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Research Article

Investigation and Development of Non-Symmetric Gear System using Matlab Graphical User Interface (GUI) ® and Autodesk Inventor

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Abstract

The paper presents a method for developing non-symmetric spur gearing system. The tooth profile of this distinct gearing is formed by involutes having two different involute profiles with different diameters of the base circles. They have best performances in relation with the traditional one. Hitherto, its gear tooth doesn't adopt any specific standard or rather use any typical notation, as they are still under the research and development phase. Presently, development of a robust simulation tool which can consider different parameters of NSPG is of great importance. In the present work, an algorithm for the development of geometry of Non-Symmetric Pinion and Gear (NSPG) tooth and its complete tooth profile is proposed. The algorithm was executed through Matlab Graphical User Interface (GUI) coding. The GUI takes the major input parameters of NSPG. The output of calculated values of the gear parameters are displayed in their corresponding text blocks. A provision on the single tooth plot provides the plot of the tooth space of the pinion or gear. The complete gear profile is obtained through a mouse click of a pushbutton provided for pinion or gear plot. The output coordinates points X_n, Y_n, Z_n of the involute and trochoidal root fillet are stored in the Excel / Text files, which is imported to develop curve and 3D modeling of gear in Autodesk Inventor or similar such CAD software and the NSPG 3D Solid model was completed. The outcome proves worthy in investigating the critical geometric parameters of standard and non-standard spur gear system, and paves a way for static, dynamic stress analysis and kinematic analysis. This tool can be extensively used by gear designers, educators, who are desirous of designing high performing gears, which can be developed with lowest possible time, that much reduces the design cost and time to market.

Keywords: Non-Symmetric Pinion and Gear; Graphical User Interface; Autodesk Inventor; Involute coordinates; Trochoidal root fillet coordinates; Forward and inverted involute.

Introduction

In many real-time gear applications, the gear power transmission and loading pattern is unique. It is widely observed that the many applications of gears require only either forward or backward rotation during operation. Few specific examples include road equipment's, internal combustion engines, water or gas turbines, reduction gears of wind turbines, etc., In all these cases, the performance during the forward motion is not same as the reverse motion. To satisfy this requirement, Non-symmetric gear system came to existence, which is characterized by profiles with different pressure angles on the forward and inverted sides. These types of gears have recently received much attention on their applications of high load-carrying capacity. The design concept of NSPG tooth has actually been around since 18th century as a method to reduce tooth bending stresses. It is evident that the gear industry and the gear tooth researchers are constantly required to provide best performing gear transmissions. This would be possible only with Non-standard gears, where nonstandard parameters are involved. A critical literature review depicts that, researchers have proposed different approaches for determining the coordinates of the involute profile of non-symmetric gears. But yet these approaches have not been unified. Author [1] has developed the basic asymmetric tooth geometry in which the formulae and equations for generating rack and gear parameters were determined. A mathematical model for asymmetric spur gears with involute

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teeth based on the gear theory and generating mechanism is provided in [2].

The performance of asymmetric teeth profile was analyzed in terms of mechanical power transmission in [1,3] which describes the design and optimization procedure for asymmetrical gears which can improve the fillet load carrying capacity in bending for applications other than in hydraulic gear machines. [3] Illustrates the design process of asymmetric teeth, showing also the potentials of this design for reducing the vibration levels, increasing the load capacity. A method of modeling the spur asymmetric gearing, where the gears are formed by gears with involute asymmetrical teeth having two different involute profiles with different diameters of the base circles is presented by [4]. They have utilised MATLAB and AutoLISP applications for executing the mathematical model.

As evident, standards like AGMA and ISO are available for designing standard gear with symmetric profile and conventional approach. In all these approaches, the tooth profile of a symmetric gear is obtained by involute generated from the base circle and limited by the outer circle and connected to fillet at the bottom. The forward and inverted side of profile is symmetrical and provides the similar performance during the forward and backward rotation. Non symmetrical gears are special gears that are characterized by asymmetric involute profiles of the tooth, having the involute generated from different diameters of the base circles of the opposite profiles [5, 11] limited by the outer circle on top and connected to the fillet at the bottom. A mathematical simulation of generation process for the symmetric and asymmetric involute gear teeth shapes based on the principle of the gear shaping process with a rack-shaped cutter has been developed. This also accounts the use of profile correction on each side of tooth with different design parameters for each side of tooth [6].

