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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.

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 Wietlak 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 Włodarczyk and Kowalski [13]. The basic random variables are the length of the yarn segment and the yarn’s drawing rigidity. Włodarczyk 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 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.

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.

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 Wietlak, 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 Elmyrch-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.

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:

$$M \frac{d^2x}{dt^2} = -s_1 - s_2 + s_3 + s_4 - T$$

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 Elmyrch-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

\[
s_1 = s_2 e^{\mu \pi}
\]  
(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; \( \mu \) - denotes the dynamic coefficient of friction within the interlacement, and \( \pi \) 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 interlacing along the principal, central axis equal to,

\[
(s_2 - s_3)R = J_d \frac{d\varphi}{dt}, \quad J_s = \frac{1}{2} m_z R^2
\]  
(3)

where \( s_2 \) in N is the breaking force of the flat spring acting on the bobbin thread, \( m_z \) in kg - the complete mass of the bobbin hook, \( R \) in m - the radius of the bobbin hook with the bobbin thread, and \( \varphi(t) \) 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

\[
\varphi \dot{R} = 2x; \quad \frac{d\varphi \dot{R}}{dt} = 2 \frac{d^2 x(t)}{dt^2}
\]  
(4)

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

\[
s_2 - s_3 = m_z \frac{d^2 x(t)}{dt^2}
\]  
(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

\[
s_4 = s_3 e^{\mu \xi}; \quad s_5 = s_4 e^{\mu \xi}
\]  
(6)

where \( \xi \) 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 Kotrycki, 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 \( \zeta = \zeta_{p1} + \zeta_{p2} = 225\pi / 180 \) 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

\[
l_i = l_{i0} + \Delta l_i; \quad \Delta l_i = l_{i0} \varepsilon_i; \quad s_i = E_i A_i \varepsilon_i; \quad \text{for } i = 3, 4, 5
\]  
(7)

where \( l_{i0} \) in m is the length of the thread under tension, \( l_m \) in m - the initial length, \( e_i \) in m the unit elongation of the thread; \( E_i \) in N/m² 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 \( \Delta l_T \). 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 \( \alpha \) 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

\[
l_i = l_0 + \Delta l + \Delta l_T; \quad \Delta l_T = l_0 \alpha \Delta T; \quad \alpha = \alpha_H + 2\alpha_L
\]  
(8)

for \( i = 3, 4, 5 \)

where \( \alpha_H, B_T \) are constants i.e. functions of the material and measurement conditions; \( T \) in K is the temperature, \( \Delta T \) in K - the temperature difference, \( \alpha \) in 1/K - the coefficient of thermal expansion, \( \alpha_H, 2\alpha_L \) 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

\[
l_i = l_0 + \Delta l + \Delta l_T + \Delta l_i; \quad \text{for } i = 3, 4, 5
\]  
(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)

\[
L = l_3 + l_4 + l_5; \quad l_4 = a + l_3 - x; \quad l_5 = l_3 + l_4 + l_5 + 2a - 2x; \quad l_4 - l_5 = a - b
\]  
(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
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 \(a\) is \((3 - 5)\times10^{-4}\) [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 \(\varepsilon_5\) has the form (equation 13)

\[
L(2A + B) - 2u(1 + A + 2B + C) + 2x(2 + A + B + 2C - BC) - a(1 - A + C + AC - 2BC + - b(1 + A - 2B - C)\varepsilon_5 + 2(2x - u) + LC)(1 - C) = 0.
\]

Equations: 11, 12, 17 and 19.

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

\[
\begin{align*}
\mathrm{s}_1 & = s_0 + m_s \frac{d^2x}{dt^2} e^{a(t)}; \\
\mathrm{s}_2 & = s_0 + m_s \frac{d^2x}{dt^2}; \\
\mathrm{s}_3 & = E_A e^{a(t)} = E_A e^{a(t)} B e^{a(t)} = \\
& = E_A B_{e} C_1 + \sqrt{L(2A + B) - 2u(1 + A + 2B + C) + 2x(2 + A + B + 2C - BC) - a(1 - A + C + AC - 2BC + - b(1 + A - 2B - C)\varepsilon_5 + 2(2x - u) + LC)(1 - C)}.
\end{align*}
\]

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

\[
\begin{align*}
\mathrm{u}(t) & = z_1^2 + z_2^2 + z_0 \quad z_1 = p_{v1} = \frac{1}{2}p_{max}^2 + m/s^2 \quad z_2 = w_{v1} = m/s, \quad z_0 = 0,
\end{align*}
\]

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 \(w_{v1}\) which is the function of coordinate \(x\).

