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Application of software solutions for modeling and analysis of parameters of belt drive in engineering

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Abstract. The application of software systems in engineering when developing the belt drive designs and evaluating their characteristics is considered. A technique for calculating and analyzing belt drives is described using the example of calculating V-belt and flat-belt drives using a software solution. As a result of the belt drive analysis, belt profiles, belt cross-sectional dimensions, drive and driven sheave diameters and power parameters are determined, and graphics images of the dependences of belt’s prestressing force and the force acting on the shaft from the diameter of the driving sheave are obtained. By approximating the results of calculations, theoretical equations for calculating the power parameters of the belt drives were derived. Carrying out the analysis of belt drives with the use of software solutions allows one to avoid computational errors and to optimize the design and performance. At the same time, a convenient and intuitive interface, as well as an integrated graphical editor, provide visibility of the output data and allow the accelerated engineering analysis of the development object.

1. Introduction
When developing new equipment, technological and design calculations are always performed. The fulfillment of these tasks in the modern world is not conceivable without the use of computer-aided design tools and the use of specialized modeling software for the processes being developed. In the world market there are many software solutions for engineering analysis of mechanical equipment and structures, for example, SolidWorks, KISSsoft, KOMPAS-3D, APM WinMachine, etc. In this case, for the analysis of typical parts and components, they allow the use of engineering methods based on analytical solutions [1-4].

The most common elements of equipment and process lines include units and aggregates with kinematic connections. These units include mechanical drives that specify the parameters of motion during the transfer of it from the electric motor to the actuator. Quite often, the drives have belt drives that are characterized by simple construction and reliability [5-6]. Transmission of the load in belt drives is carried out due to the friction forces that arise between the sheaves and the flexible element...
To increase the force of friction, the belt is subjected to pre-tensioning. Structurally, this can be done by increasing the interaxle distance between the sheaves due to the displacement of the motor or the use of tension rollers [8-9].

Belt drives are mainly used to transfer loads of less than 50 kW at medium speeds from 5 to 50 m/s and drive ratios from 2 to 3. The drive ratio of the belt drives is not constant, unlike the gears, due to slippage of the belt. In kinematic schemes of drives, the belt drive is placed after the electric motor in the place of installation of the low-loaded stage [10-11].

Depending on the belt's shape of the cross section, the drives are classified into flat-belt, V-belt and poly-V-belt [12].

Vendor belts have the greatest application in mechanical engineering. They have a trapezoidal cross-section and operate on sheaves with grooves of belt corresponding to the profile. The size of the cross section depends on the type of belt. For general purpose gears, six types of belts are identified: Z, A, B, C, D, E [13].

V-belts are used in cases of power transmission up to 200 kW, with large gear ratios, vertically arranged shafts and a small interaxial distance. Flat-belt drives are recommended at high speeds (up to 100 m/s), large interaxle distances (up to 15 m), gear ratios greater than 6 and increased requirements for smooth operation. The belt in cross section has the form of a rectangle, differing in thickness and width of the belt, and the sheave has a convex rim for better centering of the belt [14]. Poly-V-belts combine the advantages of flat-belts (flexibility) and v-belts (high traction). Due to the high flexibility of such belts, sheaves of small diameters can be used, as well as work at speeds up to 65 m/s and capacities up to 1000 kW [15-16].

Based on operating conditions, V-belt and flat-belt are widely used in agricultural machinery, engine building, machine-tool construction, automotive engineering, textile industry and other industries [17-19]. Ensuring the safety, reliability, durability and economy of equipment with belt drives, requires the need for comprehensive engineering analysis, the projected facility and the selection of optimal characteristics from the set of proposed solutions. Currently, a large number of methods for calculating various transmissions have been developed, but comprehensive analysis and optimization become possible only with the use of modern software.

2. Methods of analysis and calculation of the parameters of belt drives

When designing belts, there are the following recommendations:

- for ease of belts' installation, the sheaves of drives should be located at the ends of the shafts and as close as possible to the support (to reduce the bending moment) [20];
- to create a belt pre-tensioning and to compensate for its elongation, a belt tensioning device (usually this device is used to replace a worn belt) should be provided in the design [21];
- it is recommended that the driven part of the gear is positioned from above to increase the angle of the girth while the belt is sagging, and the tension roller should be placed near the driven part inside the belt contour [11];
- in order to avoid increased wear of belts, the roughness of the sheave working surface must not exceed Ra 2.5 µm [13];
- V-belts should not protrude beyond the outer diameter of the sheaves, since the edges of the grooves quickly destroy the belt.

