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Modelling of the Knitting Process during the Knitting-in of Elastomeric Threads Using Knitting Machines with Relanit and Classic Knitting Zone

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Abstract
An analysis of the knitting process during the knitting-in of elastomeric threads using knitting machines with a Relanit and classic knitting zone was made on the basis of simulations considering a numerical model which takes into account the most important parameters of the knitting process, viscoelastic properties of the thread and geometrical parameters of the knitting zone. The conditions of forming stitches from classic cotton yarn were presented for comparison. The results of the simulation tests were verified experimentally on a computer-aided knitting machine with a classic knitting zone.

Key words: *elastomeric threads, knitting zone, Relanit technique, modelling of knitting process, forces in threads, thread length in stitch.*

Designations:

F_0 - initial force in a thread in front of the knitting zone, in cN,

$F(i)$ - forces in threads in the knitting zone, in cN,

$F_d(i)$ - forces in threads in the knitting zone occurring as a result of dynamic longitudinal strains, in cN,

$W(i) = F(i+1)/F(i)$ - resistance of a thread pulled through the i^{th} friction barrier in the knitting zone,

$G(i)=F(i)/F(i+1)$ - resistance of a thread pulled through the i^{th} friction barrier in the knitting zone with a reversible movement of yarn,

F_A - take-up force of knitted fabric, in cN,

L - free length of thread between the feeding device and knitting zone, in mm,

c, c_1 - relative coefficients of drawing rigidity for Zener model, in cN,

η - dynamic viscosity, in cN·s,

ε - relative elongation of a thread,

t - time, in s,

$v(i)$ - velocity of pulling a thread through the i^{th} friction barrier in the knitting zone, in m/s,

$v_\varepsilon = d\varepsilon/dt$ - velocity of an increase in deformations of a thread, in s^{-1},

$z(i)$ - depth of knocking-off the needles for the ith needle, in mm,

v_c - linear velocity of a cylinder, in m/s,

k - calculation step.

Geometrical parameters of the knitting zone:

d_h - thickness of a needle hook, in mm ,

P - thickness of a sinker, in mm,

t - needle pitch, in mm,

γ - angle of knocking-off the needles, in °,

γ_p - angle of lifting the sinkers in Relanit technique, in °,

β - angle of lifting the needles, in °,

β_p - angle of lifting the sinkers in Relanit technique, in °,

R_i - curvature radius of cams in the knitting zone for needles, in mm,

R_p - curvature radius of cams in the knitting zone for sinkers, in mm,

x_F - length of the guiding part of a cam for needles, in mm,

x_{FP} - length of the guiding part of a cam for sinkers, in mm,

x_K - horizontal coordinate of the end point of lifting the needles in the knitting zone, in mm,

x_{KP} - horizontal coordinate of the end point of lifting the sinkers in the knitting zone, in mm,

z_K - vertical coordinate of the point of lifting the needles, in mm,

z_{KP} - vertical coordinate of the point of lifting the sinkers, in mm,

α_p - angle of thread feeding, in °,

$\alpha(i)$ - angle of wrapping the ith friction barrier in the knitting zone (of needles and sinkers), in °..

Thread parameters for the model of knitting:

μ – conventional friction coefficient of a needle on the forming elements for initial configuration of needles and sinkers;

η_i, η_p - relative dynamic viscosities of a thread material being pulled through the needle hooks η_i and edges of sinkers η_p in the Zener model, in cN·s;

a_i, a_p, n_i, n_p - coefficients in the general law of friction at the pulling a thread through a hook of needles (a_i, n_i) and sinkers (a_p, n_p)

D - diameter of a thread, in mm.

Introduction

There are many works [1 - 13, 15] devoted to the modelling of the knitting process on knitting machines. Knapton and Munden were the first to analyse the process of knitting on knitting machines. On the basis of the robbing phenomenon, the authors [1 - 3] developed a static model of the knitting process related to the stationary configuration of needles. Based on similar assumptions, Lawson [4] introduced a concept of the actual depth of knocking-off the needles corresponding to that of knocking-off a needle in the knitting zone, at which the loop length corresponds to that of the thread in the knitted fabric stitch, i.e. below this depth there is no drawing of the thread from the beam, instead there is the phenomenon of robbing a thread from the stitches fixed on the lifted needles. However, after careful considerations of the phenomena in the knitting zone [5, 6], it can be stated that this is a significant simplification of the mechanics of forming a knitted fabric. Aisaka was the first to use a computer simulation in order to assess the dynamic forces in individual sections of the thread in the knitting zone as a function of needle movement [7]. The model designed represents significant progress in relation to those developed by Knapton and Munden [1 - 3], and Lawson [4].

All the models designed for calculating the forces in threads in the knitting zone [1 - 9] are based on the fundamental assumption that the relationship between forces ahead of and behind the friction barrier is described by the Euler dependence. Additionally the mechanical characteristic of the thread in accordance with Hooke's law was taken into consideration in the models [8, 9]; however, the effects of the phenomenon of robbing the thread and take-up force on the conditions of the knitting process were omitted.

From the current state of knowledge, it results that previous studies related to the conditions of knitting-in of yarns mainly concerned those made of natural fibres (cotton & wool) and synthetic silks. There are no studies related to the identification of conditions of the knitting-in of elastomeric yarns using knitting machines.

Works [10 - 13] present a numerical model of the knitting process for evaluation of the length of a thread knitted-in and dynamic loads of a thread in the knitting zone, taking into consideration viscoelastic properties of the thread and rheological model of friction [14]. This model, in contrast to the well-known models of the knitting process, enables to simultaneously calculate the length of the thread in a stitch *l* and the values of dynamic loads of a thread in the knitting zone *F(i)* at constant tension of (negative) feeding the thread. For the purpose of modelling the knitting-in of elastomeric threads, this model was extended [15] to relations enabling the modelling process during constant-length (positive) feeding of elastomeric yarn.

