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THEORETICAL AND EXPERIMENTAL RESEARCH OF UNWINDING YARN OFF THE SPOOL

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Abstract. *Dynamic model of unwinding yarn off the spool has been formulated on the basis of previous research. The expressions for determination yarn tensile force have been derived at the time of yarn separation from the spool and creation of a balloon. The results obtained on the basis of this model have been compared with experimental results of the research and the evaluation of suitability of dynamic model has been made.*

Key words: *dynamic analysis, unwinding yarn off the spool*

1. INTRODUCTION

The research of winding yarn off the spool has a great importance from the standpoint of determination yarn tensile force and this fact makes possible adjustment of relevant working parameters.

Many authors from all over the world have been occupied with this problems and mainly in connection with axial unwinding of yarn from spool, because [1-7] the winding process has not been investigated enough to satisfy demand of modern machines for processing yarn, particularly loom and knitting machine [1].

Namely, the modern construction of this machine, because of a high purchase price, cannot bear in exploitation process a large number of breaks caused mainly with poorly wrapped yarn. These breaks today are significant item in price of finished products and because of this it is a reasonable desire to cut these stoppages. Increasing of unwinding speeds at the modern machines and also wide range of new and different yarns make, for each separable yarn new conditions during the unwinding process. Because of that it is

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necessary to perceive these conditions in that way which will make possible clearing up the influence of large number of parameters. When yarn is moving one of the most important variables is tensile force which if it is obove the yarn elasticity limits may cause deformity of yarn and this is usually not noticeable until textile product is finished. It is difficult to determine exact value of tensile force because of the absence of appropriate equipment which would make possible accurate measurement of the value of this force in production conditions.

2. THE MATHEMATICAL MODEL OF YARN UNWINDING FROM THE SPOOL

2.1. Determining initial tensile force

Research of winding yarn off the spool is connected with determining conditions of winding-off yarn in area of separating yarn from the spool. The elemental part of AB yarn length ds during axial winding-off and speed v have been presented in Fig. 1. Yarn is separating from spool in item C. It is possible to analyze forces for elementary part ds in item C on the basis of Fig. 2 when yarn is moving in the plane xOy.

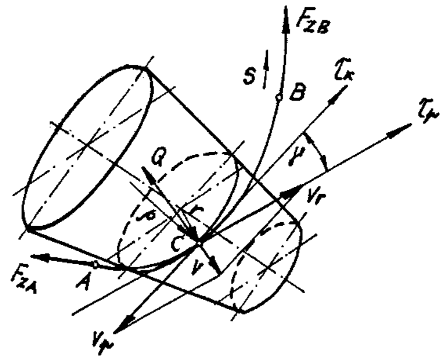


Fig. 1. Axial winding-off yarn.

Relative speed has direction of tangent line in the observed point in Fig. 2 while transmission speed has direction of spool tangent line in point C. In this case it is possible to assume that yarn is rigid because during the unwinding process there were neither break of yarn nor elastic deformity of yarn. We assume that left end of A yarn is fixed and relative speed of winding-off in item C is constant. Absolute speed of item C can be disassembled on transmission and relative component. On elemental part of yarn AB in the point where yarn is separating from spool the following forces act: F_{z0} - initial yarn tensile force when yarn is winding-off in area of free moving, F_{z1} - tensile force on left yarn end in area which is pressed on surface (on this end, any point can be fixed and moving of yarn observed.), Q - adhesion force between yarn which is winding-off and yarn on the spool. This force changes intensity direction and course in surroundings of point C in area of free moving. For elemental length yarn force works in point C and has course of absolute speed. Let us make an assumption that force works with opposite direction from direction of absolute speed.

