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DEVELOPMENT AND INNOVATIVE SOLUTION FOR WORM DRIVE OF MACHINE TOOL ROTARY TABLE

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Abstract - The article considers the modernized design of the machining center rotary table based on a new design solution for the worm-ball drive. The layout scheme of the horizontal machining center and the kinematics of the feed drive for implementing 4-axis machining are proposed. A draft design of the feed drive with a specialized spindle support bearing is developed. A 3D rotary table project is created in the Creo Parametric CAD environment using parallel design tools. In the process of 3D modeling, a multi-variant approach to the design is used, including an alternative version of the worm drive with backlash-free engagement. When constructing a circular array of worm threads, the effective functionality of Creo is used, associated with a circular shape with the ability to redefine the array. An innovative design of the worm transmission is proposed as a synthesis of a worm and ball screw gear. The main idea of the new worm-ball transmission is to find such design solutions that allow replacing the contact mechanism with sliding friction (the main problem of the classical engagement) with a rolling friction mechanism. For the new transmission, 2D and 3D sketches and models are developed and its declarative patent has been received. Analytical dependencies for calculating the main geometric parameters are given. A comprehensive calculation of the drive transmission was carried out in a specialized module ARM Trans. As a result of the numerical experiment, the effectiveness of the new design solution according to the efficiency criterion is shown.

Keywords: Feed drive, Machining center, 3D modeling, Worm-ball transmission, Efficiency.

1. Introduction

The widespread introduction of multioperational machines such as machining centers (MC), which can perform complex mechanical processing of complex shape parts is one of the main trends in modern mechanical engineering [1, 2]. To process such parts, a tool must simultaneously describe a trajectory in three Cartesian dimensions in combination with tool inclination and part rotation along one or two circular axes. This configuration of the machine's working space allows for processing a part from several sides without parts repalletization.

Along with vertical MC, there is an area of rational use of horizontal MC, which is characterized by the execution of shaping units according to a more rigid scheme with a vibration counteraction system. In addition to this property, an effective workpiece change scheme and multi-coordinate processing of parts without repositioning at one workplace are important.

A rotary table (RT), as a shaping unit, is included in the modular configuration of machine equipment. Many companies Zollern (BRD), Lehman (Switzerland), Detron (Taiwan) and others, offer their lines of rotary table designs. Standards of Modular units of machine tool construction (Rotary table – ISO 3175-1975) are known.

Despite the sufficient level of RT designs unification, work on their improvement is widely presented in the scientific literature [3, 4].

The main RT drive mechanism, regulating its operating efficiency, is a worm transmission (WT). It is associated with the main problems, including an increased level of sliding friction, relatively low transmission efficiency, intense wear and, as a consequence, deterioration in positioning accuracy.

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Some works propose replacing the drive mechanism with a roller-cam mechanism for a wide range of table sizes [5].

One of the areas of improving the drive mechanism is the search for design options for compensating for wear during the operation of the worm gear [5, 6]. This is implemented both mechanically by adjusting screws and kinematically using a duplex worm gear.

For traditional and modernized designs of drive mechanisms in a wide range of processing modes and applied loads, it is important to use the basic theoretical provisions [7]. In addition, it is important to use effective and modern calculation methods in an automated mode, as well as the use of specialized WT calculation applications [8]. In this regard, the analytical and calculation part proposed by the authors of the MEGT (Machine Elements, Gear and Transmission) method is of interest [9].

To assess the stress-strain state of the rotary table components, assess the influence of the torque transmission process during processing, and study phenomena in the contact zone, it is necessary to implement the process of creating a comprehensive 3D RT design project [10].

Thus, the issues of improving the design of a rotary table with a worm drive mechanism based on 3D modeling tools using specialized calculation modules is an urgent task in modern mechanical engineering.

2. Literature Review

One of the areas of MC improvement is the development of RT designs and the search for new drive mechanisms. Thus, the article [5] an alternative to the worm gear in the form of a roller drive based on a globoid cam and a roller mechanism mounted on needle bearings is proposed. The gap resulting from wear is compensated by pre-tensioning at the assembly level and provides high rigidity and torque.

Comprehensive RT research of five-axis machines with a driven roller transmission is devoted to a similar mechanism, with the methodology of Industry 4.0 [11]. From the standpoint of the influence on the flexibility of the machine's production functions when changing the range of processed products and the final accuracy of the processing process, an analysis of the loading system, oscillation shape and layout structure of a rotary table with a roller cam is performed. The result is associated with a decrease in weight and an improvement in natural frequencies (reduction in resonance) compared to the original design. This is achieved by optimizing the design based on the finite element method, reducing the maximum deformation due to gravity and the weight of the workpiece, and increasing natural frequencies by about 10%. This indicates the prospects of developments in this direction. At the same time, the physical nature of contact sliding friction and the corresponding problems of increased wear and low efficiency are preserved to a certain extent in this case.

