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NUMERICAL ANALYSIS OF THE DYNAMIC THREAD STRETCHING PROCESS

Aleksandra Prążyńska[1(*)], Zbigniew Mikołajczyk[2], Maciej Kuchar[3]

[1] Lodz University of Technology, Faculty of Material Technologies and Textile Design, Department of Knitting Technology and Textile Machines, 116 Żeromskiego Street, Lodz, Poland

[2] Lodz University of Technology, Faculty of Mechanical Engineering, Department of Vehicles and Machine Design, 1/15 Stefanowskiego Street, Lodz, Poland

(*) *Email:* aleksandra.prazynska@p.lodz.pl

ABSTRACT

The subject of the paper is the analysis of the dynamic thread stretching process under extreme conditions of the excitation speed with the physical phenomena described in terms of rheological models. The analysis was carried out using three basic models relating to viscoelastic bodies, i.e. the Maxwell, Kelvin-Voigt and Standard 2 models. The relationships between the reaction forces of the stretched threads and the input parameters of the process were included both in an analytical form and in a numerical model. The theoretical analysis was related to the experimental tests carried out on polyester threads with a linear mass of 84, 110 and 334 dtex, assuming the tensile speed ranging from 0.6 to 1.5 m / s. The experiment was carried out on a custom designed test stand.

In the conclusion of the obtained research, it can be stated that the most appropriate model for the description of the analysed thread stretching process is the Standard model 2 and it should be emphasized that the traditional analysis based on analytical relationships coincides with the results of numerical analysis. This proves the correctness of the adopted numerical model with specific boundary conditions.

KEYWORDS

Thread stretching dynamics, rheological models, equation of state, numerical analysis.

INTRODUCTION

Research on rheological properties is extremely important in many fields of science, including process engineering, materials engineering, biotechnology and bioengineering [1].

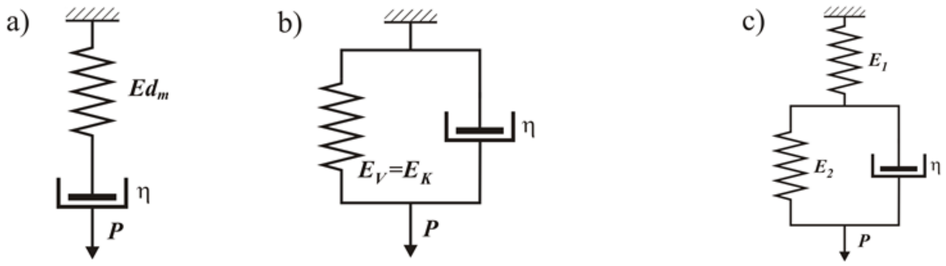
The continuous development of textile technologies leads to the improvement of their efficiency parameters, and thus to an increase in the speed of operation of the loop-forming elements of knitting machines, elements introducing weft on a loom and machines used in the processes of confectioning textile products. A linear textile product, which is a thread, is subjected to loads during various textile processes, as well as during the use of finished products. The phenomena occurring in the threads require defining their mechanical properties, which can be described using rheological models. In the case of textiles, two- and three-parameter viscoelastic models as well as integral models are used, which are a combination of the Hooke's body (spring) and the Newton's model (dashpot) [2]. More complex models are also built, taking into account nonlinear-elastic bodies and friction elements, which allow for a better representation of the behaviour of real bodies.

The 3-element Zener model [3] was used in the description of the influence of the yarn heterogeneity on the forces occurring when the threads are pulled through a friction barrier. The stretching behaviour of heterogeneous polyester monofilaments was based on a modified Żurek model taking into account the non-uniformity of their linear mass [4]. The rheological models of Vangheluwe, Żurek and Manich were analysed in the Matlab environment in order to assess their behaviour in comparison to cotton yarns with elastane added [5]. Due to tensile tests of core yarns with elastane, coefficients of nonlinear equations of rheological models were found.

The scientific goal of the research presented in the paper is the theoretical and empirical analysis of the thread stretching process in the context of dynamic excitations in knitting technologies.

