Article

Modified Drive Structure of a Knitting Machine

Josef Skrivanek *, Martin Bilek and Ondrej Batka

Department of Textile Machine Design, Faculty of Mechanical Engineering, Technical University of Liberec, 461 17 Liberec, Czech Republic; martin.bilek@tul.cz (M.B.); ondrej.batka@tul.cz (O.B.)

* Correspondence: josef.skrivanek@tul.cz; Tel.: +420-48535-3764

Abstract: This paper deals with the problematic of the drive system of small-diameter knitting machines (hereinafter “knitting machines”). An alternative design of a new drive system is presented that addresses the effective working position of selected operating elements, i.e., a cylinder, a dial, and a roller cutter. The design is protected by patent No. 303578, and the authors of this paper also authored the patent. For the description and simulation of the drive system, mathematical models have been elaborated of the existing and new drive system, which include an additional design of a more suitable stroke for the movement of the cylinder. The output of the simulations are the courses of kinematic quantities, torque, and electric current, elucidating the benefits of the new drive system. Based on the structure of the new drive system, a test device has been designed and manufactured to verify functionality and reliability. The new drive system consumes less energy, simplifies the machine frame and reduces noise emissions. The obtained results can help in researching the issue of knitting machine frames, and in addition, the new system brings new technological possibilities for knitting.

Keywords: knitting machine; stroke; drive; simulation; cylinder

1. Introduction

Knitting machines are an essential part of traditional textile engineering with a rich history, though knitting technology is relatively young [1,2] compared to other areas of this industry. In addition to classic knitting technologies and their products, extensions of classic knitted fabrics with higher added value are increasingly coming to the fore [3–7].

Previously used in the drive systems of small-diameter knitting machines were mainly an asynchronous motor with short circuit “anchor” and graduated pulleys for changing speed [2]. The term “drive system” in this paper includes the motor, its control, and the transmission that propels the required elements, while the term “drive” includes only the motor and its control. After the development of semiconductor rectifiers, DC brush control motors were used relatively briefly. Today, frequency converters or control units for servo drives are used to change speeds in asynchronous motors [8,9]. In the past, the drive systems of small-diameter knitting machines contained relatively complex mechanisms with numerous mechanical transmissions installed in intricate, voluminous frames [10]. Mechanical transmissions set the limits of use of the operating elements forming the knitted fabric in terms of effective use throughout the entire work process [11]. Working elements mean the cylinder, dial plate (abbreviated as “dial”) and the roller cutter [12]. The dial in knitting practice is called a rotary element, used mainly to create an overhanging hem especially on socks, as well as to produce a solid beginning and in some types of machine also double-faced knit fabric [1]. An integral part of the dial is a roller cutter used for cutting yarn according to technological requirements. In the overhanging mode, i.e., the formation of an overhanging hem on the sock, it is essential to uphold the technological condition of mutual rotation between the cylinder and the dial [13]. This is due to the sliding out of the sinkers from the dial between the needles during rotation. The limit of
the maximum rotation is given by the sum of the maximum plays in the gearing of the drive system given by its stiffness.

Theoretically, from the technological standpoint, the dial would be synchronized with the cylinder only for two revolutions during manufacture of the sock. The first revolution would be to catch the beginning of the knitted fabric and after knitting the hem, hanging the knitted fabric back on the needles [2]. The roller cutter is not dependent in principle on the movement of the knitting roller or the dial itself, so there is no need for synchronization [1]. In the past, there were knitting machines, especially for manufacturing delicate women’s stockings, which did not include the dial. On these machines, it was possible to create an overhanging hem even on the front side [8].

The percentage of utilization of the aforementioned operating elements (cylinder, dial, and roller cutter) is significantly different during the process of creating sock goods, ranging from 5% to 100% [8]. The mentioned workload and length of the process during knitting was based on the creation of one classic sock with the top hem designed for the foot size EU 44, Figure 1. The knitting time of one sock is different and especially depends on its size, shape, material used and the variety of uses of colors and patterns required by the customer [14]. The current concepts of the drive systems do not allow flexible control of individual operating elements according to their current needs for inclusion in the technological process. This problem occurs due to the direct mechanical connection between the dial and the roller cutter; their movement is standardly derived by constant transmission by gears from the movement of the cylinder [15].

![Figure 1. Cylinder 1, roller cutter 2, dial 3 and their percentage load during the knitting process.](image)

The application of controlled drives for the individual work elements mentioned above offers the possibility of increasing the efficiency of the knitting process and the associated significant savings in electricity consumption [16]. An indisputable advantage is the reduction of demands on the installation space and the overall simplification of the machine design due to the reduction of moving elements of the drive system [17]. It is worth mentioning that the gears making up the current drive system are also a key vibration exciter and noise source, so one expected benefit of using controlled drives is the reduction of noise pollution and ensuring improvement of health conditions for machine attendants [18]. Another important criterion for assessing the suitability of employing controlled drives is the demands on the dynamic properties of the machine, as their applications can bring an improvement in their properties, thanks to the possibility of a suitable choice of lift dependence [19,20].

This paper focuses on assessment of the new drive system compared to the existing one. The new drive system will respect the targeted inclusion of the cylinder, dial, and roller cutter in the technological process. The use of controlled drives in this area appears to be a possible way of increasing the degree of technical sophistication of small-diameter knitting machines. There are a number of varying structures of the drive system of small-diameter knitting machines. One of the most commonly used methods of designing the drive system of small-diameter knitting machines is shown in Figure 2 [2]. The principle of the system is
based on the transmission of power to the cylinder (4) and to the dial (10) from the servo drive (M1) by a system of gears (1,2,3,5,6,7,8,9) and shafts (11,12,13).

