

Karl Gotlih,
Darja Žunič Lojen,
Bojan Vohar

University of Maribor,
Faculty of Mechanical Engineering
Smetanova 17, SI-2000 Maribor, Slovenia
E-mail: gotlih@uni-mb.si
darja.zunic@uni-mb.si
bojan.vohar@uni-mb.si

Optimisation of Needle Penetration Velocity Using the Link Drive Mechanism in a Sewing Machine

Abstract

Needle movement in a standard lockstitch sewing machine is produced by a slider-crank mechanism. The needle moves in a vertical plane and penetrates the fabric on its way down. Friction between the needle and the fabric generates heat during the penetration phase. The heat causes severe problems during the sewing process, such as thread & fabric melting as well as residues around the needle's eye. These cause thread or fabric damage and may interrupt the sewing process. One possibility of reducing heat generation is to reduce the needle penetration velocity. This is a function of the geometry of the sewing machine's driving mechanism and the angular velocity of the main shaft. Since friction is a function of needle penetration velocity, the heat generated is directly dependent on the configuration of the driving mechanism, as well as the sewing speed. The aim of this work is to introduce the possibility of replacing the slider-crank mechanism, which is typically used in sewing machines, with a link drive mechanism. With this type of mechanism we may be able to reduce the penetration velocity of the needle without any loss of sewing speed. The optimal geometry of the link drive is achieved using a non-linear optimisation procedure.

Key words: sewing machine, link drive mechanism, optimisation, penetration velocity.

Introduction

Thermal damage to a fabric depends largely on the sewing speed, because it usually occurs due to excessive heating of the needle. On a medium-strong fabric and at a sewing speed of about 4000 stitches per minute, an ordinary sewing needle reaches the temperature of about 250 °C. The sewing speeds of modern industrial sewing machines can reach in excess of 7000 stitches per minute, and the temperature of the needle may rise rapidly to over 350 °C unless special precautions are taken. Such a high temperature is detrimental to needle strength, and also causes an unacceptable heating of the sewing thread and the material in the region of the needle's puncture hole.

Natural fibres can sustain needle temperatures of 350 °C for a short time, but the finishes with which many fabrics are treated cannot withstand such high temperatures. They melt or burn and smear over the surface of the needle, further increasing the friction. It is even more important to avoid high needle temperatures when the fabric is of a synthetic material.

Needle temperatures of about 200 °C maximum should not be exceeded when sewing synthetic fabric or when using a synthetic sewing thread. Synthetic fibres are thermoplastic, that is, before actually reaching the melting point they pass into a state where they can be moulded. This softening point lies between 170 °C and

235 °C for polyamide, and around 230 °C and 240 °C for polyesters.

As a consequence of excessive heating, difficulties such as fabric smearing, thread breaking, skipped stitches, and fabric damage by melted residues in the throat plate aperture arise when working on synthetic woven or knitted fabrics, and even on blended fabrics that contain synthetic fibres. The result is that components of the material melt and stick to the needle. As long as the needle is in motion, these adhered residues remain in a state where they can be moulded, and they considerably increase the friction between the needle and the fabric. When the sewing process is interrupted or stopped, the needle cools down and the melted residues solidify, making further use of the needle impossible [1].

This paper is organised in several sections. Heat generation from friction is briefly outlined after a short background to the study. The next section describes the slider-crank mechanism for moving the sewing needle. Descriptions of the path, velocity and acceleration of the needle are developed with respect to the sewing machine's main shaft rotation angle. Afterwards the link drive mechanism is introduced, together with the non-linear optimisation procedures that could be used to optimise the mechanism. In the next section, the application of the optimisation procedure to the link drive mechanism is described, and a numerical example is shown. Finally, a comparison between the slider-crank mechanism

and the link drive mechanism clearly shows the benefits of using the link drive mechanism to move the sewing needle. Attention is drawn to the velocity profiles of both mechanisms.

Theoretical background

In this section, the theory of friction heat generation is outlined, together with an introduction to the kinematic characteristics of the slider-crank and link drive mechanisms.

Heat generated by friction

The heat generated by friction between two bodies can be calculated using the expression given in [2];

$$Q = N\mu v \quad (1)$$

where N is the normal force between the bodies, μ the friction coefficient and v the relative velocity between the bodies.