Physically speaking, \(w_{v1}\) is the time-dependent distance of the mass discretised at one point during the stitch tightening. The most general description of the displacement \(u_0\) is the second-order function of time in the form [11]

\[
\begin{align*}
\mathrm{u}(t) & = z_1^2 + z_2^2 + z_0 \quad z_1 = p_{v1} = \frac{1}{2}p_{max}^2 + m/s^2 \quad z_2 = w_{v1} = m/s, \quad z_0 = 0,
\end{align*}
\]
function of time, we obtain a mean value equal to half of the maximal value $p_{\text{max}}$. The mean velocity is time-independent. Introducing Equation (18) into Equation (17), we obtain a basic dynamic correlation (Equation 19)

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

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)×10^{-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: $t_0 = 0$; $t_k = 0.0026 \, \text{s}$). The initial conditions are the location of the discretised mass $x$ and its initial velocity $x' = \frac{dx}{dt}$, equal to

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

The 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 $t = 0.0026 \, \text{s}$ according to the model curve [11] ($x = 0.347\times10^{-3} \, \text{m}$) and Figure 3 ($x = 0.493\times10^{-3} \, \text{m}$). 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 $\Pi$ rad, according to [11], to that of $225\, \text{rad}$ 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.

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

<table>
<thead>
<tr>
<th>Geometric parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length of the needle thread within the stitch tightening zone</td>
<td>$L$</td>
<td>m</td>
<td>0.3</td>
</tr>
<tr>
<td>Distance between the lower surface of the material package and the blocking point of the thread tension device</td>
<td>$a$</td>
<td>M</td>
<td>0.2</td>
</tr>
<tr>
<td>Distance between the lower surface of the material package and the blocking point of the needle thread within the previous interlacement</td>
<td>$b$</td>
<td>M</td>
<td>0.006</td>
</tr>
<tr>
<td>Radius of the bobbin hook with the bobbin thread</td>
<td>$R$</td>
<td>M</td>
<td>0.009</td>
</tr>
<tr>
<td>Diameter of the needle and bobbin thread</td>
<td>$d$</td>
<td>M</td>
<td>0.0002</td>
</tr>
<tr>
<td>Stitch stroke</td>
<td>$s$</td>
<td>M</td>
<td>0.0025</td>
</tr>
<tr>
<td>Material package thickness</td>
<td>$h$</td>
<td>M</td>
<td>0.002</td>
</tr>
<tr>
<td>Dynamic modulus of initial elasticity of the thread</td>
<td>$E_0$</td>
<td>N/m^2</td>
<td>5×10^9</td>
</tr>
<tr>
<td>Thread mass after discretisation (located within the interlacement)</td>
<td>$m$</td>
<td>kg</td>
<td>0.001</td>
</tr>
<tr>
<td>Dynamic coefficient of friction of the thread in the interlacement</td>
<td>$\mu$</td>
<td>-</td>
<td>0.4</td>
</tr>
<tr>
<td>Maximal friction force of the interlacement within the needle channel</td>
<td>$T$</td>
<td>N</td>
<td>0.3</td>
</tr>
<tr>
<td>Breaking force of the bobbin thread</td>
<td>$s_0$</td>
<td>N</td>
<td>0.2</td>
</tr>
<tr>
<td>Breaking force of the needle thread</td>
<td>$P$</td>
<td>N</td>
<td>3.5</td>
</tr>
<tr>
<td>Mean acceleration of the eye of the take-up disc during the stitch tightening</td>
<td>$z_1$</td>
<td>m/s^2</td>
<td>-14.8</td>
</tr>
<tr>
<td>Mean velocity of the eye of the take-up disc</td>
<td>$z_2$</td>
<td>m/s</td>
<td>3.5</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>$C$</th>
<th>Coordinates $x = x(t) \times 10^4$, m for selected time t, ms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0, ms</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.008</td>
<td>0</td>
</tr>
<tr>
<td>0.016</td>
<td>0</td>
</tr>
<tr>
<td>0.024</td>
<td>0</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>$L$, m</th>
<th>Coordinates $x = x(t) \times 10^4$, m for selected time t, ms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0, ms</td>
</tr>
<tr>
<td>0.35</td>
<td>0</td>
</tr>
<tr>
<td>0.45</td>
<td>0</td>
</tr>
<tr>
<td>0.55</td>
<td>0</td>
</tr>
<tr>
<td>0.65</td>
<td>0</td>
</tr>
</tbody>
</table>

FIBRES & TEXTILES in Eastern Europe 2011, Vol. 19, No. 2 (85)
within the needle channel. The tightening during interlacement creation is related to the thread, the longer the time of 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.

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.

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