Bass [3] presents a new RT design for a small-size 5-axis vertical machining center Haas OM-2 with the ability to rotate around a horizontal and vertical axis with high accuracy and repeatability. A worm gear option was selected as the drive feed as it provides sufficient torque. To improve the operation accuracy, the drive feed is mounted on duplexed angular contact ball bearings with their backs (O-shaped mounting scheme) with preliminary tension by grinding the ends. To maintain the accuracy of positioning, the design concept of a spring-loaded structure for the gap compensating in the worm gear ("Spring Loaded Gear Mesh") was used, for which a patent was received. [6 Mauro Patent].

Work on the creation of rotary tables lines is also promising. Thus, the work [12] is devoted to the study of the range of MK200 rotary tables with a compact design and increased torque of up to 570 N·m compared to the previously known standard of MR200 tables with a torque of 350 N·m. This increase corresponds to the maximum loads, at which the level of sliding friction forces on one side and the increase in processing productivity on the MC with the MK200 rotary table are permissible.

When creating new RT designs, already at the stage of preliminary design, it becomes expedient to use three-dimensional modeling in developed automated design systems. In this regard, the work of [13] is of interest. The main idea is to integrate sets of models of the main sections for a milling-type machining center, including the main form-generating units of the main drive with modular spindle heads and the feed drive with workpieces and devices. The modeling software is supported by analytical forms for studying and calculating the stress-strain state and dynamic characteristics of the machining center components as a technical system.

This approach reflects the situation inherent in a multi-axis machine, taking into account the different configurations of the axes, which will allow for the efficient prediction of the output parameters and properties of the designed equipment. Also, based on such analysis, methods for the efficient combination of experimental data and simulated models of the machine, workpiece and cutting tool in different configurations of the axes are implemented. These two procedures of automatic change of workpiece and change of cutting tool, as well as the choice of optimal modes of parts processing on the machining center provide the main component of economic efficiency.

In this regard, the work [14] is of interest, which considers the machining process on a CNC lathe from a system point of view and notes a reduction in the processing cycle time of about 18%, both due to the use of optimal cutting modes and due to auxiliary time (including automatic tool change).

The stage of creating three-dimensional models within the environment of the interaction of two automated CAD/CAM subsystems is implemented. The result is a control program for a CNC machine.

An alternative to this is the technology of rapid prototyping. An analysis of the advantages of the prototyping process for such a mechanism as the Maltese cross is given in the work [15]. The integration with the technology of rapid prototyping gives an effect even in the design of complex geometric parts of mechatronics.

Another aspect of the three-dimensional representation of mechanical engineering objects (using turbines as an example) is reflected in the work [16]. This is the stage of implementation of the finished product in the environment of the digital service of 3D modeling, where it is possible to apply the concept of "product price – consumer demand" in the formation of internal logistics flows. The authors of this work examine the issues of flexibility of the enterprise's internal logistics based on a high-precision 3D model of a turbine built in the SolidWorks CAD system.

At the stage of technical design, an important role is played by calculation modules for determining the geometric and energy characteristics of the main components of machine drives and mechanical transmissions.

In the work [9], a new approach to calculating the design of a worm pair based on the efficiency criterion is proposed. This calculation is based on analytical dependencies that allow the implementation of MEGT (Machine Element, Gear and Transmission) tribological modeling methods. A feature of this procedure is a fairly accurate determination of the local friction coefficients of the pair: worm shaft-worm wheel during engagement. This makes it possible to estimate the load distribution in the contact zone using the coefficients mentioned above, as well as take into account the type and characteristics of the lubricant.

This approach was experimentally implemented in the work [17] for the case of large-sized worm gearboxes, but already from the standpoint of increasing the efficiency of the worm gearbox operation according to the lifting capacity parameter. This characterizes the sufficient universality of the proposed method.

Combining the analytical apparatus for assessing the efficiency of the drive operation feeds based on a worm gear and 3D modeling methods [18] forms the basic toolkit for analyzing the contact geometry, determining the characteristics of the load capacity and efficiency of the main drive worm gear.

In the work [19], the calculation methods used at the stage of RT production of milling and boring machines with CNC AF type in a small range of gear ratios are considered. The kinematic diagram uses a mechanism for gap compensating in the worm gear during operation, which is implemented by a pair of worm mechanisms with worm shaft supports mounted with preliminary tension.

Calculation procedures of automated design of machine tools are implemented both in the environment of integrated CAD of various classes and with the help of specialized applications (modules). One of the promising calculation modules is the APM Trans module [20] with a built-in library of basic rack profiles, focused on calculating a wide range of mechanical transmissions, including worm gears. This module performs design and verification calculations of mechanical transmissions by obtaining full geometry, determining tolerances and control parameters, as well as with automatic generation of detail drawings.

Another example of determining the main physical parameters for modeling in the Bond Graph library for mobile robots feeding workpieces that can be used in machine tool building is presented in the work [21].

