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Short Communication

Dynamic analysis of a warp-knitting machine with pneumatic drive for producing 3D knitted fabrics

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The paper reports the construction of a warp-knitting machine for spatial knitted fabrics and a dynamic model of its basic working unit – the arrangement of a whip roller and a slider with a guide needle bar. The concept of the machine is based on a positive feeding of the knitting zone, with a little correction from the warp tension, and a rectilinear movement of the guide needle bars by using pneumatic drive. The paper also presents the results of dynamic analysis of the system movement. The influence of the dynamic parameters of the whip roller on the possibility of executing a work cycle with a certain efficiency has been determined. Dynamic load of the warp thread during the cycle is also tested. For the analyzed structure of the machine it has been established that the duration of a single cycle cannot be shorter than 0.2 s.

Keywords: Dynamic model, Pneumatic cylinder, Spatial (3D) knitted fabric, Warp beam, Warp knitting machine, Whip roller

Simulation tests of the constructed machine, which is to realize the technological process were a part of research work on the concept[1] of producing knitted spatial (3D) fabrics.

The construction of the main zone of the warp-knitting machine for feeding and creating a solid filling of the knitted fabric is shown in Fig. 1(a). In this construction, the new concept, comparing to conventional warp-knitting machines, is the use of two guide needle bars, leading the warp of the inner layer (filling), which are moving in two mutually perpendicular directions.

This reciprocating movement of the guide needle bar, which is connected to the slider **1**, is implemented by means of a pneumatic cylinder **5**. The movement cycle of the slider involves technological shut-downs in its extreme positions[2-4]. They are necessary to form loops on the needles. It is assumed that they cannot be shorter than 0.05 s (ref. 4).

Due to its properties, the 3D knitting zone requires feeding with a relatively large amount of the filling warp [2]. Therefore, the feeding method is a crucial issue during the analysis of the operation of this warp-knitting machine.

The simplest way of feeding is supplying the warp with quasi constant linear speed. This speed can be adjusted by warp tension as a feedback[3]. The parameter used for monitoring warp tension can be medium deflection of the whip roller in a number of cycles.

The whip roller **3** is a sensitive element of a certain stiffness, attenuating the momentary changes of the warp tension during the cycle[5]. At low values of initial warp tension, momentary failures of tension may take place during the cycle. This is due to the dynamics of the whip roller and, in particular, the influence of its own frequency[6]. The consequence is irregular movement of the slider with the needle bars of the warp-knitting machine **1** and tearing of the warp **4**. On the other hand, large tension of the warp leads to excessive load on the slider, counteracting its movement. Hence, there is need for dynamic analysis of the slider system with variable parameters of the whip roller. The change of the whip roller stiffness and the regulation of the initial warp tension by the whip roller are easy to introduce in the machine itself.

The aim of the analysis is to determine the feasibility of the process of manufacturing 3D *knitted fabrics* under various productivities of the machine and under the assumed dynamic conditions.

Simulation Model

Distribution of forces affecting the slider and the whip roller is presented in Fig. 1(b). The forces acting on the slider are determined according to the following relationship:

$$(m_s + m_w)\ddot{x} + F_t + S_3 + S_2 \cos\delta = F(t) \qquad \text{... (1)}$$

where m_s, m_w are the masses of the slider and the movable element of the cylinder (piston rod); F_t, the friction force of the slider on the guide rail; S_1, S_2, S_3, the forces in the warp; and F, the driving force,

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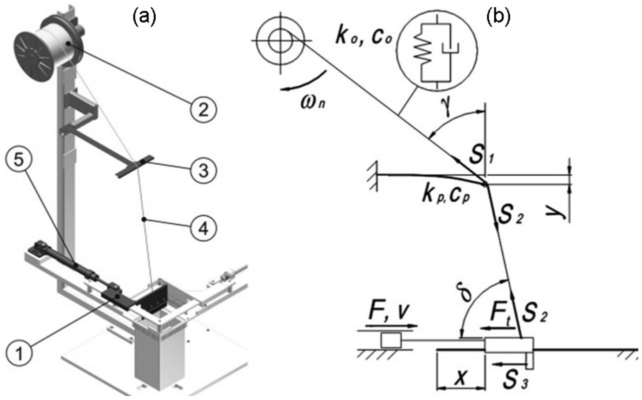

Fig. 1 — (a) Knitting machine for producing 3D knitted fabric (fragment), and (b) diagram of the dynamical system of the slider and the whip roller [1- slider, 2- warp beam, 3- whip roller, 4- warp, and 5- pneumatic cylinder]

generated in the pneumatic cylinder. The forces acting on the whip roller were determined according to the following relationship:

$$m_p \ddot{y} + c_p \dot{y} + k_p y = S_2 \sin\delta - S_1 \cos\gamma , \quad \ldots (2)$$

where m_p is the substitute mass of the whip roller.