Any increase in the temperature of the sewing needle depends on the increase in friction heat in the needle penetration phase of the stitch formation cycle. If it is assumed that the friction coefficient μ and the normal force between the sewing needle and the fabric are constant in the penetration phase, the friction heat is dependent only on the relative velocity between the sewing needle and the fabric. The relative velocity is the penetration velocity of the needle, since the fabric is fixed relatively to the needle. From equation (1), it follows that the relationship between the friction heat and the needle

velocity is linear. Therefore, a higher needle velocity contributes to more heat generation from friction and to higher needle temperatures.

A significant factor that also influences friction heat during the sewing process is the needle penetration force (the force needed to penetrate the fabric). Investigations into and simulations of this parameter's effects are stated in the literature [3 - 8]. The effects on needle velocity and acceleration caused by changing the mechanism for moving the needle are discussed in [9 - 11].

Slider-crank mechanism

Standard lockstitch sewing machines are equipped with a slider-crank mechanism for moving the sewing needle. The geometry and the structure of this mechanism are shown in Figure 1. The elements of the mechanism are the drive link r_2 , needle path s , coupler link r_3 and the eccentricity e . The needle path, penetration velocity and acceleration are illustrated in Figure 2 (see page 66). The graphs represent solutions for the analytical functions of Equation (2) for needle path, velocity and acceleration with respect to the main shaft rotation angle $\varphi_2 = \varphi_2(t)$ [12].

The initial angle $\varphi_2 = 0^\circ$ is chosen at the upper position of the needle. The velocity values of the needle, which are greater than zero, assign the needle movement from the upper point to the lowest point of the needle path.

The dimensions of the slider-crank mechanism elements in this example are:

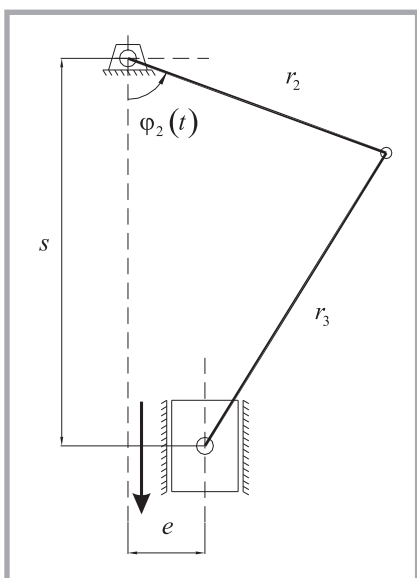


Figure 1. The slider-crank mechanism.

$$s = -r_2 \cos \varphi_2 - \frac{1}{2} \sqrt{(2r_2 \cos \varphi_2)^2 - 4(r_2^2 + e^2 - r_3^2 - 2r_2 e \sin \varphi_2)} = s(\varphi_2(t)) \quad (2)$$

$$\dot{s} = \dot{s}(\varphi_2(t)) \quad \ddot{s} = \ddot{s}(\varphi_2(t))$$

$$s = r_4 \sin \varphi_4 + r_5 \sin \varphi_5 + \frac{r_4 \cos \varphi_4 + r_5 \cos \varphi_5}{\tan(\arcsin(\frac{r_4 \cos \varphi_4 + r_5 \cos \varphi_5}{r_6}))} = s(\varphi_4(t)) \quad (3)$$

$$\varphi_5 = f(\varphi_4) \quad \dot{s} = \frac{ds}{dt} = \dot{s}(\varphi_4(t)) \quad \ddot{s} = \frac{d\dot{s}}{dt} = \ddot{s}(\varphi_4(t))$$

Equations: 2 and 3.

