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Optimisation of the Knitting Process on Warp-Knitting Machines in the Aspect of the Properties of Modified Threads and the Vibration Frequency of the Feeding System

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Abstract
Important factors determining the behaviour of the knitting process on warp knitting machines are the mechanical properties of warp threads. This is caused by the variety of the properties of threads, ranging from "rigid" threads, such as steel, aramid, basalt, and glass threads intended for technical products to "elastic" threads in the form of elastomers, intended for linen and clothing products. Great differences in the rigidity and viscosity of threads significantly influence the parameters of the knitting process. As a result of the simulations performed, it was noted that there is a correlation between the elasticity, the damping of the feeding system, the dynamic loads of threads, the vibration frequency of the feeding system and the rheological parameters of threads. In conclusion, with an increase in the rigidity of threads, the elasticity of the system and frequency of vibrations in the system increase as well. The above-mentioned parameters of the process that are dependent on the coefficient of thread damping change in an inversely proportional manner.

Key words: *core-spun yarn, coating of core part, strip-back, abrasion resistance, pilling.*

Introduction

This article is a continuation of the problems of the optimisation of the knitting process on warp-knitting machines. In the previous article, entitled 'Optimisation of the knitting process on warp-knitting machines in the aspect of the feeding zone geometry' [1], the behaviour of the knitting process was analysed with regard to the geometry of the feeding zone on warp-knitting machines.

In this article the author focused on an analysis of the knitting process with regard to physical properties of the threads modified and the vibration frequency of the feeding system. The results of the simulations presented are based on the model of the dynamics of the knitting process on warp-knitting machines, elaborated and verified empirically [2 - 5].

The mathematical model of the feeding system, which is the basis of theoretical considerations on the process, is described by a linear differential equation of the second order, in the following form [2]:

$$m \cdot \frac{d^2 y}{dt^2} + b_{zri}\frac{dy}{dt} + k_{zri}\,y = = a_i \cdot \left[k_p \cdot S'(t) + b_p \frac{dS'(t)}{dt} \right] \tag{1a}$$

or in other form:

$$\frac{d^2 y}{dt^2} + 2h\frac{dy}{dt} + \omega_0^2 y = = \frac{a_i}{m} \cdot \left[k_p \cdot S'(t) + b_p \frac{dS'(t)}{dt} \right] \tag{1b}$$

where:
- m – point mass of the tension rail reduced to one thread
- b_{zr} – coefficient of system attenuation
- k_{zr} – coefficient of system elasticity
- a_i – coefficient describing the geometry of the feeding system
- h – relative coefficient of system attenuation
- ω_o – frequency of free vibration of the non-attenuated system
- k_p – coefficient of thread elasticity
- b_p – coefficient of thread attenuation
- $S'(t)$ – kinematic input function of the feeding system.

The equations describing the deflection of the tension rail $y(t)$ and the dynamic forces in the threads $P_1(t)$ feeding the knitting zone [1] are the solution of the mathematical model. A computer program simulating the knitting process on warp-knitting machines, described as a function of input parameters of the process, was elaborated [6]. The aim of research presented in this article was to analyse the loads of threads and the frequency of vibrations of the feeding system with regard to mechanical properties of threads treated as visco-elastic objects, as described by the Kelvin-Voight model.

Analysis of the elasticity and attenuation of the feeding system with regard to the character of changes in the reduced rigidity, attenuation coefficients and optimisation of forces in threads

Analysis of the feeding system's elasticity

The coefficient of system elasticity $\boldsymbol{k_{zri}}$, presented as the product of tension rail displacement y in the equation of motion (1) of the feeding system, determines the component of the dynamic force – the elasticity force.