MATERIALS AND METHODS

The research material consisted of polyester yarns with a thickness of 84, 110 and 334 dtex, which are most often processed on cylindrical crocheting machines and warp knitting machines with medium needle counts. The yarns were subjected to a stretching process on a designed and constructed test stand that allowed the speed to be changed in the range V = 0 ÷ 10 m/s. The device was built on the basis of a rotating disk with a pin placed on it, which, when pulled out at the right moment, allowed the thread to be picked up and extended to a length of Δl = 24 mm. The length of the stretched sections of threads was in the range l = 400 ÷ 1000 mm. The following stretching speeds were assumed V = 0.66; 1.10; 1.48 m/s. The dependences of force as a function of time P = f (t) obtained as a result of the experiment, were compared with the model characteristics (Fig. 3). The analysis was performed on the basis of three linear rheological models, i.e. the Maxwell, Kelvin-Voigt model and the Standard model 2 (Fig. 1), which are most often used to describe the mechanical properties of textiles.



$$\frac{d\varepsilon}{dt} = P \cdot \frac{1}{\eta} + \frac{1}{Ed_m} \cdot \frac{dP}{dt} \qquad P = E_V \cdot \varepsilon + \eta \cdot \frac{d\varepsilon}{dt} \qquad (E_1 + E_2) \cdot P + \eta \cdot \frac{dP}{dt} = E_1 \cdot E_2 \cdot \varepsilon + \eta \cdot E_1 \cdot \frac{d\varepsilon}{dt}$$

Figure 1. Rheological models: a) Maxwell; b) Kelvin-Voigt; c) Standard 2 [2].

The numerical simulation of the yarn stretching phenomenon was carried out in the Autodesk® Inventor® Professional 2022 environment. The dynamic simulation module of this program, through the use of the ANSYS WORKBENCH environment, enables the simulation of solutions to ordinary differential equations using the Runge-Kutta convergence method [6]. An equivalent mechanical system consisting of three junctions (Fig. 2a) was built to simulate the operation of the Kelvin-Voigt rheological model.

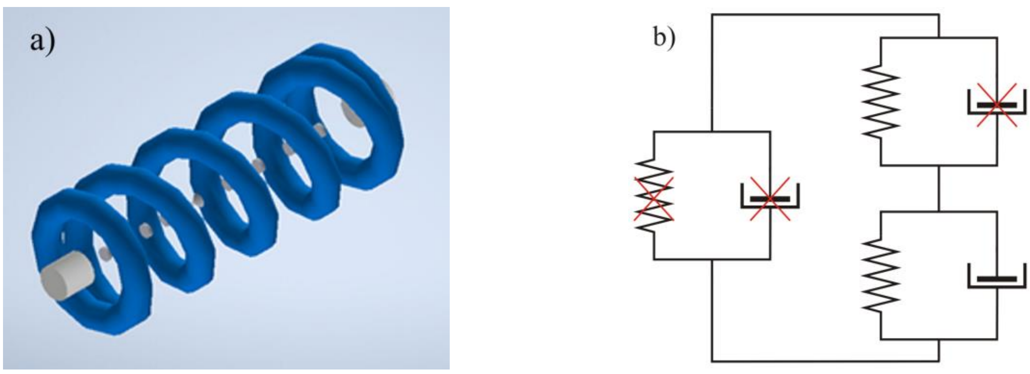


Figure 2. Equivalent mechanical model created in Inventor®: a) visualization; b) diagram - example for the Standard model 2.

The system allows to obtain an approximate solution of each of the tested rheological models by substituting zero values of the coefficients of the appropriate (unused) blocks. An example for the Standard model 2 is shown in Fig. 2b.

In order to perform the FEM simulation of the thread stretching process, the values of individual coefficients were introduced (Table 1). The constructed model also takes into account the length of the stretched section of the yarn and the speed of their stretching (V). For individual variants, the actual times of thread stretching were also declared, t = 0.0364; 0.0218; 0.0162s.

Table 1. Parameters of rheological models.