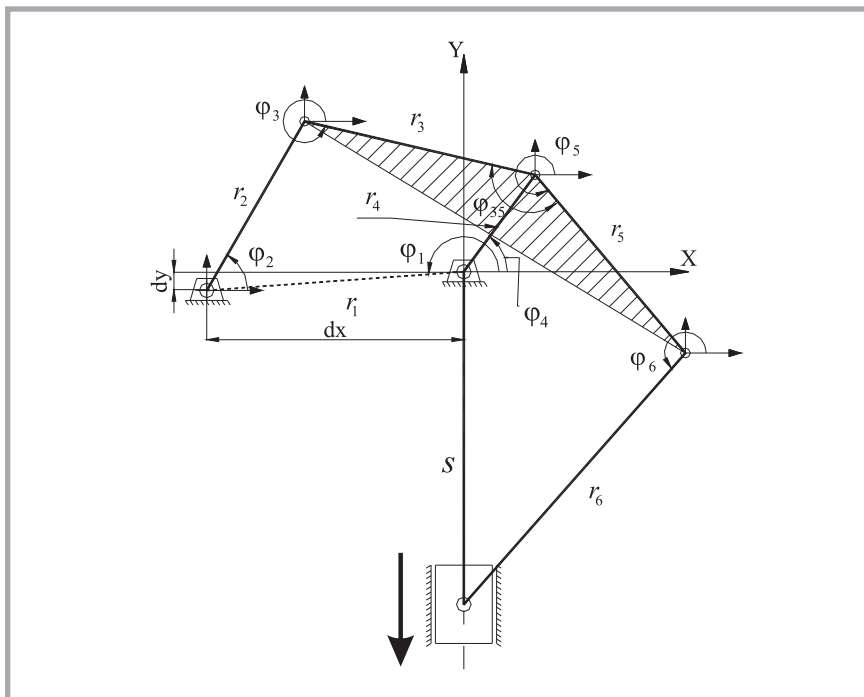


Figure 3. Geometry of the link drive mechanism

$r_2 = 15$ mm, $r_3 = 48$ mm and $e = 0$ mm (as is usual in sewing machines).

The link drive mechanism

The link drive mechanism has a more complex structure than the slider-crank mechanism. This has been investigated in [13]. The kinematic structure of the mechanism is shown in Figure 3. The elements are the drive link r_4 , triangular coupler link $r_3 - r_5$, coupler link r_6 , driven link r_2 and sewing needle path s . Kinematic relations in the link drive mechanism as a function of the main shaft rotation angle $\varphi_4 = \varphi_4(t)$ are described by the analytical functions of Equation (3).

The initial position of the angle $\varphi_4 = 0^\circ$ is chosen in the upper position of the needle. The needle path, the penetration velocity and acceleration are shown in Figure 4. The dimensions of the mecha-

nism elements for this illustration are $r_2 = 22$ mm, $r_3 = 30$ mm, $r_4 = 8.5$ mm, $r_5 = 37$ mm, $r_6 = 33$ mm, $dx = 35$ mm and $dy = 2$ mm, $\varphi_{35} = 125^\circ$.

In the above illustrations, the needle penetration phase concerns the section of the needle path between the first contact of the needle tip with the fabric to the point when the needle eye penetrates the fabric. Depending on the sewing machine's construction, this region is typically halfway between the UDP (upper dead point) and the LDP (lower dead point). The exact location depends on the position of the needle plate and the fabric's thickness.

A comparison of the diagrams in Figures 2 and 4 shows that the penetration velocity of the sewing needle is lower for the link drive mechanism than for the slider-crank mechanism. This means that the heat generated from friction, and

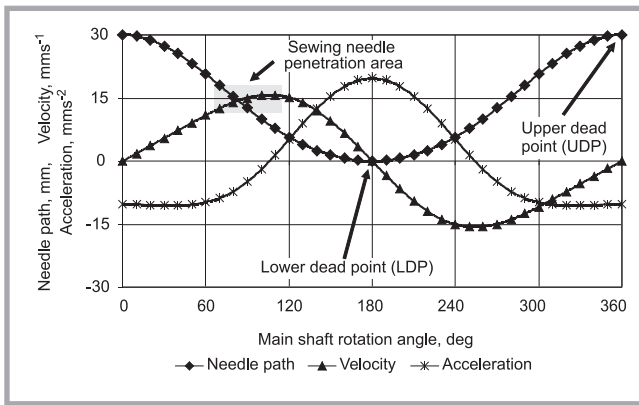


Figure 2. Needle path, velocity and acceleration with respect to the main shaft rotation for the slider-crank mechanism during constant main shaft rotation with angular velocity $\omega = 1 \text{ rads}^{-1}$.

