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Modeling of the Knitting Process with Respect to the Optimisation of the Construction Parameters of Warp-Knitting Machines

Abstract
In this article assumptions for the physical and mathematical general model of the knitting process, referring to both iso- and anisostructural warp-knitted fabrics, have been defined. In the course of the simulation and experimental research, the changability tendencies as well as the optimum construction parameters of warp-knitting machines were determined from the point of view of the minimum dynamic load of warp threads.

Key words: *warp-knitted fabrics, warp-knitting machines, knitting process model, dynamic loads, warp threads, construction parameters, working-in.*

Introduction

There are numerous approaches to the analysis of the knitting process of warp-knitting machines, including the analysis of the modelling and automation process, optimisation of the manufacturing conditions, the quality of the process itself and of fabric produced at strictly defined assessment parameters [1 - 4].

From the parameters having the strongest influence on the knitting process, one can distinguish characteristic features of the machine construction. Among them, the most important from a technological point of view are the geometry of the warp feeding zone, the type and construction of the feeding devices and the basic parameter- the needle gauge.

This publication aims to present the results of the computer simulation of knitting technology of warp-knitting machines with respect to the load dynamics of the warp threads, on the basis of certain defined assumptions of a general model of the feeding process. The analysis of changes in the forces in the threads was differentiated depending on the construction parameters of the machine.

Model of the feeding process in warp-knitted fabrics

A model of the dynamics of the feeding process in a warp-knitting machine at constant-length thread feeding was defined for the following assumptions [5]:

- a quasi-flat system, referred to '*k*' warp threads in the width of the stitch repeat R_k,
- parameters of the system described by the stiffness and reduced mass of the back rest roller as well as the elasticity and attenuation of threads. The threads are treated as weightless viscoelastic bodies,
- the model accepted reflects the geometry of the warp thread feeding zone,
- the physical model is a system subject to variable kinematic forcing $S_k(t)$, which is a sum of - $S'(t)$ forcing conditioned by the shift of the loop forming elements on the warp-knitting machine, $\Delta S(t)_r$ - forcing determined by the variable gradient of thread run-ins,
- the model allows for the hysteresis of thread loads caused by their friction against the back rest roller,
- the back rest roller is treated as inflexible element, elastically supported in such a way that it has one degree of freedom of movement.

The mathematical model of the feeding system in a warp-knitting machine at constant-length thread feeding can be described by the equation of motion (1) where:

y - shift of the back rest roller, h - relative coefficient of the system attenuation,
ω_0 - frequency of free vibration of a not attenuated system,
R_k - wale repeat of the stitch, describing the number of threads affecting the back rest roller,

$$\frac{d^2y}{dt^2}+2h\cdot\frac{dy}{dt}+\omega_0^2\cdot y=\frac{1}{R_k\cdot m}\cdot\left\{\begin{array}{l}a_1\left[k_p\cdot\sum_{k=1}^{N_1}S(t)_{k(1)}+b_p\cdot\sum_{k=1}^{N_1}\frac{dS(t)_{k(1)}}{dt}\right]+a_2\cdot\left[k_p\cdot\sum_{k=1}^{N_2}S(t)_{k(2)}+b_p\cdot\sum_{k=1}^{N_2}\frac{dS(t)_{k(2)}}{dt}\right]\\ +a_3\cdot\left[k_p\cdot\sum_{k=1}^{N_3}S(t)_{k(3)}+b_p\cdot\sum_{k=1}^{N_3}\frac{dSt()_{k(3)}}{dt}\right]\end{array}\right\} \quad (1)$$

$$b_{zr}=b_p(\cos\beta-\sin\alpha)\cdot(a_1\cdot N_1+a_2\cdot N_2+a_3\cdot N_3) \quad (3)$$

$$\begin{array}{l}k_{rz}=N_1\cdot\left[k_s+a_1\cdot(\cos\beta-\sin\alpha)\cdot k_p\right]+N_2\cdot\left[k_s+a_2(\cos\beta-\sin\alpha)\cdot k_p\right]+\\ +N_3\cdot\left[k_s+a_3\cdot(\cos\beta-\sin\alpha)\cdot k_p\right]\end{array} \quad (4)$$

$$P(t)_{war.i}=\frac{1}{l_2\cdot e^{\pm\mu\varphi}+l_1}\cdot\left[\begin{array}{l}k_p\cdot S(t)_{k(i)}+b_p\cdot\frac{dS(t)_{k(i)}}{dt}-k_p\cdot(\cos\beta-\sin\alpha)\cdot y-\\ -b_p\cdot(\cos\beta-\sin\alpha)\cdot\frac{dy}{dt}\end{array}\right] \quad (5)$$

$$\frac{d^2(y)}{dt^2}+2h\frac{dy}{dt}+\omega_0^2y=\frac{a_i}{m}[k_p\cdot S'(t)+b_p\cdot\frac{dS'(t)}{dt}] \quad (6)$$

Equations: 1, 3, 4, 5, and 6.