Technological warp expenditure during the cycle results from the movement of the slider x and the loop-forming motion of the needle bars (not shown here) in the vertical direction u. This expenditure partially complements the warp section unwound from the beam w. The momentarily missing part of the warp length is compensated by the deflection of the whip roller. This length results from the following equation whose components are shown in Fig. 2 during a cycle:

$$\Delta x = x - (w - u), \quad \ldots (3)$$

A warp consisting of 50 threads of aramid yarn (Kevlar 49)[7-9] of 3.6 GPa strength and 0.3 mm diameter (single yarn strength exceeding 120 N) was assumed for calculations. The stiffness of each thread is 1 N / mm (total stiffness of the warp k_o = 50 N / mm, and attenuation coefficient of the warp c_o = 0,02 Ns / mm). The friction coefficient of the warp on the whip roller μ_{op} is 0.12 and in the eye of the needle μ_{os} is 0.18 (refs 10, 11). The relationships between forces in the warp *S1, S2, S3* result from the Euler equation. Due to the need for a relatively large (compared to conventional warp-knitting machines) length compensation of the warp during the cycle a whip roller of great length l_p = 250 mm and weight of 0,041 kg was adopted. Stiffness of the whip roller is a parameter regulated in the range k_p = 0,1-0,5 N / mm, attenuation coefficient of the whip roller c_p = 5 Ns / mm.

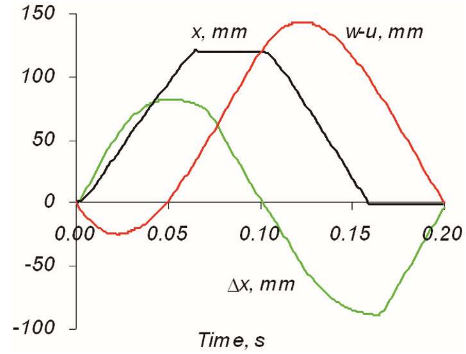

Fig. 2 — Changes of warp length during the cycle and its components

The parameters of the slider movement largely depend on the difference of two forces: the driving force F generated in the pneumatic cylinder and the resisting friction force F_t. Static force generated in the selected pneumatic cylinder (DSNU-20-125 / ISO-6432) is F_{max} = 200 N for forward movement during the first phase of the cycle, and F_{max} = 180 N during the second phase of the cycle for the backward movement[12].

A dynamic model of the cylinder assumes a decrease of the driving force as a function of the linear speed of the slider together with the piston rod v[13, 14]. The slider speed at which the cylinder does not generate any force was assumed as critical velocity (v_{kr} = 3 m / s). The friction coefficient of the slider on the guide rail μ is also dependent on the linear speed of the slider[15,16]. For steel-on-steel contact it was adopted μ_{st} = 0.12.

Dynamic characteristics of the pneumatic cylinder and the friction coefficient are shown in Fig. 3. Adopted weights are slider (m_s = 0.5 kg), the moving part of the cylinder (m_w = 0.3 kg), and stiffness and attenuating factor of the cylinder in extreme positions (k_w = 500 N / mm, c_w = 10 Ns /mm).

Simulation Results

As a result of simulations, the curves of the basic dynamic parameters during a knitting cycle of a 3D warp - knitting machine were determined. Some examples of the received curves are shown in Figs 4 and 5.

Figure 4 shows the curves of the slider shift and speed during the cycle. The speed of the slider grows rapidly, then it remains relatively constant and finally rapidly decreases. The speed in the first phase of the cycle and the return speed of the slider are similar. While analyzing the movement of the slider it can be seen that the shift time in the first phase is slightly

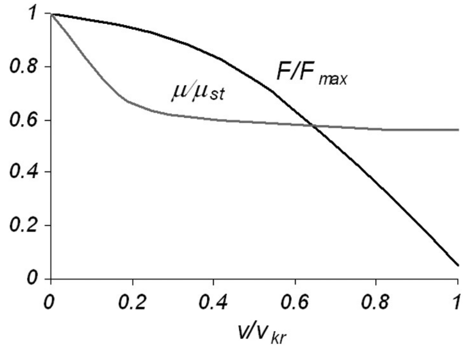

Fig. 3 — Relative values of the force generated in the pneumatic cylinder and relative friction coefficient slider-guide rail as a function of relative speed of the slider

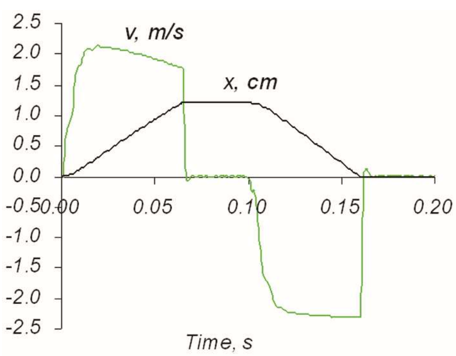

Fig. 4 — Slider shift and speed during the cycle (T = 0.2 s, k_p= 0.2 N/mm, S_o=50 N)

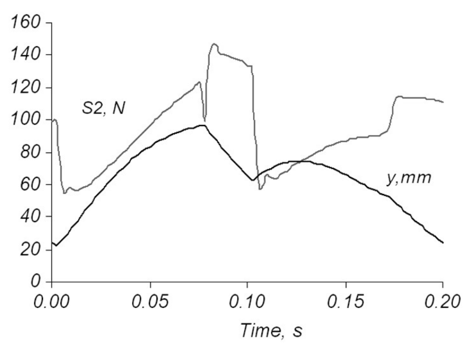

Fig. 5 — Warp tension in the section whip roller-slider and relative deflection of the whip roller during the cycle (T = 0.2 s, kp = 0.2 N/mm, S_o = 50 N)

longer than the shift time during the return movement. This is due to tightening the warp and then reducing the tension.