An algorithm for Involute Spur Gear Development by Parametric Technique Using Computer Aided Design has been proposed by [7, 12]. In their work [3] have developed non-standard rack cutters for the generation of asymmetric tooth profiles. They have concluded that there is no major significant change in the maximum fillet stress noticed in their work and with that of the direct design method proposed by [8, 10]. Matlab is well known for its problem solving power, traditionally programs written by engineers have very simple interfaces, and often only the author is the one who uses the program once it is completed. There are occasions where a more polished user interface, specifically a graphical user interface (GUI) is desired. [9, 11].

In the present investigation, a thorough literature review and analysis was carried out which reveals that there are no dedicated Graphical User Interfaces (GUI) existing for designing the NSPG systems. Moreover, the following major gap areas or need have also been identified, that need to be addressed to achieve high performing gears. It is of extreme necessity and importance, a robust tooth geometry / shape development and analysis is required to be designed and developed. This is because the existing system witnesses major drawbacks during gear design and development stage with many disadvantages. The gear designers face difficulty in understanding NSPG systems due to its inherent complexity. The design is iterative and time consuming process due to its huge ream of calculations. By specifying data for input the gear unit should be designed using calculation algorithms in accordance with any specified standard similar to DIN 3990. The NSPG tooth profile neither reflect to any specific standards recommended by professional bodies (AGMA, ISO, JIS, DIN, AFNOR, BS, BIS etc.,) nor specify typical notation or nomenclature, as they are still under research and development phase.

As like conventional gear design the addendum and profile modification is very complex and there is no specific standalone software commercially available in the market to design NSPG. The soft tool should perform strength calculation based on the modified Lewis form factor. These types of gears have recently received much attention on their applications and the design concept of non-symmetric gear tooth is acknowledged as one of the method to increase strength of the gear in metal and plastics. This tool should be capable of considering the different parameters of NSPG, calculate and publish the output parameters with graphical display having potential of using it for industrial and educational purposes.

Materials and methods

Nomenclature of Involute Profile

The nomenclature that is used in the involute curve development is shown in figure 1 and it is summarized in Table 1. The tooth profile is designed to have involute as generated from the base circle in figure 1, and a trochoidal root fillet. In figure 2, 2D single tooth profile is considered to be with four curve regions namely, a) Forward side involute profile EF b) Inverted side involute profile AB c) Forward side fillet arc - EG and d) inverted side fillet arc AC. A mathematical model based on the parametric equations of involute profile and fillet arc is developed.

Table 1. Nomenclature of NSPG involute profile

Symbol	Explanations
$\bar{r}(\theta)$	The radius at any point on the involute profile
$x(\theta)$	The 'x' co-ordinate of a point on the involute curve
$y(\theta)$	The 'y' co-ordinate of a point on the involute curve
m	module of the Pinion/Gear, mm
z_p	Number of teeth on Pinion
z_g	Number of teeth on Gear
α_f	Pressure angle of forward side profile of pinion, degrees
α_i	Pressure angle of inverted side profile of pinion, degrees
α_f_g	Pressure angle of forward side profile of Gear, degrees
α_i_g	Pressure angle of inverted side profile of Gear, degrees
a	Addendum of the pinion/Gear, (= α m, usually α is equal to 1.25)
b	Dedendum of the pinion/Gear, (= β m, usually β is equal to 1)
r_c	Tip radius of the pinion /Gear, (=γ m, usually γ =0.25)
X	Addendum modification coefficient, X=e/m, where e- cutter offset
N_{ab}, N_{ef}	Number of points on Forward and inverted (Left & right portion) of the involute curve
N_{ac}, N_{fg}	Number of points on the Left and right portion of the fillet curve
N_{be}	Number of points on curve BE

Figure 3 depicts the phases of NSPG GUI development. The GUI development has three phase approach, initial analysis phase, intermittent phase and prototyping phase. Where, user requirement and critical specifications of NSPG, design layout, real development and testing of GUI is completed. To make the GUI more effective, the components, tasks, and sequence are followed properly. Figure 4 represents the stages of NSPG GUI design and Prototype. During every stage the following were fulfilled through the consideration of the concerns like a) reduce the demands on the user b) match the user's workflow c) take the advantage of accepted interface standards d) provide flexibility e) quickly go back and forth f) not overwhelm gear designer. The Forms of GUI are planned that consider aspects like appearance, tools to be incorporated, support and help provision, interactive modes, etc., the prototyping exercise in the simplest way which was carried out using a paper and a pencil. The layout sketch of the design is hand drawn, which serves as the primary basis of the work.

