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THE INFLUENCE OF DESIGN FRICTION AND INTERNAL FRICTION ON DIRECTIONS IN DEVELOPMENT OF BELT TRANSMISSIONS

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Abstract

Design and internal friction affects quantitative and qualitative deformation processes in flexible connector belts. Thanks to internal friction it has been possible to explain the phenomena of frictional contact. Taking internal friction into account has crucially influenced directions in development of flexible connector belts.

1. Introduction

Materials that flexible connectors are made of have polymeric structure of the spacially disordered network of bonds. Not such a long time ago, materials used for rubber and plastic flexible connector belts were treated as linear elastic bodies, isotropic bodies etc., having mechanical properties similar to metals. Numerous experimental studies have proved that properties of these materials are totally different from the so far accepted physical model, and at the same time, mathematical model. Materials used for flat belts, V-belts, synchronous belts as well as special belts show significantly developed non-linear elastic, anisotropic and rheological properties. The materials undergo typical rheological processes: creeping, stress decay, elastic reversal, strong internal friction and energy dissipation, internal structure orientation and its mechanical stabilization, material memory that includes the history of load and strain, chemical relaxation, change of properties and change of the internal structure caused by the increase in positive or negative temperature. Van der Waals forces in these materials have a significant influence on the formation of mechanical and rheological properties, e.g. starting from the immediate resistance limit to rupture R_m ending on changeable values of moduli of elasticity.

Many basic phenomena significant for the frictional contact of the belt transmission such as design friction as well as circumferential and radial slip, distribution of forces in the flexible connector of the belt on the arc of contact, or the change in the outline of the transverse section of the belt occur as a result of quantitatively and qualitatively different strains in the belt on the arc of contact.

Problems connected with design friction in the machine dynamics have been described in Paper [2]. Problems and phenomena of internal friction in different elastic materials have been broadly described in Paper [3]. Physical conditions of internal friction and energy dissipation connected with the internal structure of a given material and its role in mechanical vibration damping have been presented in the fundamental Paper [4]. Energy dissipation in non-linear mechanical systems has been discussed, among others, in many of Osiñski's papers, including his earliest Paper [5].

The above listed papers [2, 3, 4, 5] as well as other numerous papers on design and internal friction written by these authors crucially influenced the creation of research methods of belt transmissions that would be adequate for their real internal structure and, resulting from the fact, physical properties of the material.

According to the research [1] cyclic deformation of the belt cross-section section during its bending over a pulley has a significant influence on the value of energy loss that occurs at the internal friction in the belt material. It also influences the increase in temperature in the belt. The greatest internal friction and energy dissipation occur in compressed layers, below the neutral axis.

All the above listed conditions have influenced both a new interpretation of the phenomena that occur at frictional contact and directions in development of belt design.

2. Directions in develpment of belt design

The recognition of the phenomena of frictional contact has presently the integral influence on the methods of designing and on directions in the development of the flexible connector belts design. The development has followed and is still following mainly the design direction and also production techniques. Here are the short characterictics of the particular ways [6]:

Directions in designs

This ways consists in improving the qualities of the already existing geometric forms of belts or designing new geometric forms of belts, which is revealed mainly in the gradual change of the outline of the cross-section. The fact that the greatest internal friction and energy dissipation occur in compressed layers of the belt has led to the direction in design aiming at diminishing or limiting to the minimum the area under the neutral axis in the belt section. The example of the gradual improvement of qualities of the already existing design is a special type of narrow V-belts used in the drive. The area of their cross-section is smaller than that of a typical belt. To increase the axial flexibility of the belt for bending, and at the same time, to decrease the work of internal friction, passive transversal toothing has been applied onto internal and external surfaces of the belt. In some designs, e.g. in V-belts concave or curvilinear working side surfaces have been designed. After bending they adopt the shape of a trapezoid and a wheel groove. Most often the geometric form of the belt changes due to the decrease in the belt height. The belt dimensions change, namely: width l_o and height h_o. Thus, the characteristic ratio of the belt dimentions: h_o/l_o decreases, too (Fig.1).

The postulate to decrease internal friction (decrease the belt height and the height under the neutral axis) and to increase susceptibility for bending at the same time as well as to use advantages of flat and V-belts has been put into practice in the construction of belts with many V-cogs that would have a triangular or trapezoidal outline of Poli-V type. (Fig.2).