Analysis of the above research in the field of modern MC drive devices showed the main directions of promising developments in this area. Further design improvement of feed drives with driven mechanical transmissions, creation of complex 3D projects, use of integrated CAD and their specialized software applications for calculating components of drive devices is the key to progress in this area of research.

This work aims to create a modernized feed drive design based on a rotary table with an innovative worm gear drive.

To achieve this goal, the following stages are proposed:

1. Development of a 3D rotary table project as a basis for creating a specialized section of the database of a drilling-milling and boring machining center.
2. Modification of the main drive gear design based on an innovative design solution: "worm-ball transmission"
3. Calculation of the main geometric and energy characteristics of the worm gear in a specialized module of the ARM Trans.

3. Design of the MC Rotary Table

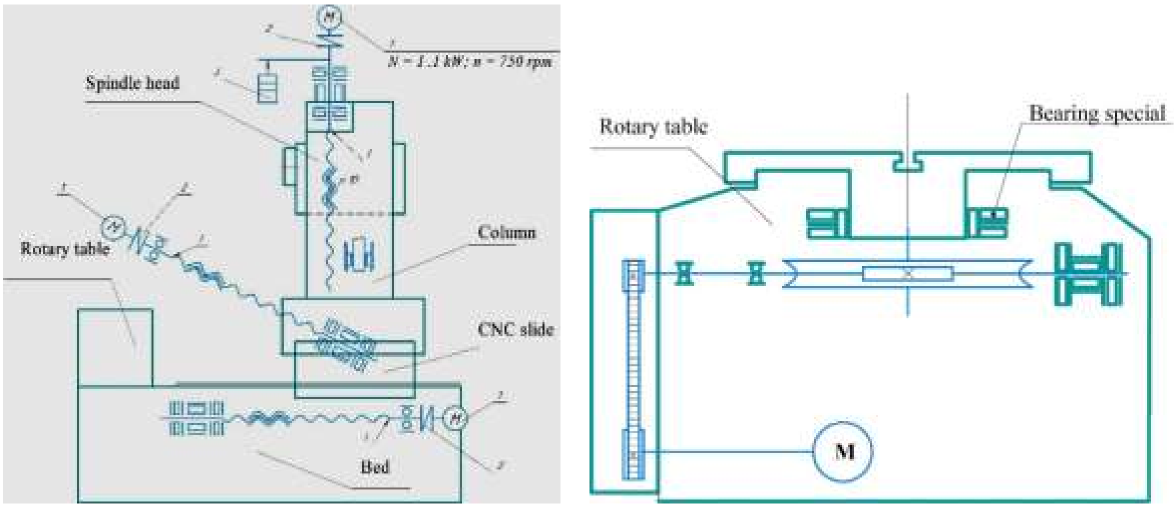
3.1. Kinematics and the Design Sketch

The use of horizontal machining centers, along with the advantages of convenient removal of coolant and chips from the cutting zone, is characterized by the possibility of a two-pallet version of the work table in combination with the 4th coordinate: rotation in the horizontal plane (axis "B") with a step of 1^0 or 0.001^0.

The RT, which is part of the feed drive, as well as the main drive [22] are the form-generating units of the machining center (MC). The independence of movements along different coordinates on these machines determined the separation of the feed drive mechanisms for each controlled coordinate with the need to use an independent drive in each of them. Drives can be electric, electrohydraulic and hydraulic. Stepper motors, as well as DC and AC motors, are used as actuators in electric feed drives. Electric drives for a type of modernized five-axis machining centers are presented in [23, 24]. Hydraulic cylinders and hydraulic motors are used in hydraulic drives [25, 26].

Depending on their design, rotary devices allow the use of a positional machining method, i.e. the ability to process various surfaces of a workpiece in different positions relative to the machine spindle (milling cutter) with one clamping and machining with a circular feed with continuous rotation of the workpiece.

Fig. 1, shows one of the draft layout options and a MS kinematic diagram of a drilling-milling-boring type (Fig. 1), developed in the Creo Parametric CAD system [26, 27]. The RT kinematics is shown in Fig. 1, b. Kinematic chains of autonomous feed drives MS assume the transmission of motion from the engine (1), through the clutch (2) to the drive ball screw transmission (I) using a hydraulic cylinder (3).



(a) MC layout (b) RT kinematics

Figure 1: Kinematics of the machining center

In the process of multi-variant layout design, the functionality of the Creo "Process Manager" is used, which has a section called Rules for creating a machine assembly. This toolkit is used to simulate the machine at the level of blocks, slideways, working and auxiliary movements. In this case, relative movements are determined between the horizontal spindle headstock and the rotary table, taking into account the movement of the portal. Concerning coordinate systems and their centers, the following are used in the MC layout:

- the absolute coordinate system MACH-ZERO, for assembling the components (blocks and slideways) of the machine;
- the coordinate system of the spindle loading position with the tool TOOL-POINT;
- The positional coordinate system of RT loading with the workpiece TABLE-POINT.

Based on the above-described layout and the nomenclature of workpieces to be processed, a design variant of the MC rotary table was developed at the stage of the preliminary design (Fig. 2).