Coefficient k_{zri}, described by formula

$$k_{zri} = k_s + a_i(\cos\beta - \sin\alpha)\cdot k_p, \tag{2}$$

(where k_s – rigidity coefficient of tension rail, reduced to one thread, α i β – angles of the thread „running-on" and „running-of" the tension rail), is a function of the rigidity coefficient of the tension rail k_s, the coefficient of thread elasticity k_p as well as the coefficient describing the geometry of the system a_i and the difference between angles α and β of trigonometric functions ($\cos\beta - \sin\alpha$).

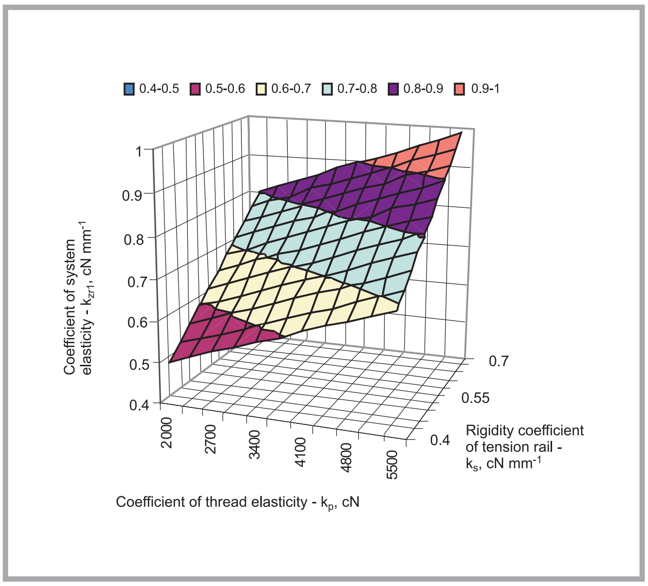

***Figure 1.** Dependence of the coefficient of system elasticity on the elasticity of threads and tension rail springs (α = 35°, β = 22°, μ = 0.2, l_1 = 400 mm, l_2 = 610 mm).*

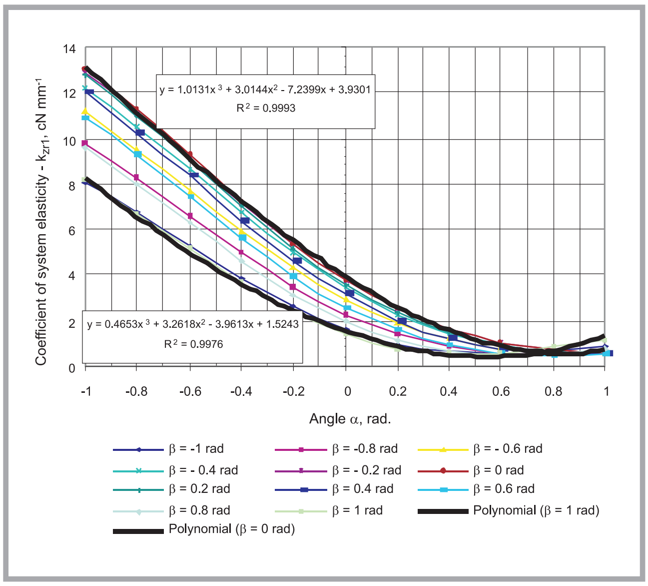

***Figure 2.** Dependence of the coefficient of system elasticity on angle α of the thread „running-on" the tension rail.*

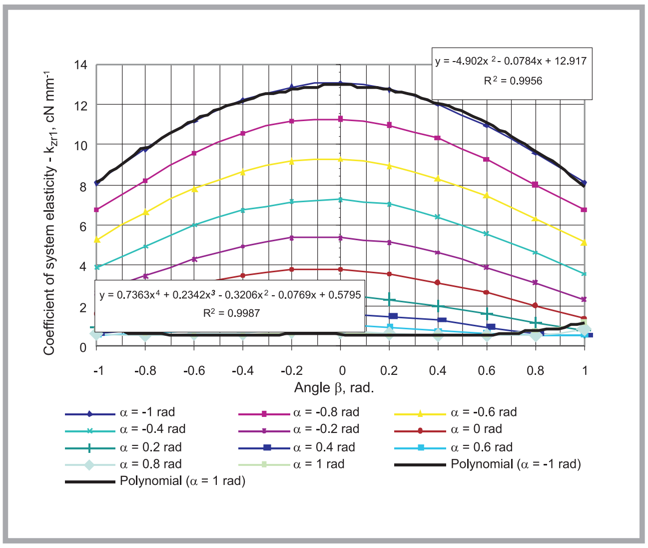

***Figure 3.** Dependence of the coefficient of system elasticity on angle β of the thread „running-of" the tension rail.*