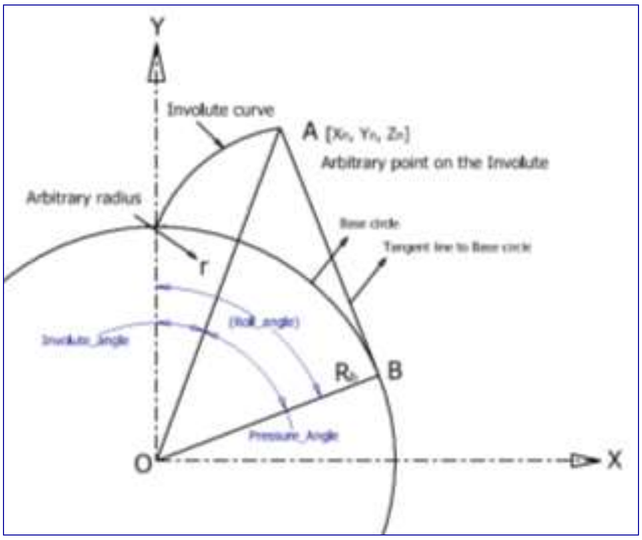

Figure 1. Defining involute Profile

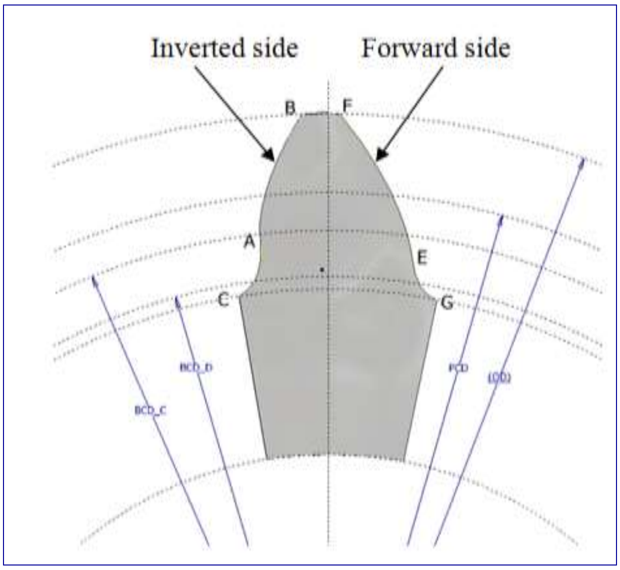

Figure 2. NSPG-2D Single tooth profile

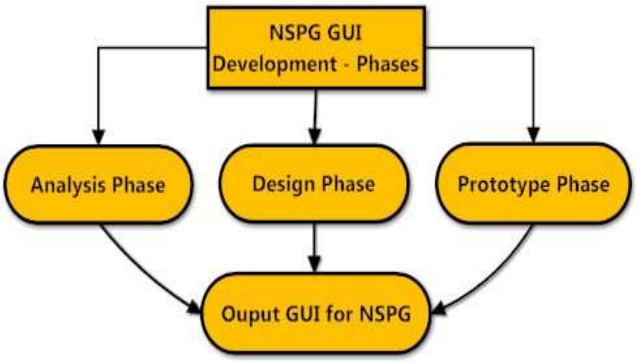

Figure 3. NSPG GUI Development Phases

Algorithm for NSPG design and Involute coordinates

An exclusive algorithm referred in figure 5, is developed with distinct objectives and step by step procedure. At appropriate juncture iterations and looping is provided, which is self-explanatory. The inputs essential for the gear design are collected and processed and finally outputs are planned to be of graphical format. Similarly an algorithm for XYZ coordinates is also developed, refer figure 6.