Mikołajczyk Z.: Modeling of the Knitting Process with Respect to the Optimisation of the Construction Parameters of Warp-Knitting Machines.
FIBRES & TEXTILES in Eastern Europe 2009, Vol. 17, No. 2 (73), pp. 76-81.

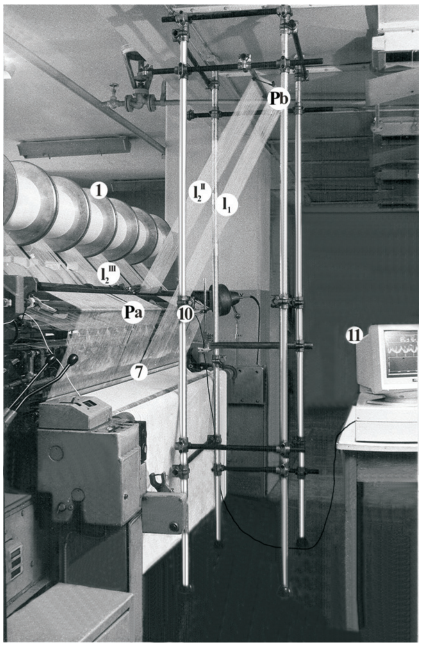

Figure 1. Photo of a measuring stand.

m - mass of the back rest roller reduced to one thread,
a_i - coefficients describing the geometry of the feeding system,
k_p - coefficient of the thread elasticity, b_p - coefficient of thread attenuation,
S_k - total kinematic forcing of the feeding system, $S_k = S^{\circ}(t) + \Delta S_i$,
$S^{\circ}(t)$ - cyclic forcing during the formation of one course of fabric,
ΔS_i - growth of forcing equal to the gradient of thread length $\Delta l_{r,k} = \Delta w_{r,k} / B$.

Depending on one of the three defined conditions of thread movements on the back rest roller, coefficients a_i have the following values:

$$a_i = (\cos\beta - e^{\pm\mu\rho}\cdot\sin\alpha)/(l_2\cdot e^{\pm\mu\rho} + l_1) \quad (2)$$

where: μ - friction coefficient between the back rest roller and the thread, ρ - angle at which the thread engirds the back rest roller, l_1 - length of the thread from the back rest roller to the guide bar, l_2 - length of the thread from the warp beam to the back rest roller, α - angle at which the thread moving onto the back rest roller deflects from the horizontal, β - angle at which the thread moving from the back rest roller deflect from the vertical.

The number of threads $N_1 + N_2 + N_3 = R_k$.

Coefficients b_{zr} and k_{zr} are determined from the relations (3) and (4) where: k_s - coefficient of the back rest roller stiffness - is reduced to one thread.

Forces in threads $P_{1k}(t)$ are determined from the relations (5).

The model of the feeding process presented above is extremely general and refers to both knitting anisotropic structures as well as the production of smooth isotropic fabrics consisting of basic warp stitches.

In the case of isotropic knitted fabrics, where one assumes the width of the wale repeat $R_k = 1$ wale and the height of the repeat $R_r = 1$ course, which determines the zero value of the forcing component $\Delta S(t)$, that is $\Delta S(t) = 0$, the equations (1) take the simplified form (6).

Theoretical and experimental research on the knitting process with respect to the diversified geometry of the feeding zone

In different types of warp-knitting machines, the largest differences in the construction of the feeding mechanisms can be observed in the changing lengths of threads l_1, l_2 and angles α, β.

The analysis of the construction of several modern warp-knitting machines produced by Karl Mayer proved that:

- the total length of the thread between the warp beam and guide bar equals from 916 to 3249 mm,
- the partial lengths of the threads are $l_1 = 591 \div 2525$ mm and $l_2 = 220 \div 1025$ mm,
- the number of barriers leading the threads is from 3 to 10,
- the total angle at which the threads engird the barriers is between 96° do 619°,
- the angle at which the threads move onto the back rest roller is $\alpha = 1 \div 62°$, whereas the angle at which the threads move from the back rest roller is $\beta = -15 \div 80°$.