A comparison of the warp tension curve and the deflection of the whip-roller (Fig. 5) proves that the deflection of the whip roller does not accurately reflect tension in the warp thread, especially in the second phase of the cycle. During the return movement of the slider in the second phase of the cycle, the increase in the deflection of the whip roller with simultaneous

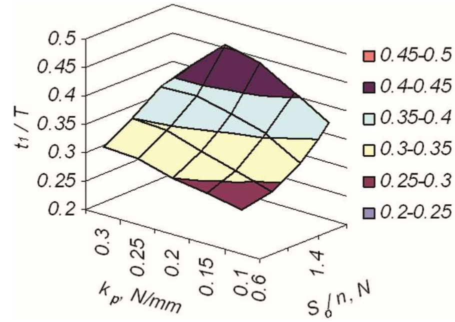

Fig. 6 — Relative time of slider shift as a function of whip roller stiffness and initial tension of the warp (T = 0.2 s)

reduction of the tension in the warp is related to the geometry of the system whip roller- slider. However, it is possible to estimate the warp tension from the deflection of the whip roller.

An important factor in choosing the cylinder is achieving the shortest possible time of the slider shift. Especially in the first phase of the cycle, while tightening warp threads, the largest forces counteract the movement of the slider. The slider shift time in the first phase t_1, determined on the basis of simulation was related to the duration of the full cycle T with variable parameters of the whip roller. The relative shift time t_1/T was determined for cycle length T = 0.2 s (Fig. 6).

With the increasing stiffness of whip roller and initial tension of the warp, relative shift time of the slider also increases. The increasing length of the cycle widens the range of relative shift times possible to obtain. Shorter relative shift times are only obtainable in longer cycles. In the shortest analyzed cycle (T = 0.16 s), relative shift time possible to obtain is 0,35T, so only 0,15T remains for the shut-down of the slider, which is 0.024 s. It may be insufficient to provide a technologically necessary time of the slider shut-down for forming a loop on the needle. In classic warp-knitting machines, the time of 0.024 s for forming a loop on the needle is achievable[3]. In case of a 3D warp-knitting machine, the loop-forming process requires an additional side shift of the slider[1] during its shut-down in the longitudinal movement. It is estimated that the minimum time of this technological shut-down is twice as long as in classic warp-knitting machines that is 0.05 s. The shortest cycle corresponding to that adopted shut-down lasts is T = 0.18 s. Thus, the relative shift time of the slider is 0.3T.

Therefore, for the effective operation of the mechanism it is suggested to apply longer cycle durations and lower values from the analyzed ranges of the whip roller stiffness and the initial tension of the warp.

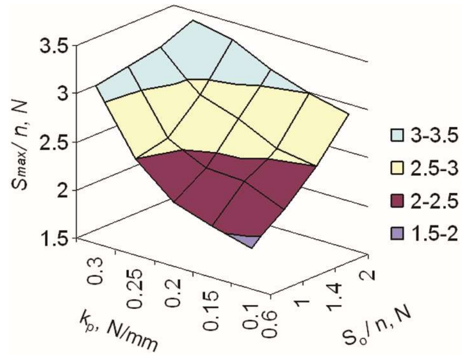

Fig. 7 — Peak tension force of a single warp thread as a function of whip roller stiffness and initial tension of the warp (T = 0.2 s)

The peak tension of the warp (S_{2max}) in the section between the whip roller and the slider was determined during simulations. The tension value of the warp was referred to the number of threads n. The peak tension force of a single warp thread for variable parameters of the whip roller is shown in Fig. 7.

Taking into account strength of aramid yarns, tension peak of the filling warp in the 3D knitting process remains in the safe range, regardless of the assumed values of the dynamic parameters of the whip roller. The smallest tension peaks of warp threads were observed within the low range of the stiffness values of the whip roller and initial warp tensions.

In dynamic conditions, the deflection of the whip roller does not accurately reflect the tension in the warp, but in practice it can provide a means of its measurement. Increasing both the stiffness of the whip roller and the initial tension of the warp causes increased load of the driving cylinder, which increases the shift time of the slider. Lengthening the cycle extends the range of relative slider shift time towards lower values. It gives a longer time reserve for proper forming of the loop of the 3D knitted fabric. In case of warp made of aramid fibers, the obtained tension peaks of the warp during the cycle are at a safe level and do not cause warp ruptures. In the assumed dynamic conditions, the optimum values of the parameters include stiffness of the whip roller k_p = 0.1 - 0.2 N / mm and initial warp tension S_o/n = 0,6 – 1 N. With the adopted pneumatic cylinder it is difficult to obtain cycle durations shorter than T = 0.2 s.

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