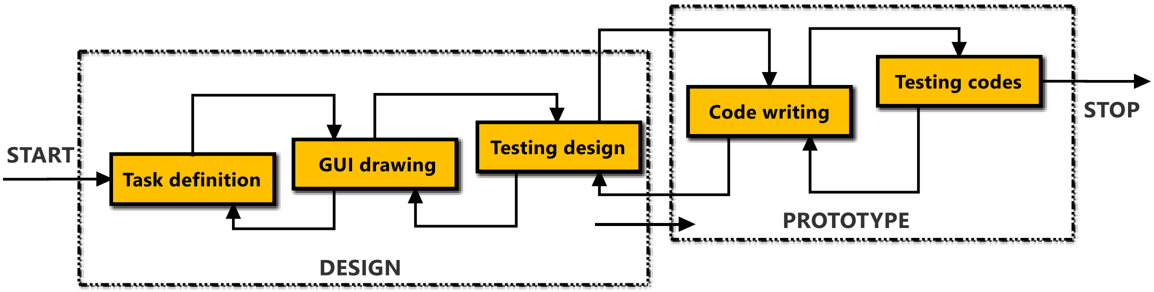

Figure 4. NSPG Design and Prototype

Design and Development of NSPG Form

This form is based on the algorithm indicated in figure 5. The input parameters for the NSPG, figure 7, are taken through two panels namely, Non-Symmetric-Pinion and Non-Symmetric Gear. The said input is collected at the edit boxes in three ways. a) This form is linked through other where the inputs for pinion and gear are already available through the designer input. One such resource is through the data NSP module push button, which brings in the number of teeth (z_p) and the module (mm) from the previous Module calculator form (not indicated in this paper). b) Manual entry of data in each of the edit box by filling the customized data. c) Third way is to get the input from the demo (GUI provides four different demo inputs). Through mouse click, these bring in the values in the edit box once at a stretch.

Input and output Parameters to NSPG

The major inputs that are essential for the geometry design of non-symmetric pinion / gear are; Number of teeth, Module, Drive side pressure angle, Coast side pressure angle, Addendum factor (considering hob), Dedendum factor (considering hob), Variation coefficient, Number of points for involute and root fillet development. In the output parameters the values calculated based on the formula is displayed by mouse click of "Calculate All" push button. The major parameters that are calculated and displayed for the non-symmetric pinion / gear are; Base circle, Pitch circle diameter for the forward and inverted side, addendum and dedendum radius, Profile angle at outer and at tip diameter for the forward /inverted side. The parameters that are common to both pinion and gear are calculated and displayed in panel. They are; Circular pitch, Base pitch, Contact length, Contact ratio, Center distance, Speed ratio, Drive / coast side tooth thickness at PCD for pinion, Root tooth thickness and Radius of HPSTC. The calculate panel has three push button for calculating and clearing the entries. The Calculate All, button makes the calculation and displays the calculated output at their respective edit box. A popup message appears indicating that verify the calculated output for NSP and NSG. The "Clear Output Only" push button upon activation clears all displays at the output edit box, but still inputs are available for further editing of any parameters. The "Clear All" push button clears all entries in the NSPG form. Apart from this panel provides the links to other forms that are relevant to the design through the push buttons. They are; a) *XYZ Pinion / Gear Involute AB:* This form displays the coordinates of the forward side of the involute. By default 20 points are displayed. b) *XYZ Pinion / Gear Involute EF*: This form displays the coordinates of the inverted side of the involute. Here again, default 20 points are displayed. c) *XYZ Pinion / Gear Fillet AC*: This form displays the coordinates of the forward side of the fillet. By default ten points are displayed. d) *XYZ Pinion / Gear Fillet FG*: This form displays the coordinates of the inverted side of the fillet. Here again, default ten points are displayed.