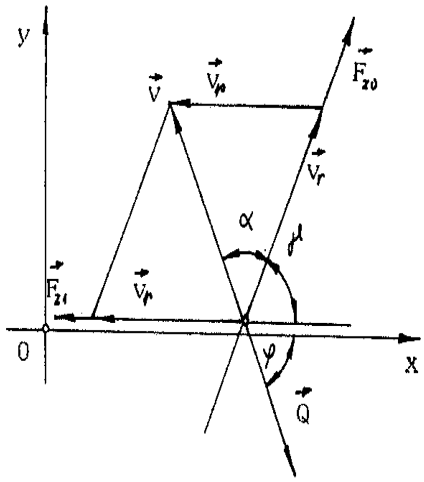


Fig. 2. The plan of speeds during the axial winding-off yarn

The schedule of speeds and forces has been presented in this kind of case in the Fig. 2. We can rely on sine theorem and start from speeds triangle in the Fig. 2 so we get:

$$\frac{v_p}{\sin\alpha}=\frac{v_r}{\sin\varphi}=\frac{v}{\sin\gamma};\qquad v_p=v\cdot\frac{\sin\alpha}{\sin\gamma}. \tag{1}$$

Separating yarn from the spool can be observed according to Korjagin, as slanting blow over the yarn with material point of constant speed-v. [2]. The law about changing quantity of moving for separate element of yarn (Yarn's section) can be used on the basis of Rahmatulin's theory about slanting blow over the supply thread [3]. If we neglect weight of elemental part of yarn and project on mobile axis x and y we can write:

$$\mu\cdot v_p\cdot v\cdot\cos\varphi=F_{z0}\cdot\cos\gamma-F_{z1}+Q\cdot\sin\varphi \tag{2}$$

$$\mu\cdot v_{p.}\cdot v\cdot\sin\varphi=F_{z0}\cdot\sin\gamma-Q\cdot\sin\varphi \tag{3}$$

If we replace (1) in (2) and (3) we'll get final expression for initial tensile force of yarn in a moment when yarn is separating from the spool in this shape:

$$F_{z0}=\frac{\sin\varphi}{\sin\gamma}\cdot\left[Q+\mu\cdot v^2\cdot\frac{\sin\alpha}{\sin\gamma}\right]. \tag{4}$$

F_{z1} - force has been determined on base of this expression:

$$F_{z1}=Q\cdot\left(\cos\varphi+\frac{\sin\varphi}{\sin\gamma}\right)+\frac{\mu\cdot v^2}{\sin\gamma}\cdot\left(\frac{\sin^2\varphi}{\sin\gamma}-\sin\alpha\cdot\sin\varphi\right). \tag{5}$$

The unwinding yarn from the spool is axial unwinding and because of this fact it is possible, according to Korjagin [2] and the Fig. 2. To. adopt that: $\varphi = \frac{\pi}{2} - \frac{\gamma}{2}$. Now, the angle is $\alpha = \frac{\pi}{2} - \frac{\gamma}{2}$. In that case expression (4) is reduced to expression:

$$F_{zo} = \mu \cdot v_p{}^2 + \frac{Q}{2 \cdot \sin \frac{\gamma}{2}}, \tag{6}$$

which has also been given by Korjagin [4].
When we have axial unwinding off yarn from the spool expression for force (5) at the left end of yarn can be written in this way:

$$F_{z1} = \frac{\mu \cdot v^2}{2} \cdot \left(\frac{1}{2 \cdot \sin \frac{\gamma}{2}} - 1 \right) + \frac{Q}{2 \cdot \sin \frac{\gamma}{2}} \cdot \left(1 + 2 \cdot \sin^2 \frac{\gamma}{2} \right) \cdot \tag{7}$$

2.2. Mathematical model of winding yarn off the spool

The spool is resting – Fig. 3. There are two points on the yarn which have been placed on the spool: point of taking off (this is point of separating parts of yarn from immobile yarn) and also point of separating yarn from the spool (this is point of crossing yarn in balloon). These two points determine share of yarn which slide down the layers of yarn wound-up on the spool. We can assume that this part of the yarn slides over the cylinder with radius *r*. Yarn separates from spool in point O where we can place two natural coordination systems:

- coordinate system τ_k, n_k and b_k, so that rectification plane is tangential plane of the spool, and vertical n_k passes through the point O_1 which has been placed on the axis of the spool and also it is center of the curved line in the point which is on the spool and coincides with point O in the observed moment.

