Lecture Notes in Networks and Systems 1129

Daniela Doina Cioboată *Editor*

# International Conference on Reliable Systems Engineering (ICoRSE) - 2024

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Daniela Doina Cioboată
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# International Conference on Reliable Systems Engineering (ICoRSE) - 2024

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# Preface

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# Improving the Drive of a Multi-operational Machine with a Multi V-Ribbed Belt

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**Abstract.** The article is devoted to the development of three-dimensional and parametric models of a modernized main movement drive for a machining center drilling-milling-boring type. The procedure for creating 3D models of parts and assemblies of the machine tool drive using the new CAD functionality Creo Parametric is presented. The features of modeling housing parts with complex geometry are considered. It is proposed to use a specialized module of the APM WinMachine system when parametric models of a multi-V-ribbed transmission of a machine drive are constructed. Using the APM Base application program, the effectiveness of developing a specialized section of the database using parametric models of drive components is shown. The idea to achieve increased traction capacity of a belt transmission by modifying the cross-sectional shape with a curved configuration has been put forward. The reasons for quantitative changes in belt performance have been identified. The identity of the main structural elements of the modified and standard design is noted. Analytical material on the modification of multi V-ribbed belts is presented. An alternative option, in which an increase in the length of the wedge side is observed for the case of a modified belt shape is shown. A comparative analysis of the main parameters of modified and standard multi V-ribbed belts is given. The most preferred standard size of belts is noted, where the greatest increase in performance indicators when modifying the profile of the belt wedges is expected. A coefficient for increasing the length of contact between the belt and the multi-V-ribbed pulley $K_L = 1.07$ has been introduced, as an indicator of the criterion for increasing the traction capacity of the transmission.

**Keywords:** Machining center · Gearbox · 3D modeling · Parametric models · Belt transmission

## 1 Introduction

In multi-operational machines of the drilling-milling-boring type, main motion drives (MMD) with step-less control of the rotation speed of the spindle assembly are widely used [1, 2]. These machines are characterized by a wide range of processed surface sizes, grades of materials and various types of machining. As a result, it must be equipped with a variety of cutting and auxiliary tools. The need for maximum intensification of machining, i.e. ensuring higher removal of processed material per unit time requires the use


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of higher-power drive motors. Another requirement is to ensure the long-term preservation of spindle rotation accuracy, as well as total rigidity, eliminating unacceptable mechanical vibrations.

Thus, the control range of the drive must cover both the spindle speeds required for high-speed finishing operations and the speeds for pre-processing and spindle positioning. The MMD includes a drive motor, a gearbox, and a belt drive that connects the drive shaft of the box to the engine [3].

One of the factors for MMD design improvement is to achieve a certain level of dynamic characteristics. This is especially true for the stages of acceleration, braking and positioning of the spindle. In this regard, it is advisable to use belt drives, which ensure highly smooth operation and, consequently, a reduction in impact loads and vibrations [4]. In addition, the effect of an absence of overloads and noiselessness operation are often decisive factors for their use as part of the MMD main components. In this regard, the multi V-ribbed transmission (MVRT) is of interest, the advantages of which are solidity, flexibility and increased belt track force. The implementation of high speeds (up to $v = 60$ m/s) and a wide range of gear ratios (up to $i = 40$) make MVRT promising for multi-operation machines for roughing and finishing [5].

As part of improving drive designs, the task of developing improved MVRT modified becomes relevant.

The MMD designs are constantly being developed and improved to increase the range of speed control, productivity and increase the reliability of their operation. When designing drive parts and assemblies, starting from the initial stages, it is necessary to implement 3D and parametric modeling tooling.

## 2 Literature Review

A significant number of works are devoted to the problems of a comprehensive study of multi-operational machine tools based on three-dimensional and parametric modeling. To solve these problems, several well-known computer-aided design software environments are used, in particular such effective ones as Creo Parametric and ANSYS.

The work [6] presents a fundamental study of a multi-operational milling machine. A 3D design project of the machine has been developed as a basis for engineering studies of its technical and economic characteristics. The effectiveness of such a project is due to the use of a structured database, including sections: 1. Machine, with components {nodes, elements, coordinates, coordinate axes}; 2. Machine retaining device and workpiece; 3. Cutting tools and auxiliary tools. The innovative approach used here is to carry out extensive calculations (strength, stiffness and vibration resistance) in advance. The results of such calculations, together with the corresponding analytical support at the component level, are stored in the appropriate sections of the database, access to which allows for future design of multi-operational machine tool designs.

