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3D modeling of a multi-operation machine drive with a spindle turret and an innovative bevel gear modeling procedure

Oleg S. Krol[1*]

[1]Volodymyr Dahl East Ukrainian National University, 17 Ioanna Pavla II str., Kyiv

Abstract

INTRODUCTION: This paper examines the problem of integrated automated design and 3D modeling of a mechanical drive for a multi-operation drilling-milling-boring machine with modular spindle heads. The task of integrated machining, including both roughing and finishing methods, is relevant for single-part and small-scale production.
OBJECTIVES: This work aims to improve the process of designing and 3D modeling a stepped mechanical gear drive and a spindle turret head of a multi-operation machine in an advanced integrated CAD environment.
METHODS: Techniques employed is based on procedures for generating layouts and kinematic diagrams for the stepped mechanical drive of a multi-operation machine tool, facilitating the creation of a 3D design project using the Creo Parametric CAD toolkit. For bevel gear transmissions, an innovative procedure has been implemented for constructing 3D models specifically for the case of circular teeth.
RESULTS: A preliminary design was developed for a MoM three-stage drive unit with a six-spindle turret, designed for milling, drilling, and countersinking operations in single-part and small-scale production. A 3D design of a three-stage gear drive with a turret head was created at the kinematic level. An innovative procedure for constructing a 3D model of a bevel gear with a circular tooth has been implemented.
CONCLUSION: Based on a Mechanism software application using the Power Drive option, completed 3D modeling of a rotary mechanism specialized design for transmitting motion and torque from the engine to the turret spindles. Innovative procedure is based on profiling by cutting a tooth groove, simulating the process of cutting teeth on a hobbing machine for spiral bevel gears. The construction process takes into account the changing cross-sectional shapes and sizes, with a helical surface-shaped cross-sectional trajectory.

Keywords: Machining center; Gear drive; Turret head; 3D modeling; Bevel gear; Innovative techniques.

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*Corresponding Author. Email: krolos.snu.edu@gmail.com

1. Introduction

One of the trends in the development of multi-operation machines (MoM) is the different organization of the workspace to ensure control over several axes of the main movement and feeds; facilitate the transportation of chips; and increase productivity based on the use of modular spindle units located in tool magazines and turret heads [1, 2].

Along with direct drives for machining centers in the Flexible Manufacturing System structure, new hexapod-type configurations offer a niche opportunity for all-purpose, MoM drilling-milling-boring type with mechanical drives [3, 4]. Such machines are highly effective in single-part and small-scale production with rapid product changeovers. For complex parts whose life cycle consists of both roughing and finishing operations, such machines with stepped gear drives are in demand.

High power transmission, reliability, and operation under variable loads are the rational applications of machine tool main drives using gearboxes [5]. Despite speed limitations, such drives can transmit high torques and have smaller overall dimensions.

In the structure of a gear drive, the most critical components and assemblies are the gears. The diversity of design types, labour-intensive technical preparation, and complex manufacturing technology pose several challenges for designers and technologists [6, 7]. The kinematics of the gear drive and the range of cutting modes (lower and upper limits of speeds and feeds) determine the technological component and the selection of optimal cutting conditions [8].

Innovative activities to search for new design options, more advanced gear-contour geometry, and new profiling algorithms are characteristic of machine-tool gear drives [9, 10].

The drive configuration with an autonomous spindle head provides higher machining accuracy, as the spindle assembly is affected by vibration and heat generated by the gearbox gears [11]. One high-performance option for an autonomous forming unit is a 6-spindle turret, the motion of which is transmitted via a bevel gear.

Trends in the development of multi-spindle turret heads (and multi-spindle drilling and tapping heads mounted in turrets) are aimed at increasing productivity, flexibility, and precision in metalworking [12]. Such turret heads are effective when simultaneously machining multiple holes, reducing cycle times, using servo drives, and implementing digital technologies.

