CAD-Based Simulation of Gear hobbing

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ABSTRACT

Gear hobbing is a common method of manufacturing high precision involute gears. The thorough knowledge of the developing cutting forces and the wear of the cutting tool are of great importance in order to produce helical and spur gears as they influence the cost of the manufacturing process and the quality of the produced gear. A novel simulation code called HOB3D was created in accordance with the above. This code can simulate the complex movements involved in gear hobbing with the best available accuracy, which is achieved by embedding the developed algorithm in a commercial CAD environment.

KEYWORDS

Gear manufacturing, Gear hobbing, Cutting forces

INTRODUCTION

Every high performance gear transmission module is composed of involute gears. External involute gears can be manufactured with a series of methods of which gear hobbing is the most widely applied. A novel simulation code was developed aiming at the simulation of the gear hobbing process. This code, called HOB3D, can simulate the cutting process in a commercial CAD environment, thus producing results determined with the optimal precision.

STATE OF THE ART

Gear hobbing process, as opposed to turning and milling, is a sophisticated metal removal technology owing to the complexity of hobbing cutters geometry and the advanced kinematics of the process. The process is based on three relative motions between the workpiece and the hob tool. Due to the generating rolling principle, complex tool geometry, different chip flow mechanisms and complex kinematics, the simulation of gear hobbing process is quite difficult. A great number of experimental-analytical methods have been established in order to calculate the developing cutting forces and tool wear progress aiming to the process optimisation [1].
As in any cutting process, the predictability of machining parameters, such as cutting tool wear, cutting forces, etc., are of immense research and industrial importance in gear hobbing. For this reason, experimental and sophisticated numerical models [2, 3] are used to simulate the cutting process in order to determine the undeformed chip geometry. In the 1970s, the FRS code was built, calculating chip dimensions and cutting force components [4-5]. This approximation model is proposed for the determination of the hobbing process results, but the main characteristic of its method is the reduction of the actual three-dimensional process to planar model, primarily for simplification reasons. The application of this former approximation is leading to planar results, without to represent the exact solid geometry of the real chips and gears, with accuracy directly dependent from various input parameters such as the number of the calculation planes [6]. Furthermore, any post-processing of the extracted chip and gear planar geometries, e.g., finite element analysis, requires additional data processing which leads to supplementary interpolations of the two-dimensional results. Nowadays, FEM and CAD software packages support chip removal calculation and analysis, while others have been developed to assist with the determination of data such as chip geometry, cutting force components, mechanical stresses and wear performance [7-8]. Focusing on the realistic and accurate simulation of the gear hobbing process, a 3D approach for the simulation of manufacturing spur and helical gears is presented in this research paper.

GEAR HOBBING AND HOB3D SIMULATION PROCESS

The kinematics of gear hobbing consists of three relative movements between the workgear and the hob. These movements have to be synchronized in order to produce the required gear. The first movement, which is marked as 1 in the left picture of Fig. 1, is the rotation of the hob around its own axis. The second is the axial feed of the hob, marked as 2 and the last movement is the rotation of the workgear around its axis, marked as 3.

![Fig. 1: Basic kinematics of gear hobbing](image)

The geometry of a gear can be defined based on six parameters: modul (m), number of teeth \( z_2 \), outside diameter \( d_g \), helix angle \( h_a \), gear width and pressure angle \( \alpha_n \). In order to fully define the kinematic chain of gear hobbing, a series of other parameters must be established. These parameters are hob diameter \( d_h \), number of columns \( n_i \), number of
hob origins ($z_i$), depth of cut ($t$), axial feed ($f_a$) and cutting speed ($v$). Finally, there are more parameters such as the helix angle of the hob ($\gamma$) and the axial pitch ($\varepsilon$) which already exist or can be calculated. The setting angle of the hob relative to the workgear is of great importance in the process and is determined by the parameters mentioned above, being equal to the difference between the helix angle of the workgear and the helix angle of the hob. The direction of the axial feed ($f_a$) defines two different hobbing strategies: the climb hobbing (CL) and the up-cut hobbing (UC). In case of helical gears, two additional variations exist, arising from the comparison between the tool helix angle ($\gamma$) and the helix of the gear ($h_a$). If the direction of the gear helix angle is identical to the hob helix angle, the type of the process is defined as equi-directional hobbing (ED); if not as counter-directional hobbing (CD). The four different hobbing strategies are illustrated in Fig.2