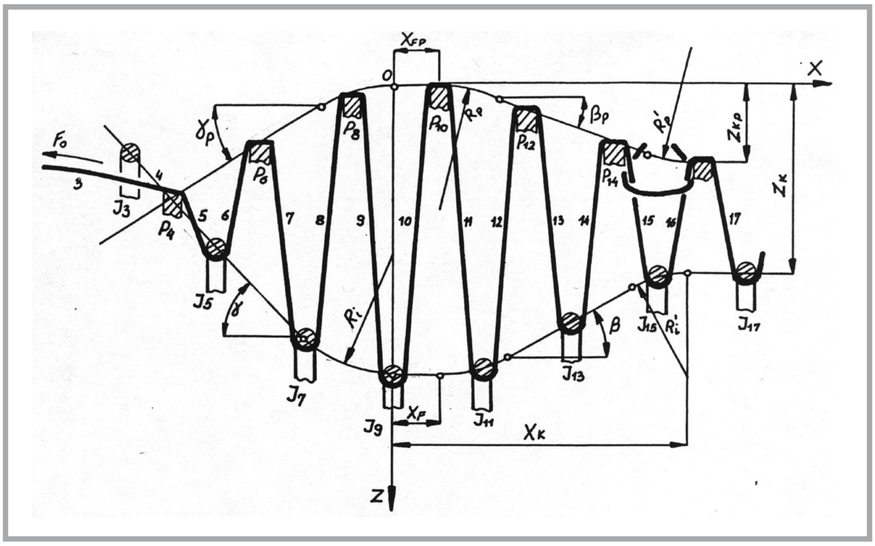

Figure 1. *Generalised geometrical model of the knitting zone [15,16]; J_3, ..., J_{17} – needles, P_4, ..., P_{14} – sinkers, (parameters are explained in Designations).*

Model of knitting using knitting machines from the numerical point of view

Figure 1 shows a geometrical model of the knitting zone of a knitting machine taking into account the Relanit knitting technique. If angles γ_p and β_p are equal to 0°, then they refer to a classic knitting zone.

Figure 2 presents a general algorithm of the model of the knitting process developed taking into account the parameters of the knitting process and input data, which are assigned to the geometrical parameters of the knitting zone as well as parameters of a thread and the knitting process.

The model designed - in contrast to those known from the literature - takes into account all the important parameters of the knitting process. One calculation loop of the program corresponds with those performed after moving the cylinder of value Δx. The main axis of the calculation of the course of forces in threads in time and the length of the thread knitted-in is examining the balance conditions of dynamic forces in the threads on the individual friction barriers after moving the cylinder by a value of Δx. Whereupon the demand for the length of a thread in the area of knocked-off needles and the reserve of a thread in the area of lifted needles are calculated. The geometric balance of the lengths mentioned for the reverse area of a thread forms the basis for calculating the length of a thread knitted-in.

The conditions of a thread's movement in the knitting zone are particularly important in the algorithm of the model. They result from the relationship of forces derived from the dynamic stretching of a thread between the friction barriers due to the movement of the elements forming the stitch $F_d(i)$ and values of the forces of dragging the threads on the friction barrier *F (i)*. The movement occurs when $F_d(i) > F(i)$.

For yarns with low elasticity, the forces are formed mainly as a result of generating them on the friction barrier, whereas for elastomeric yarns, as a result of their elasticity, the condition of a slip on the barrier can be fulfilled for higher values of relative elongation of the elastomeric yarn, at which $F_d(i) > F(i)$. Up to now, there have been no studies on the model loads of elastomeric yarns in the knitting zone nor calculations of the length knit-