Multi-operation machines with a stepped mechanical drive and a six-spindle head are characterized by a highly complex design process. This process accounts for up to 40% of the total technical preparation time for production. Creating a 3D design for the machine drive and multi-spindle head is equally challenging. Modeling bevel gears with circular teeth is particularly challenging in this regard. The choice of CAD software and specialized modules that will ensure the efficient development of the machine drive, its main components, and various mechanical transmissions is crucial.

Thus, this work aims to improve the process of designing and 3D modeling a stepped mechanical gear drive and a spindle turret head of a multi-operation machine in an advanced integrated CAD environment.

2. Literature review

The design and 3D modeling of MoM tool drives has been the subject of much research in the area of drive mechanisms, multifunctionality, and modular spindle heads that enable turning, milling, and drilling operations to be performed in a single cycle.

The machine's multifunctionality can be realized by using a main drive with an AC motor and a two-stage helical gearbox [13]. The authors solve a multi-criteria optimization problem to minimize the gearbox volume while simultaneously maximizing its efficiency. Three key design elements are considered as optimized variables: the first-stage gear ratio, as well as the gear ring width coefficients for the first and second stages. This implementation option ensures an increase in the spindle speed and torque range. This type of gear drive provides high torque during roughing and the implementation of finishing technology at high speeds of up to 1.2 10^3 min^{-1}, for a specific machine size with a 40-cone and a two-stage gear drive was considered as a limitation.

The design of a spindle drive that expands the range of constant power, including low-speed machining, is discussed in [14]. It is implemented as a motor-spindle, the functional characteristics of which depend not only on the design solution but also on the magnitude of the kinetic energy.

When creating new drive designs and forming units, it is necessary to construct a complex of three-dimensional assembly models. An integrated approach to creating such a complex is presented in [1, 15]. The authors adhere to the idea of building a modular modeling system based on three-dimensional models of parts and units of MoM milling type. Combining individual modules allows, firstly, to implement the initial stage of constructing various variants of their layouts. A special feature of these studies [15] is associated with taking into account the configurations of the rotation axes of the spindle heads and the movements of the feed drives. The scale of the work carried out is reflected in the development of the author's database (DB) system. A set of relationships in pairs of layout solutions - configuration of the axes of the forming heads, taking into account the configuration of the axes of the main movements of the basic machine units. The database is rationally structured; for example, there are corresponding DB sections for the designs of spindle units with face and end mills, as well as angular and rotary tables with workpieces. At the same time, the issues of constructing such a section of the database as multi-spindle heads, including turret heads, which are integral to the modular principle, are not considered in these works [15].

We will examine issues of automated design and modeling of machine tool drive mechanisms. Using the mechanical units of a horizontal machining center as an example, a comprehensive design and modeling procedure was implemented in CAE ANSYS Workbench [16]. The authors effectively utilize Creo Parametric CAD and the specialized Geometry Interface Workbench module in associative interaction with the developed geometric models. During the comprehensive study, a finite element analysis of static deformations was conducted, the results of which were used to improve the design of the machining center.

Two-dimensional and three-dimensional modeling of a two-support horizontal spindle assembly on radial thrust bearings mounted in tandem with preload in the form of two bushings of different heights [17]. Using an iterative procedure for calculating spindle rigidity using the FEM method, the behavior of the spindle assembly under variable load was studied. However, issues of modeling the spindle head, its positioning in the machine's working zone, and the influence of the mating mechanical transmission were not considered in this study.

An entire series of works is devoted to three-dimensional modeling and improvement of mechanical transmission designs, including various types of gears used in various mechanical engineering products and machine drives.

The efficient operation and increased durability of designed modular spindle heads directly depend on the technical characteristics and layout of the drive gears [18 19]. For general-purpose machines with a wide range of gear ratios and multi-axis machining, these studies pay close attention to bevel gears designed to transmit motion with a change in direction [20]. Therefore, increasing the durability and load-bearing capacity of main drive gears through the search for new layout and design solutions is a promising area of 3D and engineering analysis.