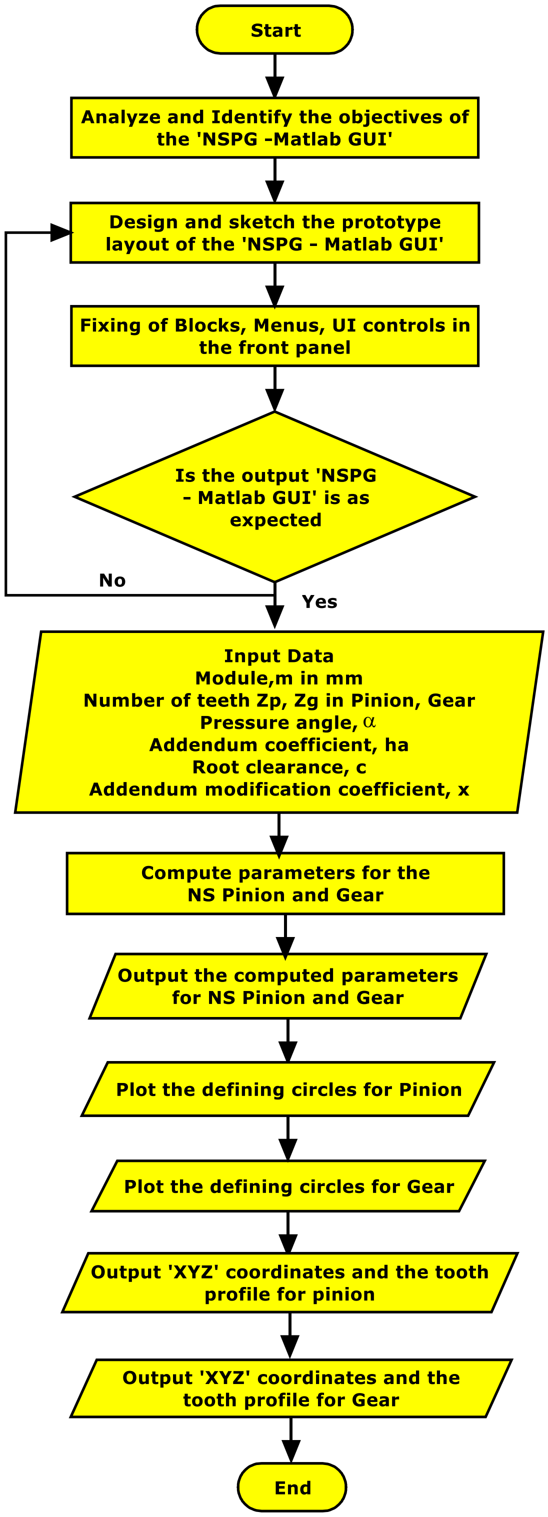

Figure 5. Algorithm for NSPG development

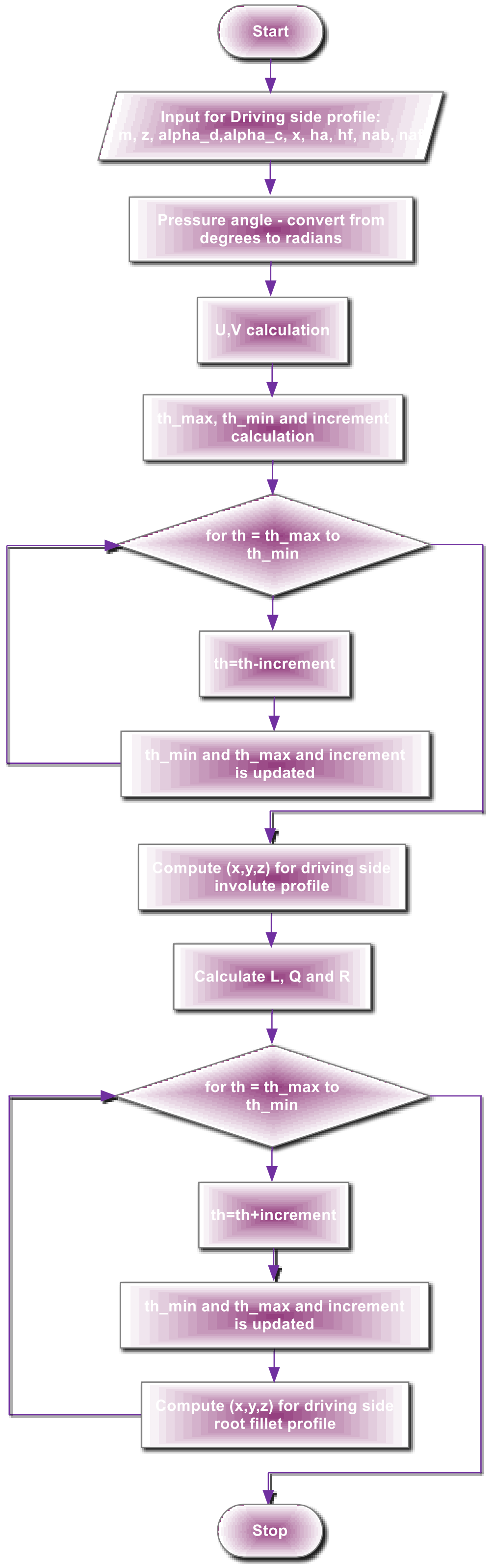

Figure 6. Algorithm for XYZ coordinates

Visualization of Pinion / Gear parameters

The reference circles like Outer circle, Pitch circle, Base circle, are plotted and displayed. It is to note that the intersections of involute with the circles are also displayed for better understanding. The final output along with the fillet radius is also plotted. Similarly, single tooth profile is rotated and it is rotated through 360 degrees to form the complete 2D view of the gear profile. The involute intersection of the forward and inverted profile of pinion and gear is calculated and displayed. This point helps in finding the profile angle that is used in most of design calculations.

E Panel – Export panel

This panel provides link to the commercial software's. The export of XYZ coordinates of involute is transferred through the *.xls, *.csv *.txt files. The software's that are linked through the push button click are; Autodesk Inventor, Solidworks, Pro Engineer, ANSYS, ANSYS Workbench, Abaqus etc., A separate provision for save / open / print are provided. The output from Autodesk Inventor is shown in figure 11. The gear with 3 module, 16T, 1:1 with 30/20° pressure angle and correction factor 0 and fillet radius 0.3. The line of action is constructed to check for the conjugate function of the non-symmetric gear.