- coordinate system τ_p, ν_p and β_p, so that τ_p is tangent line at the winding-off part of yarn, more exactly at the balloon in item O, and vertical υ_p passes through item O_2 which is center of the curved line in the point which in observed moment lies on the winding-off part of yarn and coincides with the item O. Radius of curved line in point O is ρ_1 according to Fig . 3.

The angle of winding-off process γ can be defined as angle between tangent line τ_k and τ_p. If we neglect resistance of the air the equation of moving elemental part of yarn can be written in vector form:

$$\mu \cdot a \cdot ds = dF_z + \Re \cdot ds . \tag{8}$$

If we project vector equation (8) on the axis of natural coordinate system we get:

$$\begin{gathered} \frac{\partial F}{\partial s} - F_1 \cdot \cos\alpha - \mu \cdot a_n = 0 \\ \frac{F_1}{\rho} - F_n \cdot \cos\theta - F_t \cdot \sin\alpha \cdot \sin\theta - \mu \cdot a_t = 0 \cdot \\ F_n \cdot \sin\alpha \cdot \cos\theta - F_t \cdot \sin\theta - \mu \cdot a_b = 0 \end{gathered} \tag{9}$$

Where: $\boldsymbol{F_z}$ - yarn tensile force, $\Re$ - reaction because of moving of the yarn and it has been reduced to length unit, $\boldsymbol{F_n}$- normal component of resistance force , $\boldsymbol{F_t}$ - tangent component of resistance force, μ - longitudinal mass of yarn, $\boldsymbol{a}$ - absolute acceleration of mass center of yarn element, $\boldsymbol{a_t}$, $\boldsymbol{a_n}$, $\boldsymbol{a_b}$ - the acceleration components of the center of the mass yarn elements along the axis of natural coordination system, γ - angle of winding-off yarn, α-azimuth of friction, θ - geodesial angle of moving yarn.

If we assume that speed of winding-off yarn during the winding-off process is constant and this can be taken as a real fact during the unwinding process so that system of equations can be written in this way:

$$\frac{dF_z}{ds} - F_t \cdot \cos\alpha = 0$$
$$\frac{F_z}{\rho} - F_n \cdot \cos\theta - F_t \cdot \sin\alpha \cdot \sin\theta - \mu \cdot \frac{{v_p}^2}{r} \cdot \cos\theta - \mu \frac{v^2{}_r}{\rho} + 2 \cdot \mu \cdot \frac{v_p \cdot v_r}{r} \cdot \cos\gamma \cdot \cos\theta = 0 \quad (10)$$
$$F_t \cdot \sin\alpha \cdot \cos\theta - F_n \cdot \sin\theta - \mu \cdot \frac{{v_p}^2}{r} \cdot \sin\theta + 2 \cdot \mu \cdot \frac{v_p \cdot v_r}{r} \cdot \cos\gamma \cdot \cos\theta = 0$$

where: $\boldsymbol{v_p}$ - carrying component of speed, $\boldsymbol{v_r}$ - relative component of speed.

So it':

$$\frac{d\Im_z}{\Im_z} = ctg\alpha \cdot \sin\theta \cdot d\psi, \quad (11)$$

where:

$$\Im_z = F_z - \mu \cdot {v_r}^2, \qquad d\psi = \frac{ds}{\rho} = \frac{d\gamma}{\sin\theta}, \quad (12)$$

dψ - comprehensive angle of elemental part. of thread on the basis of sine and cosine theorem for speed triangle we can write:

$$\sin\alpha = \frac{v_p \cdot \sin\gamma}{v} = \frac{v_p \cdot \sin\gamma}{\sqrt{{v_p}^2 + {v_r}^2 - 2 \cdot v_p \cdot v_r \cdot \cos\gamma}} = \frac{r \cdot \sin\gamma}{\sqrt{r^2 + {r_c}^2 - 2 \cdot r_c \cdot r \cdot \cos\gamma}}, \quad (13)$$

Where: $\boldsymbol{r_c}$ - radius of formed body of winding in the item of winding-off **($\boldsymbol{r_c \geq r}$)**.