![Fig. 2: The four possible kinematics of gear hobbing considering the direction of the axial feed and the applied gearing](image)

In order to simulate the process of gear hobbing, new software has been developed. The proposed simulation model has been embedded in a commercial CAD program, thus taking advantage of its accuracy, also resulting in more accurate calculations. The model is capable of calculating the undeformed chip geometry, the 3D gap geometry and the cutting forces involved in the production of spur as well as in helical involute gears. The new simulation code called HOB3D uses three coordinate systems in order to calculate the required results. The first (1) is positioned on the examined cutting edge and has the x axis parallel to the hob’s axis, the y axis perpendicular to x axis and finally z axis perpendicular to the prior two. Coordinate systems (2) and (3) have axis z running through the workgear’s
axis. In coordinate system (2), x axis is always rotating towards the direction of the gap center while the axes of coordinate system (3) are fixed.

The simulation process of HOB3D is initialised after the input of valid data. Due to the fact that the gear is axisymmetric, the simulation can be executed in one 3D gap thus reducing the simulation time. The first step is the calculation of the effective cutting hob teeth (N) for which the simulation is executed, as illustrated in Fig. 3. The concept of the simulation is
the creation of a 3D surface for each of the active teeth. This surface is developed by the hob’s rake edge paths in the 3D space including all movements required in order to simulate the process. This surface defines the intrusion of the specific cutting tooth on the 3D gap. In the next simulation step, the workgear and the 3D surface are assembled and the volume of the gear is split by the surface, thus defining the 3D chip and gap. The final step of the simulation is the determination of the time course of the cutting force components, which is performed with the use of Kienzle-Victor’s equations.

**HOB3D ALGORITHM**

As mentioned above, all the movements in HOB3D are transferred on the cutting edge. This means that a stationary gear and a hob rotating around it are simulated. In order to identify the cutting teeth, those are numbered. Tooth “0” is the tooth which has the local axis Y₁ parallel to local axis X₂ when it passes through the center of the gap. The tooth that passes after tooth “0” is named tooth “1” and the tooth previous to that is named Tooth “-1” respectively. Due to the symmetry of the gear, the chip produced by a specific tooth is the same in all the gear gaps.

![HOB3D Simulation Process Diagram](image)

After the calculation of the penetration curve and the determination of the active teeth, the simulation begins with the mathematical description of the cutting tooth rake edge according to DIN 3972 [11]. This profile is converted into arcs and lines in the CAD
environment in which HOB3D is embedded. The profile’s sketch is then correctly positioned in the 3D space for every step of the simulation.

A 3D point must be identified in order to position the profile in the 3D space correctly. This point is the center of the hob at that specific moment. The center of the hob’s movement forms a helix around the workgear. This helix has radius equal to \( L_2 = \frac{d_h}{2} + \frac{d_g}{2} - t \), pitch equal to \( f_a \) and its axis is the Z axis of coordinate system (2). The axis of the hob is calculated after taking into account the setting angle from this 3D point. This axis is used in order to find the plane of the cutting edge at that simulation stage. A 2D sketch is formed on the plane of the cutting edge. The coordinate system of the sketches has the axis of the hob as \( x \) and the axis that passes through the center of the hob as \( y \). The profile is positioned on the plane so that the distance between the center of the profile and the axis \( y \) is equal to \( n*e \), where \( n \) is the number of the tooth studied and \( e \) is the axial pitch of the hob. Furthermore, the distance from the hob axis to the tip of the cutting tooth is equal to \( d_h/2 \). This process is repeated for a series of times increasing the rotational angle of the hob (\( \phi \)) in every step. The result is a series of 3D placed profiles as presented on the second frame of the first line of Fig. 4. These profiles are combined resulting in a 3D surface that describes the movement of a specific tooth of the hob in the 3D space.