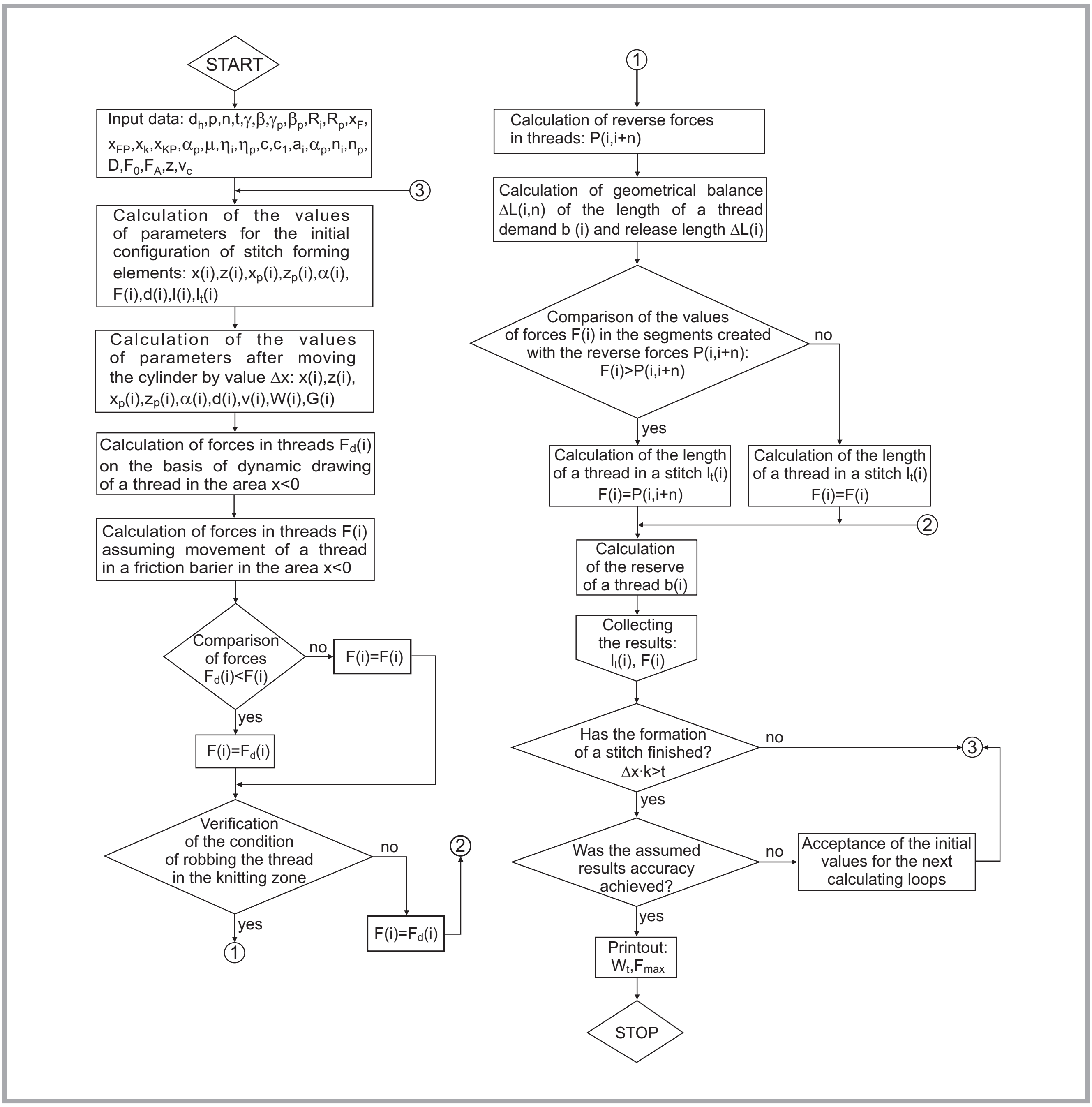

Figure 2. *General algorithm of the model of knitting using knitting machines.*

ted-in depending on the parameters of the knitting process.

The instantaneous demand for a thread for subsequent segments in the area of needles knocked-off (x <0) (***Figure 1***) is the difference between the length of the segment before and after moving the cylinder of a value of Δx.

$$\Delta L_i = L_i^{(k)} - L_i^{(k-1)} \quad i = 1, 2, \ldots, 8 \qquad (1)$$

The demand calculated according to ***Equation 1*** corresponds to the length in a stretched state. The actual length of the demand $\Delta Li'$ in the k^{th} step of calculations can be determinedafter taking into account the values of forces F_i in the individual segments of the thread.

$$\Delta L_i' = \frac{\Delta L_i \cdot c}{c + F_i} \qquad (2)$$

For the sections of a thread fixed on the lifted needles the values calculated $\Delta Li'$ (i = 9, 10, ..., 16) are negative, since the needles move from larger values of the depth of knocking-off z_j to smaller ones. In this case, $\Delta Li'$ determines the length released by the lifted needles.

For the needles which run parallel to the edge of sinkers, the values of $\Delta Li'$ are zero. The total value of the length of the thread released, which is not pulled to the stitches formed in the specific step of calculations (k), creates a reserve of a thread b_i and is recorded in every step of the calculations.

The reserve of threads in individual sections of the thread fixed on the lifted needles is determined according to ***Equation 3***.

$$\Delta K_i = b_i + \Delta L_i^{(k)} \quad i = 9, 10, ..., 16 \qquad (3)$$

ΔK_i for i = 1, 2, ..., 8 determines the demand for the thread and is equal to the demand ΔL_i ($b_i = 0$ for i = 1, 2, ..., 8).

Table 1. *Input parameters of the model for cotton yarn 20 tex.*

d_h	P	t	R_i	x_F	x_{Fp}	γ	$γ_p$	μ	$η_i$	$η_p$	c	c_1
mm						deg		-	cN·s		cN	
0.45	0.3	1.81	0.45	0.4	0.3	50	30	0.2	3.5	3.5	4800	2500

a_i	a_p	n_i	n_p	F_0	F_A	V_c
-		-		cN		m/s
0.43	0.76	0.86	0.86	17	3	0.36

Table 2. *Input parameters of the model for elastomeric yarn 44 dtex (Lycra).*

d_h	P	t	R_i	x_F	x_{Fp}	γ	$γ_p$	μ	$η_i$	$η_p$	c	c_1
mm						deg		-	cN·s		cN	
0.45	0.3	1.81	0.45	0.4	0.3	50	30	0.2	0.010	0.0034	3.8	11

a_i	a_p	n_i	n_p	F_0	F_A	V_c
-		-		cN		m/s
0.526	0.521	0.721	0.752	1.6 - 11	3	0.36

The sum of the value ΔK_i $(i = 1, 2, ..., 16)$ in a free state is the difference $\Delta L_{i,n}$ between the value of the length of the demand and the reserve of a thread in the area of a moving one. The movement range of the thread is determined by examining the conditions of the balance of forces on the subsequent friction barriers.

$$\Delta L_{i,n} = \sum_{j=0}^{n} \frac{\Delta K_{i+j} \cdot c}{F_{i+j} + c} \quad i = 8, 7, ..., 1, \quad n = 9, 8, ..., 1 \qquad (4)$$

Index *(n)* indicates from which section in the zone of lifted needles *(x > 0)* there is a robbing, while index *(i)* indicates to which section the thread from the robbing is being moved.

The instantaneous velocity of yarn is determined according to ***Equation 5***:

$$v^{(k)} = \frac{\Delta L_{i,n}^{(k)}}{\Delta t} \qquad (5)$$

Whereas the difference between the velocity of a thread, resulting from the demand in the knitting zone, and that of feeding the thread by the feeding mechanism is expressed by ***Equation 6***.

$$\Delta v^{(k)} = v^{(k)} - W_t \cdot v_c \qquad (6)$$

The instantaneous value of the force in a thread of length L between the feeding mechanism and the knitting zone, taking into account the viscoelastic properties of the thread, expressed by the rheological three-element Zener model, is described by ***Equation 7***.

$$F_0^{(k)} = F_0^{(k-1)} + c \cdot \frac{\Delta v^{(k)}}{L} \cdot \Delta t + \eta \cdot \frac{\Delta v^{(k)}}{L} \left[1 - \exp\left(-\Delta t \cdot c_1 / \eta \right) \right] \qquad (7)$$

The value of the static expression

$$c \cdot \frac{\Delta v^{(k)}}{L} \cdot \Delta t$$

corresponds to the force associated with the elongation of a spring c, while the following expression is a dynamic component which results from the velocity of an increase in relative deformations of the body with viscoelastic properties, representing the thread. The expression describes the relationship between the parameters in the Maxwell term of the Zener standard model.