Thanks to that, it is possible to use either flat-faced pulleys or sheaves in drives with such belts. These belts have a thin, inextensible carrying layer all over their width and small height, which makes them susceptible for bending. Therefore, in the transmission, it is possible to use pulleys of a small diameter (up to ϕ 20) as well as high values of velocity and power up to 200 kW. Such belts are conventionally used for the velocity of 50 m/s though some types can also be used for the velocity of 200 m/s.

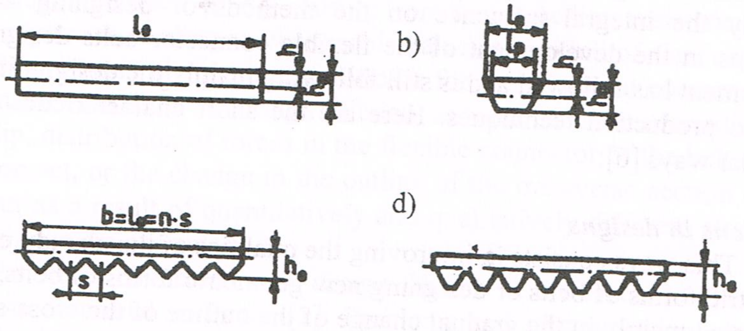

Fig.1. Change in the characteristic dimentions of the belt h_o/l_o:
a, b - traditional belt shape, flat or V
c, d - new solutions of the geometric form (belts with passive cogs)

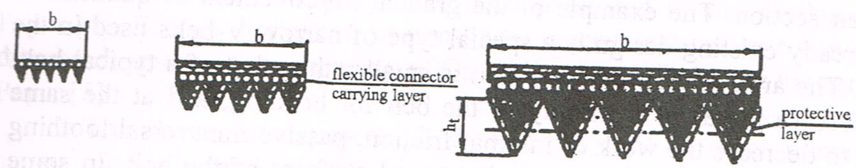

Fig.2. A combined belt of Poli-V type; a - a fine-cogged belt made without layers of covering fabric, b, c - a belt of the increased height of the cog outline, made with the protective layer

Durable combination of two or more belts (Fig.3) enables conveying large loads (this eliminates the phenomenon of circulating power) as well as conveying loads in different directions (Fig.3b).

Another trend in the changes of designs aims at substituting the flexible rubber layer with another layer that is more rigid (polyurethane, polyamide, etc.) and where the work of internal friction is smaller as well as at improving the features of the geometric belt form by lowering the belt

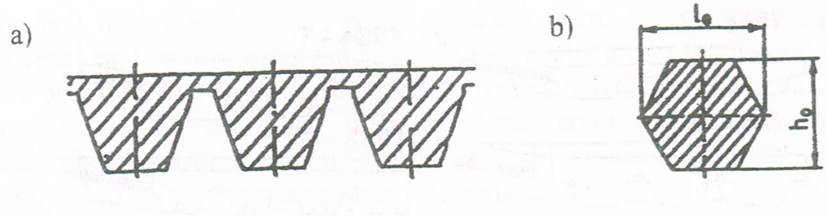

Fig.3. Special types of a V-belt; a - a kraftband, b - a hexagonal, double belt

height h_o and by increasing the value of the belt wedge angle of flare - up to 60° (Fig.4).

These belts can be used for small pulleys in the transmission and for greater transsmission ratios.

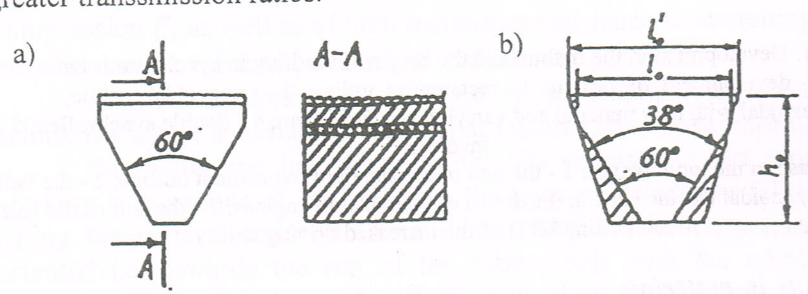

Fig.4. A polyurethane belt of the wedge angle $\gamma = 60^{0}$; a - the cross-section of the belt of the wedge angle 60^{0} , b - comparison of the belt shape of the wedge angle 60^{0} with the traditional belt of the wedge angle 38^{0}

Changes in the design of timing belts are integrated with their shape-friction way of conveying load. The development in design is visible in the improvement of the carrying layer features - the layer is becoming more inextensible and more resistant - helically coiled glass, aramid, kevral or steel fibres, improvement of the flexible layer that is most often made of polyurethane plastics (PTFE), polyamide plastics (PA), neoprene plastics etc. as well as changes in the outline and the height of toothing (Fig.5).