The 3D surface that was created is assembled with the 3D gap generated from the previous tooth. The positioning of the 3D surface on the assembly is accomplished by combining the two coordinate systems. The 3D surface path splits the volume of the workgear in two parts. The volume which is in the inner side of the surface is the undeformed chip, and the other is the 3D gap after that pass.

After the end of the simulation, the output is the final geometry of the 3D gap and all the undeformed chips in every step of the process. These chips can be analysed and data obtained regarding the maximum chip thickness, chip crosssection area and cutting forces.

HOB3D is also equipped with a fully functional user friendly graphical user interface where the user can enter the simulation data, keep track of the simulation course, view and analyse the results. The data entry window of the program is illustrated in Fig. 5.
HOB3D SIMULATION RESULTS

The developed simulation code was used to simulate the manufacturing process of a spur and a helical gear. The left frame of Fig. 6 illustrates the solid chip geometry produced at the generating position Gp=0 on a spur gear. The solid chip was sliced in the planes of the rake edge revolving positions. The crosssection area (A) and the maximum chip thickness (h_max) were calculated. The sliced solid chip is presented in the middle of the left frame of the figure. The crosssection area of the chip measured on the sections is presented on the right side, while on the left side of the figure’s left frame the maximum chip thickness is presented.

The solid chip geometry produced at the generating position Gp=5 on a helical gear is illustrated on the right frame of Fig. 6. Similar to the previous chip, this helical chip was also sliced in order to identify the crosssection area (A) and the maximum chip thickness (h_max).
Fig. 6 – Chip solid geometry characteristics

On the top section of Fig. 7, the chips that were produced during the simulation of the manufacturing of the spur gear are presented. As it can be observed, in order to form the final 3D gap, 30 teeth participate in the cutting process.

The process of cutting, as it can be observed from the 3D chips, begins with thin chips taken only from the leading flank. Next, the head of the cutter enters the machining process followed by the trailing flank. The cutting process continues in this manner until Gp=2 where the chip is divided and after a while the head of the cutter stops cutting. Eventually the chips become thinner and gradually the leading flank stops cutting followed by the trailing flank.

The solid chips for the helical case are presented in the bottom section of Fig. 7. The machining simulation of this case was realised with a three origin hob. As it can be easily noticed, the cuts required to produce the gap are considerably fewer than the ones in the spur case. In the case of the helical gear there are 18 generating positions. The main reason for this fact is the increased number of origins which produces fewer and thicker chips. The process of cutting starts with the leading flank as well but it is followed immediately after by the trailing flank and the head starts to cut from the side of the trailing flank. The two volumes of the chip are unified in Gp=1. As the machining process continues, leading and trailing flanks stop cutting leaving only the head of the cutter operating at the last GP.
In the above figure the produced results from the simulations including the 3D gaps are presented. These gaps were verified using the standard gap profiles introduced by Petri [12]. In the case of the spur gear, a section was made parallel to the $X_2Y_2$ plane, while in that of the helical gear the section was inclined relative to the $X_2Y_2$ plane in order to acquire the normal 3D gap. As it can be observed in the fig.8, the difference between the flanks of the simulated gear and the analytical ones is quite small, equal to $5 \cdot 10^{-3}$ mm in the case of the spur gear. On the helical gear, as it can be observed in the fig.9, the difference between the analytical and the simulation flanks is greater, equal to 0.1 mm. The contributing factor is the increased number of hob origins which led to fewer penetrations of the cutter in the 3D gap, thus reducing its quality.
Fig. 8 – Comparison between the simulated and the analytical flanks of spur gear cutting

![Diagram of gear tooth and difference graph]

- \( m = 4 \text{ mm} \), \( \alpha_n = 20^\circ \), \( h_a = 20^\circ \), \( z_1/z_2 = 3/136 \), \( n_i = 9 \), \( f_a = -4 \text{ mm/rev} \), \( d_h = 150 \text{ mm} \), UC-ED Hob

