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Lockstitch Tightening Model with Mechanical and Thermal Loads

Abstract
Both physical and mathematical models of lockstitch tightening are determined. The basic dynamical equation is a second-order differential correlation with respect to time; the forces applied are analysed and defined. The supplemented correlations are formulated by means of basic physical phenomena. The total angle of contact on the mobile barriers of the disc is introduced by physical analysis of the take-up mechanism. Both mechanical and thermal elongation are determined within the thread and introduced into the basic dynamical equation. The set of equations can be solved by means of any processing software (for example Mathematica) and the results obtained visualised for different parameters.

Key words: *lockstitch tightening, take-up mechanism, mechanical load, thermal load.*

Introduction

The main goal of the present paper is to analyse lockstitch tightening with respect to mechanical and thermal loads. Both physical and mathematical models are formulated. In the first phase the needle thread is elongated without feeding the next portion because the thread is broken by the flat spring. The mass of the thread analysed is discretised at one point within the stitch formation zone. The basic correlation is a second-order differential equation with respect to time, with the forces defined in advance. The supplemented correlations of the problem are formulated by means of basic physical phenomena, i.e. the friction, angle of contact, thread elongation and structural geometry. The set of equations is solved by means of approximation methods. The results obtained can be visualised for different values of the parameters. The second phase of stitch tightening is the introduction of a new part of the needle thread.

The take-up mechanism of the sewing machine applied creates a lockstitch by means of a needle and bobbin hook. The optimal number and configuration of frictional barriers have already been discussed, for example, by Wiezlak and Elmrych-Bochenska [11, 12], Krasowska et al. [6], Korycki and Krasowska [8].

The main difficulty is to introduce the mass of the thread as well as the friction forces on the frictional barriers into the physical and mathematical model. A simulation of forces within the yarns transported through the drawing zone using different friction parameters was analysed by Wlodarczyk and Kowalski [13]. The basic random variables are the length of the yarn segment and the yarn's drawing rigidity. Wlodarczyk and Kowalski [14] analysed the different factors of the friction force, i.e. the random visco-elastic rheological properties displaced through a model of the drawing zone. The variability of tensions in the displaced threads is determined by technological conditions and the non-uniformity of mechanical properties. Lomov [9] proposed the computation of the maximum needle penetration force and introduces a direct dependence between the penetration force on fabric structural parameters and the warp and the weft geometrical mechanical properties. Alagha, Amirbayat and Porat [1] compare the effect of sewing variables and fabric parameters on the shrinkage of a chainstitch by means of a positive feed. Ferreira, Harlock and Grosberg [3] studied thread interactions within a lockstitch sewing machine as a system connecting the needle and bobbin thread. A knowledge-based and integrated process of planning and control is presented by Carvalho et al [2], defined by the basic mechanical parameters during the sewing process.

There are only a few papers concerning the heat transfer problems during stitch formation. Liu, Liasi, Zou, Du [15, 16] simulated the sliding contact between the needle and material package. The parameters assumed (i.e. the needle geometry, sewing conditions, fabrics characteristics) allow to model the increase in temperature, from the initial to the final value corresponding to the steady conditions of sewing. The results obtained are verified by means of infrared radiometry. Authors have discussed some methods of reducing needle heating.

Physical and mathematical model of the stitch tightening process

It is necessary to introduce some assumptions in order to simplify and solve the problem. Certain assumptions are formulated according to Wiezlak, Elmrych-Bochenska [11], while the rest are introduced below.

1. Stitch tightening is a 3D geometrical and dynamical problem within the thread. Practically speaking, the process can be simplified to a 2D plane problem if we neglect the unimportant guide elements.
2. Stitch tightening and stitch link formation is a complex process: the needle thread introduces the bobbin thread into the needle channel. We assume that both sections of the thread have the same physical and mechanical properties.
3. Each stitch link is analysed as an independent dynamic system, thus dynamic interactions are not introduced between the links.
4. We assume linear mechanical strains of the needle thread, neglecting them for the bobbin thread because its active length is short. The resultant thermal strains are determined by the ther-

mal shrinkage and thermal elongation of the yarn.

5. The bobbin thread is located within the bobbin hook. Feeding the thread portion is a continuous process realised during the stitch tightening. Thread is permanently braked by means of a flat spring of constant resisting force. Thus, feeding the portion is realised if the dynamic reaction within the thread is greater than the resisting force of the spring.
6. The resisting forces caused by the introduction of thread into the interlacement are as follows:
   - the friction of the flat spring acting on the thread;
   - the friction within the interlacement as a reaction of feeding the thread portion;
   - the friction forces of the needle thread on the mobile barriers of the take-up disc.