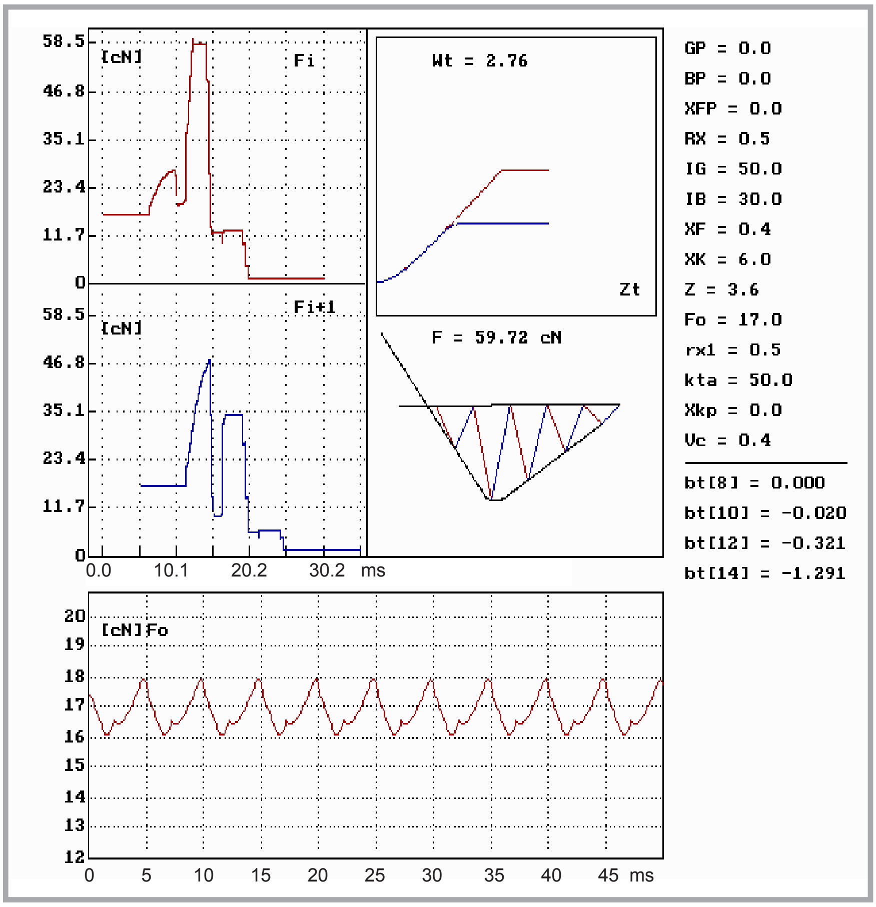

Figure 3*. Calculation parameters for a classic knitting zone: F_0 = 17 cN, z = 3.55 mm.*

Simulations of the knitting process according to the model designed

Calculations of the dynamic forces in the threads and the pitch coefficient of knitting-in during the formation of stitches made from cotton yarn of 20 tex and elastomeric yarn 44 dtex (Lycra) were performed for the input parameters presented in ***Tables 1*** and ***2***:

The other parameters which vary for particular variants of the calculations are given in the graphs. ***Figures 3*** and ***4*** show exemplary results of a computer simulation of the knitting process during the knitting-in of cotton yarn of 20 tex for a knitting machine with a classic (***Figure 3***) and Relanit (***Figure 4***) knitting zone, in the form of time courses of dynamic forces in the threads in the knitting and feeding zones and in that of curves of an increase in the pitch coefficient of knitting-in for individual sections of the stitch formed. In the lower right corner of the Figure, diagrams of the knitting zone are presented, for which the time courses of forces in the threads are presented in the left side of the Figure. The upper course refers to the forces in threads on the right side of the sinker F_i, i.e. for odd segments, while the lower course for even segments F_{i+1}. The maximum value of forces in the threads in the knitting zone during the formation of a stitch is presented above the graph of the knitting zone. Theoretical curves of an increase in the value of the pitch coefficient of knitting-in W_t, and its value are presented in the upper right corner of the Figure.

The results of simulation prove the existence of the phenomenon of robbing the cotton yarn in the knitting zone. Horizontal segments of the curves of an increase in the pitch coefficient of knitting-in W_t are the evidence. The relatively high drawing rigidity of cotton yarn causes a rapid decrease in the forces in the yarn, in the area of lifted needles, which allows a reverse movement of the yarn from the loops fixed on the lifted needles to those formed on the knocked-off needles.

Figures 5 and ***6*** show exemplary results of a computer simulation of the knitting process during the knitting-in of elastomeric yarn for a knitting machine with a classic (***Figure 5***) and Relanit type knitting zone (***Figure 6***).

During the knitting-in of elastomeric thread, characterised by a very low value of relative drawing rigidity c (c = 3.8 cN), a slow relaxation of the thread occurs in the area of lifted needles. The forces in the threads in the area of knocked-off needles are too low i.e. $F(i) < P(i, i+n)$ to cause the drawing of the thread from the stitches fixed on the lifted needles. Therefore the drawing of elastomeric yarn occurs from the side of the feeding mechanism; a low drawing rigidity causes a demand in the area of knocked-off needles to be compensated mainly by elongating the thread. Despite the absence of the phenomenon of robbing a thread, low values of the pitch coefficient of knitting-in are obtained. The results of the simulation were verified experimentally on a computer-aided knitting machine [17,18].