Machine constructors in the process of technical and commercial design focus their attention on the problems of the kinematics and dynamics of machine subassemblies, the type and properties of the materials used, as well as the optimisation of the machine dimensions, safety and ergonomics, among others [6].

In numerous cases, at the stage of working out design concepts and assumptions, aspects referring to the technology of producing knitted fabrics are neglected. An important element in the process of constructing a warp-knitting machine should be the optimisation of the geometry of the feeding zone, from the point of view of the minimum loads of the threads that are fed.

Influence of the length of the warp threads fed on the character and value of forces in the threads

Experimental and theoretical research based on the assumptions of the knitting process model was carried out on a Kokett 5223 warp-knitting machine of needle cute 28, equipped with an active device to unwind the warp-threads. On the machine a tricot fabric was made from polyamide silk threads of 44 dtex at a knitting speed of 600 courses per

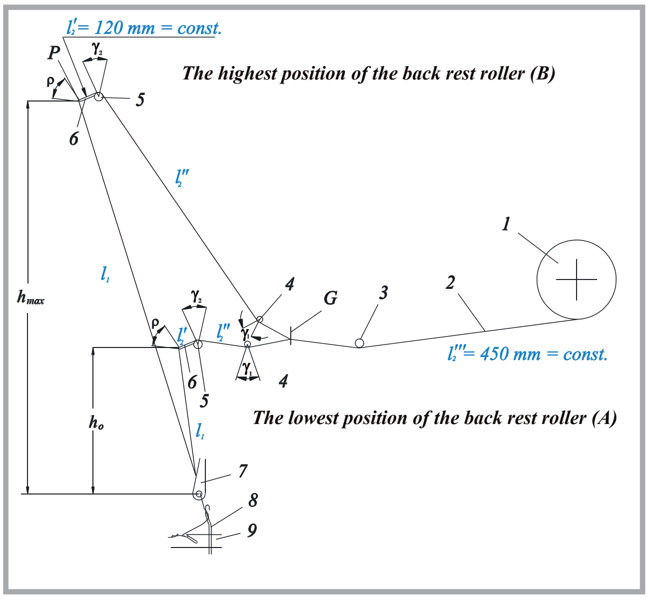

Figure 2. Diagram of the warp thread feeding zone (1 warp beam, 2 warp, 3 leading rod, 4 guiding rod, 5 roller, 6 spring, 7 guide bar, 8 needle bar, 9 holding down and knocking over sinker, G separating bar, P back rest roller).

minute, for three variants of thread length in the loop and two speed levels of receiving the fabric. During the research, the length of the thread being fed was changed by lifting the back rest device from the initial position $h_0 = 440$ mm to the position $h_{7(\max)} = 1400$ mm. For the extreme positions of the back rest rollers the total thread lengths L_c were equal to 1120 and 3050 mm.

A photo of the measuring stand is shown in ***Figure 1***. The scheme of the warp feeding zone for the changing positions of the back rest roller together is presented in ***Figure 2***.

Some examples of the empirical characteristics of dynamic thread loads are presented in ***Figure 3***.

Research was also conducted on anisostructural fabric, with the height of stitch repeat $R_{rz} = 16$ courses, with eight courses of tricot stitches of $l_t = 2.20$ mm and eight courses of satin stitches, n = 3, of $l_a = 4.16$ mm. Diversified lengths of threads in the loops, average length $l_{po} = ½ (l_t + l_a) = 3.18$ mm, were fed into the warp-knitting machine. The experiment was carried out for extreme thread lengths in the feeding zone. ***Figure 4*** presents the distribution of tensions in the warp threads for the anisotropic fabric produced. The experimental research carried out showed that

- In the organoleptic assessment no differences were distinguished in the surface structure of the two sides of the fabric, depending on the changing length of the warp feeding zone,
- in the case of isotropic knitted structures, together with an increase of 172% of the total length of the thread between the warp beam and knitting zone, the average force dropped by 54%, the minimum force by 45%, the maximum force by 61%, and the amplitude of these forces dropped by 65%,
- for an anisostructural fabric, due to decreasing forces, their differences are $\varepsilon P_{\max} = 78\%$, $\varepsilon P_{\text{śred.}} = 71\%$, $\varepsilon P_{\min} = 55\%$, and $\varepsilon \Delta P = 51\%$.

Simulation research of the knitting process with respect to changes $P = f(L_c)$ was carried out allowing for the real parameters of the process.