   The friction on the curvilinear surface is described by Euler's formula, whereas the coefficient of friction is calculated according to Wiezlak and Elmrych-Bochenska [11]. The angle of contact on the frictional barriers of the take-up disc are determined according to a cyclogram and are time independent.
7. The total mass of thread is concentrated at one point within the interlacement. Thus, we can formulate a dynamic equation for the concentrated mass during stitch formation which simplifies the description considerably.

Introducing the assumptions above, we simplify the 3D space model of the stitch tightening to a 2D plane one. The problem is illustrated in ***Figure 1***.

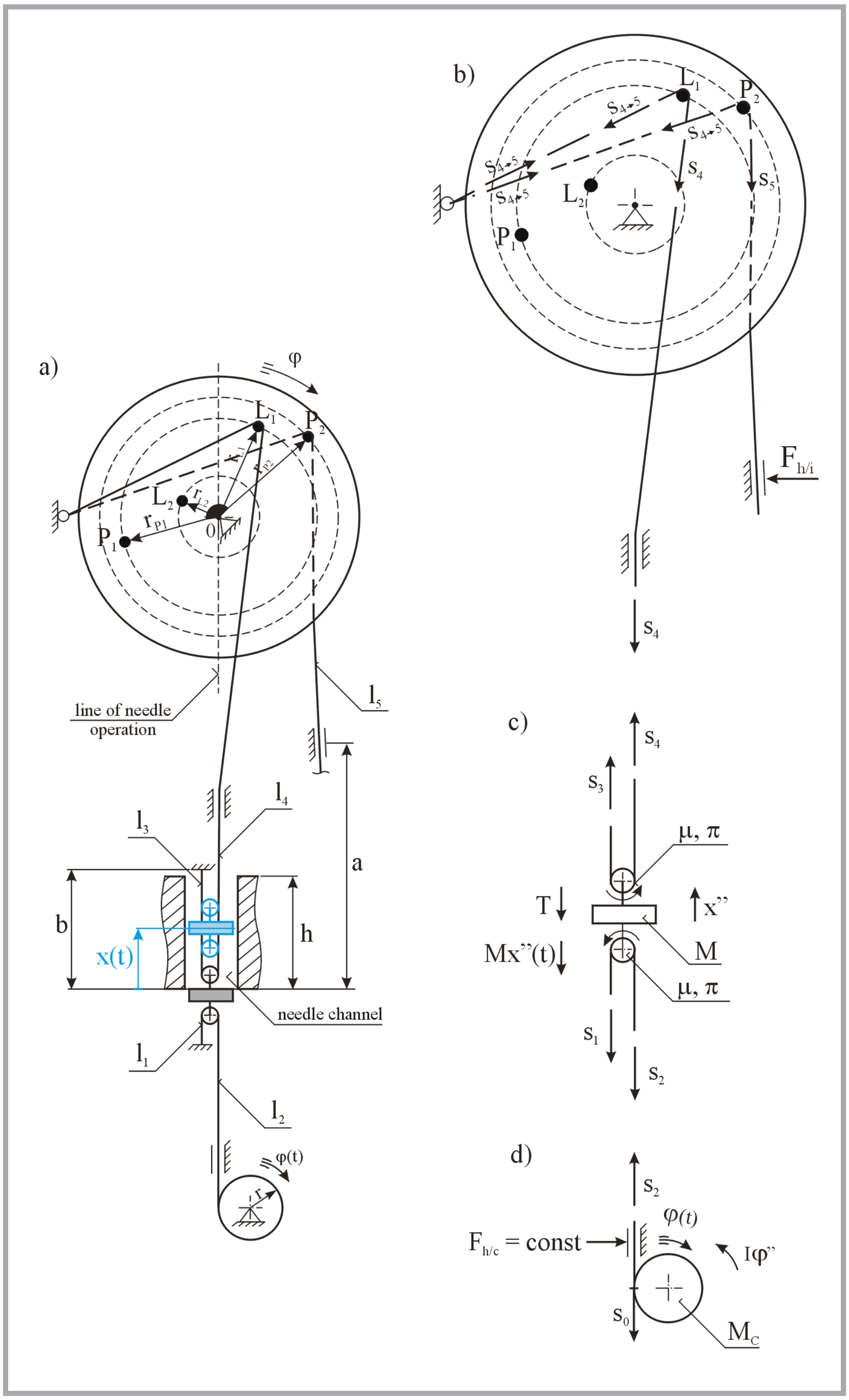

Figure 1. *2D plane physical model of the interlacement location within the needle channel.*

The model of the interlacement location within the needle channel introduces two phases of the thread dynamics: First the needle thread is introduced into the interlacement by simple elongation, blocked by the spring. The mobile barriers of the take-up disc as well as the blocking process cause the thread elongation. The needle thread is subjected to:

- an elastic strain proportional to the geometrical imperfection u(t);
- thermal strains caused by the thermal shrinkage and thermal elongation of the textile material.