![Diagram of the drive system](image)

Figure 2. Structure of the present concept of the small diameter knitting machine: (a) schematic view (b) 3D model.

The main movement of the knitting machine is performed by a brushless alternating servo drive (M₁), a pinion (1), and a toothed rim (2), which is part of the cylinder (4). The dial drive system begins by transmission from the toothed rim (2) to the gear (3). The system continues through the shaft (11) to the gearing (5 and 6). The shaft (12) is fitted with a clutch. This clutch must ensure that its original position is precisely reset after the dial arm has been tilted (10), i.e., after disconnection of the drive system. Furthermore, the system connects the gears (7,8,9 (V)) to the shaft (13) of the dial (10), which is mounted and firmly connected to the roller cutter. The gears ensure the same angular velocity of the dial (10) and the cylinder (4). The delimitation of plays between gear teeth is realized by changing the axial distance between the gears in combination with split gears [21].

2. Mathematical Models

2.1. Existing Drive System of a Small-Diameter Knitting Machine

An analysis was performed of the existing design to assess the impact of the changes to the new drive system. The results of the analysis are compared with those obtained by analyzing the modified drive system in the following chapter.

To investigate the dynamic behavior of the drive system of a small-diameter knitting machine, a discrete model was elaborated, including the torsional compliance of all main shafts and the cylinder. The actual mathematical model of the knitting machine drive system in Figure 3 was formulated while considering the following assumptions:

- Gears (0–7) and the dial (8) are considered as perfectly rigid bodies.
- Each of the shafts (R0, 23, 45, 78) is replaced in the model by two geometrically identical shapes whose moments of inertia are included in the moments of inertia of the corresponding gears. In the case of the shaft (78), the moment of inertia of its lower part is included in the moment of inertia of the dial (8). The relevant shapes are connected by non-material elastic elements with torsional stiffnesses and viscous damping elements.
- The cylinder (9) is replaced in the model by two geometrically identical shapes, whereas the moment of inertia of the lower shape is included in the moment of inertia of the cylinder (4), which is replaced in the model by two geometrically identical shapes, whereas the moment of inertia of the lower shape is included in the moment of inertia.
inertia of the gear (1). Both shapes are connected by non-material elastic elements with torsional stiffnesses and viscous damping elements.

- The moments of inertia of the needles and sinkers are included in the moment of inertia of the cylinder (9).
- The moments of inertia of the sinkers are included at the moment of inertia of the dial (8).
- In the calculation, plays in gears are considered, which are simply entered into the mathematical model using angular deflections of shafts R0, 19, 23, 45, 78; the play in the shaft bearing is not considered by the model.
- The model does not consider the bending compliance of shafts and the thermal expansion of materials.
- The model does not consider gravitational and friction forces and forces caused by the tension of the yarn.
- The model does not consider the force required for cutting the ends of the yarn.

![Diagram of existing small-diameter knitting machine drive system](image)

**Figure 3.** Existing small-diameter knitting machine drive system—(a) Mathematical model, (b) 3D model.

The required moments of inertia of the individual elements of the drive system were determined using the cad model of the drive system, see Table 1. Conversions appearing in the equations of motion are given in Table 2. The designation and position of the elements correspond to the diagram in Figure 4.

![Graph of needle cylinder position](image)

**Figure 4.** Input stroke.
Table 1. Moments of inertia of the considered parts of the drive system.

| Component          | Position | Moment of Inertia \( I \) [kg \( \cdot \) m\(^2\)] |
|--------------------|----------|-----------------------------------------------|
| gear 0             | 0        | 9.83 \times 10^{-6}                          |
| gear 1             | 1        | 2.13 \times 10^{-2}                          |
| gear 2             | 2        | 1.34 \times 10^{-3}                          |
| gear 3             | 3        | 3.07 \times 10^{-4}                          |
| gear 4             | 4        | 2.87 \times 10^{-4}                          |
| gear 5             | 5        | 1.86 \times 10^{-4}                          |
| gear 6             | 6        | 2.52 \times 10^{-4}                          |
| gear 7             | 7        | 1.49 \times 10^{-4}                          |
| dial               | 8        | 2.40 \times 10^{-4}                          |
| rotor              | R        | 8.10 \times 10^{-4}                          |
| needle roller      | 9 (V)    | 3.38 \times 10^{-2}                          |
| shaft R0           | R0       | 9.02 \times 10^{-6}                          |
| shaft 23           | 23       | 7.26 \times 10^{-5}                          |
| shaft 45           | 45       | 8.42 \times 10^{-5}                          |
| shaft 78           | 78       | 1.06 \times 10^{-5}                          |

Table 2. Gears appearing in equations of motion.

| Gearing          | 0–1 | 0–2 | 3–4 | 5–6 | 5–7 |
|------------------|-----|-----|-----|-----|-----|
| Designation      | \( \mu_{01} \) | \( \mu_{02} \) | \( \mu_{34} \) | \( \mu_{56} \) | \( \mu_{57} \) |
| Value            | 1/6 | 1/3 | 1/2 | 1   | 1   |

Lagrange equations of the second kind were used to elaborate the actual equations of motion of the discrete model of the drive system. This is among the most widely used methods of analytical mechanics, especially in more complex mechanical systems [22,23].