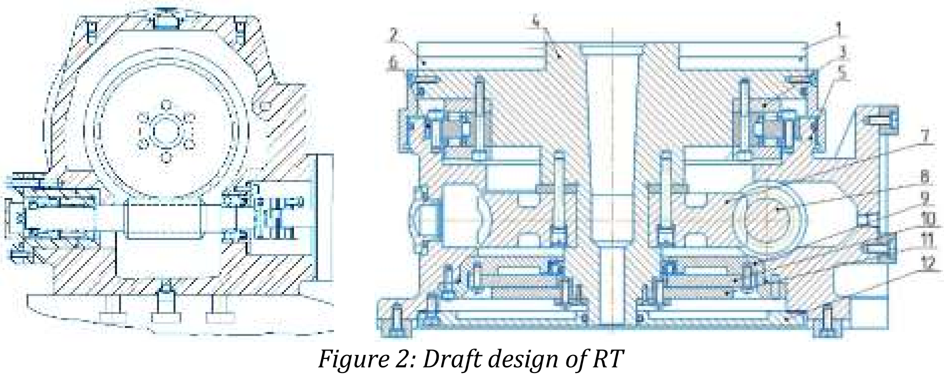


Figure 2: Draft design of RT

The rotary table controlled by the CNC and having a continuous rotation of the faceplate 1 and plate 2 is mounted on the main vertical table, based on two horizontally located keys. Faceplate 1 has T-shaped grooves, which mount and fasten a fixture or workpiece (a complex housing part of a gearbox is considered a workpiece). The central RT carrying part is the housing-type part 5 (with cover 9, disk 10 and rings 11, 12) in which the spindle 4 is mounted on a rigid special bearing of the YRTS 3 series (6), driving the rotary table into rotation. The main drive is a worm gear: worm shaft 8 and worm wheel 7 transmitting motion from the high-torque motor to the actuator – the faceplate.

The rotary table is controlled by the CNC through the circular inductosyn PUI-18A. The rotation of the faceplate to a given angle is controlled by an optical sensor mounted on the vertical axis of the rotary table. The change in the working speed of the RT faceplate is performed smoothly within the range from 0.1 to 3.5 min^{-1}, the accelerated movement is 6.5 min^{-1}.

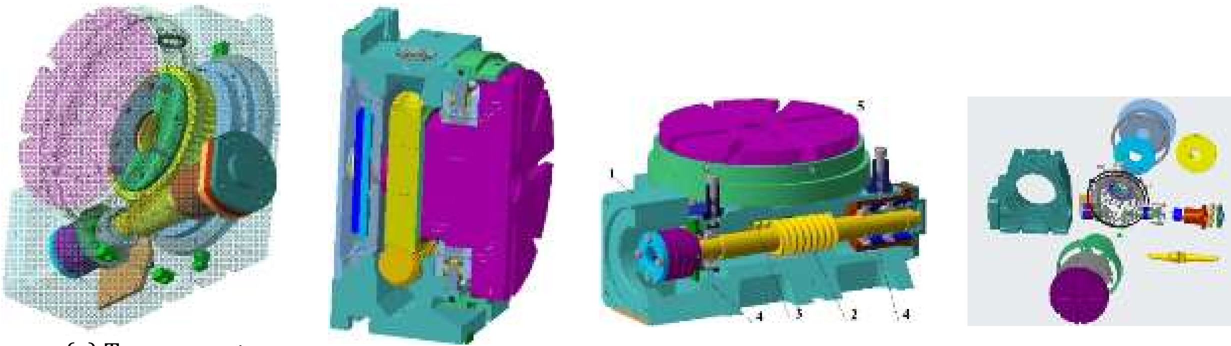
3.2. Three-dimensional Modeling of the Rotary Table

The construction of a 3D project for the MC rotary table is carried out in the integrated CAD Creo Parametric [27, 28].

This system enables to manage data and use the advantages of the parallel design environment, as a result the integration of Creo applications and the PTC Windchill software product, which stores all user data on the central server. This is especially important in terms of creating a MC comprehensive project in which the RT is one of the form-generating units.

On the Windchill PDM (Product Data Management) server, RT designers can load the current version of its design, and when it is changed, an alternative version (in the multi-variant design mode) becomes available to designers of other MC units. In this case, the RT upgrade version is stored on the Windchill PDM server together with the previous RT versions. The presence of MC various units makes the aggregate-modular principle promising, the methodological aspects are presented in the work [29]. For these various options, the stress-strain state will be calculated in the Ansys CAE at the next stages using the finite element method. An example of using such a methodology is presented in the work [30].