If we assume that tangent line force of resistance has the same course like absolute speed and opposite direction as it is presented in Fig. 3, then we can write:

$$\frac{dF_z}{F_z - \mu \cdot {v_r}^2} = ctg\alpha \cdot \sin\theta \cdot d\psi = ctg\alpha \cdot d\gamma. \quad (14)$$

If we take expression (13) in consideration then we can write expression (14) in this way:

$$\frac{dF_z}{F_z - \mu \cdot {v_r}^2} = \frac{r_c}{r} \cdot \frac{d\gamma}{\sin\gamma} - ctg\alpha \cdot d\gamma. \quad (15)$$

If we assume that $\boldsymbol{v_r}$ = const. solution of differential equation (13) has this form:

$$F_z = \mu \cdot {v_r}^2 + [1 + \cos\gamma]^{-\frac{r_0}{r}} \cdot \sin\gamma^{\frac{r_0}{r} - 1} + C. \quad (16)$$

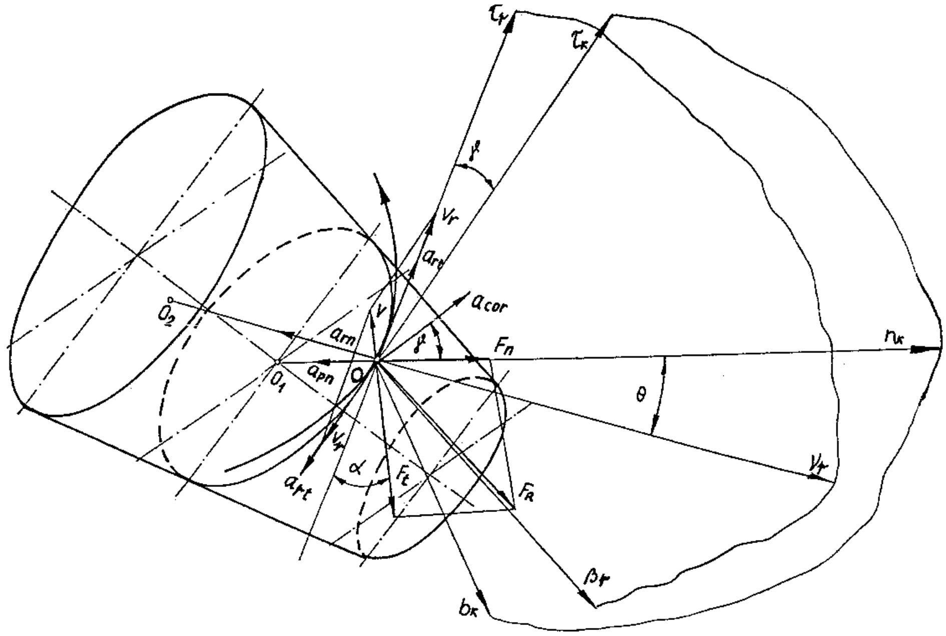


Fig. 3. The schedule of speeds, accelerations and forces at the winding yarn off the spool.

Integration constant C is determined from condition that in moment $t = 0$, $\gamma = \gamma_o$, $F_z = F_{z0}$ and $v_r = 0$.

If we replace integral constant determined in this way C in (16) we get:

$$F_{zk} = \mu \cdot v^2{}_r + F_{z0} \cdot \left(\frac{1+\cos\gamma_0}{1+\cos\gamma} \right)^{\frac{r_c}{r}} \cdot \left(\frac{\sin\gamma_0}{\sin\gamma} \right)^{1-\frac{r_c}{r}} . \qquad (17)$$

If we replace (4) in (17) we get:

$$F_{zk} = \mu \cdot v_r{}^2 + \frac{\sin\varphi}{\sin\gamma} \cdot \left(Q + \mu \cdot v^2 \cdot \frac{\sin\alpha}{\sin\gamma} \right) \cdot \left(\frac{1+\cos\gamma_0}{1+\cos\gamma} \right)^{\frac{r_c}{r}} \cdot \left(\frac{\sin\gamma_0}{\sin\gamma} \right)^{1-\frac{r_c}{r}} . \qquad (18)$$