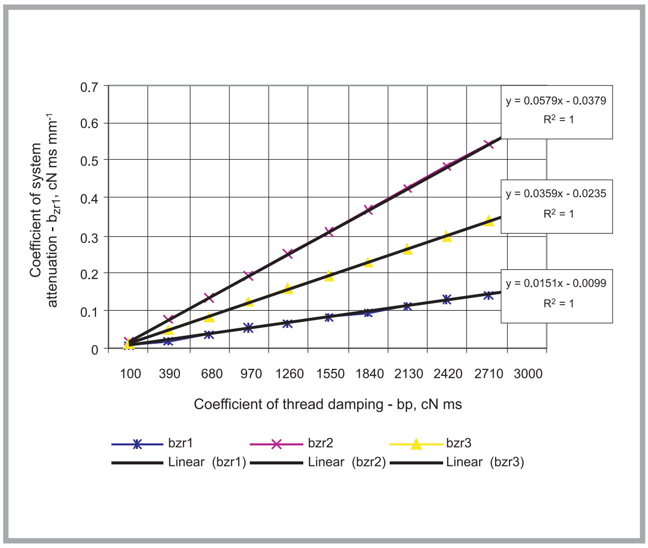

***Figure 4.** Dependence of the coefficient of system attenuation on the coefficient of thread damping.*

For constant parameters of the thread's feeding geometry, that is $a_i(\cos\beta - \sin\alpha) = = k =$ const., and assuming that the conditions of forcing the threads are constant, ***Equation 2*** can be presented in the following form:

$$k_{zri} = k_s + k \cdot k_p \qquad (3).$$

This dependence describes the linear character of function: $k_{zri} = f(k_s \;\&\; k_p)$. The plane, which is a graphical presentation of dependence (2), is a net of crossing parallel linear functions (***Figure 1***).

In view of the diversified structure of warp-knitting machines, the character and the values of elasticity k_{zri} should be considered in the aspect of the variation of the coefficient describing the geometry of feeding system a_i and angles α & β. ***Figures 2*** and ***3*** present graphs describing the dependencies of k_{zr1} of function α and β. The field describing function $k_{zr1} = f(\alpha$ and β) for (μ and l_1) = const has a decreasing character within the range of a decreasing angle α from -60 to +50°, while above 50° a slightly increasing tendency can be observed. As results from the graph k_{zr1} = f(α) for β = const presented (***Figure 2***), a decrease in the value of coefficient k_{zr1} reliably describes a function of a polynomial of the third degree, depending on angle α, with correlation coefficients of boundary curves $R^2 \geq 0.998$. Variation k_{zr1} = f(β) (***Figure 3***) takes values symmetrical to OY (for $\beta = 0$), and it can be described by a parabolic equation in the form of $k_{zri} = -a\beta^2 - b\beta + c$, although in reality it is a complex function describing the dependencies of trigonometric functions sinus and cosine, the power function and exponential function. The character of these changes is determined by that of changes in coefficient a_i and the following term ($\cos\beta - \sin\alpha$).