A significant body of work focuses on the 3D modeling and design optimization of mechanical transmissions and various types of gears used in machinery and machine tool drives. For instance, the authors of [21] note the absence of universal solutions capable of generating gears with complex tooth-surface geometries. At the same time, most software products provide only 2D graphical representations of gears, while CAD system libraries offer merely simplified models—typically based on standard profiles.

The work [22] by Byanovsky discusses the complex geometry of bevel gear tooth profiles, which is used to construct 3D gear models. The basic calculation procedure is based on calculating the tooth tip width and recommendations for the cutting edge radius in accordance with AGMA Standard 929-A06. This procedure involves selecting control points in accordance with the standard, which are used to determine not only the tooth tip thickness but also a sufficiently accurate tooth geometry. The accuracy of the obtained data is assessed by comparison with the actual physical part. The author emphasizes the need to include a method for creating a 3D gear model in appropriate integrated CAD systems in the designer's toolkit. The advantage of this approach is that it is independent of any machine settings, taking into account only the basic geometric parameters of the cutting tool, the workpiece, and the teeth themselves. It is from this set of points that reliable solid models are constructed, which are then used to study the gear's key characteristics.

In the study by [23], a program developed in the MATLAB environment is used to calculate the key design parameters of a bevel gear pair in accordance with the ISO standard. The results of this calculation are utilized to create a 3D model of the gears within a CAD system. The complexity of modeling bevel gears with curved teeth is highlighted, as the tooth geometry depends on the manufacturing technology—such as the use of a 5-axis milling machining center. In this context, the choice of CAD software and specialized modules is crucial for ensuring the efficient development of the machine drive, its main components, and various mechanical transmissions.

The study by [24] examines a novel approach to modeling bevel gears with circular-arc teeth. The author uses a tooth-generation method based on a constructed point array and coordinate-transformation matrices, emphasizing the importance of accounting for the gear manufacturing process. The tooth shape is created by removing a specific volume—determined by the cross-sectional profile—from the gear blank. The results were verified by assessing a discrepancy of approximately 7.1 μm, demonstrating the reliability of the proposed method.

However, increased reliability achieved through design often conflicts with technological advancements. For example, within the framework of the JSME RC-268 committee, a new bevel gear, the Invo-Planar [25], was developed. Its tooth flank is flat, and its transverse tooth profile is straight. This significantly simplifies the manufacturing process and reduces production costs.

Specialized equipment is also being developed in this area. For example, a Gleason Heller 5-axis machine, using the Heller uP-Gear CAM [26], is used to machine gears with optimal tooth flank geometry and contact patterns. Circular knives are used as the cutting tool to implement the gear cutting process from roughing to finishing operations. This method of cutting a simplified tooth flank contour enables tooth profiling using single-pass machining and significantly reduces the processing time for a standard gear contour.

Moreover, the tooth flank surface offers increased precision compared to curved tooth flank contours. This flank surface is formed by enveloping multiple trajectories of the tool's cutting blades. Furthermore, the advanced capabilities of 5-axis centers enable an express method for producing complex tooth flank contours.

A number of literary sources emphasize the absence of universal solutions for generating gears with complex tooth-surface geometries. Meanwhile, most software products offer only 2D graphical representations of gears, while CAD system libraries provide merely simplified models—typically based on standard profiles.

An approach similar to the one proposed in this article is presented in the work by [21]; it bases tooth-surface geometry on a software suite that simulates gear cutting using a generating rack profile. This approach was implemented for spur and helical gears within the Autodesk Inventor environment.