Analysis of research results

Analysis of research results of forces in threads in the knitting zone

Figure 7 shows that an increase in the initial force of the elastomeric thread within the range from 1.6 to 11 cN causes

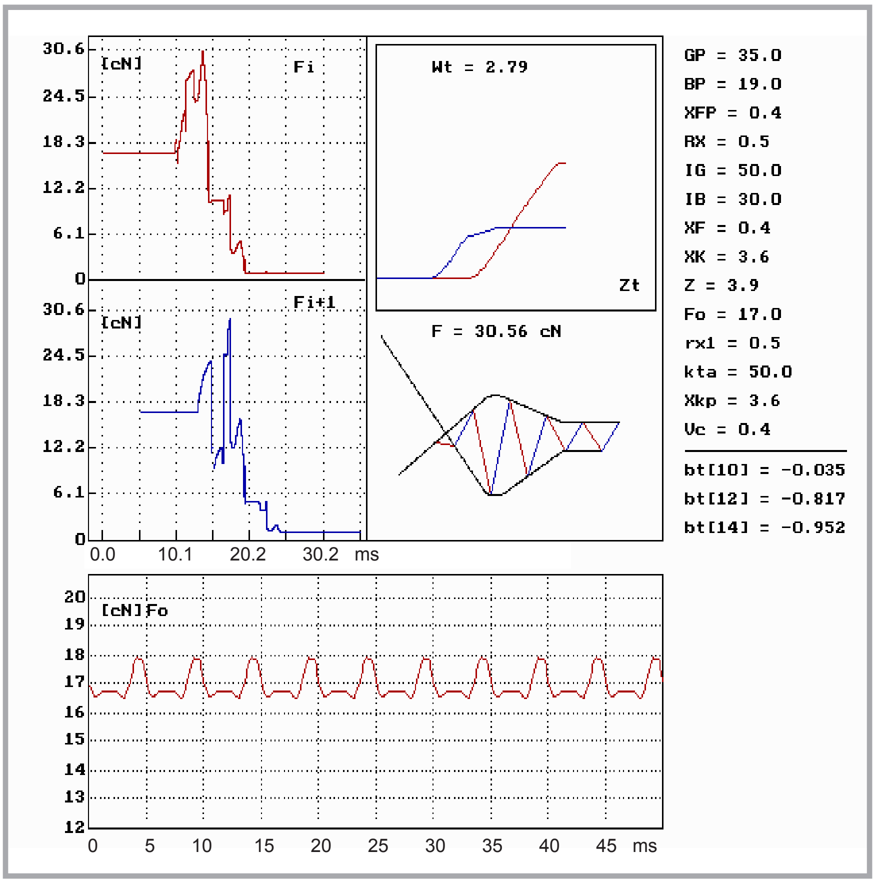

Figure 4. *Calculation parameters for a Relanit knitting machine: F_0 = 17 cN, z = 3.90 mm.*

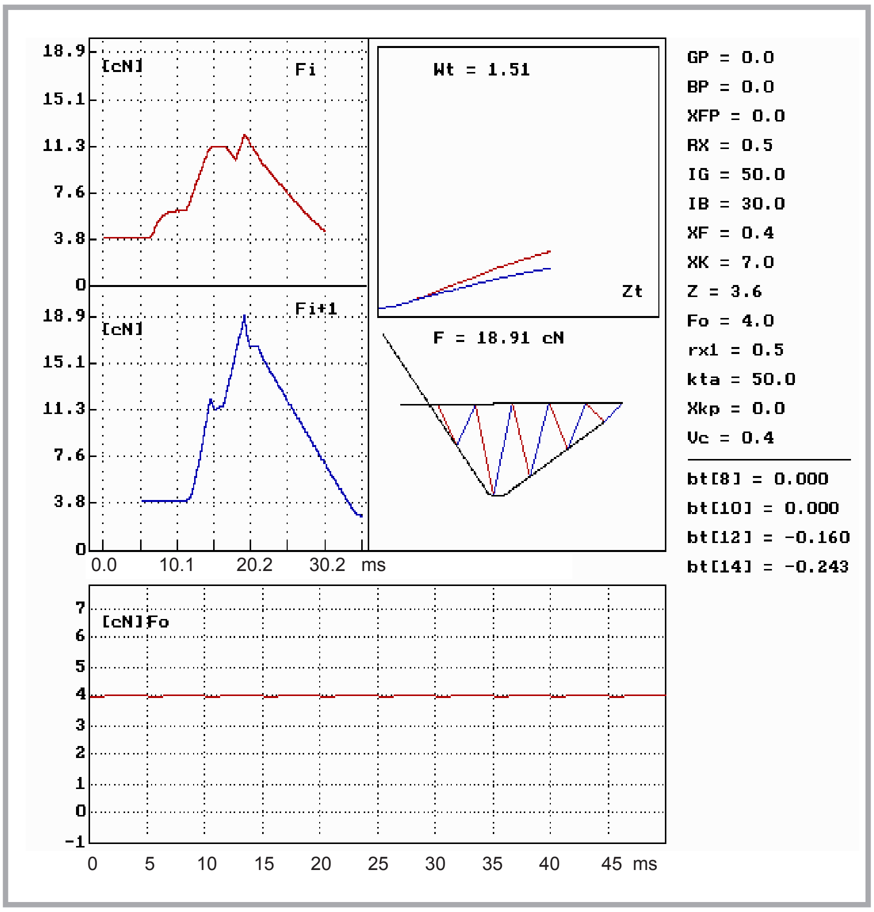

Figure 5. *Calculation parameters for a classic knitting zone: F_0 = 4 cN, z = 3.55 mm.*