A new section of the needle thread is introduced during the second phase because the force within the thread is greater than the spring resistance. Feeding the thread portion is realised by the tension device, and we now assume the negligible elongation of the needle thread by the geometrical impulse.

Dynamical model of lockstitch formation. Elongation of the needle thread blocked by the tension device

A basic dynamic equation for the needle thread within the interlacement is formulated for the mass discretised at one point, as follows:

$$M\frac{d^2x(t)}{dt^2} = -s_1 - s_2 + s_3 + s_4 - T \qquad (1)$$

where M in kg is the discretised mass of the thread within the interlacement, x = x(t) in m - the coordinate of the location of the mass, s_1, s_2, s_3, s_4 in N - the reactions within the thread sections, and T in N is the friction force discretised within the needle channel, determined according to Wiezlak and Elmrych-Bochenska [11].

The bobbin thread is subjected to friction forces s_1, s_2, determined on the curvilinear surface by Euler's formula in the form

$$s_1 = s_2 e^{\mu\pi} \quad (2)$$

where s_1 in N is the reaction within the interlacement, s_2 in N - the reaction of the bobbin thread, e - the Napierian base; μ - denotes the dynamic coefficient of friction within the interlacement, and π in rad is the angle of contact.

Let us formulate a rotation equilibrium equation for a bobbin hook subjected to the feeding of a thread portion. The bobbin hook has a cylindrical shape at the moment of interia along the principal, central axis equal to,

$$(s_2 - s_0)R = J_z \frac{d\varphi_c}{dt^2}, \; J_z = \frac{1}{2} m_c R^2 \quad (3)$$

where s_0 in N is the breaking force of the flat spring acting on the bobbin thread, m_c in kg - the complete mass of the bobbin hook, R in m - the radius of the bobbin hook with the bobbin thread, and $\varphi_c(t)$ in rad denotes the angle of rotation of the bobbin hook determined by the length balance of the bobbin thread, which is subjected to geometrical and thermal loads.

The location of the bobbin thread within the interlacement is denoted as coordinate x = x(t). The elongation is negligible because the section of bobbin thread is short

$$\varphi_c R = 2x \quad ; \quad \frac{d\varphi_c}{dt^2} R = 2\frac{d^2x(t)}{dt^2} \quad (4)$$

Introducing equation (4) into equation (3), and after simple transformations we obtain

$$s_2 - s_0 = m_c \frac{d^2x(t)}{dt^2} \quad (5)$$

The first phase of stitch formation is the elastic tension of the needle thread blocked by the tension device. According to ***Figure 1***, dynamic reactions within the thread and Euler's formula are equal to

$$s_4 = s_3 e^{\mu\pi}; \; s_5 = s_4 e^{\mu\zeta} \quad (6)$$

where ζ in rad is the total angle of contact on the mobile barriers of the take-up disc, which can be determined by means of different methods, cf. for example Korycki, Krasowska [8]. The first phase of stitch tightening is described by the rotation angle of the motion element, equal to $(40–115)\pi/180$ in rad with two active mobile barriers L_1 and P_2. From [8] we conclude that the changes in both angles are time-dependent but nearly constant (see ***Figure 2***).

The difference is equal to about $5\pi/180$ in rad for barrier P_2 and $3\pi/180$ in rad for barrier L_1. Thus, the differences can be neglected, and the angle of contact can be finally assumed to be equal to $\zeta = \zeta_{L_1} + \zeta_{P_2} = 225\pi/180$ in rad.

The needle thread during the first phase of stitch tightening is subjected to mechanical and thermal strains. The mechanical strains are described by Hooke's Law. The thread lengths and strains within the thread for the i-th segment are determined, respectively, by the correlations

$$l'_{iM} = l_{iM} + \Delta l_{iM}; \quad \Delta l_{iM} = l_{iM} e_i;$$
$$s_i = E_n A_p e_i; \quad \text{for } i = 3, 4, 5 \quad (7)$$

where l'_{iM} in m is the length of the thread under tension, l_{iM} in m - the initial length, e_i in m the unit elongation of the thread; E_n in N/m^2 denotes the dynamic modulus of elasticity, and A_p in m is the area of the thread cross-section.