The calculation of V-belt and flat-belt drives performed based on the APM WinMachine program using the APM Trans module is considered in this material. This module is intended for the design and calculation of mechanical transmissions, and the methods used by the system for calculations have sufficient accuracy for engineering practice [22]. Using the module APM Trans allows you to determine the geometric dimensions of the drive and the design of the belt, calculate the cross section of the belt, the number of belts and their service life.

The main criteria for the performance of belt drives are traction (the belt's bond performance with sheave) and the durability of the belt. Calculation of traction performance is a design calculation of
belt drives and is necessary to determine the strength of the belts and the bearable load. The calculation for durability is a test [7].

According to the methods incorporated in the APM Trans module, the calculation of the flat-belt drive by traction capability is limited to determining the cross-sectional area of the belt:

\[ b = \frac{F_t}{[p]} \]  

(1)

Depending on the design of the belt, the maximum permissible specific operating load is calculated by the formula:

\[ p_0 = p_{01} \cdot z \cdot \beta \]  

(2)

The permissible circumferential force is calculated by the formula:

\[ [p] = \frac{C_a \cdot C_v}{C_p} \cdot p_0 \]  

(3)

where \( C_a \), \( C_v \), \( C_p \) – coefficients that take into account the difference between real operating conditions and basic ones.

The expression for determining the useful voltage satisfying the strength and traction conditions can be represented in the form:

\[ \sigma_{10} = \frac{5.55}{v_{0.09}} \cdot 6 \cdot \frac{w_p^{1.57}}{d_p} \cdot 10^{-3} \cdot V^2 \]  

(4)

For the given operating conditions, the allowable useful voltage has the form:

\[ [\sigma] = \frac{\sigma_{10} \cdot C_a}{C_p} \]  

(5)

V-belt drive includes several belts, the number of which is determined by the formula:

\[ z = \frac{F_t}{C_z \cdot A_1 \cdot [\sigma]} \]  

(6)

The durability of the belt determines its ability to resist fatigue failure. Durability depends on the values of stresses, the nature of their changes per cycle and the number of such cycles. Since the bending stress exceeds the total value of other stresses in the belt, its durability largely depends on the number of bends on the sheaves. The run frequency is also an indication of the longevity of the belt. The higher the frequency of runs, the less durability at the same level of stress. The average durability of the belts varies from 2000 to 3000 hours.

One of the drawbacks of belt drives is the increased load on the shafts and bearings from the belt tension. Therefore, the force of the pretension of the belt (at \( 0 \leq \chi \leq 1 \)) and the resultant force from the load in the leading and trailing parts of the belt, at a given tension are determined:

\[ F_0 = 0.5 \cdot (F_1 - F_2) - \chi \cdot F_c \]  

(7)

\[ F_r = (F_1^2 - F_2^2 - F_1 \cdot F_2 \cdot \cos \alpha_1)^{1/2} - 2F_1 \sin \left( \frac{\alpha_1}{2} \right) = F_0 \cos \left( \frac{\beta}{2} \right) \]  

(8)

The forces in the belt from the centrifugal forces depend on the material, the dimensions of the belt and the sheave and is determined by the formula:

\[ F_c = b \cdot g \cdot \omega^2 \cdot R^2 \cdot 10^{-3} \]  

(9)
3. Results of the analysis and discussion

To calculate the belt transfer in the APM Trans module of the WinMachine AWM software, it is necessary to select the type of drive to be calculated (flat or V-belt) and the calculation method (design or test) and to specify the initial data: power on the drive shaft, drive shaft speed, gear ratio, dynamic load coefficient. It is also necessary to specify the value of the interaxle distance, the maximum number of belts and the angle of inclination of the drive.

For an approximate calculation, the design calculation of the flat and V-belt drives was chosen and the following basic calculation parameters were established: power on the drive shaft = 1.5 kW; the number of revolutions of the drive shaft = 1000 min\(^{-1}\); gear ratio = 2.0; coefficient of dynamic load = 1.05; center distance = 500 mm; maximum number of belts = 6; drive angle = 0. The type of drive adjustment is set to "tension by displacement".

In the design calculation, the APM Trans module calculates the basic geometric dimensions of the drive, based on the criteria for traction and longevity of the belt. As a result, the program prints a table with various variants of the dimensions of the cross sections of the belts, the diameters of the drive and the driven sheaves and the power parameters (Figure 1).