Belts of the half-round outline are characterized by the greatest tooth heights. They are used for great power transmissions e.g. in marine engines. Belts with double teeth (Fig.5a.) are characterized by the greatest uniformity of their run.

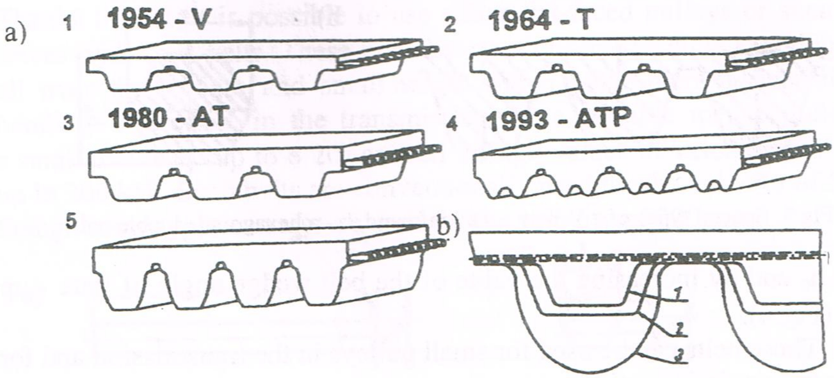

Fig.5. Development in the outline and the height of toothing in synchronous belts;
a - development of design: 1 - rectangular outline, 2 - trapezoidal outline,
3 - trapezoidal with new material and carrying reinforcement, 4 - double synchroflex, 5 - involute;
b - increase in the tooth height: 1 - the belt of the standard trapezoidal outline, 2 - the belt of the trapezoidal outline used in the drives of combustion engines, 3 - the belt of the half-round outline HTD of the increased driving ability

Directions in materials

The trend concerning materials aims at the improvement of the mechanical and rheological properties of those materials that are used for belt constructions so that the materials could better meet different demands. The most important are features making the belt and pulleys coupling easier, ensuring longer durability and better reliability as well as the ability to transmit the greatest moment at possibly greatest tangential velocity. Large coefficicent of friction μ, adequate features of internal friction and energy dissipation in the direction of loading: tension and compression ensure good belt coupling in the transmission. The belt durability is determined by its fatigue strength, which in turn depends on the belt susceptibility for bending and energy dissipation resulting from the internal friction. Furthermore, another important feature is the material resistance to permament, non-reversible strain iniciated at operating the transmission [7]. Large energy dissipation increases the temparature in the belt flexible connectors and diminishes its mechanical and rheological properties [1]. It influences the belt durability and the transmission efficiency. Therefore, in the belt design and the choice of materials, there is a trend to keep the internal friction and energy dampening in the area above the neutral axis in the belt material. It is useful because it dampens well the material own mechanical vibrations as well as those coming from outside the transmission; moreover, it makes the drive more flexible. Energy dissipation below the neutral axis is harmful and we should try to eliminate it. One of the ways is minimizing, in the belt cross-section, the area under the neutral axis which undegoes the process of compression (Fig.1).

It has been proved, on the basis of the experiment results (1, 7) that using materials of high values of Young's modulus at stretchning E_r and possibly greatest flexibility defined by the modulus of elasticity at compression E_c as well as of high temporary resistance to stretching R_m and possibly lowest value of permament strain is well justified.

The V-belt presented on Fig.6 is an example of such design solutions - where material and functional features have been improved.

Improving the belt design (Fig. 6b) consists in not closing the working side surface of the belt with the layer of protective fabric and in filling the surface under the neutral axis with the mixture transversely oriented i.e. towards the run of the rubber belt with the admixture of synthetic fibres. Thanks to that, large belt elasticity towards run (small bending moment), high transversal rigidity, wear resistance and the decrease in permament strain are obtained. As a result, the trapezoidal shape of the belt is slightly deformed at the arc of contact under the neutral axis, which diminishes the work of internal friction and energy dissipation. Belts with the open side surface have the side surfaces sanded - as a result surfaces of high smoothness and presition are obtained. The designs of the combined belt of Poli-V type and the V-belt of the incresed value of the wedge angle of flare 60°, made of polyurethane (PTFE) are other examples of not closing the working belt surface - Fig.4. It influences the improvement of driving abilities.