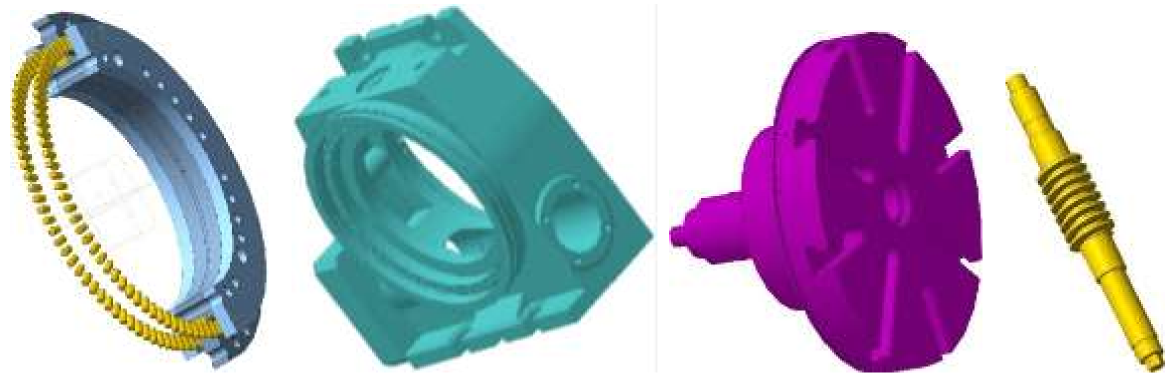
The results of multivariate 3D modeling of the MC rotary table for the drilling-milling-boring type are shown in Fig. 3.



(a) Transparent version (b) Section (c) Alternative version (d) Spacing

Figure 3: Three-dimensional models of rotary table

As an alternative version, the RT design (Fig. 3, c) with an innovative solution [31] of a gap-free connection of the worm gear (2-3) mounted on supports in the form of duplexed angular contact ball bearings (4) mounted in the housing (1) and faceplate 5 is considered. Using the Creo Part Spacing option (Fig. 3, d) enables to evaluate the manufacturability of the future design is one of the means that ensures the efficient construction of the technological process for RT assembly. To implement the process of manufacturing the table parts in the Creo environment, 3D models of the basic parts were built: a special bearing (Fig. 4, a), housing (Fig. 4, b), faceplate (Fig. 4, c) and worm (Fig. 4, d).



(a) Special bearing (b) housing-type part (c) faceplate (d) worm shaft

Figure 4. Three-dimensional models of RT components

When modeling the design of a RT special bearing YRTS series (Fig. 4, a) the Creo toolset is used for building an array (Pattern) of bearing rollers. To fill the area between the bearing rings with rollers (Fig. 4, a), a circular grid template is selected. In the circular template, the following is specified: the radial step for the circular grid, the minimum distance between the centers of the array elements, and the rotation of the grid relative to its starting point. It is possible to redefine the filling array by changing the above parameters: step, rotation angle, and minimum distance, which makes it possible to carry out the process of multi-variant design and select an alternative version of the bearing design in express mode.

The same method of building an array is used when building the threads of the worm shaft (Fig. 4, d). The procedure of building is supplemented by selecting a sketch curve using a spiral grid template. This curve limits the area that will be filled by the array. Moreover, the members of the worm thread array can track the shape of the selected surface (in this case, the leading member of the array and the sketch plane must be located tangent to the selected surface).

It should be noted that when creating or redefining the worm thread array, the radial step for spiral meshes can be changed. In addition, the array elements can be rotated along the Spiral template, as well as rotated around the origin.

In Creo CAD, the issue of automatically constructing a helical angle for a worm gear pair is effectively solved. To do this, on the “Properties Tab”, the diameter of the pitch circle, the number of worms starts (spirals) and the number of worm wheel teeth are specified.

In this case, the helical lead angle will be automatically adjusted to match the angle of the helical line on the worm shaft.

4. Innovative Design of the RT Worm Transmission of the MC Rotary Table

4.1. Design and Calculation of a New Worm-ball Transmission

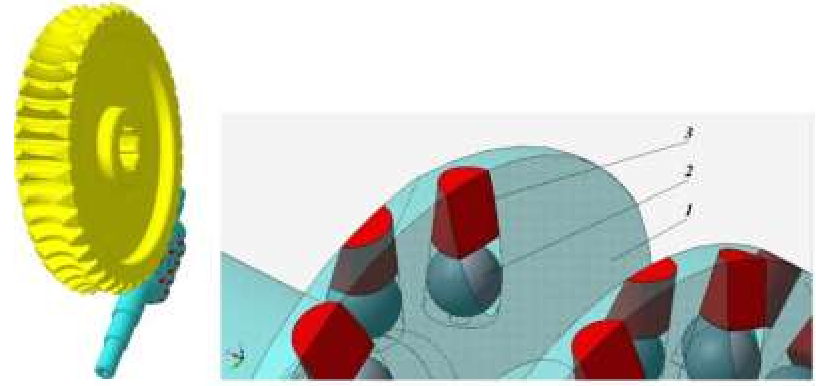
As is known, a large gear ratio of a single worm pair as part of the worm drive of a machine tool with a large gear ratio is much more compact and lighter than the equivalent gear and is characterized by lower material consumption. The advantages of the worm gear include the self-locking effect at certain ratios as well as increased kinematic accuracy.