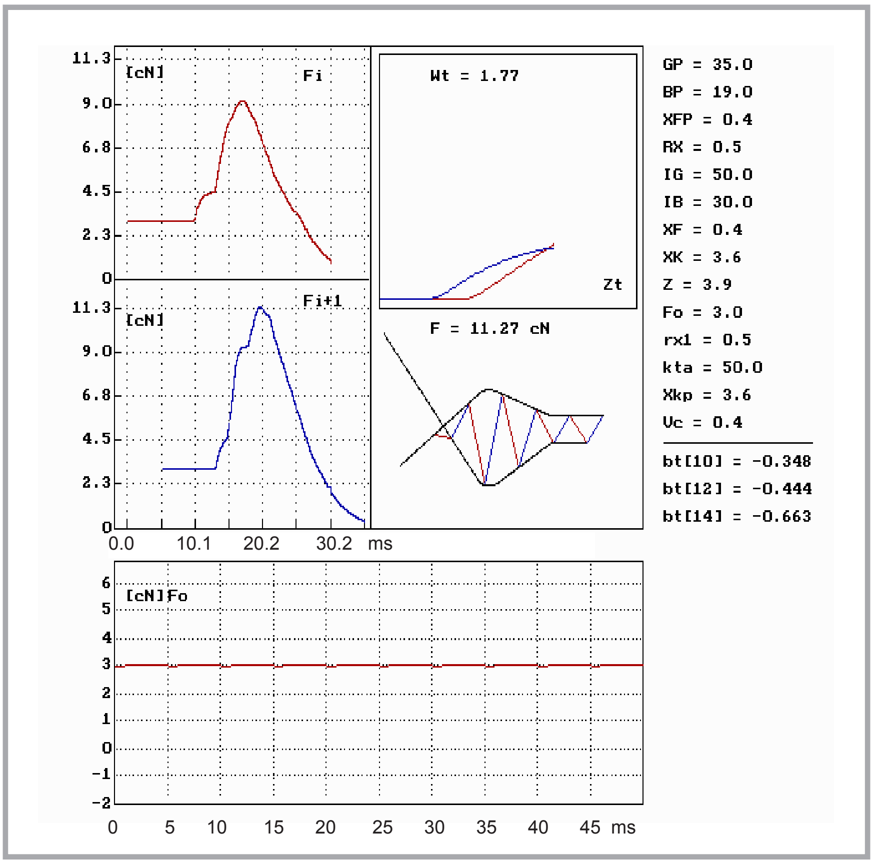

***Figure 6**. Calculation parameters for the Relanit knitting machine: F_0 = 3 cN.*

a linear increase in the force in the elastomeric thread in the knitting zone from 9.48 to 33.05 cN. Consequently the maximum total force from cotton and elastomeric yarns increases linearly. Theoretical values of maximum forces in the knitting zone for cotton yarn are much higher than for elastomeric yarn, at the level of F = 59.72 cN. The values of forces in the threads calculated and measured are close to each other, while the experimental values are slightly lower, of about 5 - 7%. In the Relanit knitting technique, the sinkers, besides the movement in a horizontal direction, move in a vertical direction, which reduces the angles of wrapping the elements forming stitches with a thread in the area of knocked-off needles. Consequently the values of forces in threads during the formation of stitches are lower.

Figures** 7* and ***8 show that in comparison to the classic knitting zone, where the maximum value of the force in the knitting zone during the knitting-in of cotton yarn 20 tex was close to 60 cN, the maximum value of force in the Relanit knitting zone is twice lower. The value of the force in the elastomeric thread reaches similar values to those for the classic knitting zone. As for the classic knitting zone, the characteristic of the process forming stitches for the Relanit knitting zone during the knitting-in of elastomeric yarn 44 dtex (Lycra) is the absence of the phenomenon of robbing a thread.

The outlines of cams in the knitting zone on the knitting machines are not unified. This refers, in particular, to the value of angle β of lifting the needles. The values of this angle can be within the range from 0° to γ, where the lifting angle γ most often is equal to 50°. Therefore simulations of the knitting process during the knitting-in of elastomeric threads was made for a wide range of values of angle β from 0° to 50° at an angle of knocking-off the needles of γ = 50°.

Figure 9 presents the results of a computer simulation for model elastomeric yarns differing in the value of relative

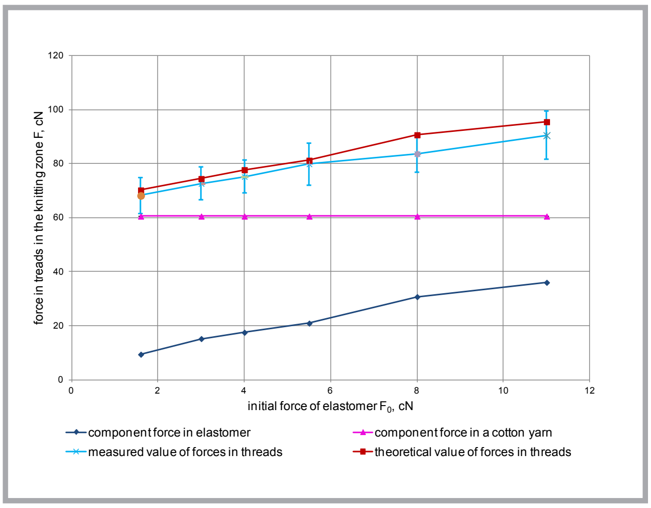

***Figure 7.** Calculated and measured values of forces in threads for a classic knitting zone during the knitting-in of cotton yarn 20 tex and elastomeric yarn 44 dtex (Lycra). Pitch coefficient of knitting-in for cotton yarn $W_t \approx 2.76$. Calculation parameters z = 3.55 mm, γ = 50°, β = 30° i.e. sinker 50°/30°, F_0 = 17 cN for cotton yarn 20 tex.*