The drawback of rubber elastomers used for flexible connectors is some impact of permament strain during their deformation. Replacing the carrying layer made of threads and lines of natural fibres with the one made of synthetic fibres and using such synthetic plastics as e.g. polyurethane (PTFE), polyamide (PA), polyethylene terephthalate (PTE), thermosetting

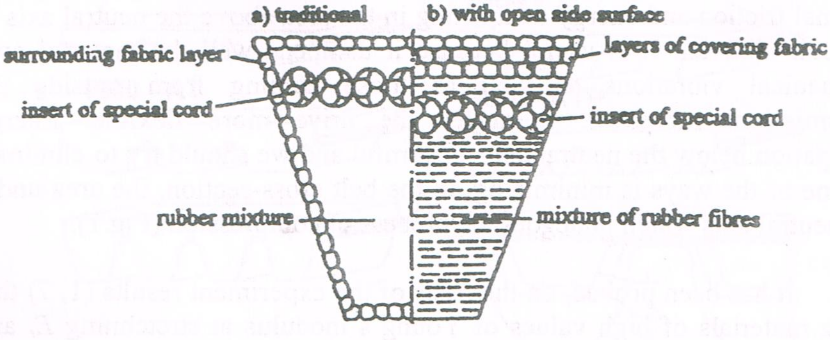

Fig.6. Improving the material features in the V-belt;
a - traditional solution,
b - new solution with the open side surface

plastics including phenolic resins for the flexible layer can significantly diminish permament strain.

Directions in production techniques of belts

The above mentioned directions are integrated with the general development of science and technology [8]:

- improvement of technical possibilities of adequate choice and estimation of properties of material mixtures, mainly rubber or plastics at particular stages of material processing,
- new ways of inicial forming and belt vulcanization,
- new possibilities of combining the features of geometric forms for vulcanization (e.g. forms for synchronous belts and pulleys),
- using new materials for the carrying, inextensible and abrasive layer (rubberlike types of materials).

3. Examples of the author's own research concerning the minimalization of the internal friction work

The method of minimalizing the belt deformation at the arc of contact is an example of designing features of the geometric form in a V belt cross-section and taking into account the criterion of internal friction work and techniques of production (vulcanization).

The method can be put into practice thanks to designing, among others: thanks to the proper choice of the belt cross-section geometric form. The method allows us to design the belt cross-section geometric form - in the initial stage its geometry should be designed in such a way that in the actual stage, after the belt has been roller bent around the belt pulley, the obtained shape shall meet the requirements of the criterion of internal friction work and pressure between the belt and the pulley (Fig.7).

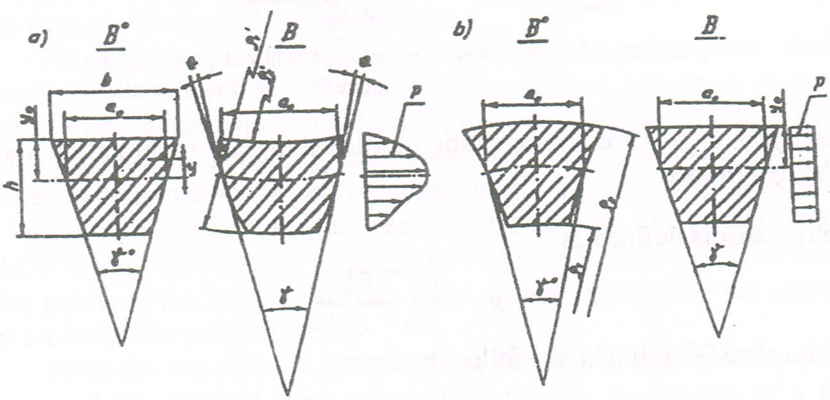

Fig.7. Deformation geometry of the cross-section of a belt being bent where:
a). belt of a traditional design
b). belt of a new geometry: state B^0 - initial configuration, state B - final configuration

An initial state B° of dimentionally undefined in its cross-section rubber V-belt undergoes deformation as a result of belt gird around a pulley. For a deformation state B the belt assumes a cylindrical form of inner radius $r_1 = r_w$ and outer radius $r_2 = r_z$, pulley bend angle 2α and trapezoidal cross-section (Fig.8). It is convenient to use for an actual state B the cylindrical co-ordinate system x_i (r, α, z) while the Cartesian co-ordinate system X_i for an initial state B^o.