2.1.1. Form of the Lagrange Equation of the Second Kind

\( E_K \) is the kinetic energy of the system, \( E_P \) is the potential energy of the system, \( R_d \) is the Rayleigh dissipation function, and \( q_i \) is the generalized coordinate.

\[
\frac{d}{dt} \left( \frac{\partial E_K}{\partial q_i} \right) - \frac{\partial E_K}{\partial q_i} + \frac{\partial E_P}{\partial q_i} = - \frac{\partial R_d}{\partial q_i} \tag{1}
\]

for: \( i = 1, 2, \ldots, n \).

Matlab R2022a software and its Simulink module were used to solve the system of equations of motion. The individual equations were written in matrix form (1) and then solved by gradual integration in the Simulink environment, see Figure 4.

\[
[I] \cdot \{\ddot{q}\} + [B] \cdot \{\dot{q}\} + [K] \cdot \{q\} = 0 \tag{2}
\]

2.1.2. Listing of Matrices Used in the Equation (2)

Moment of Inertia Matrix I

\[
\begin{bmatrix}
I_0 + I_1 \cdot \mu_{01}^2 + I_2 \cdot \mu_{02}^2 & 0 & 0 & 0 & 0 \\
0 & I_9 & 0 & 0 & 0 \\
0 & 0 & I_3 + I_4 \cdot \mu_{34}^2 & 0 & 0 \\
0 & 0 & 0 & I_5 + I_6 \cdot \mu_{56}^2 + I_7 \cdot \mu_{57}^2 & 0 \\
0 & 0 & 0 & 0 & I_8
\end{bmatrix}
\]
Damping Matrix B

\[
B = \begin{bmatrix}
    b_{R0} + b_{19} \cdot \mu_0^2 + b_{23} \cdot \mu_0^2 & -b_{19} \cdot \mu_0 & -b_{23} \cdot \mu_0 & 0 & 0 \\
    -b_{19} \cdot \mu_0 & 0 & 0 & 0 & 0 \\
    -b_{23} \cdot \mu_0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

Stiffness Matrix K

\[
K = \begin{bmatrix}
    k_{R0} + k_{19} \cdot \mu_0^2 + k_{23} \cdot \mu_0^2 & -k_{19} \cdot \mu_0 & -k_{23} \cdot \mu_0 & 0 & 0 \\
    -k_{19} \cdot \mu_0 & 0 & 0 & 0 & 0 \\
    -k_{23} \cdot \mu_0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

Listing of vectors of generalized coordinates \( q \) and their derivatives

\[
q = \begin{bmatrix}
    \phi_0 \\
    \phi_9 \\
    \phi_3 \\
    \phi_5 \\
    \phi_8
\end{bmatrix}, \quad \dot{q} = \begin{bmatrix}
    \dot{\phi}_0 \\
    \dot{\phi}_9 \\
    \dot{\phi}_3 \\
    \dot{\phi}_5 \\
    \dot{\phi}_8
\end{bmatrix}, \quad \ddot{q} = \begin{bmatrix}
    \ddot{\phi}_0 \\
    \ddot{\phi}_9 \\
    \ddot{\phi}_3 \\
    \ddot{\phi}_5 \\
    \ddot{\phi}_8
\end{bmatrix}
\]

where \( I \) is the moments of inertia matrix, \( B \) is the damping matrix, \( K \) is the stiffness matrix, and \( q \) is the rotation vector of the selected elements of the drive system. The coefficients of torsional stiffness \( k \), viscous damping \( b \) of the selected elements of the drive system were taken from a study [24]. Furthermore, in the equations of motion, conversions \( \mu \) appear between the individual stages of the drive system. In the mathematical model of the drive system, the toothing plays are respected. These plays were included in the drive system using the conditions specified in the study, which replace the actual plays with angular deflections [25].

For Ange series knitting machines, a lift dependence is often used containing a polynomial of the 3rd degree describing the desired position of the cylinder in the start-up and run-out areas of the drive system. Linear sections appear in the lift dependence in which a constant velocity of the cylinder is required. The position of the cylinder is a function of a virtual cam corresponding to one of its revolutions, during which the cylinder performs a symmetrical reciprocating rotational movement between two dead centers from the start position to the end position in the range of \( 0-\frac{3}{4} \pi \), see Figure 4 [26].

Through the use of the elaborated solver [27] (see Figure 5) of differential equations, the gained motion Equation (2) was solved [28], and responses were observed in the relationship between the drive system and the kinematic excitation of the system, which was the desired course of acceleration of the drive system drive element during reverse motion. The reverse motion mode was selected for analysis due to the highest degree of dynamic loading of the entire knitting machine [24].

The output of the analysis are the courses of kinematic quantities of individual elements of the drive system (see Figures 6–8), the designation of the elements corresponds to the diagram in Figure 3. The achieved angular velocity of the 16.8 rad⋅s\(^{-1}\) cylinder technologically corresponds to the highest recommended operating velocity of the Ange series small-diameter knitting machine in the reverse motion of the drive system using standard materials for production of sock goods [2].
The results of the analysis point to the theoretical influence of plays in the system of the knitting machine drive. These cause shock forces during their delimitation; this phenomenon can be clearly observed during the acceleration of the system in the form of maximum oscillation values (see Figure 8). Similarly, although not so significantly, delimitation of plays appears in the course of angular velocities of Figure 7, and there are evident oscillations, especially in the areas of motion dead points. In addition to play, these oscillations are also influenced by dynamic system parameters. Some of the curves overlap in the courses, and this phenomenon is particularly evident in the course of the position.
2.2. Modified Drive System of a Small-Diameter Knitting Machine

The newly designed structure (see Figure 9a) is protected by a patent [17]. The structure removes the part of the existing drive system that sets the dial with roller cutter in motion and further extends the basic driving unit (P₁) by two additional controlled drives (P₂) and (P₃) for individual control of the dial (10) and the roller cutter (11). The functional model of the roller cutter drive system comprises a friction transmission mechanism in which the power transfer between the drive (P₃) and the roller cutter is performed by a flexible shaft (13) fitted with a drive wheel (12).