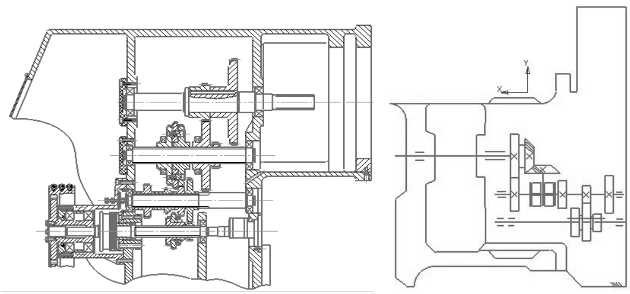
Thus, the analytical review of the research presented above demonstrates the potential of developments and procedures for 3D modeling of MoM with mechanical drives and modular spindle heads, particularly 6-spindle turrets. Advanced and innovative gear designs and solid modeling methods play a key role in creating efficient drives.

3. Sketch design of MoM drive

The design object is the main drive of a MoM vertical drilling-milling-boring type of the second model size. These machines are used in single-part and small-scale production and are designed for multi-operation machining of wide, frequently changing structures of complex-shaped parts made of steel, cast iron, light and non-ferrous metals. The machine can process vertical, horizontal, and inclined surfaces, shaped surfaces, holes, and grooves using various technological methods: milling, drilling, countersinking, and reaming. These machines are designed for both roughing and finishing operations.

The main drive of this machine is provided by a DC electric motor via a V-belt transmission to the gearbox (Fig. 1, a). These electric motors feature dual-zone speed control – down from the nominal speed at nominal torque, and up at constant power. This speed range and gear drive enable a wide range of machining operations, from roughing to finishing, ensuring a complete manufacturing cycle [27].

From the gearbox, rotation is transmitted to the spindle through a rotation mechanism using a bevel gear and a helical gear. The kinematic diagram of this mechanism is shown in Fig. 1, b.



a) b)

Figure 1. Sketch of the main drive

In the design of these machines, automatic tool change is implemented in various ways, one of which is the rotation of a six-spindle turret head (TH). The design of spindle assemblies and 3D modeling are discussed in [28, 29]. The tool is clamped using special clamping devices [30]. In this case, the tool is selected using special cams, and the head is rotated by means of a gear engagement using a hydraulic motor. Along with such TH advantages as high productivity due to the automatic change of six tool blocks and the performance of multi-operation machining of a workpiece from a single mounting, the ability to implement a full machining cycle for a complex part is very important. The developed TH design at the draft design stage is shown in Fig. 2.

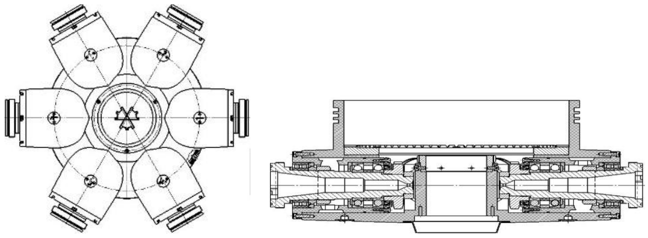
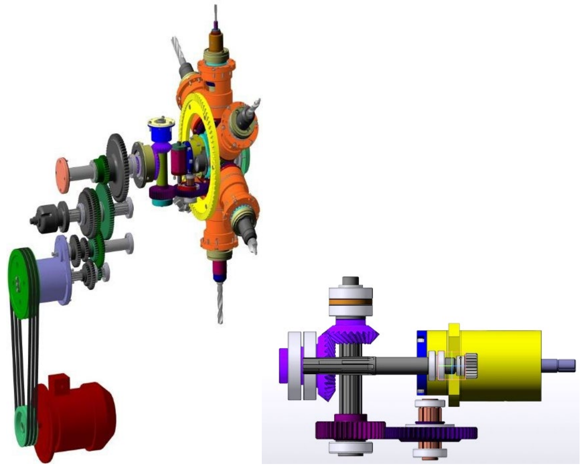


Figure 2. Six-spindle turret head

Torque is transmitted from the electric motor to the six-spindle turret head using various types of gears. The design and parameters of these gears limit the efficiency of the main drive and the machine as a whole. Design and modeling of pinions and gears of various types is accomplished using various integrated computer-aided design systems [31].