Belt deformation can be described as follows:

$$X_1 = f(r) - az$$
$$X_2 = b \cdot \alpha$$
$$X_3 = c \cdot z, \tag{1}$$

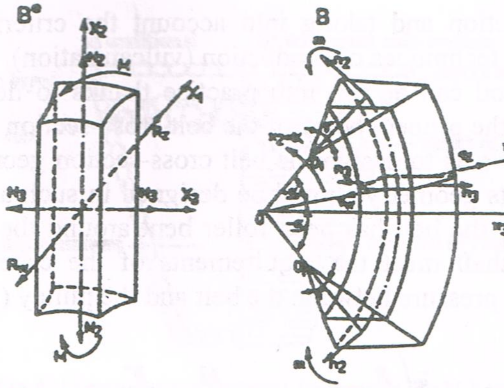

Fig.8. Belt deformation geometry: state B° - initial configuration
state B - final configuration.

where *f(r), a, b, c* are characteristic quantities for belt deformation and are to be determined.

Metric tensors defined as

$$g_{ij} = \frac{\partial X^m}{\partial x^i}\frac{\partial X^m}{\partial x^j}$$

for the state B° will take the following form:

$$g_{ij} = \begin{bmatrix} \left(\frac{\partial f}{\delta r}\right)^2 & 0 & -a\frac{\partial f}{\delta r} \\ 0 & b^2 & 0 \\ -a\frac{\partial f}{\delta r} & 0 & a^2+c^2 \end{bmatrix} \qquad (2)$$

and for the state B

$$G_{ij} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & r^2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (3)$$

After determining the invariant I_3 on the basis of metric tensors

$$I_3 = \frac{\det \underline{G}}{\det \underline{g}} = \frac{G}{g}$$

and after comparing it to a unit and taking into account the condition of rubber incompressibility

$$f(r) = \frac{1}{2bc} r^2 + C \,. \tag{4}$$

The constant C will be determined from the boundary conditions, which result from the assumed design conditions.

An effective determination of belt cross-section form design principles for a natural state B° using the method of non-linear elasticity requires proper assumptions conformable to design criteria. The final effect of deformation is integrally connected with the assumed geometric parameters determining the belt cross-section for the state B°. Assumptions of : 1). constant height in the belt central cross-section, 2). variable wedge angle $(\gamma^o > \gamma)$ for the state B° or constant wedge angle $(\gamma^o = \gamma)$, 3). A and B border points of the belt side surface fixed during deformation are justified from the technical point of view.

From the deformation geometry and the state of stress a co-ordinate system will be obtained from which characteristic parameters of a new geometric belt form a, b, c, and r 1 can be determined.

$$r_1 + r_2 = 2bc \tag{5}$$

$$\frac{b^2c^2}{A^2} \ln \frac{r_2^2\left(A^2 - r_1^2\right)}{r_1^2\left(A^2 - r_2^2\right)} - b^2c^2\left(\frac{1}{r_2^2} - \frac{1}{r_1^2}\right) - \frac{1}{b^2}\left(r_2^2 - r_1^2\right) = 0 \,. \tag{6}$$

$$L\left[\frac{3}{8b^2}\left(r_2^4-r_1^4\right)-\frac{b^2c^2}{2}ln\frac{r_2}{r_1}+\frac{3}{4}b^2c^2L\,ln\frac{A^2-r^2}{A^2-r_1^2}+\right.$$

$$\left.+\frac{1}{2}\left(r_2^2-r_1^2\right)\left(\frac{b^2c^2}{2A^2}ln\frac{r_1^2}{A^2-r_1^2}-\frac{b^2c^2}{2r_1^2}-\frac{r_1^2}{2b^2}\right)\right]+$$

$$+K\left[\frac{1}{2b^2}\left(r_2^3-r_1^2\right)+\frac{b^2c^2}{2}\left(\frac{1}{r_2}-\frac{1}{r_1}\right)-\frac{b^2c^2}{A}ln\frac{(A+r_2)(A-r_1)}{(A-r_2)(A+r_1)}+\right. \qquad (7)$$

$$\left.+\left(\frac{2b^2c^2}{A^2}+D\right)\left(r_2-r_1\right)\right]+\frac{b^2c^2}{2A^2}K\left(r_2\,ln\frac{A^2-r_2^2}{r_2^2}-r_1\,ln\frac{A^2-r_1^2}{r_1^2}\right)-$$

$$-\frac{b^2c^2}{4A^2}L\left(r_2^2\,ln\frac{A^2-r_2^2}{r_2^2}-r_1^2\,ln\frac{A^2-r_1^2}{r_1^2}\right)=0\ ,$$

where: $L=\dfrac{a_2-a_1}{h}$, $K=a_1\dfrac{a_2-a_1}{h}r_1$,

D - will be determined from the boundary conditions for $r=r_1$ or $r=r_2$

$$D=\frac{b^2c^2}{2A^2}ln\frac{r_1^2}{A^2-r_1^2}-\frac{b^2c^2}{2r_1^2}-\frac{r_1^2}{2b^2}\,.$$

Fig.9 presents an example of designing an optionally chosen belt cross-section.