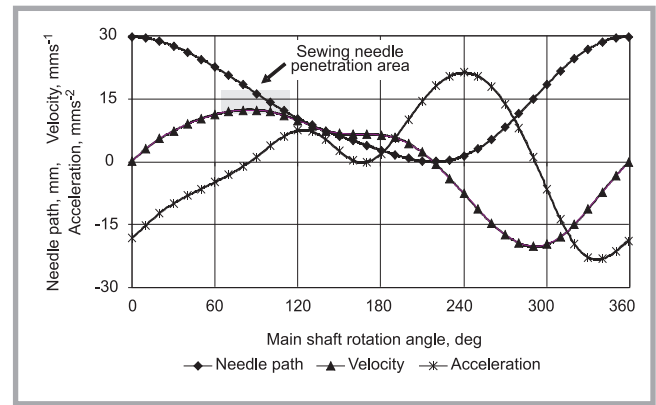


Figure 4. Needle path, velocity and acceleration with respect to the main shaft rotation for the link drive mechanism during constant main shaft rotation with angular velocity $\omega = 1 \text{ rads}^{-1}$.

hence the needle temperature, will also be lower when using the link drive mechanism. However, an important restriction to consider is that the altered or substituted needle-drive mechanism (in this case, the link drive mechanism) must fit in the available space provided in existing sewing machines. In addition, the needle's path must be almost identical to that achieved using the conventional slider-crank mechanism. It is thus appropriate to apply an optimisation procedure to meet these requirements and achieve an optimal reduction in the needle penetration velocity at an unchanged sewing speed.

Optimisation procedure

The structure (Figure 3) and the kinematic response (Figure 4) of the link drive mechanism show potential for improvements of their performance characteristics. In the optimisation process, the link lengths should be modified with respect to the objective function and constraints, in order to achieve the optimal characteristics. A mathematical model for optimising the design of the mechanism was developed in the following form:

$$\min_{\mathbf{x} \in \mathfrak{R}^m} (\max_{t \in [0, \tau]} F(\mathbf{x}, \mathbf{z}, t)) \quad (4a)$$

subject to

$$g_i(\mathbf{x}, \mathbf{z}, t) \leq 0, \quad i = 1, \dots, n, \quad t \in [0, \tau] \quad \mathbf{z} \in \mathfrak{R}^p \quad (4b)$$

and the state equation

$$h(\mathbf{x}, \mathbf{z}, \mathbf{u}) = 0 \quad t \in [0, \tau]. \quad (4c)$$

In the statement (4a-c) $\mathbf{x} \in \mathfrak{R}^m$ is the vector of the design parameters, and $\mathbf{z} \in \mathfrak{R}^p$ is the vector of state variables that describe the system's behaviour. The objective function is $\max_{t \in [0, \tau]} (F(\mathbf{x}, \mathbf{z}, t)) \in \mathfrak{R}$,

and is dependent on the design parameters, state variables, and time. The constraints are collected in a function $g_i(\mathbf{x}, \mathbf{z}, t) \leq 0$. The state equation $h(\mathbf{x}, \mathbf{z}, \mathbf{u}) = 0$ represents the mathematical formulation of the mechanical system given by Equation (3), to be optimised. In order to apply the optimisation statement of Equations (4a-c) to the link drive mechanism, the latter will have to be redesigned.

The method of non-linear programming, typically used in the optimisation processes, is not directly applicable to this problem, unless the max-value function is removed and there is a reformulation of the problem's time dependency. An auxiliary design parameter x_{m+1} and constraint are introduced for this purpose:

$$F(\mathbf{x}, \mathbf{z}, t) - x_{m+1} \leq 0, \quad t \in [0, \tau] \quad (5)$$

and the objective function in Equation (4a) is replaced by

$$F_0 = x_{m+1}. \quad (6)$$

The authors of [14] suggested substituting Equations (4b) and (5) with equivalent integral constraints. For a continuous function $a(t)$, it is possible to replace the inequality

$$a(t) \leq 0, \quad t \in [0, \tau] \quad (7)$$

with an equivalent integral constraint:

$$\int_0^\tau \langle a(t) \rangle dt = 0, \quad (8)$$

where $\langle \cdot \rangle$ is defined by

$$\langle a \rangle = \begin{cases} a, & a \geq 0 \\ 0, & a < 0 \end{cases} \quad (9)$$