The thermal strains are caused by two phenomena: The first is the thermal shrinkage of the material microstructure, described by Urbanczyk [17] as thread shortening Δl_T. The second is the thermal elongation of the yarn, which is typical for textile structures subjected to a positive temperature difference. The coefficient of thermal expansion α can be additionally expressed, according to Urbanczyk [17], by means of directional coefficients of expansion. The length of the i-th thread segment is determined by the following correlations

$$l'_{iT} = l_{iT} + \Delta l'_{iT} + \Delta l''_{iT}; \; \Delta l'_{iT} = -l_i A_T \exp\frac{T}{B_T};$$
$$\Delta l''_{iT} = l_i \alpha \Delta T; \; \alpha = \alpha_{II} + 2\alpha_{\perp}; \quad (8)$$
$$\text{for } i = 3, 4, 5$$

where A_T B_T are constants i.e. functions of the material and measurement conditions; T in K is the temperature, ΔT in K - the temperature difference, α in 1/K - the coefficient of thermal expansion, α_{II}, $2\alpha_{\perp}$ in 1/K are, respectively, coefficients of the thermal expansion along the longitudinal axis and that orthogonal to the main axis of the yarn. The total length of the i-th thread segment is also the simple expression

$$l'_i = l_i + \Delta l_{iM} + \Delta l'_{iT} + \Delta l''_{iT}; \quad \text{for } i = 3, 4, 5 \quad (9)$$

Let us formulate the length balance of the needle thread during stitch formation by means of the geometry of the system (cf. ***Figure 1***)

$$\begin{cases} L = l_3 + l_4 + l_5; \\ l'_4 = a + l'_5 - x; \\ l'_3 + l'_4 + l'_5 = l_3 + l_4 + l_5 + 2u - 2x; \\ l'_4 - l'_5 - l'_3 = a - b. \end{cases} \quad (10)$$

Introducing equations (6) – equations (9), we can transform the relationship of strains into one of elongations and temperatures as equations (11).

Solving the above set by the elimination of l_3, l_4, l_5, and after some simple calculations, we obtain elongation e_5 as the

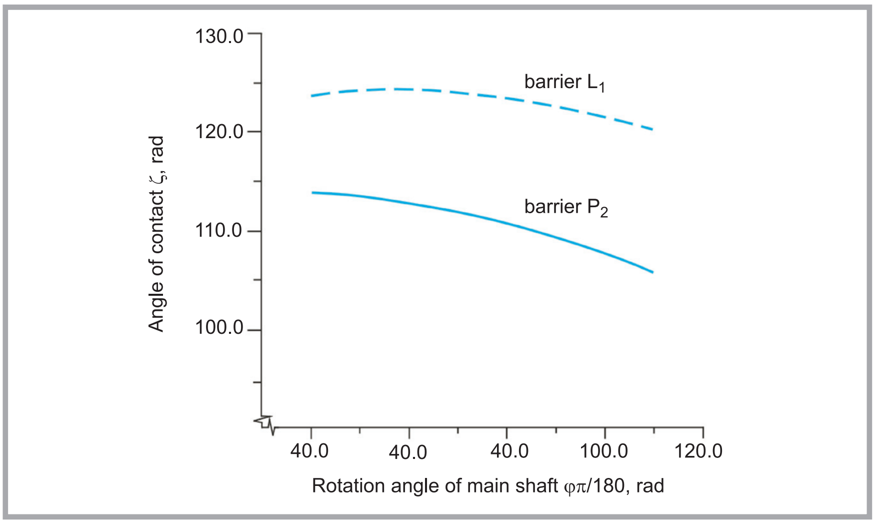

Figure 2. *Angle of rotations for frictional barriers L_1 and P_2, active during stitch tightening.*

following function (equation 12) of the temperature T.

Thus we have to introduce processing software and formulate three roots of the equation, for example Mathematica v. 5.0.0 or Calculation Center v. 1.0.0. Each root contains about 400 components and is too complicated to solve the basic dynamical equation. Thus we simplify the problem. The coefficient of friction, according to Wiezlak, Elmrych-Bochenska [11], is equal to μ = 0.4. Both angles of contact are equal to Π; 225/180 π in rad, cf. [8], and consequently $A,B \in (0,1)$. The product of parameters A & B is therefore negligible (i.e. $A \cdot B \to 0$) in relation to parameters A and B when determined separately.