4. 3D modeling of MoM main drive

3D models of the gearbox and rotation mechanism of a six-spindle turret were constructed in Creo Parametric at the kinematic level. Figure 3 shows the 3D kinematic models, focusing on the kinematic chains of mechanical transmissions from the electric motor to the tool blocks of the milling and axial tools (drill, reamer, countersink, etc.).



a) B)

Figure 3. 3D kinematic models: a) main drive; b) turret head rotation mechanism

Modern CAD systems such as Creo Parametric have an extensive Standard Base and specialized modules [31] for designing, modeling and calculating mechanical transmissions: basic rack profile and series of modules (AGMA 201.02, ASAB6b, DIN 3972-52, ISO 53:1998).

The Specialized Modules reflect calculation and optimization methods for various types of gearing: cylindrical external gearing, rack and pinion gearing, and orthogonal gearing (with a cylindrical involute worm gear and a cylindrical helical gear). Calculations included in the modules include: contact strength, bending strength, wear resistance, and seizure resistance, among others.

To implement calculation operations and geometric constructions, it is effective to use the Creo Parametric CAD application, as reflected in the Mechanism tab. The application offers the option to select a Force Motor drive linked to the force and torque energy parameters from the Driven Quantity list. When constructing gear models, a complex set of loads can be used by entering numerical values for a user-defined load. It should be noted that the use of a Force Motor drive is limited to generating motion in the direction of a single degree of freedom (translational or rotational). This implies the need to assign Force Motors to each axis of motion for the machine's main drive (Fig. 3, a) and the rotation mechanism (Fig. 3, b).

In the Creo applications, the Gears module built the cylindrical gear models (Fig. 4) used in the aforementioned multi-operation milling-drilling-boring machines. Identification of applied loads was implemented with reference to the Power Drive application.

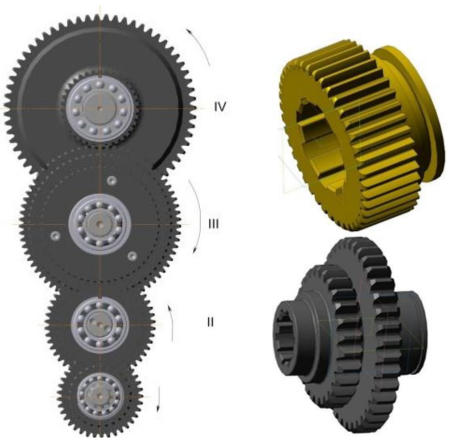


Figure 4. Cylindrical gears

In Creo CAD, parts such as gears are modeled using a conceptual sketch and solid, feature-based modeling. The first step is to create a preliminary sketch in PTC Creo Parametric Options, from which precise geometry is created, and then dimensions and constraints are added.

When sketching, a number of options are available, such as specifying the number of decimal places for rounding the created angular dimensions. For a gear sketch, tolerances (the difference between the nominal angular distance between the teeth and the actual one) are used to determine the angular pitch. They are measured in µm when converted to reference diameter or in angular seconds. This allows the future design to comply with established standards (AGMA, DIN, etc.) at the sketch stage.

When creating geometry in the sketch environment, various graphical constructs are used, including line chains, arc construction options, creating a circle tangent to three objects, and splines. These graphical constructs are used to create the involute tooth profile, the basic rack profile, and the fillet surfaces of the tooth. Thus, when constructing an involute contour by points, it is effective to use a graphical primitive – a spline, which is constructed in two steps: selecting the spline's endpoint and selecting additional points.

When creating dimensions, two modes are available: a) dimensions created during the development of a 3D model with the same dimensional constraints as the model; b) dimensions created in drawing mode. The latter is typical for modeling sliding gear units. In this case, dimensions changed in the drawing environment are updated in 3D model mode.

Another feature offered by Creo is the ability to impose constraints on geometric or structural objects. For example, the "Tangential" constraint on pairs of objects is applied to the pair: Pitch Circle – Radius Vector of the involute profile of the tooth flank.