According to the calculation results, the values of the force parameters (the force of the belt pretensioning, the force acting on the shaft) are represented in the form of graphical dependences on the diameter of the driving sheave. The graphical dependences for the flat and V-belt drives for different belt sections: Z, A, B, C, are shown in Figure 2, Figure 3 and Figure 4.
Analysis of graphical dependences (Figure 2) shows that for the selected belt sections the nature of the lines of force is practically the same. Consequently, the forces acting in the belt drive depend little on the selected cross-section, but depend on the diameter of the driving sheave, and with increasing diameter, the force value decreases. By approximating the results using the TableCurve, the following equations were obtained:

- for the pre-stressing force
  \[ y = -0.00004 x^3 + 0.0284 x^2 - 7.0269 x + 725.3 \]  \hspace{1cm} (10)

- for the force acting on the shaft
  \[ y = -0.0001 x^3 + 0.00703 x^2 - 16.425 x + 1556.2 \]  \hspace{1cm} (11)

Analysis of the calculation results (Figure 3, Figure 4) shows that the diameter of the driving sheave depends on the cross section of the belts and their number. When choosing the calculation option, it is necessary to take into account the following: from the possible values when selecting the belt section, preference should be given to a smaller area and height, since such belts have a minimum bending stress, and the resource and efficiency are high. However, when choosing a smaller section, the number of belts in the V-belt drive increases. Due to differences in the length of the belts (within tolerance) and the mechanical characteristics of the fabrication materials, the load distribution between the individual belts will be different. As a result of the calculation of the belt drive, the program displays a table with a variety of solutions for different belt thicknesses. Statistical data processing in the TableCurve obtained the following approximating relationships for the flat-belt drive at belt thickness \( m = 4 \) mm

\[ F_r = 24.25 d^2 - 293.55 d + 1337.8 \]  \hspace{1cm} (12)

\[ F_0 = 3.5 d^2 - 85.5 d + 628 \]  \hspace{1cm} (13)

and for V-belt drive with belt section \( Z \) with a number of belts equal to 2

\[ F_r = 54.75 d^2 - 322.25 d + 627.75 \]  \hspace{1cm} (14)

\[ F_0 = 6 d^2 - 55.8 d + 262.5 \]  \hspace{1cm} (15)

Based on the graphical dependences (Figure 3, Figure 4), a nomogram can be constructed to select transmission parameters with different sizes of cross sections and belt numbers.

4. Conclusions

The use of software systems for calculating and simulating belt drives makes it possible to significantly reduce the computation time in comparison with the classical design methods. With automated design, the number of calculation errors is greatly reduced and the accuracy of calculations is increased. Also there is an opportunity to optimize the design of belt drives, which makes it possible to ensure the economy of the mechanism. A convenient and intuitive interface, as well as an integrated graphical editor, provide visibility of the output data and allow for accelerated engineering analysis of the development object. By selecting a specific calculation option, the graphics editor generates a drive or driven sheave drawing with the specified geometric dimensions and the type of coupling of the hub to the shaft. When entering new initial data, provided that the strength characteristics of the previously obtained data are saved, a comparative calculation can be made, for example, in the case of a change in operating mode with increasing power. Such functionality of the software packages allows
choosing the optimal variants of the belt drive design to ensure safe operating conditions and reduce the cost of the equipment. Also, when solving complex engineering problems, software systems use world and domestic experience using international databases, ensuring a reduction in the likelihood of errors in the performance of calculations. Thus, the use of automated design mechanisms increases the productivity of the design department and reduces the dependence of the results of design and construction work on the skills of employees.

**Notation**

- $F_t$ – circular force, N;
- $[p]$ – allowable specific circumferential force transmitted by a unit of belt width, N/m;
- $z$ – number of operating layers in the belt section, pcs;
- $p_{01}$ – nominal circumferential force, N;
- $C_a$ – girth angle effect coefficient; $C_r$ – coefficient of influence of centrifugal forces; $C_p$ – coefficient that takes into account the mode of operation of the drive; $ν$ – frequency of runs, 1/s; $V$ – belt speed, m/s; $w$ – the estimated width of the belt, m; $d_e$ – equivalent diameter, m; $A_t$ – sectional area of the belt, $m^2$; $F_1$ and $F_2$ – tension forces of the driving and driven part of the belt, N; $F_0$ – force of the pretension of the belt, N; $F_2$ – force in the belt from centrifugal force, N; $β$ – the angle between the belt parts; $χ$ – coefficient, taking into account the reduction of forces of pressing the belt to the sheave; $b$ – width of flat belt, m; $g$ – the surface density of the belt material, kg/m$^2$; $ω$ – angular velocity of the drive sheave, 1/s; $R$ – the radius of the drive sheave, m.

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