The thermal shrinkage of yarns made from polyamide or polyester is equal to (4 – 6)% for a temperature of about 100 °C, cf. [17]. The coefficient of thermal expansion α is $(3 – 5) \cdot 10^{-4}$ [17]; the temperature difference depends on the operating conditions, but it is not greater than 100 K. The sum of both components is also no larger than a few percent. The second power and different products of component C are negligible in relation to the other parameters. Under the above assumptions, the equation of elongation e_5 has the form (equation 13)

$$\begin{aligned}&L(2A + B) - 2uB + 2x(A + B) - aB+\\&- b(2A - B)]e_5^2 + [L(1 + A + 3C) +\\&- 2u(1 + A + 2B + C) + 2x(2 + A +\\&+ B + 2C) - a(1 - A + C) - b(1 + A +\\&- 2B + C)]e_5 + 2[2(x - u) + LC] = 0\end{aligned} \quad (13)$$

We solve this correlation by using Mathematica v. 5.0.0 and obtain a positive root

$$e_5 = \frac{C_1 + \sqrt{8[CL + 2(x-u)]C_2 + C_1^2}}{C2_2};$$

$$\begin{aligned}&C_1 = a(1 - A + C) + b(1 + A - 2B +\\&+ C) - (1 + A + 3C)L + 2(1 + A +\\&+ 2B + C)u - 2(2 + A + B + 2C)x;\\&C_2 = -b(2A - B) - aB + (2A + B)L +\\&- 2Bu + 2(A + B)\ x.\end{aligned} \quad (14)$$

Elongations of the other thread sections are determined by Equation (11) as follows (Equation 15)

$$e_4 = Ae_5 = A\frac{C_1 + \sqrt{8[CL + 2(x-u)]C_2 + C_1^2}}{C2_2}$$

(15)

$$e_3 = Be_5 = B\frac{C_1 + \sqrt{8[CL + 2(x-u)]C_2 + C_1^2}}{C2_2}.$$

$$\begin{cases} L = l_3 + l_4 + l_5; \\ l_4(1 + Ae_5) = a - l_4C - l_5C + l_5(1 + e_5) - x; \\ l_3(1 + Be_5) + l_4(1 + Ae_5) + l_5(1 + e_5) = l_3 + l_4 + l_5 + 2u - 2x - l_3C - l_4C - l_5C; \\ l_4(1 + Ae_5) - l_5(1 + e_5) - l_3(1 + Be_5) = a - b + l_3C - l_4C + l_5C; \end{cases} \quad (11)$$

$$A = e^{-\mu\Pi}e^{-\mu\zeta}; \quad B = e^{-\mu\zeta}; \quad C = -A_T \exp\frac{T}{B_T} + \alpha\Delta T.$$

$$\begin{aligned}&[2LAB]e_5^3 + [L(2A + B + AB + 2BC - 2ABC) - 2u(1 + A)B + 2x(A + B) +\\&- a(1 - A)B - b(2A - B - AB)]e_5^2 + [L(1 + A + 3C + AC + 2C^2 - 2BC^2 - 2AC^2) +\\&- 2u(1 + A + 2B + C - AC) + 2x(2 + A + B + 2C - BC) - a(1 - A + C + AC - 2BC) +\\&- b(1 + A - 2B + C - AC)]e_5 + 2[2(x - u) + LC](1 - C^2) = 0.\end{aligned} \quad (12)$$

$$\begin{aligned}&\left[M + m_c\left(1 + e^{\mu\Pi}\right)\right]\frac{d^2x}{dt^2} =\\&= E_nA_pe^{-\mu\zeta}\left(1 + e^{-\mu\Pi}\right)\frac{C_1 + \sqrt{8[CL + 2(x-u)]C_2 + C_1^2}}{C2_2} - s_0\left(1 + e^{\mu\Pi}\right) - T\end{aligned} \quad (17)$$

$$\begin{aligned}&\left[M + m_c\left(1 + e^{\mu\Pi}\right)\right]\frac{d^2x}{dt^2} - E_nA_pe^{-\mu\zeta}\left(1 + e^{-\mu\Pi}\right)\frac{C_1 + \sqrt{8\left[CL + 2\left(x - \frac{1}{2}p_{0\,max}t^2 - v_{s}t\right)\right]C_2 + C_1^2}}{C2_2}\\&\qquad - s_0\left(1 + e^{\mu\Pi}\right) - T = 0;\end{aligned}$$

(19)

$$\begin{aligned}&C_1 = a(1 - A + C) + b(1 + A - B2 + C) - (1 + A + C3)L + 2(1 + A + B2 + C)\left(\frac{1}{2}p_{0\,max}t^2 + v_{sr}t\right)\\&\quad - 2(2 + A + B + C2)x,\\&C_2 = -b(2A - B) - Ba + (A2 + B)L - 2B\left(\frac{1}{2}p_{0\,max}t^2 + v_{sr}t\right) + 2(A + B)x.\end{aligned}$$

Equations: 11, 12, 17 and 19.