In work [7], the issues of research and the design of a three-axis milling machine based on the constructed 3D models are considered. An algorithm for the step-by-step formation of a finite element model of a machine tool is presented, at the first stage of which a finite element grid is constructed and meshed structural components, such as the machine bed, columns, spindle housing, spindle unit and workpiece. In the second stage, these components are positioned relative to each other and connected by hinges (three-dimensional spring-damping elements). A feature of the proposed approach is the identification of constraints used when assembling individual machine components. Particular attention is paid to the moving components of the machine and their axes, in particular the components of the main movement drive.

Another aspect of the three-dimensional representation of mechanical engineering objects (using the example of turbines) is reflected in the work [8]. This is the stage of implementing a finished product in the environment of a digital 3D modeling service, at which you can apply the concept of "product price - consumer demand" when forming internal logistics flows. The authors of this work explore the issues of flexibility of internal logistics of an enterprise based on a high-precision 3D model of a turbine built in the SolidWorks CAD system.

The composition of technological operations implemented on multi-operational machines is varied: milling of flat surfaces; ledges; grooves; milling of spatial surfaces; drilling and reaming holes with precise coordinate locations; boring and others. When using such multi-operational machines, it is important to find optimal modes for various technological operations. An interesting approach based on the use of the Six Sigma Methodology apparatus in the Minitab-16 software environment is presented in [9]. A set of variable factors influencing the selection of optimal solutions was analyzed and factor graphs were constructed to determine the contribution of important parameters. This leads to a reduction in cycle time and increased processing productivity on machine tools.

The processes of 3D modeling of structures and technology on CNC machines against the background of comparison with rapid prototyping technology using the example of a Maltese cross transmission are presented in [10]. The authors emphasize the promise of integrating rapid prototyping and computer-aided design technologies, which makes it possible to obtain complex geometric shapes of mechatronics parts.

The creation of a three-dimensional machine design in a modern CAD environment involves the use of a history-based parameterization apparatus, which was developed in 1987 in the form of the Pro/ENGINEER application program, now PTC Creo [11]. The basic idea of parametric design was to create the 3D geometry of a product piece by piece, turning 2D sketches into 3D elements with constraints and relationships that are properly applied according to the designer's intent. At the same time, parametric modeling is effectively used for fairly typical engineering products, when the model is controlled by parameters that may include dimensions, various profiles, the wall thickness of the housing part, diameters and depths of holes, etc. According to the author, parametric modeling based on history is still the dominant paradigm in the CAD world.

In [12], a generalized method of parametric modeling is considered using the example of the geometry of the end mill cutting part. The shape of the cutting part is presented in the form of a connection of a circular arc and a straight segment (edge) on one side and a circular arc with a conical spiral on the other. Analytical dependencies that form the basis of parametric rib models have been constructed as spirals and arc ribs. Parametric modeling of end mill cutting edges with multiple functions can be used to optimize the cutter design for different options by changing the values of the appropriate set of parameters. Once the optimal cutter design has been achieved, the corresponding grinding method is also ready for effective use in cutter production.

The well-known CAD/CAE system APM WinMachine [13, 14] does not use an expensive borrowed parameterizer but implements its software to create a drawing and graphical parametric editor APM Graph, which can be used both as part of the system and on your own. The combination of parametric profiles in 2D graphic editors with subsequent export to a 3D editor seems to be effective. This compromise option is constructively implemented in the well-known CAD system "APM WinMachine".

In parametric modeling applications, the process of designing certain types of mechanical transmissions, such as various types of belt drives, appears to be efficient.

Based on the conducted research, we can conclude that it is advisable to research the main units and parts of multi-operational machine tools of various designs in the environment of developed integrated CAD systems such as Creo Parametric. A separate effect is associated with the use of application programs (modules) specialized for specific types of components (mechanical transmission), implementing the process of their computer-aided design.

The main emphasis in this work is on a comprehensive solution to the problem of improving the design of the drive part for a multi-operational machine tool, including the stages of 3D modeling in the integrated CAD Creo Parametric, parametric modeling using a specialized APM Graph module and, on this basis, constructing a fragment of the Database of multi V-ribbed elements. This approach provides a significant reduction in design time, and the multivariate parametric modeling procedure underlies the improvement in the quality of design solutions.