Fig. 9 – Comparison between the simulated and the analytical flanks of helical gear cutting

![Diagram of helical gear cutting and detail A]

- \( m = 3.79 \text{ mm} \), \( \alpha_n = 20^\circ \), \( h_a = 0^\circ \), \( z_1/z_2 = 1/56 \), \( n_i = 9 \), \( f_a = 4 \text{ mm/rev} \), \( d_h = 150 \text{ mm} \), Climb Hobbing
CALCULATION OF CUTTING FORCE COMPONENTS WITH HOB3D

The prediction of the cutting force components is a crucial parameter in gear hobbing. HOB3D uses the equations of Kienzle-Victor so as to calculate the 3D components of the cutting forces based on the undeformed chip geometry. In order to calculate the cutting forces, a series of crossections are made on the 3D chip on the plane of the cutting edge, see Fig. 10, where the outline of the chip is obtained for each one of them. The section is discretised as seen in detail A. The discretisation is made with lines vertical to the cutting edge. For each elementary area, like the one highlighted in red in the middle line of Fig. 10, the cutting force components must be calculated.

The first step of the calculation is the identification of the elementary chip equivalent width and thickness, marked as b and h. The calculation is simple on the linear parts of the chip whereas it becomes more complex on the head of the cutter, where the elementary chip
takes an odd shape. This shape consists of one arc, two non parallel lines and one B-Spline and is simplified to a rectangular one with the use of geometric equations and integrals. Next, the Kienzle-Victor’s equations are implemented to produce the magnitude of the cutting force components on the cutting edge. The force’s point of application is in the middle of the elementary chip’s side which belongs to the cutting edge. The three force components are rotated in order to match the local coordinate system (1) and then added up in order to produce the total cutting forces on every crossection. After all the sections are calculated, the total forces on the tooth are obtained, as presented on the bottom of Fig. 10. After the calculation of the cutting forces on the coordinate system (1) the cutting forces are rotated with the aid of rotation matrices and the cutting forces on systems (2) and (3) are calculated.

In Fig. 11 an example of the above described procedure is illustrated. The crosssections made on the 3D chip that has been produced by the HOB3D are presented on the top right side of the figure whereas the chip thickness on six of the crosssections is illustrated on its left side. The cutting forces on coordinate system (1) are illustrated on the bottom line of the figure.

**Fig. 11 – Cutting force calculation in one Generating Position**

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CUTTING FORCE COMPONENTS VERIFICATION

The verification of the force calculation module was conducted using experiments carried out by Bouzakis [6]. The cases of climb and up-cut hobbing of a spur gear were examined and the cutting forces simulated on specific teeth were compared to the ones measured.

In Fig. 12 the results of the climb hobbing case is presented. As it can be seen, each column of the figure illustrates the measured and calculated cutting forces on one generating position. These cutting forces are measured on the coordinate system of the 3D gap (2). In most of the cases, the simulation code predicts not only the form but also the magnitude of the cutting forces. Especially in generating positions -6, and 2 the simulation results are almost identical to the ones measured.

![Fig. 12 – Comparison between calculated and measured cutting forces in climb hobbing](image)

Fig. 13 illustrates the simulated and measured cutting force components in four generating positions in the case of up-cut hobbing. The simulation results of this case confirm the validity of the calculation code, predicting the developed cutting force components in all three axes accurately.

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SUMMARY AND CONCLUSIONS

In this paper a novel simulation code for the manufacturing process of gear hobbing was presented. The simulation code, called HOB3D, was embedded on a commercial CAD environment and can simulate the cutting process accurately. The resulting gap was successfully verified using analytical equations. The cutting force components were determined based on the undeformed chip as calculated from HOB3D. The cutting forces where also verified through experiments.

Fig. 13 – Comparison between calculated and measured cutting forces in up-cut hobbing

REFERENCES


ASME Journal of Manufacturing Science and Engineering, 124 (2002), No. 4, pp. 784-791

ASME Journal of Manufacturing Science and Engineering, 124 (2002), No. 4, pp. 792-798


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