The gearbox containing the gearing (0–1) and the drive (P₁) were taken from the existing machine structure to control the cylinder (9 (V)). In reverse motion of the modified drive system, only the cylinder is driven. This fact corresponds to the elaborated mathematical model of the part of the modified drive system in which only the cylinder is driven, see Figure 9b. The dynamic analysis of this part of the modified drive system was carried out in a similar way, considering the same assumptions and using the same solver of differential equations as the dynamic analysis of the existing structure of the drive system (Section 3), see the following list of matrices.

Matrices moment of inertia $I$, damping $B$ and stiffness $K$

$$I = \begin{bmatrix} I₀ + I₁ \cdot μ₀₁² & 0 \\ 0 & I₉ \end{bmatrix}, \quad B = \begin{bmatrix} b₀₀ + b₁₀ \cdot μ²₀₁ & -b₁₀ \cdot μ₀₁ \\ -b₁₀ \cdot μ₀₁ & b₁₀ \end{bmatrix}, \quad K = \begin{bmatrix} k₀₀ + k₁₀ \cdot μ²₀₁ & -k₁₀ \cdot μ₀₁ \\ -k₁₀ \cdot μ₀₁ & k₁₀ \end{bmatrix}$$
The modified drive system is conceptually divided into three independent subsystems, each of which has its own drive (P₁, P₂, and P₃). Individual subsystems are placed in service with different requirements for the prescription of movement depending on the technology being implemented. For this reason, individual theoretical movement cycles have been introduced for the cylinder, the machine and the roller cutter.

Based on the previous analysis of the existing drive system, a lift dependence was proposed containing a polynomial of the 7th degree for the system start-up and run-out areas, see Equations (3)–(5). The chosen polynomial degree appears to be a suitable means to suppress shocks in the drive system, to achieve more favorable courses of kinematic quantities, and it is also assumed that the drive is more capable of maintaining the required course.

\[
\varphi(\psi) = C_0 + C_1 \cdot \psi + C_2 \cdot \psi^2 + C_3 \cdot \psi^3 + C_4 \cdot \psi^4 + C_5 \cdot \psi^5 + C_6 \cdot \psi^6 + C_7 \cdot \psi^7
\]

\[
\dot{\varphi}(\psi) = C_1 \cdot \psi + 2C_2 \cdot \psi \cdot \dot{\psi} + 3C_3 \cdot \dot{\psi} \cdot \psi^2 + 4C_4 \cdot \dot{\psi} \cdot \psi^3 + 5C_5 \cdot \dot{\psi} \cdot \psi^4 + 6C_6 \cdot \dot{\psi} \cdot \psi^5 + 7C_7 \cdot \dot{\psi} \cdot \psi^6
\]

\[
\ddot{\varphi}(\psi) = 2C_2 \cdot \dot{\psi}^2 + 6C_3 \cdot \dot{\psi} \cdot \ddot{\psi} + 12C_4 \cdot \ddot{\psi} \cdot \dot{\psi}^2 + 20C_5 \cdot \ddot{\psi} \cdot \dot{\psi}^3 + 30C_6 \cdot \ddot{\psi} \cdot \dot{\psi}^4 + 42C_7 \cdot \ddot{\psi} \cdot \dot{\psi}^5
\]

Figures 10–12 show the courses of the position, angular velocity and angular acceleration of the elements of the modified drive system. The dial with roller cutter and their corresponding part of the drive system are no longer in the dynamic analysis of the drive reverse motion mode, so the results do not indicate their corresponding courses. By using a polynomial of the 7th degree in the stroke, the course of kinematic quantities was smoothed. This benefit contributed to a significant reduction of the oscillation amplitudes of the modified drive structure compared to the existing structure in which a polynomial of the 3rd degree was used. This decrease is best apparent on the courses of angular velocity and angular acceleration, see details in Figures 11 and 12, in these courses there was a significant reduction of oscillations, especially in transition areas.

Figure 10. Courses of positions of individual drive system elements.

The working speed is intended for classic materials of sock goods (Cotton, Lycra, Polypropylene, Moira and others). The knitting machine would be able to work at higher speeds and therefore it would be possible to achieve higher productivity, but the classic sock materials set a limit in the form of yarn strength [1].
2.3. Modified Drive System of a Small-Diameter Knitting Machine

A reduction in the number of elements in the modified drive system caused a decrease in the moment of inertia and plays, which then led to a noticeable suppression of transient oscillating phenomena resulting from delimitation of plays. Differences between drive systems are particularly pronounced in angular acceleration courses. The maximum values during acceleration decreased significantly by up to 51%, and proportionally thereby the dynamic forces generated in the drive system as well. By increasing the degree of the polynomial in the lift dependence, we achieved more favorable courses of kinematic quantities of the drive system elements, as well as enhanced the ability of the drive to maintain the desired value.