Reactions within the thread sections can be formulated according to Equation. (2, 5, 6, 7) in the form

$$s_1 = s_2e^{\mu\Pi} = \left(s_0 + m_c\frac{d^2x}{dt^2}\right)e^{\mu\Pi};$$

$$s_2 = s_0 + m_c\frac{d^2x}{dt^2};$$

$$s_3 = E_nA_pe_3 = E_nA_pBe_5 =$$

$$= E_nA_pB\frac{C_1 + \sqrt{8[CL + 2(x-u)]C_2 + C_1^2}}{C2_2};$$

$$s_4 = E_nA_pe_4 = E_nA_pAe_5 = \quad (16)$$

$$= E_nA_pA\frac{C_1 + \sqrt{8[CL + 2(x-u)]C_2 + C_1^2}}{C2_2};$$

$$s_5 = E_nA_pe_5 =$$

$$= E_nA_p\frac{C_1 + \sqrt{8[CL + 2(x-u)]C_2 + C_1^2}}{C2_2};$$

and the basic dynamic equation can be expressed as follows (Equation 17)

This is a second-order differential equation for coordinate x with respect to time. The parameter is the geometrical displacement caused by the take-up disc u_W, which is the function of coordinate x. Physically speaking, u_W is the time-dependent distance of the mass discretised at one point during the stitch tightening. The most general description of the displacement u_W is the second-order function of time in the form [11]

$$\begin{aligned}&u(t) = z_1t^2 + z_2t + z_0\\&z_1 = p_{sr} = 1/2p_{0\,max} \text{ in m/s}^2\\&z_2 = w_{sr} \text{ in m/s}, z_0 = 0,\end{aligned} \quad (18)$$

where u in m is the geometrical displacement of the discretised mass, z_0 in m - the initial distance for the time t = 0: $z_0 = 0$, z_1 in m/s^2 - the mean acceleration of the mobile frictional barriers of the take-up disc during the stitch tightening, and z_2 in m/s is the mean velocity of the mobile frictional barriers of the take-up disc $v_{śr}$. The first phase of stitch tightening is characterised by a deceleration changing from the initial maximal value to the final value, which is equal to zero. Approximating typical deceleration as a linear function of time, we obtain a mean value equal to half of the maximal value p_{max}. The mean velocity is time-independent. Introducing Equation (18) into Equation (17), we obtain a basic dynamic correlation (Equation 19)

The equation obtained can be solved by means of approximate methods or processing software, cf. Mathematica v. 5.0.0. We introduce the module NDSolve to solve the second-order differential equation, supplemented by a prescribed set of initial conditions within the time interval t defined. The needle thread is introduced into the needle channel in a time with initial and final values of $t_0 = 0$; $t_k = 0.0026$ s. The initial conditions are the location of the discretised mass x and its initial velocity x' = dx/dt, equal to

$$x(t = 0) = 0; \quad x'(t = 0) = 0 \quad (20)$$

The important factor is introducing the thermal deformations. The thermal shrinkage of yarn made of Polyamide is presented by Urbańczyk [16]. For typical working conditions of the take-up disc we assume the thermal shrinkage to be equal to (4 – 6)%. According to [16], the coefficients of thermal expansion are equal to $(3 – 5)\cdot10^{-4}$. The structure of yarn is complicated, and the thermal deformation of material is not representative for the twisted yarn. Thus, we determine the variable thermal parameter C from the range (0 – 0.028). All other parameters introduced are listed in ***Table 1***.

The calculations obtained are visualised by means of Mathematica software (command: Plot/Evaluate, time range: $t_0 = 0$; $t_k = 0.0026$ s). Equation (19) is complicated and should be solved numerically. It is also impossible to determine the analytical form of the objective functional and analyse the sensitivity by means of classical methods. The numerical sensitivity of coordinate x = x(t) for parameter C is shown in ***Table 2*** and ***Figure 3***.