In sufficiently loaded feed drives of machine tools, the worm gear during the engagement process is characterized by significant heat generation due to sliding friction. Another disadvantage is the increased sensitivity to manufacturing errors and elastic deflections of the worm shaft due to the presence of a linear contact between the worm threads and the teeth of the worm wheel [32].

This paper puts forward an innovative design solution based on the synthesis of a worm and ball screw transmission, called a worm-ball transmission (WBT) and confirmed by a patent solution [33].

The useful model is based on the following tasks: increasing the efficiency of meshing without the use of non-ferrous copper-based alloys; reducing heat generation; reducing the sensitivity to manufacturing errors and elastic deflections of the worm shaft.

The task is achieved by the fact that the teeth of the worm wheel, cut by the generating Archimedean worm ZA, engage with the modified working worm shaft ZA (Fig. 5, item 1), the threads of which contain radial channels with balls 2 located in them, which contact the surfaces of the worm wheel teeth. The locks 3, pressed into the radial channels, prevent the balls from rolling out of them. Fig. 5 shows a three-dimensional model of a worm-ball transmission developed by the authors.

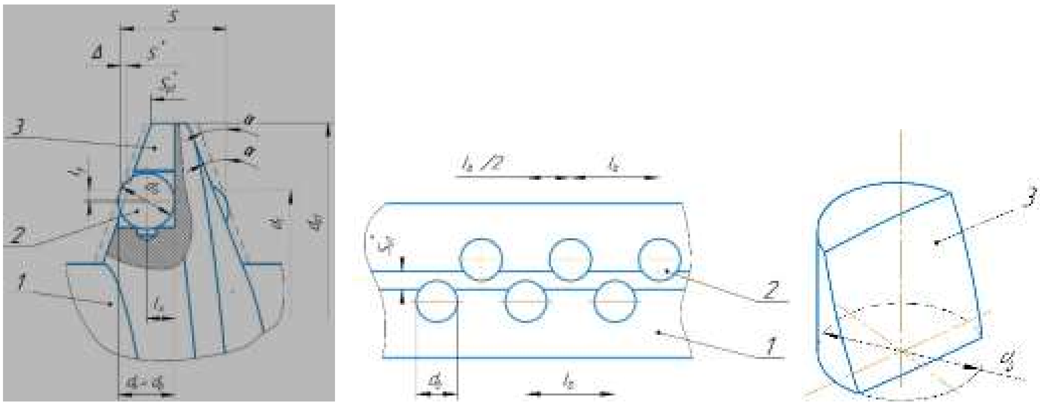


(a) worm-ball pair (b) worm-ball shaft (3D section)

Figure 5. Worm-ball transmission

As a result of such a design solution in the transmission realizes rolling friction between the worm and worm wheel, which enables to refuse non-ferrous alloys based on copper for the teeth of the worm wheel, and the point character (as opposed to linear in the traditional version) contact balls with the teeth of the wheel reduces the sensitivity of the transmission to manufacturing errors and elastic deflections of the worm shaft.

Let's consider the design features of the components of the innovative worm-ball transmission (Fig. 6).



(a) Worm-ball thread (b) Surface development (c) Ball lock

Figure 6: Worm-ball transmission

Modified worm with balls (item 2) diameter d_b, located in radial channels with diameter $d_k = d_b$ by fit with guaranteed clearance H7/f6, which contacts the surface of the worm wheel teeth. The thickness of the threads of the modified worm S_1^* (the parameters of the modified version are marked with an asterisk) at the reference diameter d_1 is reduced compared to the thickness S_1 of the prototype worm by Δ.

To determine the main parameters of the modified worm-ball transmission, analytical dependencies are formed:

The dependence determines the diameter of the ball $d_b = 0.8 \cdot m$; the difference in the thicknesses $\Delta = 0.1 \cdot m$.

Then, the parameter of the thickness of the threads is calculated as:

$$S_1^* = S_1 - 2 \cdot \Delta \approx 1.47 \cdot m;$$
$$S_{a1}^* \approx m \cdot (1.47 - 2 \cdot tg\alpha). \tag{1}$$

The axis misalignment of the ball in the groove l_x, l_y is determined by the dependencies:

$$l_x = m \cdot (0.25 \cdot \pi - 0.4 \cdot \cos\alpha);$$
$$l_y = 0.4 \cdot m \cdot (1 + \sin\alpha), \tag{2}$$

where m – the axial module of the worm; $\alpha = 20^0$ – the axial angle of the profile of the threads

Let us consider the surface development of one thread of the modified working worm ZA (Fig. 5, b), which shows the arrangement of balls 2 on both sides of the threads in a checkerboard pattern with a pitch of $l_b = 2 \cdot d_b$. The number of balls on each side of the threads (rounded to an integer) is determined by the ratio:

$$z_b \approx 2 \cdot \frac{q+2}{\cos\gamma_a}, \tag{3}$$

where q – the worm diameter factor; $\gamma_a = arctg\left(z_1 / q + 2\right)$ – the lead angle of the threads of the worm ZA at the diameter of the vertices d_{a1} ; z_1 – the number of turns of the worm).