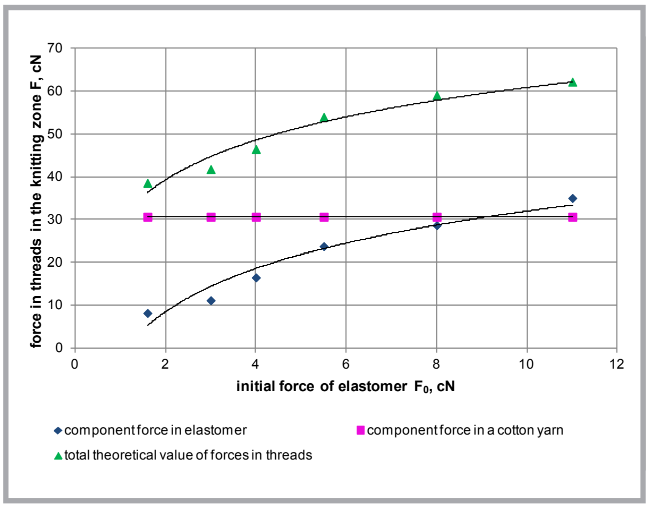

***Figure 8.** Calculated values of forces in threads in a knitting zone during the knitting-in of cotton yarn 20 tex and elastomeric yarn 44 dtex (Lycra) for a Relanit knitting machine. Pitch coefficient of knitting-in for cotton yarn W_t = 2.79. Calculation parameters z = 3.9 mm, cam of needles 50°/30°, cam of sinkers 35°/19°, F_0 = 17 cN for cotton yarn 20 tex.*

drawing rigidity c within the range from 1.6 to 50 cN. The calculations were made with the assumption that the value of the pitch coefficient of knitting-in for cotton yarn for each variant of the cam is $W_t = 2.76$.

The value of depth of knocking-off the needles for each variant of cam for pitch coefficient $W_t = 2.76$ is within the range 2.10 - 4 mm. A simulation was made for the value of relative elongation ε of elastomeric threads of 100% in the feeding zone

It results from this assumption that the value of the initial force F_0 in the feeding zone for individual variants of model elastomeric threads will be equal to that of the relative drawing rigidity c.

For the sinker 50°/0° - 4t/50°, at which the phenomenon of robbing the thread (x_F = 4t) is not present, we observed a continuous increase in the value of the pitch coefficient of knitting-in, while the intensity of the increase in its value decreases with an increase in drawing rigidity c.

In contrast, for sinkers for which the occurrence of the phenomenon of robbing the thread is possible, we can observe that after exceeding the specified value of drawing rigidity c, the value of the pitch coefficient of knitting-in W_t decreases. This is due to the phenomenon of robbing the threads, which appears for the smaller values of the relative drawing rigidity c with an increase in the angle β of lifting the needles.

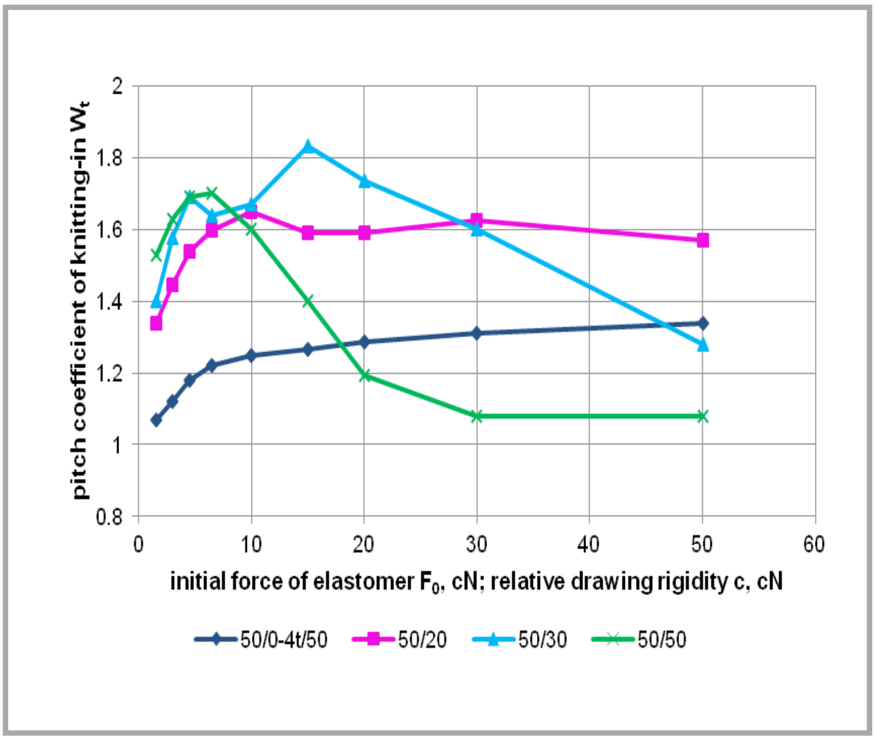

__Figure 9.__ Influence of the drawing rigidity of elastomeric threads on the value of the pitch coefficient of knitting-in for a relative elongation of ε = 100% in the feeding zone.

Another important observation is that the feeding of elastomeric threads at a constant value of relative elongation does not guarantee equal values of the pitch coefficient of knitting-in, as its value depends greatly on the geometric parameters of the knitting zone, which may vary for knitting machines of different manufacturers. For example, for boundary values of lifting angles β = 0° - 50° at an angle of knocking-off of γ = 50° and initial tension of the elastomeric thread of F_0 = 4 cN, the values of coefficient W_t were within the range from 1.08 to 1.56.