The diagram obtained for C=0 is close to the model determined by Wiezlak and Elmrych-Bochenska [11]. Both curves contain a part corresponding to the coordinate of the interlacement location close to zero $x = x(t) \rightarrow 0$. Thus the geometrical displacement u = u(t) does not cause the motion of the discretised mass still located under the material surface. The time boundary value is $\Delta\tau \sim 0,0005$ s, which produces a positive value of the interlacement location x = x(t) and the

Table 1. *Geometric parameters of the stitch tightening model [11].*

Geometric parameter	Symbol	Unit	Value
Total length of the needle thread within the stitch tightening zone	L	M	0.3
Distance between the lower surface of the material package and the blocking point of the thread tension device	a	M	0.2
Distance between the lower surface of the material package and the blocking point of the needle thread within the previous interlacement	b	M	0.006
Radius of the bobbin hook with the bobbin thread	R	M	0.009
Diameter of the needle and bobbin thread	d	M	0.0002
Stitch stroke	s	M	0.0025
Material package thickness	h	M	0.002
Dynamic modulus of initial elasticity of the thread	E_n	N/m^2	5×10^9
Thread mass after discretisation (located within the interlacement)	M	kg	0.001
Dynamic coefficient of friction of the thread in the interlacement	μ	-	0.4
Maximal friction force of the interlacement within the needle channel	T	N	0.3
Breaking force of the bobbin thread	s_0	N	0.2
Breaking force of the needle thread	P	N	3.5
Mean acceleration of the eye of the take-up disc during the stitch tightening	z_1	m/s^2	-14.8
Mean velocity of the eye of the take-up disc	z_2	m/s	3.5

Table 2. *Coordinates x = x(t) for selected values from the time range $t_0 = 0$; $t_k = 0.0026$ s and different values of thermal elongation parameter C.*

C	Coordinates x = x(t) ×10⁴, m for selected time t, ms				
	0, ms	0.65, ms	1.30, ms	1.85, ms	2.60, ms
0	0	0.14033	0.77195	1.94379	4.92667
0.008	0	0.21700	1.08175	2.57546	6.18129
0.016	0	0.29171	1.38347	3.19021	7.40066
0.024	0	0.36445	1.67703	3.78789	8.58447

Table 3. *Coordinates x = x(t) for selected values from the time range $t_0 = 0$; $t_k = 0.0026$ s and different needle thread lengths L.*

L, m	Coordinates $x = x(t) \times10^4$, m for selected time t, ms				
	0, ms	0.65, ms	1.30, ms	1.85, ms	2.60, ms
0.35	0	0.32695	1.46857	3.25582	7.20654
0.45	0	0.28902	1.26129	2.73628	5.89815
0.55	0	0.27016	1.15760	2.47892	5.26122
0.65	0	0.25924	1.09690	2.32643	4.88097

introduction of the needle thread into the needle channel within the material package. The second part of the curve grows more rapidly in the model results, as presented in ***Figure 3*** for C = 0. Let us compare the coordinates for time t = 0.0026 s according to the model curve [11] ($x = 0.347\cdot10^{-3}$ m) and ***Figure 3*** ($x = 0.493\cdot10^{-3}$ m). The decrease obtained is equal to about 30%. The difference is caused by the bigger value of reaction force s_4, because the angle of contact z grows from the value Π rad, according to [11], to that of $225\pi/180$ in rad, now assumed. The cause is the mobile frictional barriers within the take-up disc. Consequently, the thread is located higher than previously within the material package in relation to the lower edge of the material.

The results obtained for variable parameter C indicate that every curve has the same nonlinear shape. According to ***Table 2*** and ***Figure 3***, we can conclude that coordinate x is very sensitive to changes in parameter C. At the same time the differences in x obtained are comparable to the different parameters C. The changes in coordinate x = x(t) are always minimal for the minimal time, and considerably greater for the second part of the curve.

The length of the needle thread for the take-up disc is considerably greater than for the reference model and the classical mechanism of stitch tightening [11], the reason for which being the multibarrier frictional structure. Our next goal is to determine the value of coordinate x = x(t) for the same thermal parameter C = 0.024 and different lengths L of the needle thread from the interval <0.3;0,65> m. The coordinates x = x(t) obtained for different lengths L during stitch tightening are listed in ***Table 3*** and depicted in **Figure 4**.