The aforementioned adjustments appeared in more favorable courses of theoretical torques and theoretical electricity consumption of the modified drive system in comparison with the existing system, see Figures 13 and 14, using different lift dependences. The decrease in total electricity consumption reached 10%. 

![Figure 11. Courses of angular velocities of individual drive system elements.](image1)

![Figure 12. Courses of angular accelerations of individual drive system elements.](image2)

![Figure 13. Course of torques during one period of reverse motion of the P1 drive of the investigated systems, application of polynomials of the 3rd and 7th degree in the lift dependences describing the position of the cylinder.](image3)
Figure 14. Course of power inputs during one period of reverse motion of the $P_1$ drive of the investigated systems, application of polynomials of the 3rd and 7th degree in the lift dependences describing the position of the cylinder.

3. Experimental Verification of the Drive System

For testing purposes and verification of the modified drive system of the small diameter knitting machine, a mechatronic test dial was assembled, see Figure 15, on which the previously acquired knowledge was applied. The test equipment is primarily adapted to verify the applicability of the modified system, i.e., to simulate the overhanging mode with emphasis on meeting the requirement for the maximum position deviation between the rotation of the cylinder and dial, and for application of lift dependences to the cylinder drive. The issue of cylinder and dial deviation with the replacement of mechanical bond by electronics was addressed in the study [26]. The test equipment contains no transmissions compared to the real machine. To capture the transmission between the cylinder and its motor, the flywheel 1 representing the cylinder rotates at a six-fold angular speed. Flywheel 2 represents the machine. Using the law of conservation of (kinetic) energy, we determined their reduced moments of inertia [29]. Flywheel 1 has two geometric designs. In the case of the existing drive system, the moment of inertia is $5.09 \times 10^{-4}$ kg·m², and in the case of the modified drive system, it is $4.15 \times 10^{-4}$ kg·m². The flywheels are mounted on the output shafts of servo drives 3 and 4, which are mounted to the frame 5. Type of servo motors used CTM4-07 (Control Techniques). Another part of the measuring dial were frequency converters 6, 7 UNI1405 (Control Techniques) and a computer 8 with the corresponding control system of the MotionPerfect V4 Program, Control Techniques software, Stafford Park 4, United Kingdom, distributor for the Czech Republic Control Techniques Brno s.r.o.

Figure 15. (a) Apparatus used during measurement-measuring workplace (b) CAD model of the test equipment of the modified knitting machine drive system.
The structure of the control and simultaneously measuring system is composed of two complementary parts. The lower control level contains the basic settings of motion feedback control parameters using CTSoft software. These low-level settings allow the user to control strokes, properties and speed feedback loops and current controller parameters, but are not able to ensure the generation of more complex trajectories. For that reason, the higher program platform was created for the Motion Processor Plus module using the SyPPTPro (System programming toolkit for drive automation systems) development environment. The APC (Advanced Position Controller) programming tool was used to create user programs. A complex control program was created implementing the synchronization of servo drives, automated parameter setting, measuring and recording system, and the desired position generator. The basis for obtaining information for both used servo drives (CTM4-07, Control Techniques, Stafford Park 4, Telford, UK, distributor for the Czech Republic Control Techniques Brno s.r.o.) is their own integrated sin-cos encoder, the output of which is information about the position of the shaft depending on the position of the virtual cam. The sin-cos encoder has a 32-bit resolution.

A sampling step of one tenth of an angular degree was chosen as a compromise solution. One revolution of the virtual cam was thus sampled into 3600 discrete values. Programs created in the APC requiring the sampling period to be set to 500 µs so that the control unit is able to properly complete all operations related to the main control loop period with generator, synchronization, measurement and data storage. The sampling frequency during the measurement was therefore corresponding to 2 kHz or 0.5 kHz. For individual measurements, the length of the measured section was chosen for 5000 samples, which corresponds to 2.5 s or 10 s in the time domain at the given sampling frequency. The measured data was stored in the integrated memory of the module and after stopping the run, it was downloaded separately via a serial communication channel to the PC, where it was interpreted using the mathematical programming tool Matlab. In the program created in the APC interface, the only controlled quantity is the position, which is also given by the feedback.

The movement mode of reverse motion of the machine was investigated on the test equipment. During reverse motion measurement, two flywheels differing in mass were applied, which simulated the existing and modified system, as well as two different lift dependences. Measurements were used to verify the findings of previous analyses, which confirm that a reduction in the moment of inertia of the modified roller drive system in combination with an appropriate lift dependence can pave the way for a reduction in the maximum acceleration at the limits of movement intervals during reverse motion of the drive system. These changes resulted in a 38% decrease in the maximum value of position deviation (see Figure 16) and in a 31% decrease in the value of active current (see Figure 17). The biggest differences were observed in the area of transitions at the limits of movement intervals, especially when changing the sense of rotation. Kinematic values were obtained from the data of the connected sin-cos encoder.

Figure 18 shows the courses of the position deviation in the standard velocity range during steady cylinder running conditions. The velocity range (160–200 min⁻¹) recommended by the manufacturer [21] is used during the knitting of the tubular part of the sock, depending on the type of material used. When operating the drive in the specified velocity range, it can be concluded that the value of deviations depending on RPMs is negligible. In a real knitting machine, a transmission is installed due to the technological and dynamic parameters of the cylinder drive system, therefore the resulting value is usually extended by the value of the play in the transmission. This play may reflect in the position control accuracy of the cylinder. The possibility of eliminating this play to achieve higher accuracy can be achieved, for example, by direct control of the position of the cylinder using appropriate position sensors, or by using a gearbox without play. It can be assumed that the obtained measurement results, in particular the deviations of the position between
the cylinder and the dial, will also correspond to the real modified drive system using optimal drives, their control and adjustment.