The problem with Equations (4a-c) yields the form

$$\min_{\mathbf{x} \in \mathfrak{R}^{m+1}} (x_{m+1}) \quad (10a)$$

subject to

$$F_i = \int_0^\tau \langle g_i(\mathbf{x}, \mathbf{z}, t) \rangle dt = 0 \quad i = 1 \dots n \quad (10b)$$

and

$$F_{n+1} = \int_0^\tau \langle F(\mathbf{x}, \mathbf{z}, t) - x_{m+1} \rangle dt = 0. \quad (10c)$$

The design parameters and the state variables are connected by the state equation:

$$\mathbf{u}(t) = G(\mathbf{z}(t), \mathbf{x}), \quad t \in [0, \tau]. \quad (10d)$$

Application to the link drive mechanism

In order to achieve lower penetration velocities in the observed interval of the needle path, the objective function of Equation (4a) in the optimisation process is chosen in the form:

$$f = \max |\dot{s}(\mathbf{x}, \varphi_4)| \quad \text{with}$$

$$\varphi_{4min} \leq \varphi_4 \leq \varphi_{4max} \quad \text{and} \quad \varphi_4 = \varphi_4(t). \quad (11)$$

The objective function represents the highest absolute acceleration of the needle as a function of the main shaft's rotation $\varphi_4 = \varphi_4(t)$ within the interval $\varphi_{4min} \leq \varphi_4 \leq \varphi_{4max}$ (Figure 3). This function will be minimised, since low accelerations in the interval ensure low penetration velocities. The interval is defined from the UDP of the needle to the position when the needle eye fully penetrates through the fabric. The vector of design parameters is a combination of link lengths r_2 to r_6 and the position of the fixed rotational joint of link r_2 , dx and dy , as shown in Figure 3. The vector of design parameters has the following form:

$$\mathbf{x} = [r_2, r_3, r_4, r_5, r_6, dx, dy]^T. \quad (12)$$

$$r_{i,min} \leq r_i \leq r_{i,max} \quad i = 2, 3, 4, 5, 6 \quad (13a)$$

$$dx_{min} \leq dx \leq dx_{max} \quad (13b)$$

$$dy_{min} \leq dy \leq dy_{max} \quad (13c)$$

An important restriction in the optimisation procedure requires the needle path to remain almost unchanged, regardless of any changes to the design parameters. The path of the needle is bounded with

$$s_{min} \leq s \leq s_{max}. \quad (13d)$$

The constraint of Equation (13d) is non-linear, since it is derived from the non-linear state equation (10d), which connects the sewing needle movement with the rotation of the sewing machine's main shaft through time:

$$s = s(\varphi_4, t), \quad t \in [0, \tau]. \quad (14)$$

The objective function is time-dependent, and the max-value function must be removed. An artificial design parameter x_8 is introduced to overcome these two difficulties. The transformed problem now has the following form.

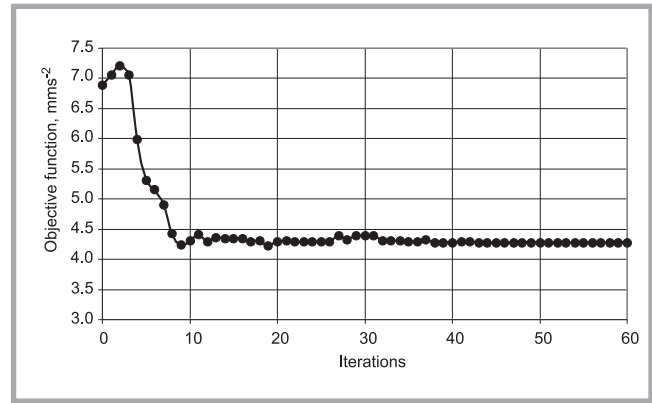
Find such a vector:

$$\mathbf{x} = [r_2, r_3, r_4, r_5, r_6, dx, dy, x_8]^T, \quad (15a)$$

to minimise

$$x_8 \in \mathfrak{R}, \quad (15b)$$

Figure 5. Optimisation history.



with respect to the constraints

$$\int_{t_{min}}^{t_{max}} |\ddot{s}(\varphi_4(t)) - x_8| dt = 0, \quad (15c)$$

$$t \in [t_{min}, t_{max}].$$

Now the optimisation problem is in a form suitable for solving. These are two non-linear constraints in the problem: the additional constraint of Equation (15c) and the constraint on the sewing needle path, Equation (13d). The state equation of the link drive mechanism, Equation (10d) is also non-linear. The non-linear nature of the optimisation problem favours the use of the SQP (Sequential Quadratic Programming) solver from the Fortran Library NAG [15], and the code E04UCF.