In the rotation mechanism, motion from the output shaft to the 6-spindle turret is transmitted via bevel gears. The Gears module contains models of bevel gears (Fig. 5) used in the multi-operation milling-drilling-boring machines.

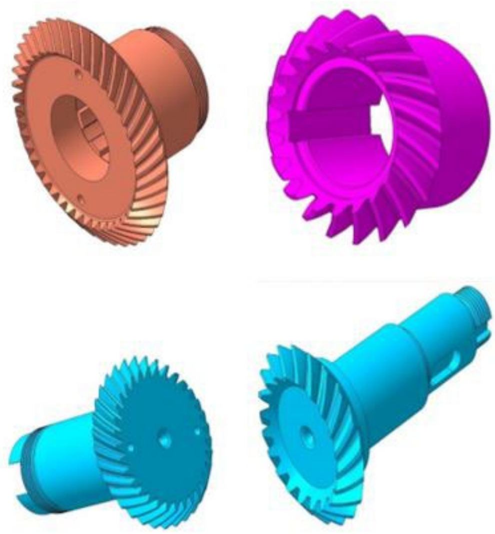


Figure 5. Bevel gears

As is known, a bevel gear is modeled by two cones rotating relative to each other at the point of contact of the diameters of the pitch circles. In the Gear module, the Gear Pair Definition dialogue box implements the process of creating a bevel gear pair using data from the Power Drive application.

On the Gear Engagement tab for the first gear, Gear 1, the rotational axis and the value of the pitch circle (Diameter) are selected, along with the bevel gear apex and the support (pitch) circle. The location of the pitch circle (Gear 2) is automatically calculated to match that of Gear 1. These calculations and graphical operations result in the formation of the pitch cones of the gear engagement, represented as two circles with conically defined diameters centred on the selected axis of motion.

5. A new approach to modelling bevel gear

Modern CAD systems can model various types of gears with a fairly high level of surface visualization accuracy. When modeling bevel gears with circular teeth, visualization is far from complete – the system does not generate the teeth (or, more precisely, the roots (tooth space) between them), so such models are rather conditional. A new modeling method is proposed to obtain a complete 3D model of a bevel gear with circular teeth.

The calculation of the geometric parameters for the turret head rotation mechanism's spiral bevel gear drive is performed using the specialized APM TRANS module [32]. Input data: torque on the driven shaft $T_1 = 329.0\ \mathrm{N \cdot m}$; spindle rotational speed $n_1 = 173\ \mathrm{min}^{-1}$; gear ratio $u = 1.27$; and gear service life $T_r = 5000$ hr. The calculation yielded the following results: spiral tooth inclination angle at the mean gear diameter $\beta = 35^0$; normal gear module, outer transverse module $m_n = 3.149$ mm; outer cone distance $R_e = 72.035$ mm; mean cone distance $R = 61.535$ mm; and face width $b = 21$ mm. Accuracy control values obtained include the constant chord and the height to the constant chord $s_{c1} = 4.296$ mm; $s_{c2} = 4.439$ mm; for the pinion (index 1) and the gear (index 2). Tolerance values obtained for the bevel gear drive include the minimum deviation of the mean constant tooth chord $E_{sc1} = -0.044$ mm; $E_{sc2} = -0.048$ mm; the tolerance for the mean constant tooth chord $T_{sc1} = 0.065$ mm; $T_{sc2} = 0.065$ mm; the lower deviation of the mean constant tooth chord $Ei_{sc1} - 0.109$ mm; $Ei_{sc2} - 0.113$ mm and others.

Based on the calculated data (reference geometry)—utilizing a circular-tooth modeling method and the precise, fixed positioning of five key profile points—it is possible to generate a circular-tooth profile that meets standard geometric parameters.