![Position deviation graph](image1)

**Figure 16.** Courses of needle cylinder position deviations, during reverse motion, in all designs at a velocity of 160 min\(^{-1}\).

![Current graph](image2)

**Figure 17.** Course of current in drive M1, during reverse motion, in all designs at a velocity of 160 min\(^{-1}\).

![Position deviation graph](image3)

**Figure 18.** Courses of needle cylinder and dial position deviations after stabilization of their movement, for velocities of 160–200 min\(^{-1}\).

4. Verification of the Implementation of the Individual Roller Cutter Drive System into the Existing Structure

Figure 19 shows the implementation of a functional model of an individual roller cutter drive system into the existing installation of a small-diameter knitting machine. The CAD model is comprised of several subgroups and was created in the software Creo parametric 7.0.1.0. The first structural unit is a modified dial 1 serving as a bearing for the
roller cutter 2. Another subgroup is formed of the pinion 3 fitted with a rubber ring in the
circumferential groove and its installation in the bearing 4 built into the defined machine
space. The roller cutter and the pinion form the whole of the friction transmission. The last
part is the pinion drive, which is implemented by means of a stepping motor 5 and flexible
shaft 6. A flexible type of shaft was used due to the position of the motor outside the lift
arm 7 on the joint. This solution led to preventing an increase in arm weight, which would
mean a reduction in ergonomic comfort for the machine attendant.

![Figure 19. CAD-model of the installation of a functional model of the individual roller cutter drive system into the Ange 18.1 small diameter knitting machine.](image)

The pinion placement allows vertical movement of the fork, which is influenced by
the pressure of the spring 8. This design variant has been designed for two reasons. The
first ensures the regulation of the normal force by pre-stressing the spring and its optimum
setting, so as to avoid pinion slipping or unnecessary overload. The second reason is the
function of creating a flexible element compensating for manufacturing inaccuracies, in
particular the flatness of the contact surfaces of the roller cutter and the pinion.

Figure 20a shows the installation of an individual roller cutter drive system on a
real machine. A small-diameter knitting machine Ange 18.1 (Uniplet Trebic a.s., Czech
Republic) was selected for positioning the drive system; its drive structure corresponds
to the diagram in Figure 2, Section 1. The Ange knitting machine is designed for knitting
classic and sports socks. It is a single cylinder fully electronic knitting machine with several
knitting systems. The option of one or several additional auxiliary knitting systems for
the production of sock classic or plush goods. Pattern production is possible in all parts of
the knit and the machine includes a device for knitting wrapped elastomer. The machine
includes electronically controlled retraction locks with electronically selected heel and toe.
The lever selection of needles for patterning is controlled electromagnetically.

The installation of the main part of the system (see Figure 20b) consisted of fitting a
part of the dial 1 with a modified supporting flange 2 and a lower pan to form a bearing
for the roller cutter 3. The test cutter had the same internal and external diameter and
thickness defining its functional surfaces for proper placement in the bearing in the dial as
a real roller cutter. Figure 20c shows a detailed view of the drive 4 and its used accessories
needed to connect the flexible shaft 5.
The aim of the measurement was to verify the function of the designed individual drive system of the roller cutter at maximum velocity and the suitability of the drive used. The 103H7123-1710 stepping motor (Sanyo Denki, Tokyo, Japan) was selected to drive the cutter due to the assumption of power sufficiency and good speed control. The motor was controlled using the stepping motor drive box NDC69A (R.T.A., Düsseldorf, Germany), which is equipped with a built-in oscillator. It therefore does not require an external clock signal to determine the velocity for the constant velocity running function. The drive can then only be controlled with a start/stop signal. The driver furthermore provides start-up functions, and the drive current can also be adjusted. Another function is the automatic reduction of the drive current when stopping.

The time course of the voltage from the sidewall was recorded by the measuring control panel (HBM) and converted to the current value, see Figure 21. The outputs from the measurement of electrical values of the individual roller cutter drive system are presented in Table 3. Practical verification of the aforementioned design solution revealed that the roller cutter can move independently within the range of normal working velocities (0–320 min⁻¹) of the considered knitting machine independently of the cylinder and the dial.

![Figure 20. Installation of the individual roller cutter drive system into the Ange 18.1 small diameter knitting machine and detailed display of the basic nodes of the individual roller cutter drive system.](image)

**Figure 20.** Installation of the individual roller cutter drive system into the Ange 18.1 small diameter knitting machine and detailed display of the basic nodes of the individual roller cutter drive system.