The purpose of the research of this article can be formulated as *Improving the design of the main drive for a multi-operational machine with a modernized belt transmission using 3D tools and parametric modeling.*

## 3 Research Methodology

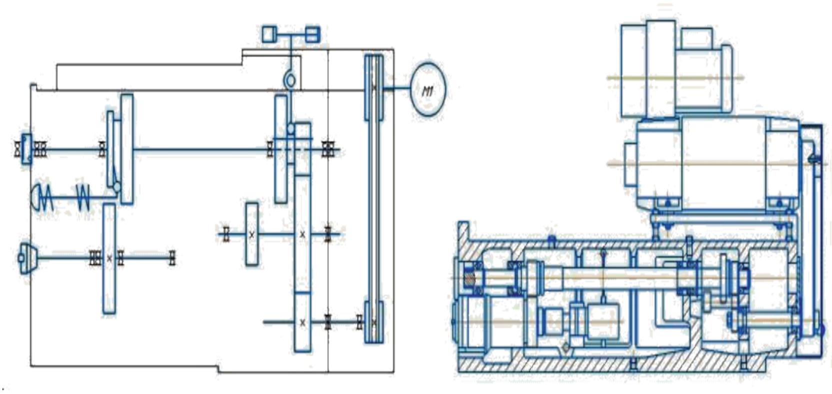
### 3.1 3D Modeling of the Multi-operational Machine Tools

At the draft design stage, the layout of the machine and its drive is developed using 3D modeling tooling [15, 16]. Among the design versions of the drive, its hydro- and electro-hydraulic variants occupy a large weight [17, 18].

Let's consider the design of the widely universal milling-drilling-boring machine SF68VF4, which implements high-performance processing of parts made of steel, cast iron, non-ferrous metals and alloys, as well as plastics.

The design of the SF68VF4 assumes that a column is fastened to a cast iron base, on which all the main parts of the machine are mounted. The spindle head ("Z" axis) moves along the horizontal shears of the column, to which a vertical head or additional devices and accessories are attached. The support ("Y" axis) moves along the vertical shears of the column, and along its horizontal shears the main vertical table ("X" axis), to which, depending on the configuration, a rigid corner table or a rotary one is attached, which is used for mounting workpieces on them. The backlash-free worm gearing of the rotary table of this machine is considered in [19].

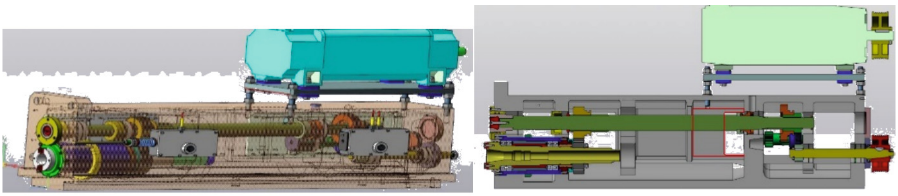
The MMD unit is mounted in a cast iron housing, the basis of which is a two-stage gearbox (Fig. 1b). The spindle rotates along a kinematic chain (Fig. 1a) from the electric motor through a multi V-ribbed belt and is transmitted to the input shaft. Next to the camshaft, from which rotation is transmitted to the clutch of a vertical or slotting head or the gear of a horizontal spindle.



a b

**Fig. 1.** Design of MMD unit: a – kinematics; b – assembly sketch

To further MMD research, its 3D project is being developed in the Creo Parametric CAD environment [20, 21]. Figure 2 shows a three-dimensional implementation of the design (Fig. 1b) using the developed functionality of the Creo system.



a b

**Fig. 2.** Three-dimensional model of SF68VF4 MMD unit: a – transparent assembly; b – section

CAD Creo has advanced capabilities for visualizing the project for the formation of a realistic project, as an image of the final product. In Fig. 3 shows a rendering of the drive of a multi-operational machine.

The most difficult task when creating a drive is modeling a housing part of a complex configuration [22]. A three-dimensional model of the gearbox housing of a multi-operational machine tool was developed in the CAD Creo environment (Fig. 4).