An important problem in designing every flexible connector belt is designing the location of the neutral axis during its bending over the pulley arc of contact. Out of physical components of the state of stress $\sigma_{22}=r^2t^{22}=0$, a dependency of the neutral axis radius r_o from bend radii at the arc of contact will be achieved.

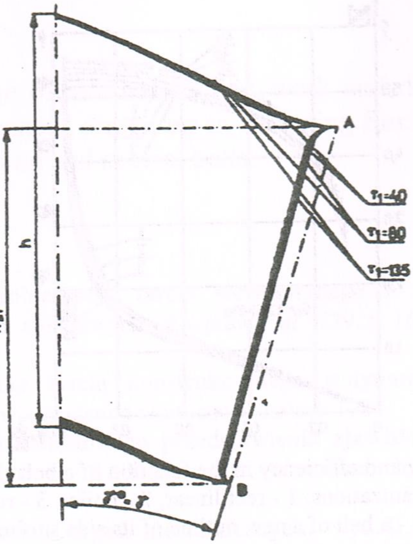

Fig.9. Deformation of a belt cross-section for the assumed fixed location of operating surface extreme points A, B: $\gamma^{o} = \gamma$

$$\frac{1}{b^4 c^2}\left(3r_0^2 - r_1^2\right) - \left(\frac{1}{r_0^2} + \frac{1}{r_1^2}\right) - \frac{1}{A^2} \ln \frac{r_0^2\left(A^2 - r_1^2\right)}{r_1^2\left(A^2 - r_0^2\right)} - \frac{2}{A^2 - r_0^2} = 0 \; . \quad (8)$$

Examples of practical usage of the method of internal friction minimalization for designing new geometric belt forms and the vulcanization method are shown on Fig.10 and Fig. 11.

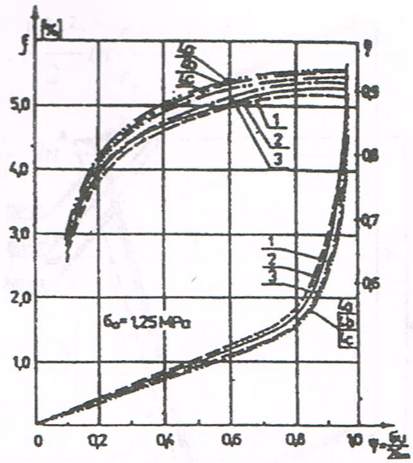

Fig.10. Driving ability and efficiency in the function of a belt slip out of the following vulcanizations: 1 - rectilinear, 2 - boiler, 3 - rotary,
4 - a belt of a new outline of its side surface;
a - rotary vulcanization, b - boiler vulcanization,
c - rectilinear vulcanization

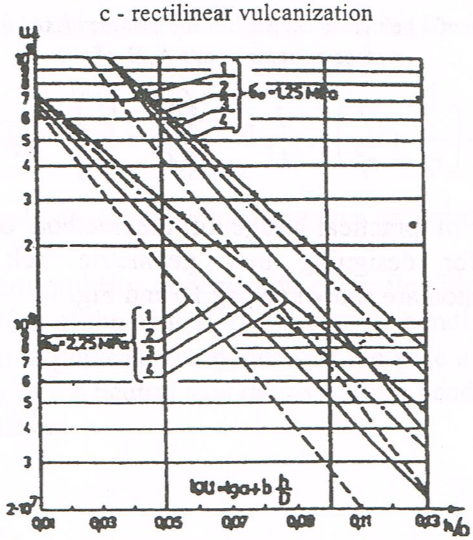

Fig. 11. B17x11 V-belt resistance as dependant on the bending diameter in the transmission at idle running:
1 - a belt out of the rectilinear vulcanization, 2 - boiler, 3 - rotary,
4 - a belt of a new curvilinear outline - rotary vulcanization

Conclusion

Practical usage of internal friction work and design friction work has significantly influenced directions in designing flexible connector belts: flat belts, V-belts, timing and special belts.

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