Figure 5 presents diagrams showing results of experimental and simulation

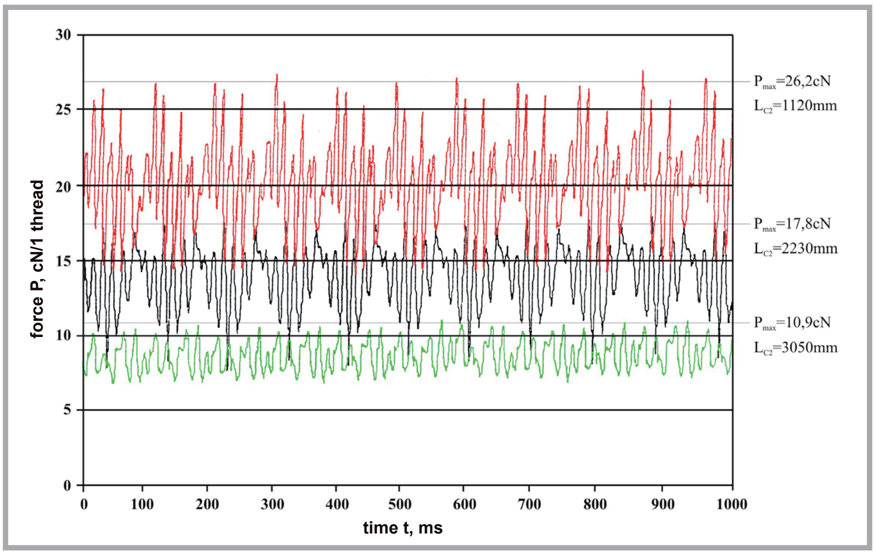

Figure 3. *Characteristics of the forces in the thread for changing lengths of the feeding zone.*

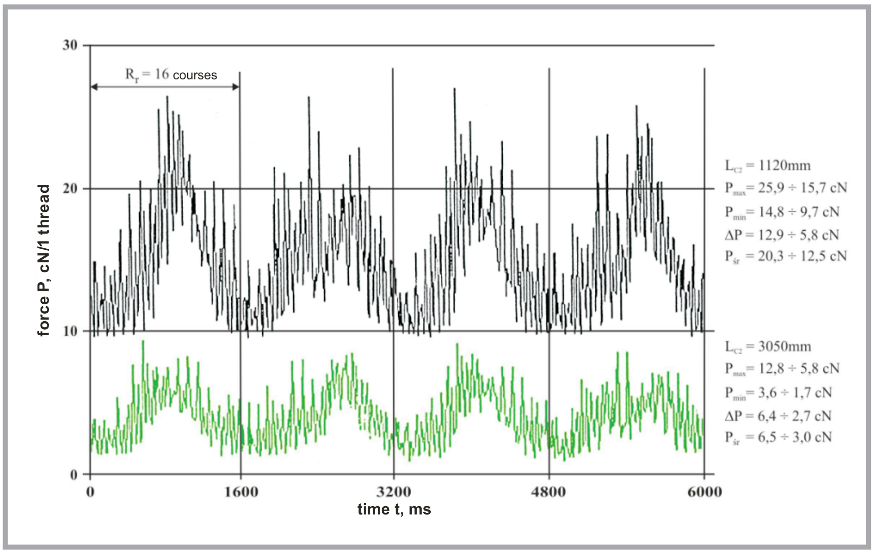

Figure 4. *Distribution of tension in the threads of an anisostructural stitch for two extreme lengths of the feeding zone.*