The problem is that the primary design model differs from the foundry implementation of the housing. This difference consists of the absence of data on the casting shrinkage, slopes and roundings characteristic of the housing casting model in the first

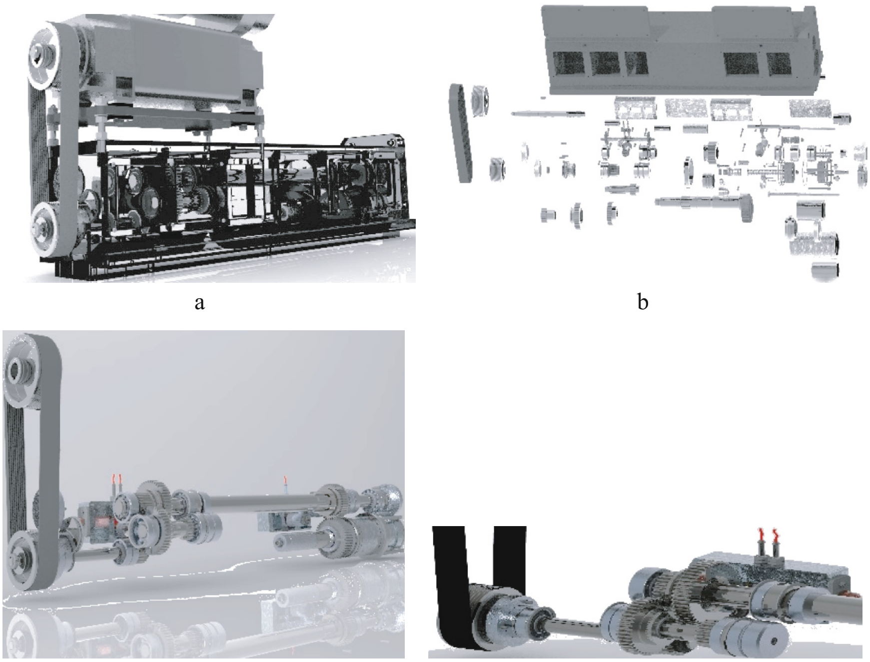



**Fig. 3.** Rendering of the drive of a multi-operational machine: a – drive assembly; b – spacing; c, d – kinematics rendering

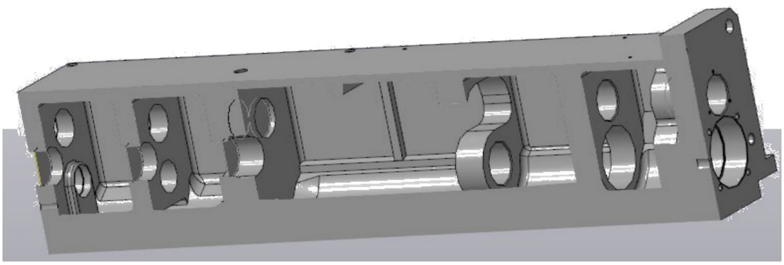


**Fig. 4.** Drive housing part

one. CAD Creo offers a tooling and corresponding system functionality called “Inheritance”. So, for example, shrinkage can be set by scaling it (Shrink by scale) taking into account the coordinate system. In this case, you can set different shrinkage coefficients for each coordinate. If shrinkage is specified in mold and mold modes, it will only be taken into account in the casting model and will not affect the design model. To calculate shrinkage, the formula $1/(1–S)$ is used, which sets the shrinkage factor based on the final dimensions of the original part after applying shrinkage. In this formula $S$ – shrinkage factor).

In Creo Parametric, when building 3D drive models, parameterization tools have been widely used, with which you can set specific values for a dimension, control the value of one dimension depending on the behavior of another dimension, dynamically suppress elements depending on changes in the part, etc. Universal toolkit Creo allows you to work with a wide range of objects with various shapes and sizes, as well as with a variety of graphic primitives.

At the same time, there are alternative options for parametric modeling, focused on a certain type of object of similar shapes, but of different sizes (for example, drive belt drives). Such software modules include the APM Graph module [23, 24].

### 3.2 Creation of Parametric Models of Multi V-ribbed Transmission in the APM Graph Module

In the APM Graph module, the parametric model is a sequence of drawing commands with specified parameters in the environment of this two-dimensional graphic editor. In the first stage, the selection of input parameters and the degree of their influence on the structure properties under consideration is important. Such a problem of a detailed analysis of various parameters influence using the example of the problem of identifying free and constrained vibrations of the crankshaft is presented in [25]. Another example of determining the main physical parameters to model in the Bond Graph library for mobile robots that can be used in the machine tool industry is presented in [26].