Pinion XYZ Coordinates Form

This GUI layout is designed that the form serves the purpose of calculating and displaying the coordinates of the involute portion of NSP. The equation 8 and 9 calculates the involute coordinates. Similarly 5 and 6 are used in calculating the fillet coordinates. This is done through the algorithm depicted in figure 6**.** The layout has four panels namely XY coordinates of forward and inverted involute profile of pinion**.** On the extreme right side the input for the pinion is gathered, the input is linked with the previous forms**.** Alternatively the inputs may be provided by the designer, meaning that the form can work in standalone mode to provide the involute coordinates. The fourth panel is the calculate XY panel, which is provided with five push buttons**.** The pull down menus is provided at the top, for the file options like New, save, save as, and Exit. Demos having sample inputs for understanding the working mode of the GUI is provided**.** The coordinates are calculated and displayed through the 'coordinates' pull down menu**.** The coordinates are displayed in the edit box and could also be exported and saved in an excel file through click on the push button and refer to the X, Y and Z coordinates of the involute.

Mathematical formulation of NSPG

The research work presented follows the involute theory presented in Gear Geometry and Applied Theory. A hob tool is developed and mathematically revolved around a gear is used by various authors. The major formulae involved in the development of the involute profile with sample calculations are detailed below. The involute function is expressed indicated in equation 1.

$$inv(\alpha_{ocp}) = tan(\alpha_{ocp}) - (\alpha_{ocp}) \qquad (1)$$

$$inv(20) = tan(20) - \left(20 * \frac{pi}{180}\right)$$

$$0.364 - 0.349 = 0.015$$

Where, $\alpha_{ocp} - in\ radians$

Considering $\alpha_{ocp} = 20°$, then

The coefficient of asymmetry (K)

$$K = \frac{D_{bcp}}{D_{bdp}} = \frac{\cos\vartheta_{cp}}{\cos\vartheta_{dp}} = \frac{\cos\alpha_{ocp}}{\cos\alpha_{odp}} \qquad (2)$$

Parametric representation of the involute

The existing formulas are extracted and used in this work. The parametric representation coordinates of the involute profile (curve AB and curve FE) is given by the radius, $\bar{r}(\theta)$ at any point on the involute profile is,

$$\bar{r}(\theta) = \begin{Bmatrix} x(\theta) \\ y(\theta) \end{Bmatrix} \qquad (3)$$

Parametric representation of the fillet

The parametric representation coordinates of the fillet profile (curve AC and curve EG) is given by the radius, $\bar{r}(\theta)$ at any point on the involute profile is,

$$\bar{r}(\theta) = \begin{Bmatrix} x(\theta) \\ y(\theta) \end{Bmatrix} \qquad (4)$$

Where the coordinates of the involute curve is given by the equation (14) and (15),

$$x(\theta) = m(P\cos(\theta) + Q\sin(\theta)) \qquad (5)$$

$$y(\theta) = m(-P\sin(\theta) + Q\cos(\theta)) \qquad (6)$$

The parameter θ, in radians, of the fillet curve is limited to the following range.

$$\theta_{min} \le \theta \le \theta_{max} \qquad (7)$$

Where the coordinates of the involute curve is given by the equation (8) and (9),

$$x(\theta) = \frac{Nm}{2}\left\{\sin(\theta) - \left[\left((\theta) + \frac{\pi}{2N}\right)\cos(\emptyset) + \frac{2X}{N}\sin(\emptyset)\right]\cos(\theta + \emptyset)\right\} \quad (8)$$

$$y(\theta) = \frac{Nm}{2}\left\{\cos(\theta) - \left[\left((\theta) + \frac{\pi}{2N}\right)\cos(\emptyset) + \frac{2X}{N}\sin(\emptyset)\right]\sin(\theta + \emptyset)\right\} \quad (9)$$

Results and discussions

The figure 7 Indicates the collected sample input collected / retrieved from other forms of the NSPG gear design tool. This is worked out for 18 teeth with 7.5 module, 30/20° pressure angle. The output parameters are calculated and displayed which can be checked for its accuracy. The common parameters like contact ratio, centre distance, gear ratio etc., are also presented. The tooth profile, its intersection, intersection coordinates are displayed in the separate plot window. Finally the file is saved in the directory for future retrieval for analysis and optimisation. A separate GUI indicating the XYZ coordinates is seen figure 12, and its output in Table 2 and 3. Figures 8 is the output plot of single tooth plot and its rotation based on the number of teeth. Apart from the forward and inverted side involute profile, the top land for the NSPG is also completed. Further, figure 9 and figure 10 are the completed output of 2D profile of the non-symmetric pinion and non-symmetric gear. In this the trochoidal root fillet is also completed. Figure 11 is an assembly of NSPG system which is created in Autodesk Inventor.