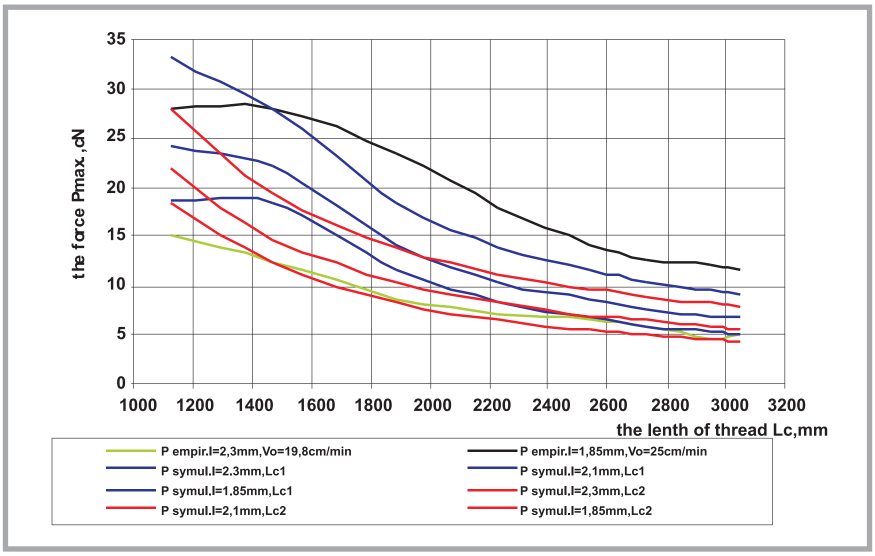

Figure 5. *Dependence of the extreme forces on the length of the threads fed.*

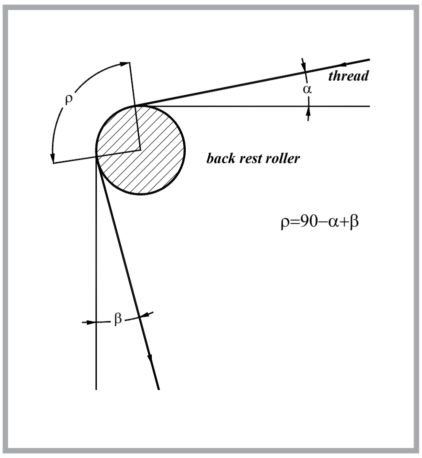

Figure 6. *Geometry of the arrangement of threads on the back rest roller.*

research of the dependence between the experimental force P_{max} and length L_c.

To make the Figure clearer, only two extreme experimental characteristics and six variants of the theoretical characteristics were chosen. Theoretical calculations showed a drop of 72% with respect to force P_{max} within the accepted borders of L_c.

The diminishing character of the course of $P_{max} = f(L_c)$ is identical for both the experimental and theoretical dependencies.Differences in the values of maximum forces $P_{max.ter.}$ and $P_{max.exp}$ are within 9.8 and 26.2%.

The analysis given above presents not only the character of the changes $P = f(L_c)$, but in the context of empirical verification of the results of digital simulation of the feeding process, it confirms the correct reaction (response) of the accepted model to changes in selected parameters of the geometry of the feeding zone.

Simulation research of the dependence between the force in the threads, angles α, β and friction coefficient μ of the thread against the back rest roller.

Calculations of the forces of the functions for “moving onto” α and “moving from” β angles of the threads (***Figure 6***), depending on the engirding angle ρ, were made for a K2 MPS warp-knitting machine by Karl Mayer using the following input data: E 20,
n = 700 courses/min,
l_1 = 400 mm, l_2 = 610 mm,
k_s = 0.6 cN·mm^{-1}, l_{ocz} = 4 mm,
k_p = 3150 cN, b_p = 1050 cN·ms (for thread J PE 110/24f dtex), y_0 = 4 mm.

Research results are presented in ***Figures** 7* and ***8***. The calculations show that

- within the angle α = -30 ÷ 10° at an initial constant force value of about 12 cN, there is a drop in P_{max} by 24% and then within the range of 0° (10°) to 40°, there is a sudden increase in the force of up to 21.5 cN (by 65%), whose stabilisation occurs at the angle 40 - 80 (90°),
- function P_{max} = f(β) is parabolic (***Figure** 7*). The function minimum is for angle β, close to 0, which equals from 13.2 to 21.8 cN, For the border values: for β = -80 ÷ -50° the force P_{max} = 21.7 cN, and for β = 70° the force $P_{max} \cong$ 25.5 cN,
- for engirding angles ρ = 0 ÷ 30°, forces P_{max} have high values at the level 20 ÷ 22 cN; from 30 ÷ 60° (70°) there is a drop in the forces to 13 cN, whose stabilisation occurs at a level of 17 cN within 70 to 110° of angle ρ (***Figure 8***),
- function P_{max} = f(μ) increases, and the engirding angle ρ determines the degree of changability of P_{max} from the friction coefficient μ. For a linear function of regression ($y = ax + b$) of changes P_{max} = f(μ), the directional coefficients of the straight lines equal a = 54.9 cN for ρ = 20°, a = 16.8 cN for ρ = 70° and a = 4.4 cN for ρ = 120º.

Analysis of the variability of the process of knitting anisotropic structures.