The basic idea is to profile a tooth by cutting (excision) the root, similar to how a gear-cutting machine removes material. In practice, the cutting is performed using constructed and positioned end sections using the "Cut Element by Sections" command. The following features of circular teeth must be considered: a) the geometric similarity of the profiles is not maintained along the tooth root (the section constantly changes in shape and size); b) the trajectory of the sections is a helical surface, so the sections occupy complex spatial positions.

The solution to this problem can be divided into the following stages:

1. Determination of the spatial position of the end sections (planes on which they are constructed);
2. Calculation of additional geometric parameters of the gear wheel, based on which end sections are constructed;
3. Construction of sections;
4. The actual cutting (excision).

For geometric constructions, as well as for calculating the parameters of an equivalent cylindrical wheel, the following data, determined during the standard geometric calculation of a bevel wheel, must be known: z – number of teeth of the bevel gear; δ – pitch angle of the bevel gear; m_n – normal module; β_n – reference angle of inclination of the center line of the bevel gear tooth; R – average conical distance; h_a; h_f – the height of the reference tooth addendum and the reference tooth dedendum, respectively; θ_a; θ_f – the angle of the reference addendum and the reference dedendum of the bevel gear tooth, respectively; d_0 – diameter of the gear cutting head; α_n – normal pressure angle on the reference circle of a bevel gear with circular teeth.

The position of each section is determined by the cone distance R_x, which has its own value adopted for each section. To obtain a tooth groove surface without sharp change between sections, five sections are sufficient.

To justify the use of five cross-sections, a calculation of the bevel gear drive was performed using the APM Trans module [32]. This calculation makes it possible to identify the positions of five key cross-sections: at the tooth root surface (section 1) and the tooth tip surface (section 2); at the transition surface between the flank profile and the tooth root (section 3); at the mid-section (section 4); and at the surface defined by the constant chord (section 5). The positions of these surfaces are shown in Fig. 9 of this article.

The outer sections should be located at some distance from the ends of the bevel gear ring (2…5 mm), and for ease of calculation, the middle section should be located along the length of the average cone distance R. Then, the parameters in this section are equal to the average calculated ones for the bevel gear.

The position of the planes on which the section sketches are located is determined by the intersection points of the cylindrical surface (created using the "Extrusion Full" command), which simulates the tool and has a corresponding diameter (d_0) and position in space (taking into account reference angle of inclination βn and the direction of the helix) and the surface of the reference cone of the bevel gear. The sketch of the cylindrical surface (circle) is constructed on a plane tangent to the reference cone of the bevel gear.

The circle is positioned so that at a point located at the mean cone distance R (usually this is the middle of the gear ring) between the tangent to the circle at this point and the generatrix of the cone passing through this point, an angle β_n is formed (Fig. 6).

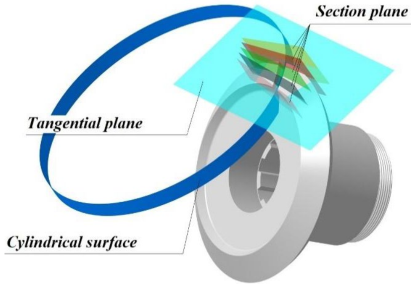


Figure 6. Position of section sketch planes

Also, for each section at distances R_x, conical surfaces are constructed, which are additional cones, the generatrix of which is perpendicular to the generatrix of the reference cone. The planes on which the section sketches will be constructed are tangent to the additional cones and pass through the intersection points of the cylindrical surface, the reference cone, and the additional cones. These same points will subsequently serve as reference points when constructing section sketches.

To construct the face section, the bevel gear must be conditionally replaced by an equivalent cylindrical gear. The parameters of the basic rack of the equivalent cylindrical gear correspond to the face parameters of the bevel gear. The parameters of the equivalent cylindrical gear required to construct the tooth groove sections are determined using known analytical relationships [7]. Based on the obtained data, involutes are constructed, forming the lateral surface of the tooth in the section (Fig. 7). Tooth thickness (to simplify calculations) is not calculated, but assumed in the graphical plotting, based on the angular pitch of the equivalent cylindrical gear. As practice has shown, this requires an additional expansion of the tooth groove by an amount approximately equal to the upper tolerance on tooth thickness for a given bevel gear.