A numerical example

The initial values of the design parameters are those used in section 2.3: $r_2 = 22$ mm, $r_3 = 30$ mm, $r_4 = 8.5$ mm, $r_5 = 37$ mm, $r_6 = 33$ mm, $dx = 35$ mm, $dy = 2$ mm and $\varphi_{35} = 125^\circ$. The design parameters are all bounded by geometric constraints: $19 \leq r_2 \leq 24$ mm, $27 \leq r_3 \leq 32$ mm, $7 \leq r_4 \leq 10$ mm, $34 \leq r_5 \leq 39$ mm, $30 \leq r_6 \leq 35$ mm, $33 \leq dx \leq 24$ mm and $0 \leq dy \leq 4$ mm. The sewing needle path was restricted to $29.9999 \leq s \leq 30.0001$ mm. The penetration region (pr) of the needle is defined with respect to the LDP of the needle path $12 \leq pr \leq 25$ mm, and represents that part of the needle path where the needle is moving downwards to penetrate the fabric. The artificial design variable was bounded by $0 \leq x_8 \leq 10$ mms⁻². The convergence of the numerical procedure

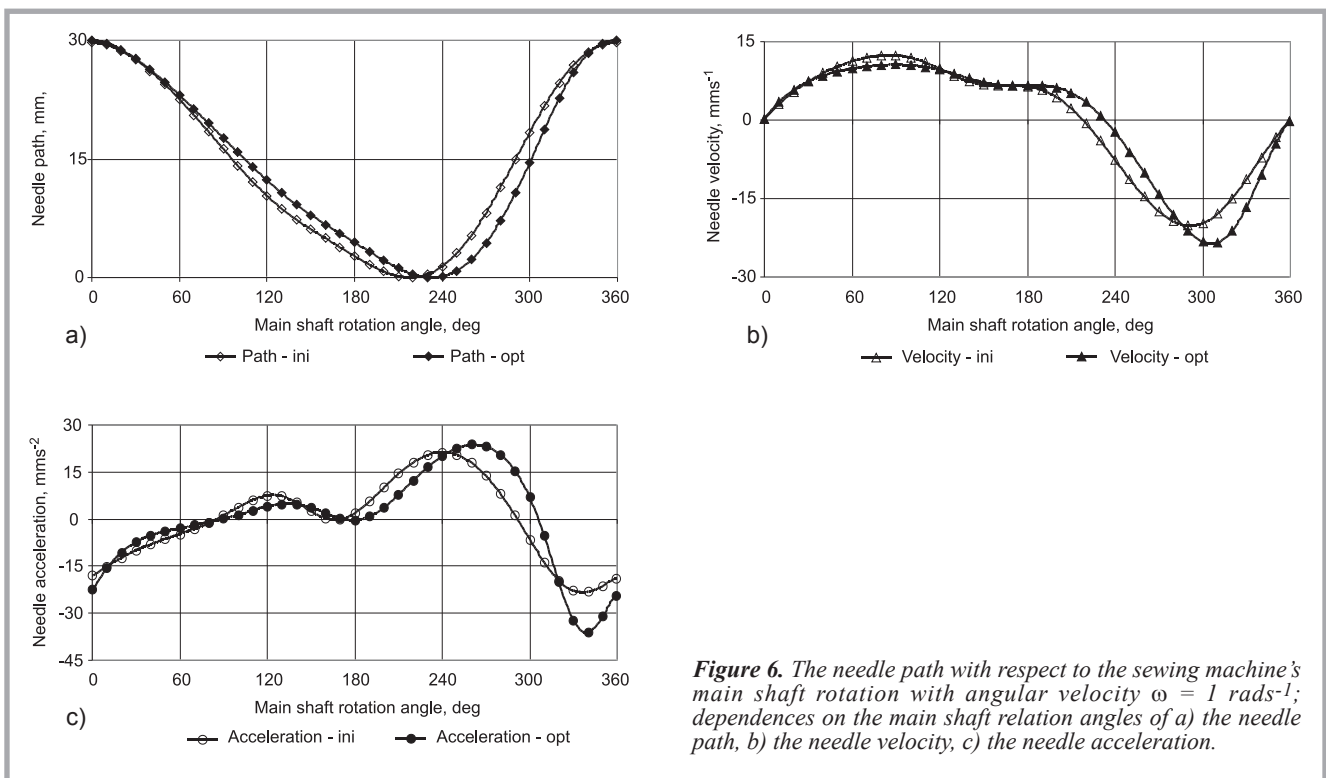


Figure 6. The needle path with respect to the sewing machine's main shaft rotation with angular velocity $\omega = 1$ rads⁻¹; dependences on the main shaft relation angles of a) the needle path, b) the needle velocity, c) the needle acceleration.

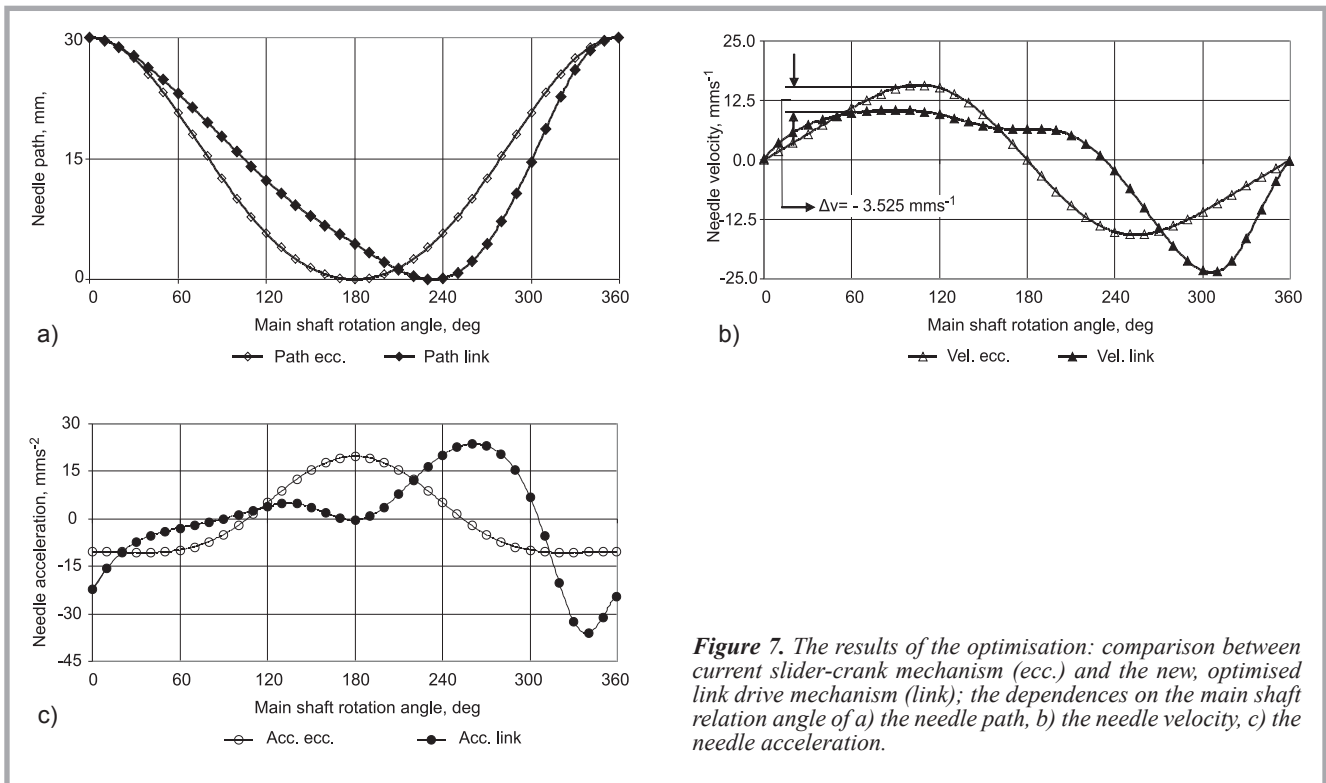


Figure 7. The results of the optimisation: comparison between current slider-crank mechanism (ecc.) and the new, optimised link drive mechanism (link); the dependences on the main shaft relation angle of a) the needle path, b) the needle velocity, c) the needle acceleration.

is presented in the optimisation history in Figure 5, where the value of the objective function with respect to the number of main process iterations of the solver are shown.