Summing up the analysis of k_{zri} mentioned above, it can be stated that the coefficient of system elasticity depends in a linear manner (increasing) on the in-

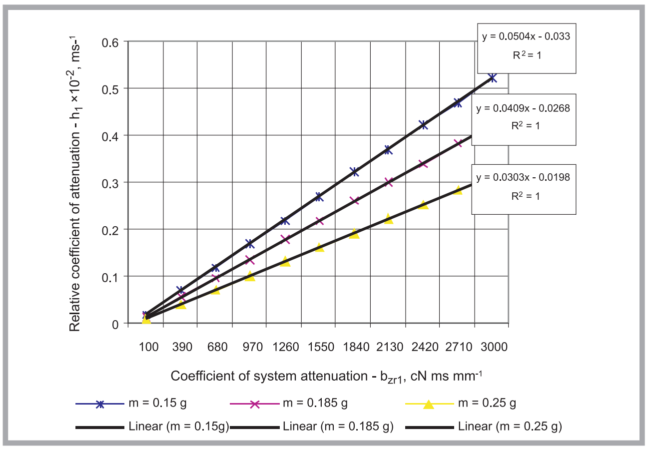

__Figure 5.__ Dependence of the relative coefficient of attenuation on the coefficient of system attenuation.

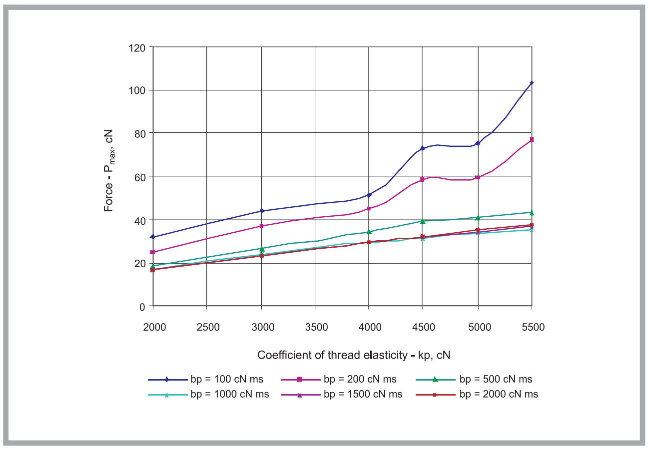

__Figure 6.__ Dependence of force P_{max} on the coefficient of thread elasticity.

creasing values of the rigidity of the tension rail springs k_s and on the elasticity of the thread k_p as well as on the parameters of the feeding system geometry.

Analysis of the damping of the feeding system

Coefficient b_{zr} is a coefficient of the linear dependence of the viscose damping force on the speed of tension rail dislocations of the feeding system: $b_{zr} = dy/dt$. Coefficient b_{zr} describes the following dependence:

$$b_{zri} = b_p(\cos\beta - \sin\alpha)\, a_i \quad (4).$$

In the simplified form

$$b_{zri} = k_i \cdot b_{p,} \quad (5)$$

and for a constant geometry of feeding

$$k_i = a_i(\cos\beta - \sin\alpha) = \text{const.}$$

The linear character of function $b_{zri} = f(b_p)$ is presented in ***Figure 4***, from which it results that the only (assumed) factor defining the damping of the feeding system from the point of view of the visco-elastic properties of the thread is the coefficient of thread attenuation b_p.

Equation 5 is also determined by the values of coefficient k_i, which depends on the parameters of the feeding system geometry $k_i = f(l_1, l_2, \mu, \alpha, \beta)$, where: l_1 – length of thread from the tension rail to the guide bar, l_2 – length of thread from the warp beam to the tension rail, μ - coefficient of friction between the tension rail and thread. The character of function: $b_{zri} = f(\alpha, \beta)$ is identical to the following dependence: $k_{zri} = f(\alpha, \beta)$. The dependence $k_{zr} = f(\alpha, \beta)$ can be referred to the quality analysis of function: $b_{zr} = f(\alpha, \beta)$.