The best example of the anisotropic structures of warp-knitted fabrics are jacquard inlaid fabrics. In the technology of producing warp-knitted jacquard fabrics, the threads creating the pattern are fed individually from separate beams placed on a creeling frame. The optimum supply solution is a system of active feeding with a programmable length of the thread fed. It ensures a compact way of storing the warp in the form of warp beams, enables to apply high knitting speeds and makes it possible to produce many complex stitches. In the case of active feeding of warp threads in the process of knitting anisotropic structures, differences occur between the lengths of the threads fed and required in the elements of the knitted structure. Determining the differences in the thread take-up, in reference to the structure of jacquard knitted fabric and the accepted way of feeding the knitting zone with thread, creates a basis for modelling the dynamics of the process of producing such a type of fabric.

Identification of thread take-up gradient in warp-knitted anisotropic fabrics

The thread take-up gradient $\Delta w_{r,k}$ for structural element $a_{r,k}$ is expressed as the difference between the relative length of

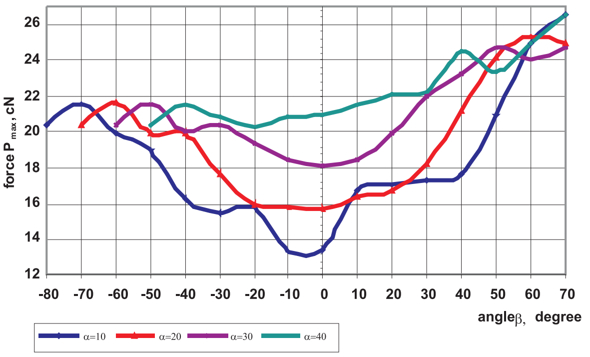

Figure 7. *Dependence of force P in the threads on angles α and β.*

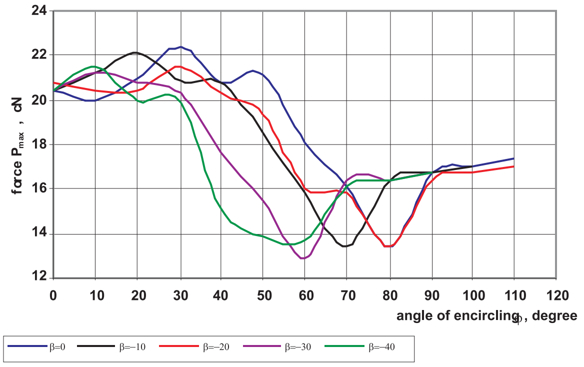

Figure 8. *Dependence of force P in the threads on the angle of encirding φ.*

the fed-in thread $(w_{r,k})_{po}$ and the take-up $(w_{r,k})_{zp}$ of the thread required in a t-th course and k-th wale:

$$\Delta w_{r,k} = (w_{r,k})_{po} - (w_{r,k})_{zp} \qquad (7)$$

An algorithm of identification $\Delta w_{r,k}$ was formulated according to four methods of analysis of the take-ups V_i (Methods „A", „B", „C" and „D") [7]. These methods correspond to the relevant thread feeding methods (concepts).

Method „A" - feeding a constant length of thread equal to the average length required in the stitch repeat.

Method „B" - feeding a constant length of thread equal to the average length required in the group of threads at the stitch repeat height.

The basis for the adopted analysis of the take-ups is the feeding method in which groups of threads of constant value $\left(\overline{w_r}\right)_k$ are unwound from separate warp beams.

Method „C" - feeding a variable thread length, equal to the average requirement for the course of fabric. According to the idea accepted, it is possible to feed warp threads from a single warp beam, programming the unwinding rate of the threads for each course. The variable feeding lengths can be realised by using EBC computer systems .

Method „D$_i$" (Method „B" + Method „C") – Feeding a variable thread length in the group of threads equal to the average requirement for the courses made of separate thread groups. Method „D" is a combination of methods B and C, which are described above. The method divides the threads of a given compound stitch into several warp beams, which are individually controlled with a variable feeding rate for each course.

Analysis of the take-up gradient of the threads in the function of the feeding method

On the basis of a computer programme analyzing thread lengths in the elements of the anisotropic fabric structure, identification of the take-up gradient was carried out for eleven stitch variants – patterns of jacquard and decorative fabrics. These patterns are recommended by K. Mayer - a producer of warp-knitting machines - as the most frequently used mesh structures for curtain backgrounds [8].