In the APM Graph module, a sequence of commands is formed in a special dialog box ("Command Window"). In this case, the parameters are set either numerically or through analytical expressions in a special dialogue box ("Variable Window"). The finished parametric model can be inserted into a regular drawing as a parametric block. When inserting a parametric block, it is enough to fill in only the source data. The parametric model can also be added to the database using the APM Base editor [14].

It should be noted that parameterization is an integral part of three-dimensional modeling. It is the creation of a working 3D model of mechanical transmission elements, according to [27], that is one of the main goals at the initial stage of contact geometry analysis, visual identification and assessment of the relationships of many mechanical transmission geometric parameters. At the stage of constructing 3D models of MMD parts and assembly units, 3D models of pulleys and belts for multi V-ribbed transmissions (Fig. 5).

Let's consider the procedure for constructing a parametric model for the class of designed objects "Multi V-ribbed Transmission". In the process of constructing 3D models, parametric models of their components were developed at various stages of modeling. Figure 6, shows interactive parameterization tools, consisting of two dialogue boxes: "Variable Window" (Fig. 6a) and "Command Window" (Fig. 6b).

At the initial stage of constructing a parametric model of a multi V-ribbed belt and pulley, the initial data is entered in the window variables using the CAD syntax APM WinMachine (Fig. 6a). The initial data includes the following variables: $N$ – power of the drive electric motor, kW; $n$ – rotation speed of the drive pulley, min$^{-1}$; $\tau$ – permissible shear stress, MPa (useful stress in the belt).

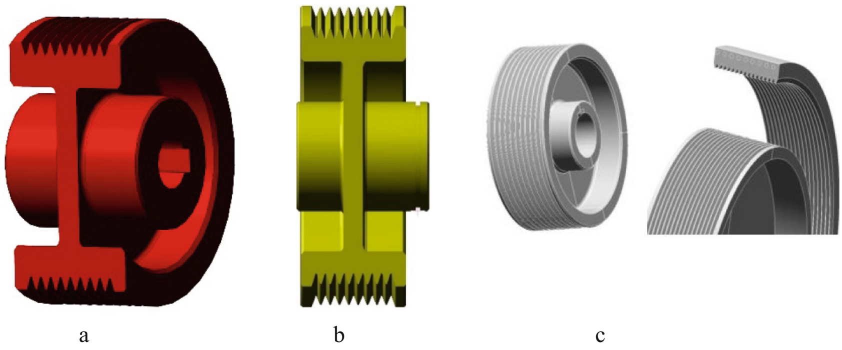



**Fig. 5.** Three-dimensional models of pulleys: a – driven; b – driving; c – assembled

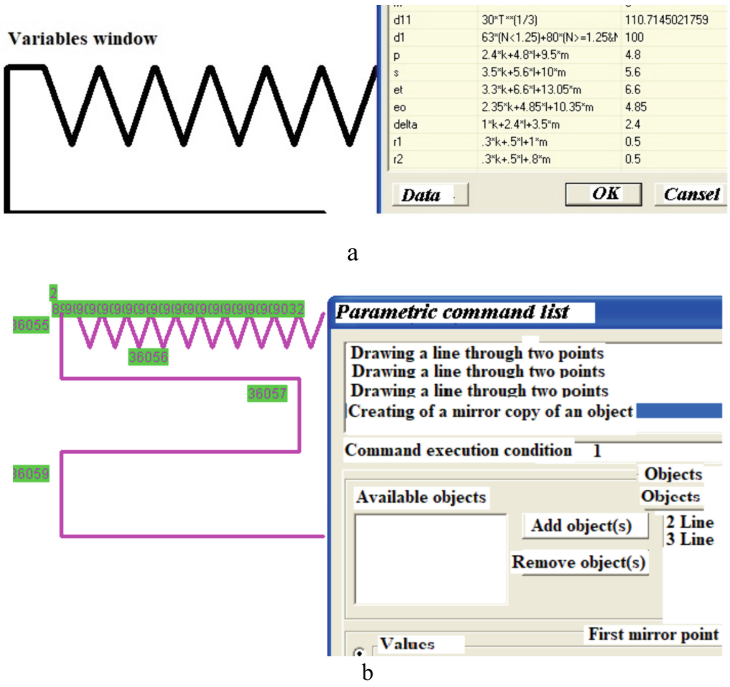


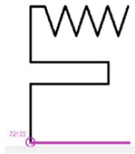

**Fig. 6.** Parameterization tooling: a – variable window; b – command window

The first step in the calculation is the selection of the belt section (K (PJ); L(PL); M(PM) – depending on the drive power (designations under DIN78671/ISO9982 are indicated in parentheses). The belt wedge is parameterized using analytical expressions (Table 1) for the parameters:

– belt length $L_w$ and distance from the end of the pulley to the groove axis $s$ (left column of Table 1);

- rectangular single-line array ($x = 1$) taking into account the length of the mirror part ($m_p$). These parameters are functions of the pitch of the belt grooves $p$ and the number of belt wedges $z$;
- forming the pulley disk through the parameter $b_d$ and the pulley hub with a height $h_h$, that depends on the width of the pulley $M$, the width of the pulley disk $c$,, the diameter of the hub $d_h$ and the mounting hole $d_{mb}$.

**Table 1.** Parameterization of the MVRT-transmission profile

| Creating a wedge shape | Creating a rectangular array of wedge | Create a disk and hub |
|---|---|---|
|  |  |  |
| $L_w = \frac{h}{\cos(rad(20))}$; $s = 3.3*pj+5.6*pl+10*pm.$ | Rows: $x = 1$; Column: $m_p = p*z+2*(s-p/2)$ | $b_d = M/2-c/2$; $h_h = d_h/2-d_{mb}/2.$ |

This approach to the design of specific types of mechanical transmissions is supported by the possibility of using the APM Base application module – a database creation module [28]. The components MVRT Base are parametric models of individual elements and structures of transmission. In addition to the geometric contour of the belt and pulley, parametric models contain some characteristic data, for example: rated power, rotation speed, efficiency of electric motors; dynamic and static load capacity of bearings on the shafts of which the MVRT is mounted. In this regard, the functionality in terms of using the database as a reference book is expanded. This article proposes a specialized MVRT database for multi-operational machine tools (Fig. 7).

Based on the proposed three-dimensional and parametric modeling tooling, the possibilities for MVRT constructive improvement in the multivariate design mode are expanded. In a practical application, the use of the APM Graph parametric modeling module opens up the possibility of choosing the best belt drive option for all standard sizes of belt sections, and the introduction of a parameterized database makes this process more efficient.

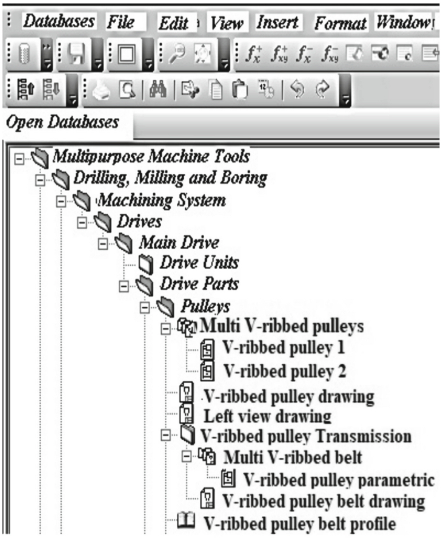



**Fig. 7.** Fragment of the MVRT database

## 4 Results

### 4.1 Theoretical Part

One of the ways to increase the traction capacity and durability of multi V-ribbed belts (MVRB) is associated with modifying the shape of the belt wedges. In the traditional version [29] under DIN 7867/ISO9982, the wedge profile is outlined by straight lines. This article presents the results of research on a modified form of wedges with a concave profile. Giving the wedges a concave configuration, proposed by the authors [30], leads to quantitative changes in the performance of the belt for two reasons: 1) the width of the wedges at the base increases; 2) the length of the side (working) parts of the wedges increases. The consequence of the first reason will be an increase in the strength of the wedges, which will lead to an increase in the traction capacity and durability of the belt. The second reason is an increase in the contact area of the belt wedges with the grooves on the pulley, as a result of which the friction force between them will increase, which also increases the load capacity of the belt transmission.

The cross-section of a modified MVRB with 4 wedges is shown in Fig. 8a. It should be noted that in the proposed MVRB-variety, the main parameters: pitch $t$, height of the belt section $H$, height of the wedges $h$ and coordinate of the cord location $\delta$, are taken to be the same as in the standard belt for sections {PJ; PL; PM}. In this regard, the designations for the modified MVRB are adopted accordingly: {PJ*; PL*; PM*}.

The parameters characterizing the shape of the modified wedges are given in Fig. 8b (for clarity, the outline of the wedge for the belt according to standards is shown here with a dotted line).