Figure 7. Input and calculated for NSPG

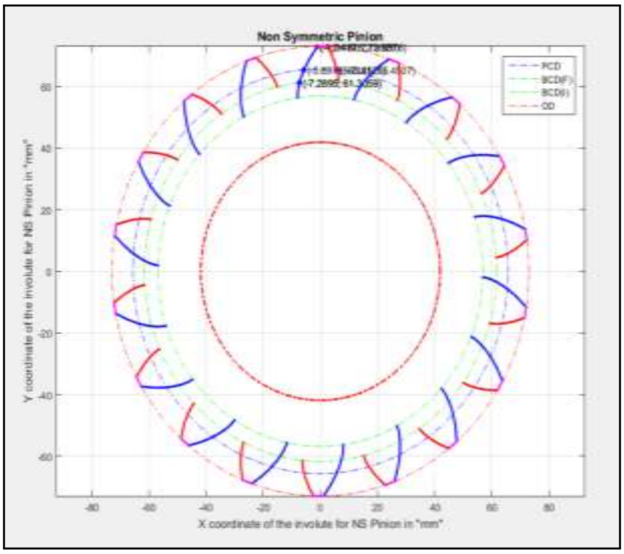

Figure 8. NSP tooth profile

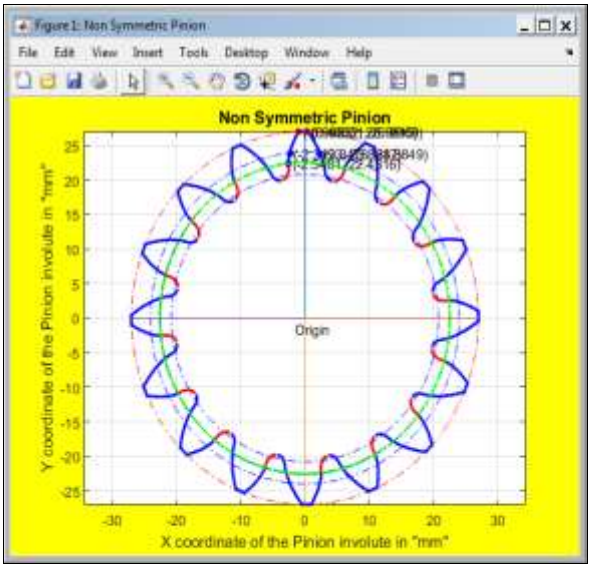

Figure 9. NSP tooth profile

Table 2. Coordinates of Involute

Involute left coordinates 20 degrees			Involute right coordinates 30 degrees		
X	**Y**	**Z**	**X**	**Y**	**Z**
-3.0262	21.888	0	2.5502	22.559	0
-2.9865	22.065	0	2.5489	22.639	0
-2.9399	22.252	0	2.5447	22.734	0
-2.8859	22.449	0	2.5368	22.846	0
-2.8241	22.655	0	2.5242	22.974	0
-2.7539	22.871	0	2.506	23.119	0
-2.675	23.096	0	2.4815	23.279	0
-2.5867	23.33	0	2.4497	23.455	0
-2.4888	23.572	0	2.4097	23.646	0
-2.3806	23.822	0	2.3607	23.852	0
-2.2619	24.08	0	2.3018	24.073	0
-2.1322	24.345	0	2.2323	24.308	0
-1.9911	24.617	0	2.1513	24.556	0
-1.8381	24.896	0	2.0581	24.819	0
-1.673	25.181	0	1.9517	25.094	0
-1.4952	25.472	0	1.8316	25.381	0
-1.3046	25.768	0	1.6969	25.68	0
-1.1007	26.069	0	1.5469	25.99	0
-0.883	26.375	0	1.3809	26.311	0
-0.652	26.684	0	1.1983	26.642	0

