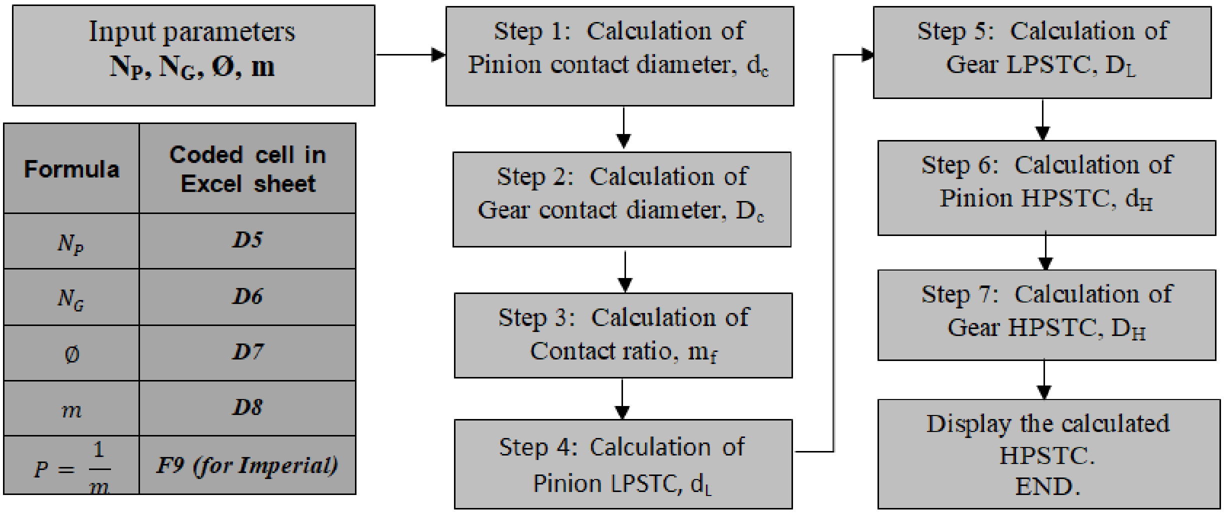

Fig. 4. Methodology for HPSTC calculation

Validation of the Excel Spreadsheet

To validate the developed excel spreadsheet, two case studies were conducted. The input parameters taken into consideration were referred from the previous research works [18, 19], and it is provided in the table 1 and table 2. Further, in the same table, the calculations pertaining to the HPSTC and LPSTC, were completed through spreadsheet and the outputs are displayed in the respective rows. The major stages and the results of the parameters obtained are: r_{bG}, r_{bP}, m_f, r_{cG}, r_{bG}, r_{cP}, r_{LG}, r_{LP}, r_{HG} and r_{HP}.

Results and discussion

A closer comparison reveals is discussed herewith. In case 1, the input gear and Pinion teeth are 18 are 18 respectively. The standard pressure angle with 20° and module 1.5 is considered. In this scenario, the HPSTC radius for pinion and gear are both noted to be 13.89. It is observed the previous research work [18], has determined this value to be 13.89 and hence there is no deviation in the results calculated through the excel spreadsheet. This indicates that the tool can be put in use for calculating the HPSTC and LPSTC parameters of the gear.

Table 1. Comparison of results from previous work and Excel Spreadsheet

Input parameters				Results obtained from Excel									Previous work [18]
N_G	N_P	ϕ	m	r_{bG}	r_{bP}	m_f	r_{cG}	r_{cP}	r_{LG}	r_{LP}	r_{HG}	r_{HP}	r_{HP}
18	18	20	1.5	12.68	12.68	1.52	12.74	12.74	13.18	13.18	13.89	13.89	13.89
35	25	20	2.0	32.88	23.49	1.64	33.67	23.76	34.69	24.63	35.40	25.33	25.33
36	36	20	1.5	25.37	25.37	1.69	25.95	25.95	26.77	26.77	27.24	27.24	27.24
80	35	20	6.0	225.52	98.66	1.75	235.31	100.62	239.47	104.08	240.96	105.53	105.54
80	80	20	20	751.75	751.75	1.82	783.20	783.20	798.25	798.25	801.77	801.77	801.77

Table 2. Comparison of results from previous work and Excel spreadsheet

Input parameters				Results obtained from Excel									Previous work [19]
N_G	N_P	ϕ	m	r_{bG}	r_{bP}	m_f	r_{cG}	r_{cP}	r_{LG}	r_{LP}	r_{HG}	r_{HP}	r_{HP}
45	25	20	2	42.28	23.49	1.67	43.60	23.74	44.73	24.63	45.40	25.27	25.27

Conclusions

A closer comparison reveals that there is no deviation in the results calculated through the excel spreadsheet. This indicates that the tool can be put in use for calculating the HPSTC and LPSTC parameters of the gear. This would reduce the time required for calculations and not only that the study will help in identifying the coordinates points on involute where the gear is load, thereby pave easier way in the gear analysis. It is noted that Excel spreadsheet in Microsoft Office allows the integration of gear calculations supporting the traditional mechanical engineering design. Further this work can be extended to carryout Lewis approach with AGMA standards to find the bending stress manually and stress analysis can also be carried out through ANSYS mechanical APDL.

Nomenclature

Symbol	Explanations
a	Addendum, *mm*
b	Dedendum, *mm*
d	Pitch circle diameter, *mm*
d_b	Base circle diameter, *mm*
d_{bG}	Drive side base circle dia of Gear, *mm*
d_{bP}	Drive side base circle dia of Pinion, *mm*
d_{cG}	Contact diameter in Gear, *mm*
d_{cP}	Contact diameter in Pinion, *mm*
d_G	Pitch circle diameter of Gear, *mm*
d_{HG}	HPSTC diameter in Gear, *mm*
d_{HP}	HPSTC diameter in Pinion, *mm*
d_{LG}	LPSTC diameter in Gear, *mm*
d_{LP}	LPSTC diameter in pinion, *mm*
d_{oG}	Addendum circle diameter of Gear, *mm*
d_{oP}	Addendum circle diameter of Pinion, *mm*
d_P	Pitch circle diameter of pinion, *mm*
P	Diametral pitch
p	Circular pitch, *mm*
p_b	Base pitch, *mm*
r	Pitch circle radius, *mm*
r_b	Base circle radius, *mm*
r_{bG}	Drive side base circle radius of Gear, *mm*
r_{bP}	Drive side base circle radius of Pinion, *mm*
r_{cG}	Contact radius in Gear, *mm*
r_{cP}	Contact radius in Pinion, *mm*
r_G	Pitch circle radius of Gear, *mm*
r_{HG}	HPSTC radius in Gear, *mm*
r_{HP}	HPSTC radius in pinion, *mm*
r_{LG}	LPSTC radius in Gear, *mm*
r_{LP}	LPSTC radius in pinion, *mm*
r_{oG}	Addendum circle radius of Gear, *mm*
r_{oP}	Addendum circle radius of Pinion, *mm*
r_P	Pitch circle radius of pinion, *mm*
m	Module, *mm*
m_f	Contact ratio
N	Number of teeth
N_P	Number of teeth in Pinion
N_G	Number of teeth in Gear
θ	Involute angle, *degrees*
ϕ	Pressure angle, *degrees*
ψ	Roll angle, *degrees*
$\mathrm{A}, \alpha, \mathrm{B}, \beta, \mathrm{E}, \varepsilon, F, f$	Angles, *degrees*

Conflicts of interest

Authors declare no conflict of interest.

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