The optimal values of the design variables within the prescribed optimisation tolerance 10^{-3} were found after 60 iterations and are:

$r_2 = 19 \text{ mm}$, $r_3 = 29.3651 \text{ mm}$,
 $r_4 = 8.2679 \text{ mm}$, $r_5 = 34 \text{ mm}$,
 $r_6 = 30.4405 \text{ mm}$, $dx = 38 \text{ mm}$, and
 $dy = 4 \text{ mm}$. The results of the optimisation are shown in Figures 6.a, 6.b and 6.c (see page 67) with a comparison of the sewing needle path, the penetration velocity and the acceleration of the initial and optimised link drive mechanisms.

A comparison between the slider-crank (ecc.) mechanism currently in use, and the optimised link drive mechanism (link) is shown in Figures 7.a and 7.b, where the needle path and velocity are shown, and in Figure 7.c where the accelerations are presented.

Discussion of results

The features of the link drive mechanism outlined above allow the following observations to be made:

- When using the optimised link drive mechanism, the penetration velocity

is lower than with the standard slider-crank mechanism. The penetration velocity at a point 15 mm below the UDP on the needle path in the case of the slider-crank mechanism is $v_{ecc} = 14.054 \text{ mms}^{-1}$, while the needle velocity for the link drive mechanism at the same position is only $v_{link} = 10.527 \text{ mms}^{-1}$. The difference with respect to the slider-crank mechanism is $\Delta v = -3.527 \text{ mms}^{-1}$ or $\Delta v\% = -25.1\%$. This means that the penetration velocity when using the link drive mechanism is only 74.9% of the penetration velocity of the slider-crank mechanism. The velocities are calculated for a main shaft rotation velocity of $\omega = 1 \text{ rads}^{-1}$.

- About 25% lower needle penetration velocity is generated, and according to Equation (1) less heat, but keeping the temperature of the needle lower at the same time the sewing speed may rise.
- The path profile is non-symmetric for the link drive mechanism. The LDP of the needle shifts from 180° for the slider-crank mechanism to 233° for the link drive mechanism. The hook and the feeder must be modified when using the link drive mechanism.
- Due to the non-symmetric path profile, the needle moves from the UDP to the LDP at low velocity, followed by a much faster reverse movement upwards. This causes higher needle

accelerations, that could cause oscillations and the rough operation of the sewing machine.

Summary

This work was done in order to demonstrate the possibility of reducing the sewing needle's penetration velocity during the sewing process. A conventional slider-crank mechanism, which is used in lockstitch sewing machines, was replaced with a link drive mechanism. A non-linear optimisation procedure was used for fine adjustment of the mechanism's geometrical parameters to further reduce the needle penetration velocity. During this process, it was possible to reduce the needle velocity in the needle penetration area by around 25% in comparison to a conventional slider-crank mechanism. Such reduction in velocity results in less generated heat from friction between the needle and the fabric, and lower needle temperatures. This is important for preserving sewing thread integrity, preventing fabric damage (melting) and disturbances during the sewing process.

When using a link drive mechanism, the needle's LDP moves from 180° towards the position of 233° which requires precautions to be taken. The period of the downward needle movement is longer (low velocities), but it is followed by a

rapid upward movement (high velocities and high accelerations). Such high periodical accelerations in the sewing machine produce oscillations, which must be taken into account. Damping these oscillations will be the future interest of our research.



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For more information please contact:

**University of Bielsko-Biała,
Institute of Textile Engineering and Polymer Materials**

Willowa 2, 43-309 Bielsko-Biała, Poland
tel. (+48 33) 82 79 114, fax. (+48 33) 82 79 100

Jarosław Janicki – Chairman, e-mail: jjanicki@ath.bielsko.pl
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