Table 3. Coordinates of Involute

Involute left coordinates 20 degrees			**Involute right coordinates 32 degrees**		
X	**Y**	**Z**	**X**	**Y**	**Z**
-3.15293	21.754	0	2.5502	22.559	0
-3.10297	21.946	0	2.5489	22.639	0
-3.04558	22.147	0	2.5447	22.734	0
-2.9803	22.357	0	2.5368	22.846	0
-2.90668	22.575	0	2.5242	22.974	0
-2.82428	22.803	0	2.506	23.119	0
-2.73267	23.038	0	2.4815	23.279	0
-2.63142	23.282	0	2.4497	23.455	0
-2.52012	23.533	0	2.4097	23.646	0
-2.39836	23.791	0	2.3607	23.852	0
-2.26576	24.056	0	2.3018	24.073	0
-2.12192	24.328	0	2.2323	24.308	0
-1.96648	24.605	0	2.1513	24.556	0
-1.79908	24.889	0	2.0581	24.819	0
-1.61938	25.178	0	1.9517	25.094	0
-1.42703	25.472	0	1.8316	25.381	0
-1.22172	25.770	0	1.6969	25.68	0
-1.00313	26.072	0	1.5469	25.99	0
-0.77099	26.378	0	1.3809	26.311	0
-0.52499	26.687	0	1.1983	26.642	0

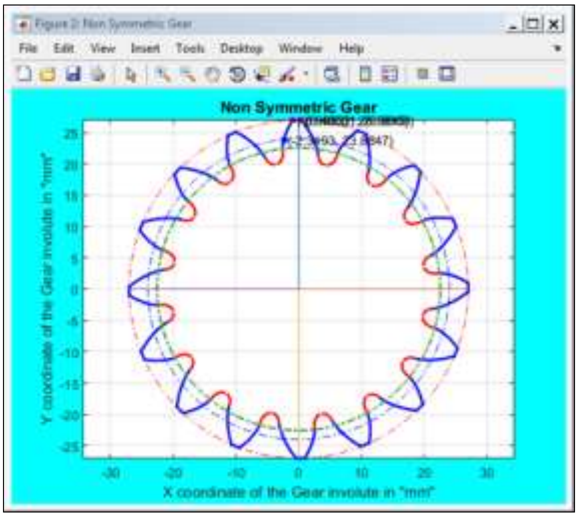

Figure 10. NSG tooth profile

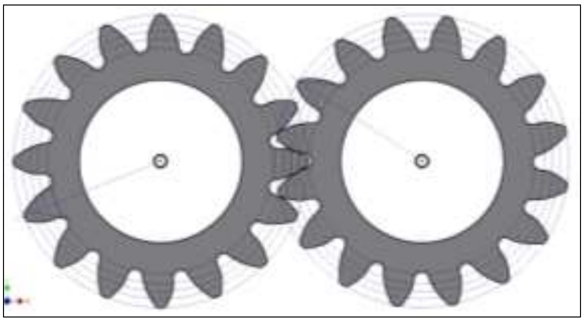

Figure 11. Assembly of NSPG

Conclusions

The present work has successfully developed an algorithm that supports design and development of standard and non-standard non-symmetric gear systems. The algorithm was embedded in Matlab® GUI using GUIDE tool and appropriate coding. Prior to the development an investigation on the existing research works on asymmetric gear tooth systems was carried out. This NSPG GUI can work exclusively or collectively with other forms. The following the benefits are reported from this work. a) The user interface is kept very simple and user friendly, b) The working of NSPG tool does not require Matlab installation and it can work as a standalone soft tool after bundling, c) Help files/demonstrations/context help is provided on the appropriate juncture, which supports the gear designer to use the soft tool systematically, d) This supports Gear design engineers / educators, who are serious of designing high performing gears of non-standard gear systems, e) Machine design engineers who are involved in conventional and non-standard gear applications, e) Product designers, who are interested in developing high strength gears with lower volume and lighter weight applications, f) Students who are involved in gear design study and solving related problems. Mainly, this work outputs and plots the XYZ coordinates of the involute and fillet curves, which could be imported in many of the commercial CAD modeling packages. A specific case of 3 module, 16 teeth with pressure angle 20°/30° gear with trochoidal root fillet was considered and constructed whose coordinates were presented in the previous section. The involute coordinates was accurately transferred to Autodesk Inventor environment and output 3D model of Gear is developed as seen in Figure 11. Further, the developed model could further be used in stress analysis and kinematic analysis. Further, Contact ratio, Coefficient of asymmetry, Backup ratio, HPSTC, Tooth thickness of NSPG with different combinations of parameters can be studied using the developed GUI.

Figure 10. Gear XY coordinates form

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