	VARIANT	SPRING COEFFICIENT DETERMINED AT DYNAMIC THREAD LOADS, E_D (DESIGNATION IN FIG.1)	SPRING COEFFICIENT DETERMINED DURING KINEMATIC EXCITATION, E_K	VISCOSITY COEFFICIENT, η
		N	N	N·s
MAXWELL MODEL (M)	1	60 (Ed_m)		1.5
	2	12 (Ed_m)		3.0
KELVIN-VOIGT MODEL (K-V)	1		25	2.0
	2		50	3.5
ZENER MODEL (Z)	1	44 (Ed_z)	35	1.5
	2	88 (Ed_z)	70	2.5

The spring coefficient for the kinematic excitation E_K at the thread stretching speed dε /dt → 0 was determined by the method of tangents to the characteristics P = f (ε). The length of the stretched yarn was l = 500 mm. The dynamic spring coefficient Ed occurring in the Maxwell and Standard 2 models was determined according to the following formula:

$$Ed = \frac{P_{max}}{\varepsilon}, N, \quad [1]$$

and for the Zener model from the formula:

$$Ed_z = \frac{P_{max}}{\varepsilon} - E_K, N, \quad [2]$$

where, P_{max} – maximum force, N, ε – elongation, E_K - spring coefficient for kinematic excitation, N.

The values of the force P_{max} and elongation ε were read from the files of the measured force values as a function of time during the dynamic stretching of the yarn.

Viscosity coefficient η was determined from the formula:

$$\eta = \frac{P_{max}}{\omega} - \frac{E_K \cdot \varepsilon}{\omega}, N \cdot s \quad [3]$$

where, P_{max} – maximum force, N, ε – elongation, E_K – spring coefficient for kinematic excitation, N, ω – speed of increment of relative elongation, 1/s; ω = ε/t (where t – stretching time, s).

The analysed models were verified in analytical and numerical terms in the Excel environment.

RESULTS AND DISCUSSION

A comparative analysis of the actual and model characteristics has shown that in most cases the model that best describes the process of polyester thread stretching is the Standard model 2. The example diagram (Fig. 3) shows a comparison of the thread stretching process recorded in real conditions and modelled on the basis of the state equations (Fig. 1).

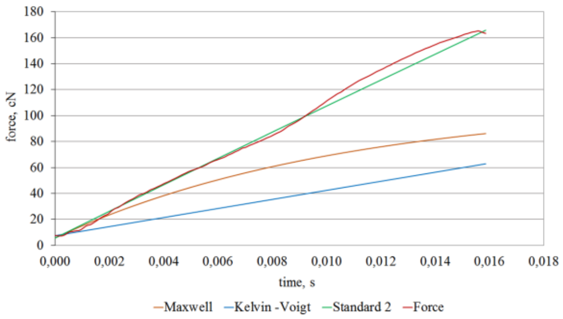


Figure 3. Real and modelled thread stretching process characteristics for the variant PE110 dtex, l=1000mm, V=1,48m/s, E_K=2327,38 cN, Ed=6883,75 cN, η=500Cn.

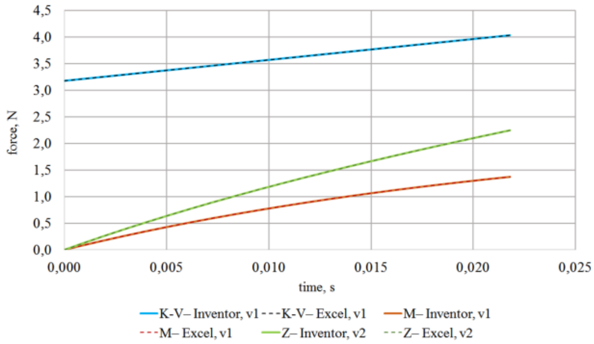


Figure 4. Model characteristics of the thread stretching process obtained as a result of numerical simulation in Inventor® and calculations in the Excel environment (l=700 mm, V=1,1 m/s).

The verification of the correctness of the numerical simulation is presented in Fig. 4 with reference to three selected rheological models: the Maxwell, Kelvin-Voigt and Zener model. The presented characteristics of the analytical and numerical calculations coincide, which proves the correctness of the assumptions of the numerical model of the thread stretching process.

CONCLUSION

In the final summary of the obtained test results, it can be stated that the Standard model 2 is the most adequate model in the description of the thread stretching process. The correctness of the assumptions of the numerical model with specific boundary conditions was also proven in relation to the traditional analytical results of the considered models.

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