![Figure 21. Current course measurement.](image)

**Figure 21.** Current course measurement.
Table 3. Outputs from the measurement of the individual cutting disc drive system.

| Parameter                                | Designation | 0–2   | 3–4   |
|------------------------------------------|-------------|-------|-------|
| Driver supply voltage at rest Value      | $U_{\text{no}}$ | 42.1 V | V     |
| Driver supply voltage-during running     | $U_n$       | 40.7 V | V     |
| Driver current consumption-off running  | $I_{\text{no}}$ | 125 mA | mA    |
| Driver current consumption-during running| $I_n$       | 594 mA | mA    |
| Power input-off running                  | $P_{\text{no}}$ | 5.2 W  | W     |
| Power input-during running               | $P_n$       | 24.1 W | W     |

5. Conclusions

In the context of the production of classic stocking and sock goods, knitting is divided in practice into two modes. The first involves knitting the heel or toe of the sock, and the second generally involves making tubular knitted fabric. The first mode was subjected to a dynamic analysis, as the system performs rotational reverse motion within the range of the cylinder movement $0-3/4 \pi$. This movement method of the drive system is classified as the dynamically least favorable load case of the entire machine. For a better understanding of the dynamic behavior of the drive system in reverse motion, two mathematical models have been elaborated for the existing and for the (patented) modified structure that now includes use of controlled drives. Mathematical models were created in the Matlab-Simulink programming environment. The findings of the performed dynamic analysis of the existing drive structure indicate (a) a significant influence of plays, whereas shocks occur upon their delimitation, and (b) the accompanying influence of the moment of inertia.

As a rule, a linear acceleration course cannot be achieved in the true configuration of the drive system, especially in transition areas of movement intervals due to sudden changes occurring in these areas. In the modified structure of the drive system, a reduction was achieved in the moment of inertia and the targeted use of the cylinder, dial and roller cutter according to the technological process. These adjustments appeared in more favorable courses of torques and power consumption of the modified drive system in comparison with the existing system while using more suitable lift dependences.

The use of fewer elements in the modified drive system achieved a significant suppression of the impact of plays and a decrease in dynamic effects adversely affecting not only this system, but also the entire machine and the technology performed. Another monitored parameter was the load on the drives in the individual phases of system movement and determination of the courses of their power inputs, especially in the area of rotational reverse motion. Here, the reduction of moment of inertia in the modified drive system was most evident, which significantly affected the decrease in electricity consumption during the start-up and run-out of the drive system. There was a 10% decrease in total electricity consumption in the creation of one sock in the modified drive system compared to the current one. The value of real electricity consumption will be higher due to the exclusion of certain effects; see Section 2.

In the past, the design of an individual dial drive system has been addressed by various studies, but its movement was always tied to the movement of the roller cutter, which still did not provide efficient use of the drive system of small-diameter knitting machines. For this reason, a design has been elaborated of an individual drive system of the roller cutter. The design was conceived in such a way as to influence the other construction nodes of the knitting machine as little as possible with respect to the existing installation possibilities. The result of the design is a drive system structure capable of independently driving the roller cutter and can be used modularly with possible structural modifications on the existing knitting machines of the analyzed type. Changing the structure of the drive brings the possibility of simplifying the overall concept of the knitting machine. With a reduction of rotating elements, especially gears—which generate noise, vibrations, and reduce the efficiency of power transmission from the drive to the main individual operating elements (dial, roller cutter and needle cylinder) and increase the demands on installation space and maintenance of the machine—the possibility of a conceptually completely different
machine is offered. In light of the obtained results, the new concept of the knitting machine would bring, above all, a more energy-saving solution with a lower noise level on operators. Another benefit can be gained in the individual and programmable control of the mentioned operating elements and the expansion of technological possibilities in terms of production knitted products.

**Author Contributions:** Conceptualization, J.S. and M.B.; methodology, J.S.; software, J.S. and M.B.; validation, M.B.; formal analysis, J.S. and M.B.; investigation, J.S. and M.B.; resources, O.B. data curation, M.B. and O.B.; writing—original draft preparation, J.S.; writing—review and editing, J.S.; visualization, M.B.; supervision, O.B.; project administration, J.S.; funding acquisition, J.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Student Grant Competition of the Technical University of Liberec under the project No. SGS-2022-5046 and the Institutional Endowment for the Long Term Conceptual Development of Research Institutes, as provided by the Ministry of Education, Youth and Sports of the Czech Republic.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data presented in this study is available on request from the corresponding author.

**Conflicts of Interest:** The authors declare no conflict of interest concerning the research, authorship and publication of this article.