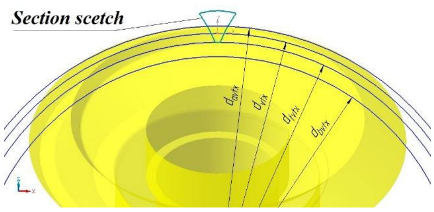


Figure 7. Construction of the involute of the tooth lateral surface

After all sections have been created, the "Cut Element by Sections" command is used. This creates a groove on the wheel (Fig. 8). Then, using the "Array by Concentric Grid" command, the number of tooth grooves is increased to *z*.

This method produces 3D models of bevel gears with a circular tooth that are sufficiently high degree is similarity real gears. The described tooth groove profiling method does introduce some simplifications and geometric errors, but these can be ignored as they are relatively small and have virtually no impact on the visual perception of the 3D model (Fig. 9).

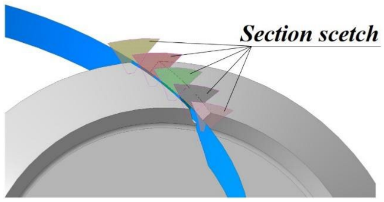


Figure 8. Sketches of sections

The proposed method for modeling bevel gears with circular teeth allows one to obtain a complete understanding of the design and geometry of the tooth profile and increases the reliability of the stress-strain state assessment procedure during the modeling process.

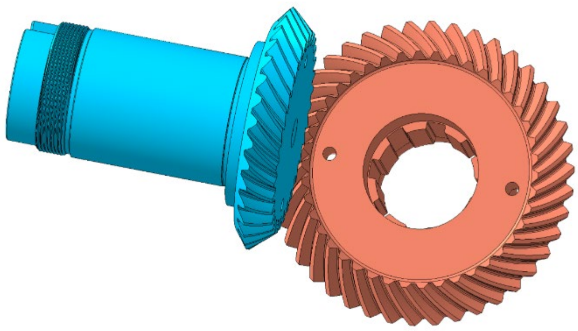


Figure 9. Engagement of bevel gears with a circular tooth

6. Conclusion

Based on the conducted research, the following results were obtained:

1. A preliminary design was developed for a MoM three-stage drive unit with a six-spindle turret, designed for milling, drilling, and countersinking operations in single-part and small-scale production. The development process utilized tools and graphic primitives from the integrated Creo Parametric CAD system.

2. A 3D design of a three-stage gear drive with a turret head was created at the kinematic level. Based on a Mechanism software application using the Power Drive

option, completed 3D modeling of a rotary mechanism specialized design for transmitting motion and torque from the engine to the turret spindles.

3. Using the Gears module, a design algorithm (sketching, defining dimension chains and constraints) and a set of 3D operations were used to develop 3D models of various cylindrical and bevel gear constructions. For example, when constructing involute tooth profiles, the "Tangential" option is used as a constraint for the Pitch Circle – Vector-Radius pair. A distinctive feature of bevel gear construction is the geometric shape of the cones, consisting of a set of smaller segments representing the helix angle.

4. An innovative procedure for constructing a 3D model of a bevel gear with a circular tooth has been implemented. This procedure is based on profiling by cutting a tooth groove, simulating the process of cutting teeth on a hobbing machine for spiral bevel gears. The construction process takes into account the changing cross-sectional shapes and sizes, with a helical surface-shaped cross-sectional trajectory. The stages of creating a circular tooth profile are structured, specifying the number of sections (five sections are sufficient), specifying the distance (in the range of 2–5 mm) from the ring face, and positioning the midsection along the average conical distance. As a result, solid models of bevel gears with a circular tooth have been developed, providing the potential for increasing transmitted power by up to 30%, ensuring quiet and smooth engagement with gradual tooth engagement.

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