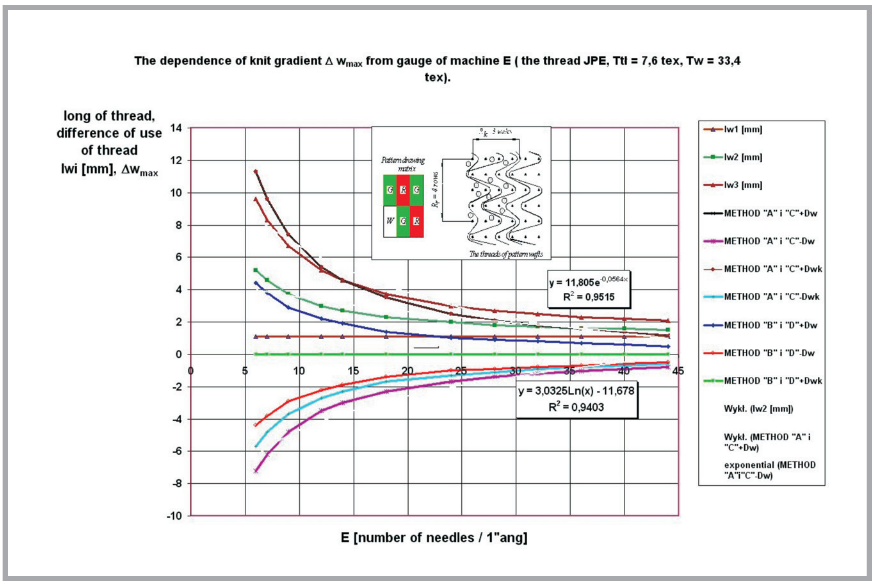

***Figure 8.** Dependence of the take-up difference Δw on the method of threads feeding.*

Counting the take-up differences $\Delta w_{r.k.}$ was undertaken for two changing parameters of the machine construction:

- four ways of feeding the pattern thread, which determine the construction of the thread feeding devices,
- needle gauge E of the jacquard warp-knitting machines within the range from 6 to 44 needles/1 eng. cal.

Results of calculations for an example pattern of knitted fabric are presented in ***Figure 9***.

The research has confirmed that

- the smallest values of absolute extremes, Δw_{max} , can be observed for feeding according to methods B and D1, where the differences Δw are, on average, 82% smaller than in the case of methods A and C .
- the higher the gauge number E, the smaller the difference Δw. The take-up gradients are the smallest for warp-knitting machines with a high needle gauge of E 28 to 44.
- the characteristics of thread surplus in the feeding zone $+\Delta w = f(E)$ and thread shortage $-\Delta w = f(E)$ in most of the examples analysed are symmetrical to the o\x-axis.

The diminishing character of function $\Delta w = f(E)$ can be explained by the fact that the length of the horizontal threads of the pattern wefts decreases when the width of wale A, determined by the needle pitch t_u: $A = t_u = 25.4$ mm $/E$, diminishes.

Referring the diminishing lengths of weft elements l_{w2} i l_{w3} to the constant length of the vertical weft l_{w1} (***Figure 8***), we receive a diminishing tendency of the take-up differences $|\pm\Delta w|$. One can expect that the diminishing values of the thread length gradient $\Delta l = \Delta w/B$ in function E, which directly influence the forcing component $\Delta S = -\Delta l$ of the feeding process model, will determine the decrease in the value of forces in the fed warp threads.

Simulation of the dynamic loads of threads in the context of changing construction characteristics of the warp-knitting machine

In reference to the research described in the previous subchapter, simulation calculations of thread loads were made for changing construction characteristics of the machine, which are the method of thread feeding and the needle gauge of the machine. In the input data the pattern of the fabric (***Figure 10***) and parameters characteristic for a = 7.8 tex T_W = 16.7 tex, were processed. ***Figure 10.b*** and ***c*** present the time - dependant distribution of forces in a randomly selected weft thread 2 for the following extreme feeding variants: A- feeding the threads from one beam, D2- programmable unwinding of threads separated into three warp beams, and for four values of the needle gauge of the machine E = 7, 12, 18 and 24 needles/1 eng. cal. The bold lines stand for trends regarding the changes in the force values. The minus values of the forces on the diagrams have no physical sense, and they only represent the scale of the phenomenon of the threads relieved (free). The optimum variant of active feeding D2 in the segment arrangement of three warp beams controlled in the EBC system can be an alternative to the methods of active feeding: A, B and C because of the lowest force values and their amplitudes. It can replace traditional ways of unwinding individual threads from the creeling frame.