**References**

1. Kopal, J. *Knitting, Stitch-Knitting and Stranding 1*, 1st ed.; Technical University of Liberec: Liberec, Czech Republic, 2006; ISBN 80-7372-119-8.
2. Kopal, J. *Knitting, Stitch-Knitting and Stranding 2*, 1st ed.; Technical University of Liberec: Liberec, Czech Republic, 2007; ISBN 978-80-7372-246-3.
3. Abbas, A.; Asim, A.; Zahid, A.; Anas, S.; Basra, S.A.; Azam, Z. Development of Knitted Reinforced Structures with Self-Diagnostic Function for Composite Applications. *J. Ind. Text.* 2022, 51, 1528037221098438. [CrossRef]
4. Ertekin, G. Analysis of Thermo-Physiological Comfort and Moisture Management Properties of Flat Knitted Spacer Fabrics. *Tekst. Konfekcija* 2017, 27, 241–250.
5. Ogłackioglu, N. Design of Functional Knitted Fabrics for Medical Corsets with High Clothing Comfort Characteristics. *J. Ind. Text.* 2016, 45, 1009–1025. [CrossRef]
6. Supuren, G.; Ogłackioglu, N.; Ozdıl, N.; Marmarali, A. Moisture Management and Thermal Absorptivity Properties of Double-Face Knitted Fabrics. *Text. Res. J.* 2011, 81, 1320–1330. [CrossRef]
7. Zhou, L.; Feng, X.; Du, Y.; Li, Y. Characterization of Liquid Moisture Transport Performance of Wool Knitted Fabrics. *Text. Res. J.* 2007, 77, 951–956. [CrossRef]
8. Spencer, D.J. 12-Electronics in Knitting. In *Knitting Technology*, 3rd ed.; Spencer, D.J., Ed.; Woodhead Publishing Series in Textiles; Woodhead Publishing: Sawston, UK, 2001; pp. 134–144, ISBN 978-1-85573-333-6.
9. Jindal, H.; Kaur, S. Robotics and Automation in Textile Industry. *Int. J. Sci. Res. Sci. Eng. Technol.* 2021, 8, 40–45. [CrossRef]
10. Skřivánek, J.; Bilek, M. Dynamics of the Frame of Small-Diameter Knitting Machine. Dynamika ramy malośrednicowej maszyny dziewiarskiej. *ACC J.* 2010, 14, 1–7.
11. Goch, G. Gear Metrology. *CIRP Ann.-Manuf. Technol.* 2003, 52, 659–695. [CrossRef]
12. Ray, S.C. 7-Circular Weft Knitting Machine and Mechanism. In *Fundamentals and Advances in Knitting Technology*; Ray, S.C., Ed.; Woodhead Publishing: Delhi, India, 2012; pp. 69–85, ISBN 978-0-85709-108-6.
13. Power, E.J. Chapter 12-Yarn to Fabric: Knitting. In *Textiles and Fashion*; Sinclair, R., Ed.; Woodhead Publishing Series in Textiles; Woodhead Publishing: Sawston, UK, 2015; pp. 289–305, ISBN 978-1-84569-931-4.
14. Lucia, T. *Consigliia: A Complete Guide to Machine Knitting*; Hoakibooks S.L.: Barcelona, Spain, 2021; ISBN 84-17412-86-7.
15. Subhankar, M.; Sohel, R.; Pintu, P.; Kunal, S. *Advanced Knitting Technology* Libristo-Czech Republic; Elsevier Books: Amsterdam, The Netherlands, 2021; ISBN 978-0-323-85534-1.
16. Paprocki, M.; Erwirski, K. Synchronization of Electrical Drives via EtherCAT Fieldbus Communication Modules. *Energies* 2022, 15, 604. [CrossRef]
17. BILEK, M.; Škřivánek, J.; Kopal, J.; Váša, P. *Okrouhlý Pletací Stroj, No. 303578*; Czech Patent Office: Prague, Czech Republic, 2012.
18. Zaw, A.K.; Myat, A.M.; Thandar, M.; Htun, Y.M.; Aung, T.H.; Tun, K.M.; Han, Z.M. Assessment of Noise Exposure and Hearing Loss Among Workers in Textile Mill (Thamine), Myanmar: A Cross-Sectional Study. *Saf. Health Work.* 2020, 11, 199–206. [CrossRef]
19. Dini, P.; Saponara, S. Design of an Observer-Based Architecture and Non-Linear Control Algorithm for Cogging Torque Reduction in Synchronous Motors. *Energies* 2020, 13, 2077. [CrossRef]

20. Zheng, B.; Jiang, G.; Dong, Z.; Liu, H. Design of Warp Knitting Electronic Shogging System Based on Mixed-Velocity Planning Curve. *Text. Res. J.* 2021, 91, 1594–1608. [CrossRef]

21. Intellectual Property of Uniplet Trebič a.s. *Technical Documentation of the Small-Diameter Knitting Machine Series Ange 18.1;* Intellectual Property of Uniplet Trebič a.s.: Trebič, Czech Republic, 2014.

22. Negrean, I.; Crişan, A.-V.; Vlase, S. A New Approach in Analytical Dynamics of Mechanical Systems. *Symmetry* 2020, 12, 95. [CrossRef]

23. Negrean, I.; Crişan, A.; Ţerdean, F.; Vlase, S. New Formulations on Kinetic Energy and Acceleration Energies in Applied Mechanics of Systems. *Symmetry* 2022, 14, 896. [CrossRef]

24. Skřivánek, J.; Bílek, M. Analysis of Dynamic Model of the Drive of Small Diameter Knitting Machines Ange 18.1. Analiza modelu dynamicznego napędu małośrednicowej maszyny dziewiarskiej Ange 18.1. *ACC J.* 2011, 15, 1–8.

25. Mrázek, J. Theoretical Analysis of Dynamics of Four-Bar Beat-up Mechanism of a Loom. *Mech. Mach. Theory* 1992, 27, 331–341. [CrossRef]

26. Skřivánek, J.; Bílek, M.; Kašpárek, M. Control Optimisation of the New Drive of Small Diameter Knitting Machines. *Autex Res. J.* 2016, 17, 1–5. [CrossRef]

27. Alam, S.N.; Islam, S.; Patel, S.K. *Advanced Guide to MATLAB: Practical Examples in Science and Engineering;* IK International Publishing House Pvt. Ltd.: Delhi, India, 2015; ISBN 978-93-84588-35-9.

28. Hairer, E.; Nørsett, S.; Wanner, G. *Solving Ordinary Differential Equations I, Nonstiff Problems;* Springer: Berlin, Germany, 1993; ISBN 978-3-540-56670-0.

29. Rotational Kinetic Energy—An Overview! ScienceDirect Topics. Available online: https://www.sciencedirect.com/topics/engineering/rotational-kinetic-energy (accessed on 3 June 2022).