Locks (item 3, Fig. 6, c), pressed into the radial channels, prevent the balls from rolling out of them.

The modified worm gear operates as follows. The teeth of the worm wheel, cut by the generating Archimedean worm ZA with a thickness of threads S_1 on the reference diameter d_1, contact with the balls (item 1) mounted in the radial channels of the threads of the modified working Archimedean worm ZA with a reduced thickness of threads S_1^* on the reference diameter d_1.

The distance between the balls 1 on the thread opposite sides of the reference diameter d_1 is equal to the thread thickness S_1 of the generating Archimedean worm ZA. This ensures equality of the axial pitch of the worm shaft threads and the circumferential pitch of the worm wheel teeth.

When the modified worm rotates, the balls 1 roll over the teeth of the worm wheel. As a result, the engagement of the worm shaft with the wheel occurs with rolling friction and a point-like nature of the contact of the worm transmission working surfaces.

4.2 Automated Calculation and Determination of the RT Worm Transmission Efficiency

Advanced design calculation of the worm transmission implemented in the module for designing mechanical transmissions of rotation “APM Trans” [8, 20].

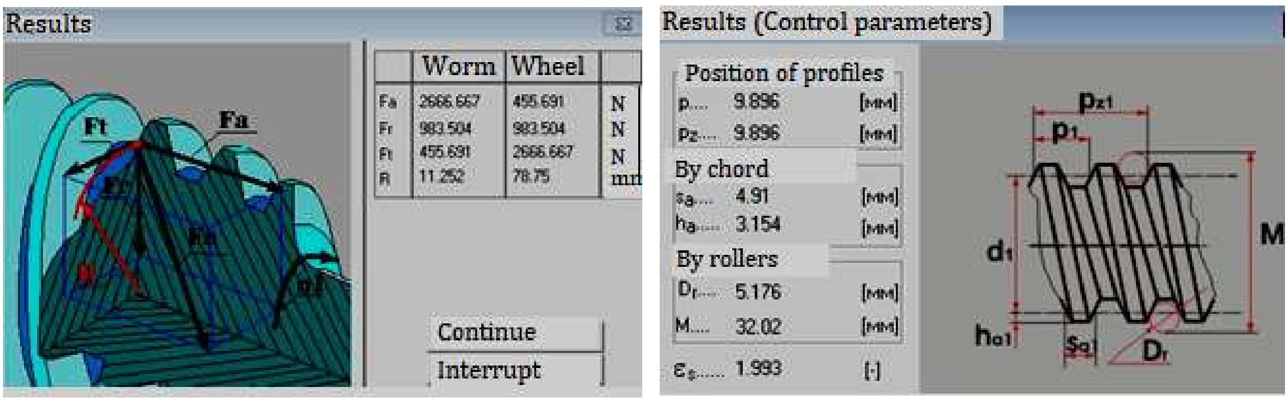
This module works with the "Mechanical Data" database, which has a "Basic rack profile" section of the tool used to cut teeth of various types of mechanical transmissions.

The initial generating worm determines the proportions of the real worm threads and the corresponding worm wheel. For the worm wheel, the height proportions of the teeth are specified in the middle end plane, in which the common perpendicular to the axes of the worm shaft and wheel lies. In this case, the angle of the Archimedes worm threads profile is taken to be 20^0 in the axial section.

The Mechanical Data database manager also works with other user databases. Connecting such databases is focused on new designs of mechanical transmissions. The designer can select the Calculation Standard by ISO and AGMA (USA). The APM Trans module performs both the design calculation of the transmission and the verification calculations for: a) the maximum moment (at a given resource) and b) at a given resource with a given load.

Let us calculate the worm transmission of the rotary table (Fig. 1, Fig. 2). With the given values: external load (T_1 = 7.16 N m); worm material (Steel 40X, HRC 45 ... 50) and wheel (high-tin bronze Bro5c5s5), type of heat treatment (carburizing) we will determine, by the analytical formula [32].

The main geometric parameters of the transmission, the forces acting in it (Fig. 7, a), the parameters for monitoring the position of the side surfaces (Fig. 7, b), as well as tolerances and fits in the engagement.



(a) Forces in contact: worm shaft – worm wheel (b) Control parameters

Figure 7: Result of calculation in APM Trans module

As is known, a cylindrical worm transmission is a synthesis of a gear transmission (worm gear ring) and a screw (the worm has a screw shape with a trapezoidal thread). This drive uses an Archimedes worm ZA, characterized by the shape of the Archimedes spiral in the cross section.

As noted above, the disadvantages of the worm gear are primarily associated with the high level of engagement friction, which results in large losses of friction power in the engagement and a relatively low efficiency. In the process of verification calculation for contact endurance, it is also possible to estimate the value of the efficiency.