The research on the influence of needle gauge *E* on the force values in threads, which is partly presented on diagrams ***b*** and ***c*** in ***Figure 9***, prove that function *P* = f(*E*) has a diminishing character. It confirms the assumption that from the point of view of the lowest thread loads, it is best to produce jacquard knitted fabrics on warp-knitting machines with the highest needle gauges.

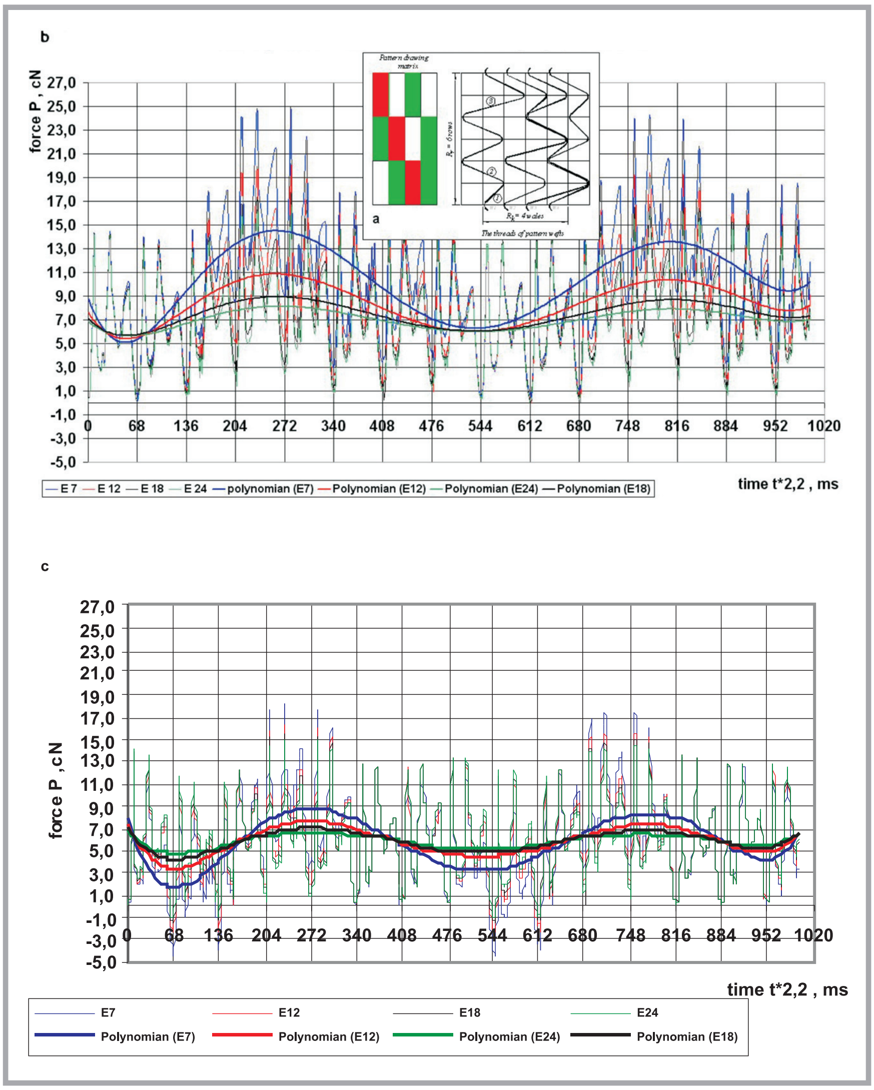

Figure 10. *Dependence of the dynamic loads of thread 2 on the needle pitch of the warp-knitting machine for two methods of thread feeding: a) squared paper of the pattern and the real path of the pattern threads, b) method "A", c) method "D2".*

Conclusions

- The mathematical model of the feeding process, referring to both isotropic and anisotropic warp-knitted fabrics with defined assumptions for the dynamic system of constant-length thread feeding and for the force reflecting variable parameters of the fabric structure and features of the knitting process on warp-knitting machines, should be helpful in selecting optimum conditions for the knitting process.
- Experimental and simulation research proves that among the construction parameters of warp-knitting machines analysed that have an influence on the optimum knitting conditions, the following are considered to be of great importance: lengthening by more than 100% of the thread segments fed, angle α within the range of 30 to 70°, and angle $\beta \cong 0°$. In the case of anisostructures, it is most important to produce them on warp-knitting machines of high needle pitches, by segment feeding of threads from several warp-beams, controlled by the EBC system.

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Received 17.06.2008 Reviewed 15.12.2008