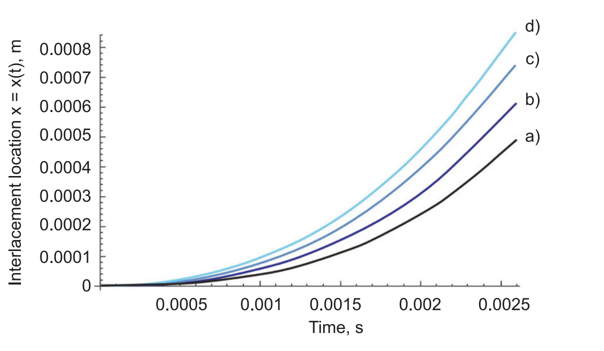

Figure 3. Variable coordinate of the interlacement location x = x(t) within the stitch link for different thermal elongation parameters: (a) C = 0, (b) C = 0.008, (c) C = 0.016, (d) C = 0.024.

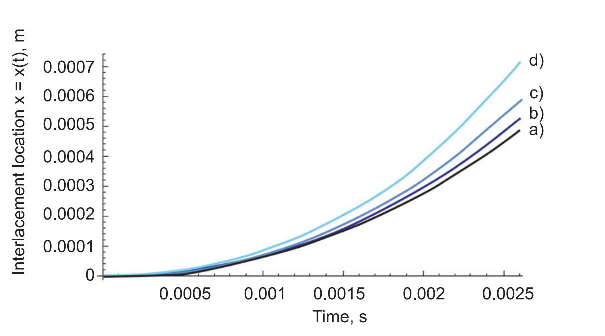

Figure 4. Variable coordinate of the interlacement location x = x(t) within the stitch link for different needle thread lengths: (a) L = 0.35 m, (b) L = 0.45 m, (c) L = 0.55 m, (d) L = 0.65 m.

The curves obtained have the same strong nonlinear shape. The coordinate of the interlacement location x = x(t) is considerably less for the multibarrier frictional structure of the take-up disc (the needle thread length L = 0.65 m) than for the reference model [11] (the needle thread length L = 0.30 m). Considering the time $t = 0.65 \cdot 10^{-3}$ s, the change in length (from L = 0.35 m to the assumed value L = 0.65 m) decreases coordinate x by about 21%. Considering the time $t = 2.6 \cdot 10^{-3}$ s, the same change in length L decreases coordinate x by about 32%. The bigger the active length L, the bigger the thread elongation, as described by the linear correlation according to Hooke's Law. We see at once that the changes in coordinate x = x(t) are not proportional to the increase in the length of the needle thread. The needle thread is also more sensitive to the location of frictional barriers for the minimal than for the maximal permissible length.

The changes in coordinate x are difficult to describe because the geometry of the needle thread is complicated, and the shape is not a straight line. The main geometric disturbances are caused by the frictional barriers within the take-up disc zone, which is also the main cause of the length increase within the model of the take-up disc presented in relation to that of Wiezlak and Elmrych-Bochenska [11]. The bigger the active length L of the needle thread, the longer the time of stitch tightening during interlacement creation within the needle channel.

Conclusions

The number and configuration of the mobile barriers within the take-up disc are the basic parameters during stitch tightening, cf. Korycki, Krasowska [8]. The needle thread and bobbin thread have the same material parameters. Thus the dynamics of the lockstitch formation are determined together for the complete stitch link.

The behaviour of the thread was deeply analysed, and mechanical as well as thermal elongations were introduced. The assumed dependence stress–strain is linear, which allows to introduce Hooke's Law, thereby simplifying the dynamical equation. Some components within the basic dynamical equation can be neglected, and the description of roots is relatively easy. The thermal behaviour is described by two parallel phenomena: the shrinkage and the simple elongation of the yarn. The main mathematical difficulty is to obtain a unique solution, which was found for different values of the thermal parameter C.

Taking off the thread from the bobbin hook is a complex process: the needle thread is subjected to elongation, and a new part of the thread is introduced from the bobbin hook. The superposition principle allows to analyse both problems separately.

The frictional forces during stitch link formation and on the mobile frictional barriers of the take-up disc are variable, a description of which is difficult. The diameters of mobile barriers do not influence the final result of the dynamical reactions significantly, and the errors are no greater than a few percent. Thus these diameters are neglected in the model proposed.

The model contains the mass of needle thread discretised at one point. The alternative is to introduce a few points of the mass divided along the thread and connecting elements between these points. Hence a basic dynamical equation should be formulated separately for each part of the thread. Of course, the greater the number of points, the more complicated and time-consuming the calculations. The results obtained can be finally applied for the optimisation of the needle thread during lockstitch tightening.

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