Initial data for calculating the efficiency of the worm transmission (Fig. 2; Fig. 3): transmission module $m = 3.15$; worm material 40X HRC 45 ... 50;

number of worm threads $z_1 = 1$; reference angle thread lead $\lambda = 4^0 34'26''$; reference diameter of worm shaft $d_1 = 39.375$ mm; worm shaft rotation frequency $n_1 = 1000\ \text{min}^{-1}$; number of wheel teeth; worm wheel: $z_2 = 50$; $m = 3.15$; wheel ring material Grades Bro5c5s5 Tin foundry bronzes.

The efficiency of a worm transmission is determined by the relationship:

$$\lambda_{wt} = \frac{tg\lambda}{tg(\lambda+\rho)}, \tag{4}$$

where ρ – the friction angle, $\rho = \text{arctg} f$; f – the friction coefficient, determined depending on the worm shaft sliding speed V_s, m/s:

$$V_s = \frac{\pi \cdot d_1 \cdot n_1}{1000 \cdot 60 \cdot \cos\lambda} = \\ = \frac{\pi \cdot 39.375 \cdot 1000}{1000 \cdot 60 \cdot \cos\ 4^0 34'26''} = 2.069. \tag{5}$$

Based on the actual sliding speed in the gear, the coefficient f_{sb} (steel-tin bronze) and the friction angle ρ are determined:

$$f_{sb} = \left(\frac{A+B}{V_s + C}\right) \cdot 10^{-2} = \\ = \left(\frac{1.04 + 6.4}{2.069 + 0.843}\right) \cdot 10^{-2} = 0.0256; \\ \rho_{sb} = arctg\left(f\right) = 1.467^0. \tag{6}$$

Assuming the efficiency of one bearing pair η_b to be: $\eta_b = 0.98$ we obtain the efficiency value η_{wt} for the worm transmission as a whole:

$$\eta_{wt} = 0.98 \cdot \frac{tg\lambda}{tg\left(\lambda + \rho_{sb}\right)} = 0.748. \tag{7}$$

For the case of a new design of a worm-ball transmission (WST), we select the friction coefficient $f_{ss} = 0.001$ for the pair "hard steel ball on steel" from the recommended range: 0.0005…0.001 at its upper limit. In this case, the friction angle is $\rho_{ss} = 0.573^0$, and the efficiency is $\rho_{wst} = 0.874$. Thus, the proposed innovative solution allows increasing the efficiency of the worm transmission of the rotary table drive by about 15%.

5. Conclusions

This work creates a modernized design of the MC rotary table with an innovative worm-ball transmission, which implements a sharp reduction in sliding friction, a decrease in the level of heat generation and, as a result, an increase in the efficiency value.

2D and 3D RT designs table with a worm transmission drive and a specialized bearing of the YRTS series were developed in the environment of the integrated CAD Creo Parametric. At the level of layout design, the functionality of Creo "Process Manager" was used for multi-variant selection of layouts at the level of blocks, slide ways and movements in absolute and positional coordinate systems.

In the process of RT 3D modeling, a parallel design environment is used, with the integration of Creo applications and the PTS Windchill software product on the central server in terms of creating a comprehensive machining center project. In this case, in the process of multi-variant design, an alternative option (RT with a backlash-free engagement of the worm) is developed. Generated alternative variant becomes available to designers of other MC units. In this process of integrating software products, a table design spacing is built for each alternative option. In this case, using Creo Part Spacing option, which can be effective at the stage of manufacturability analysis, is implemented.

For the construction problem of three-dimensional modeling of a special bearing and worm shaft, the Creo Parametric toolkit has been effectively used. First of all, it refers to 3D operations of circular greed pattern creation with the possibility of multivariant sketch curve selection. An additional option, a radial step along the "Spiral" template in multiple ways, is effectively used. To speed up the construction process, an express procedure for constructing a helical surface for a worm gear pair is used.

An innovative design solution WBT (confirmed by the author's patent) for the RT drive transmission has been implemented, which is a synthesis of a worm gear with an Archimedean worm ZA and a ball screw transmission. For the new WBT design, a transition from sliding friction to rolling friction is carried out (like: a hard steel ball on steel). It is possible to replace high-tin bronze as a worm wheel material on alloy steel. Based on this idea, a 3D model of the new design has been built and a sketch of the design documentation has been developed.

The main WBT geometric characteristics have been determined using the proposed analytical apparatus. An automated calculation of the drive worm gear has been performed in a specialized module for designing mechanical transmissions APM Trans. This module is integrated with the "Mechanical Data" database to use information about the basic rack contour of the cutting tool for generating worm threads following ISO and AGMA standards. The main geometric characteristics of the worm gear, the forces acting in the engagement and the efficiency for cases of traditional and innovative drive transmission are determined. The possibility of increasing the efficiency of the new WBT design by at least 15% is proven by calculation and experiment.

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