Influence of drawing rigidity of elastomeric thread in the feeding zone on the value of the pitch coefficient of knitting-in and forces in threads in the Relanit knitting zone

In order to indicate the influence of the drawing rigidity of elastomeric yarn on the value of the pitch coefficient of knitting-in and that of forces in the threads for the Relanit zone, computer simulations were performed for model elastomeric yarns differing in the value of relative drawing rigidity c, within the range from 1.6 cN to 25 cN. Therefore the assumptions taken

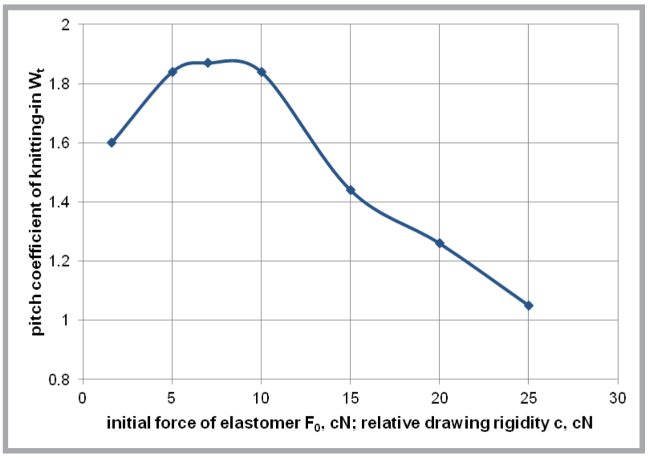

__Figure 10.__ Influence of drawing rigidity of elastomeric threads on the value of the pitch coefficient of knitting-in for a relative elongation in the feeding zone of ε = 100%. Calculation parameters: z = 3.9 mm, cam of needles 50°/30°, cam of sinkers 35°/19°.

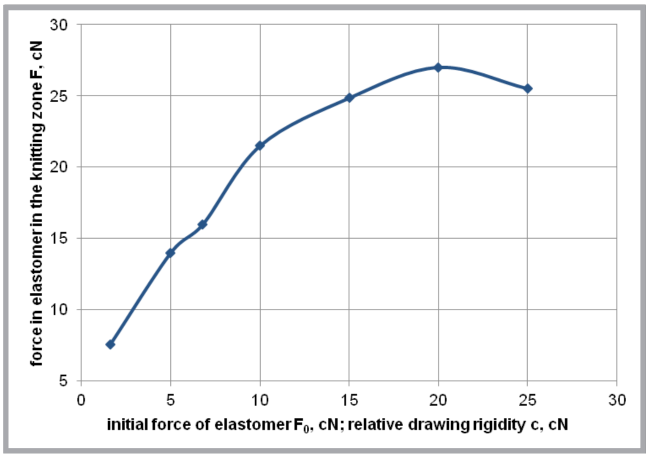

__Figure 11.__ Influence of drawing rigidity of elastomeric threads on the value of maximum forces for a relative elongation in the feeding zone of ε = 100%. Calculation parameters: z = 3.9 mm, cam of needles 50°/30°, cam of sinkers 35°/19°.

are exactly the same as those for a classic knitting zone. The results of the simulations are presented in ***Figures 10*** and ***11***.

Analysis of ***Figure 10*** shows that the loss of length of the knitted-in elastomeric thread expressed by the value of the pitch coefficient of knitting-in can be seen from a relative value of drawing rigidity greater than c = 10 cN, indicating the occurrence of robbing the thread. The consequence of this phenomenon is also a slower increase in the maximum forces in the threads in the knitting zone, which, as is shown in ***Figure 11***, do not increase as dynamically for values of the initial forces in the feeding zone larger than F_0 = 10 cN, despite increasing the values of F_0.

Conclusions

Identification of the conditions of knitting-in of elastomeric threads on warp-knitting machines was performed. The identification of producing cotton knitted fabrics with plated elastomeric threads was carried out on the basis of the simulation of dynamic loads of threads and lengths of knitting-in according to a mathematical model. The results of the dynamic loads of threads and lengths of knitting-in obtained on the basis of a computer simulation were verified experimentally on a computer aided measuring warp-knitting machine.

It was noted that existing technological recommendations concerning the knitting-in of elastomeric threads on warp-knitting machines do not guarantee a uniform knitted structure involving these threads, because the length of the knitted-in elastomeric threads does not only depend on the value of the initial force but also on the geometrical parameters of the knitting zone, which are not unified on the warp-knitting machines. The above conclusion is confirmed by the results of a computer simulation.

1. The results of the computer simulation show that depending on the angle of lifting the needles in the knitting zone, the feeding of elastomeric thread at a constant value of the initial force will lead to different values of the pitch coefficient of knitting-in the elastomeric thread at a constant value of this coefficient for a basic yarn. For boundary values of lifting angles of $\beta = 0° - 50°$ at an angle of knocking-off of $\gamma = 50°$ and for an initial force of elastomeric thread of F_0 = 4 cN, the range of coefficient Wt obtained was from 1.08 to 1.56 .
2. The general recommendation for the knitting-in of elastomeric threads at a value of the initial tension of 0.1 cN, a value of linear density expressed in dtex, will lead to different values of the length of knitting-in of elastomeric thread, depending on the value of the β angle of lifting the needles, and hence to different values of the structural parameters of the knitted fabrics and their properties. This hinders the production of knitted fabrics with elastomeric threads of homogeneous structure taking into account only the recommended rule of knitting-in elastomeric threads related to the values of the initial tension of relative elongation in the feeding zone.
3. Similar to the classic knitting zone, a characteristic of the mechanics of forming stitches for the Relanit knitting zone during the knitting-in of elastomeric thread of 44 dtex (Lycra) is the lack of robbing the thread. The demand in the zone of knocking-off the needles is compensated at the expense of the thread fed from the beam, and largely at the expense of its elongation due to a small value of drawing rigidity. For these reasons, despite the smaller value of the angle of wrapping the forming elements with a thread in the zone of knocked-off needles in the Relanit technique, the value of the force is determined by the elongation of elastomeric thread. Lower loads of threads in the knitting zone on warp-knitting machines of the Relanit type during the production of knitted fabrics plated with elastomeric threads are determined by the forces generated by a low-elastic basic yarn.
4. Low values of relative drawing rigidity of elastomeric threads $c < \sim 10$ cN make the values of dynamic loads of these threads in the Relanit knitting zone similar to those of the loads of threads on warp-knitting machines in a classic knitting zone.

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