The relative coefficient of system attenuation h_i is described by the ratio of the coefficient of system attenuation b_{zri} to the mass of the tension rail reduced to one thread m:

$$h_i = b_{zri}/2m, \quad (6).$$

The dependence of h_i on coefficient b_{zri} is determined by an increasing linear function in the following form: $h_i = k \cdot b_{zri}$, in which proportionality factor $k = 1/2m$, (***Figure 5***). The damping of feeding system h_i decreases with an increase in the mass of tension rail $2m$. The dependence of the coefficient of system attenuation h_i on the coefficient of thread attenuation b_p is also described by a linear function. Coefficient h_i increases along with an increase in the viscose damping of thread b_p.

Analysis of dynamic loads of threads with respect to their mechanical parameters

Computer simulation of the knitting process was performed to enable variation analysis of forces in threads considering the function of mechanical parameters of threads, that is the coefficient of elasticity and attenuation k_p and b_p. Calculations were performed for input data with reference to the K2 (E20) warp-knitting machine made by K. Mayer.

Figures 6 and ***7*** present the dependencies of $P_{max} = f(k_p$ and $b_p)$, from which it results that extreme forces in threads increase with their increasing elasticity and decreasing viscose damping.

This character of variation in forces relates to literature data [7, 8], which indicates that in the case of processing of the elastomer threads joined, textured, and characterised by low values of rigidity and high values of attenuation, the knitting process is performed at low values of forces in the threads and low values of thread breakage.

For 'rigid' threads, such as synthetic monofilaments PA & PE, steel monofilaments, aramid and glass threads, there are high values of forces in the feeding zone, two or three times bigger than the average values, being within the range from 20 to 40 cN and even more, which are the cause of frequent breakings. And in the case of threads of high values of tensile strength, damage to loop forming elements of the machine also occurs (breaking or permanent deformations).

The dependencies presented in ***Figures 6*** and ***7*** confirm the correctness of the model while calculating the effect of forces acting at assumed mechanical (rheological) parameters.

It should be noted that parameters k_p and b_p are the basic factors in the technological aspect of the knitting process, significantly influencing the quantity character of dynamic loads of threads.

Analysis of the vibration frequency of the feeding system

In the mathematical model elaborated, the free vibration frequency of the feeding system is determined by two quantities:

- ω_0 as the free vibration frequency of the non-attenuated system, being a square root of a fraction of the coefficient of system elasticity k_{zr}, referring to the reduced mass of the tension rail m:

$$\omega_0 = (k_{zr}/m)^{1/2} \quad (7);$$

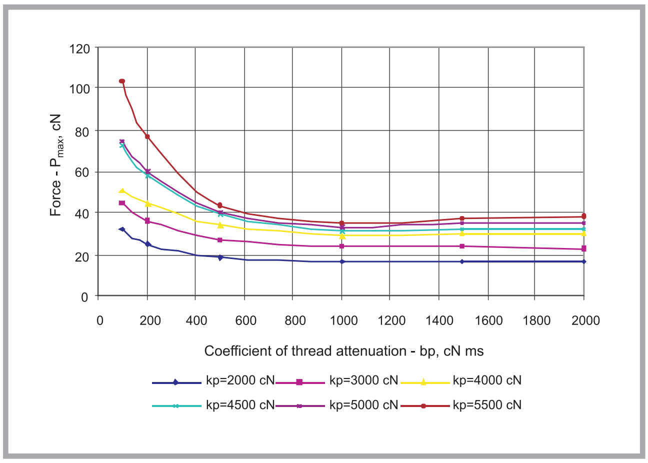

***Figure 7.** Dependence of force P_{max} on the coefficient of thread attenuation.*

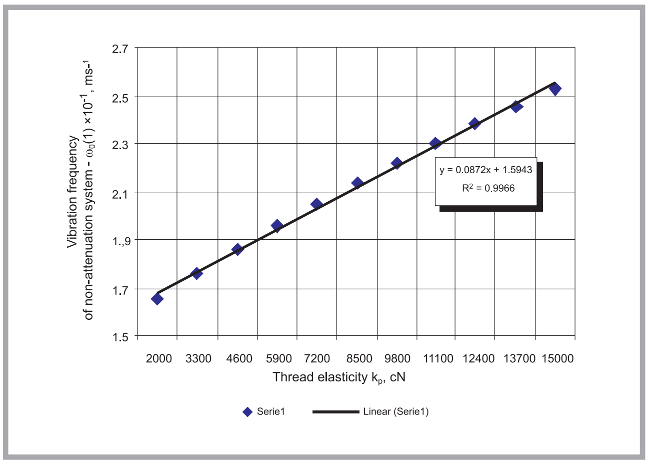

***Figure 8.** Dependence of the vibration frequency ω_0 of the system on thread elasticity k_p.*

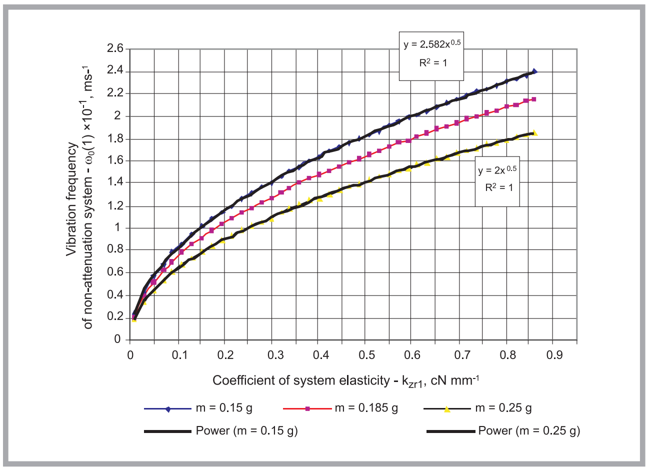

***Figure 9.** Dependence of the vibration frequency of the system ω_0 on the elasticity of the system k_{zr}.*

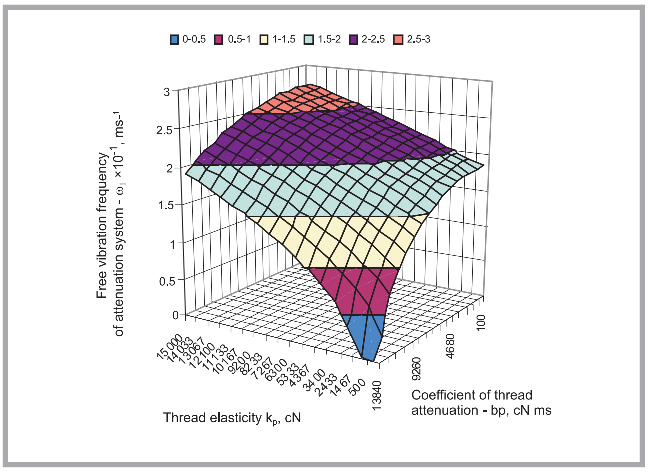

***Figure 10.** Dependence of the free vibration frequency of the attenuated system ω_1 on the viscoelastic properties of threads k_p and b_p.*

- ω as the free vibration frequency of the attenuated system, being a square root of the difference in the squares of frequency ω_0 and relative coefficient of attenuation h:

$$\omega = (\omega_0^2 - h^2)^{1/2} \quad (8).$$

Both frequencies ω and ω_0 are determined by the same input parameters of the process, such as the rigidity of the tension rail spring k_s, the coefficient of thread elasticity k_p and the coefficient of thread attenuation b_p. For the geometry of the system and mass of the tension rail given:

$$\omega_{0i} = \left[k_s + a_i\left(\cos\beta - \sin\alpha\right)\cdot k_p\right]^{\frac{1}{2}}\cdot m^{-\frac{1}{2}} \quad (9)$$

$$\omega_i = \left[k_{zri}/m - \left(b_{zri}/2m\right)^2\right]^{\frac{1}{2}} = \\ = \left\{k_s + a_i\left(\cos\beta - \sin\alpha\right)\cdot k_p + \right. \quad (10) \\ \left. - b_p^2\cdot\left[\left(\cos\beta - \sin\alpha\right)\cdot a_i/2m\right]^2\right\}^{\frac{1}{2}}$$

The free vibration frequency of the non-attenuated system ω_0 increases with increasing values of thread elasticity k_p (system elasticity k_{zr}) and rigidity of the tension rail spring k_s according to power function $y = ax^{1/2}$ with different values of coefficient $a = (1/m)^{1/2}$.

Figures 8 and ***9*** present the character of function $\omega_0 = f(k_p)$ and $\omega_{01} = f(k_{zr.1})$.

In ***Figure 9***, within the whole range of k_{zr} 0.0075 – 0.8421 cN mm^{-1}, the graph is of the character of a power function, while in the real range (physically real) for k_p it is from 2000 to 15000 cN. The dependence $\omega_0 = f(k_p)$ or $\omega_{01} = f(k_{zr.1})$ can be described by the linear regression equation $y = 0.87x + 1.6$ for $R^2 = 0.9966$ or power equation $y = 1.727x^{0.572}$ for the coefficient of regression $R^2 = 0.9972$

.

According to ***Equation 10***, the free vibration frequency of the attenuated system ω is a function whose values increase with an increase in the elasticity of threads k_p (coefficient of system elasticity k_{zr}) according to the linear or power function (depending on the range of the independent variable of regression assumed) for a different b_p, and also a function whose values decrease with increasing values of thread attenuation b_p (coefficient of system attenuation b_{zr}), described mathematically by equations of polynomial regression of the third degree for $R^2 \leq 0.996$. The dependencies mentioned above are presented in ***Figure 10***. In the case of the frequencies ω_0 and ω analysed, it should be noted that the frequencies of the vibration of the un-attenuated system are determined by the parameters of thread elasticity and tension rail rigidity, whereas in the case of vibration frequencies of the attenuated system, an additional factor determining this frequency is the viscose damping of the thread b_p.

Conclusions

- Simulation tests of the knitting process were performed on warp-knitting machines in the aspect of the optimisation of this process, using an analysis of the dependencies of forces in the threads on their mechanical properties. The analysis also described particular correlations of the free vibration frequency of the feeding system on the parameters of threads. The tests were performed in a "technological" aspect, that is investigating the relations of changes in the parameters of the knitting process on warp-knitting machines depending on the rheological properties of the threads modified, often ignoring research problems of the knitting process in the aspect of structural properties of machines presented in literature.
- From the tests on the knitting process performed, it results that:
  - The elasticity coefficient of the feeding system determining the dynamic component (elasticity force) of mechanical vibrations increases linearly depending on the increase in rigidity of tension rail springs and the elasticity of threads. The coefficient also depends on the parameters of the feeding system geometry.
  - Attenuation of the feeding system using the threads of the knitting zone increases in a linear manner along with the viscosity coefficient of the threads, with the intensity of the increase depending on the mass of the tension rail and the parameters of the geometry of the feeding zone.
  - The free angular frequency of the feeding system increases (with high probability) in a linear manner with the elasticity of the thread and elasticity of the system, and decreases (polynomial of the third degree with $R^2 \leq 0.996$) with an increase in the coefficient of thread attenuation.
  - The dependencies of forces in threads determined by their mechanical parameters indicate a correct reaction of the model in the aspect of a cause-effect analysis. Forces in the threads increase with an increase in the coefficient of thread elasticity, whereas with an increase in the coefficient of the viscose damping of the thread, the forces decrease, which confirms the industrial practice of processing "rigid" threads, such as synthetic monofilaments, steel threads, glass and aramid threads, as well as "elastic" threads of the textured and elastomeric type.
- The results obtained can be useful in the optimisation of the knitting process in the aspect of selecting mechanical parameters of threads with additional conditions, which can provide correct (minimum) loads of threads and lead to a state in which the frequencies of attenuated vibrations of the tension rail system will be out of the resonance range.

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