Since $\varphi = \alpha = \frac{\pi}{2} - \frac{\gamma}{2}$ during the axial winding-off, expression (18) can be written in this way:

$$F_{zk} = \frac{\mu \cdot v^2}{4 \cdot \sin^2 \frac{\gamma}{2}} + \left(\frac{\mu \cdot v^2}{4 \cdot \sin^2 \frac{\gamma}{2}} + \frac{Q}{2 \cdot \sin \frac{\gamma}{2}} \right) \cdot \left(\frac{1+\cos\gamma_o}{1+\cos\gamma} \right)^{\frac{r_c}{r}} \cdot \left(\frac{\sin\gamma_o}{\sin\gamma} \right)^{1-\frac{r_c}{r}} . \qquad (19)$$

If the winding-off is from the cylindrical spool we can put this $\boldsymbol{r_c = r}$ after that we get:

$$F_{zk} = \mu \cdot {v_r}^2 + \left(Q + \mu \cdot v^2 \cdot \frac{\sin\alpha}{\sin\gamma} \right) \cdot \frac{1+\cos\gamma_0}{1+\cos\gamma} . \tag{20}$$

Expressions (16) and (17) are giving dependence of yarn tensile force when yarn is winding-off from the spool.

Expression (19) has been obtained on the basis of mathematical model. In real conditions, the influence of friction should be taken into consideration and second article in the equation (19) multiplied with the coefficient of friction (k). This coefficient is equal to k = 0,275 and adhesion force is Q = 0,145 cN in examinational conditions (determining valve of tight force yarn during the winding-off yarn from the spinal pipe).

Yarn tensile force at the top of the spinal pipe can be defined against relation which has been given by Korjagin [4]:

$$F_v = F_{zk} + \frac{\mu \cdot v^2 \cdot {r_n}^2}{2 \cdot 10^6 \cdot r_c^2} + \frac{v^2 \cdot l}{1.08 \cdot 10^6} \cdot \sqrt{\frac{\mu}{\delta}} \tag{21}$$

Where: r_n - radius of yarn of spinal winding expressible in (mm), r_c - radius of top empty pipe expressible in (mm), l - length of the yarn in balloon expressible in (mm), $1.08 \cdot 10^6$ - coefficient of the correlation and δ - volume mass of yarn expressible [mg/mm^3].

With this relation Korjagin is calculating the value of yarn tensile force at the point which has been placed at the top of a pipe and also on the size of yarn's winding where the balloon has stable shape. If we want to determine yarn tensile force in the peak of balloon and also on the whole size of yarn's winding it is necessary to introduce parameters into previous expressions which will increase yarn tensile force in that part of its moving. This part of yarn is the most difficult for mathematical description because during the winding-off process yarn is sliding over the yarn pipe also yarn is getting irregular shape and this shape mainly isn't balloon so that large number of windings has been taken-off. These windings have been pulled by parts of yarn which is winding-off. Yarn is winding-off easy at the beginning because of non existence of the friction at winding layers but yarn is later usually tangling, also stretch is increasing and result is breaking of yarn. This part of yarn moving is usually described in experimental results because of finding some other dependence is very difficult. The third article in relation (21) presents force of air resistance during the unwinding process.

In addition to this concrete parameters of machine as shape and size of the way which yarn is passing during unwinding process and type, way of machine influence upon moving and size of yarn tensile force in formulating mathematical model have been coordinated with other parameters (for example: high of balloon - h) over the parameter of machine P_m which, in the observed case, has the value P_m = 23.944. Final shape of formulating mathematical model for calculating yarn tensile force at the top of balloon can be written as:

$$F_{zk} = \frac{\mu \cdot v^2}{4 \cdot \sin^2 \frac{\gamma}{2}} + \left(\frac{\mu \cdot v^2}{4 \cdot \sin^2 \frac{\gamma}{2}} + \frac{Q}{2 \cdot \sin \frac{\gamma}{2}} \right) \cdot \left(\frac{1+\cos\gamma_o}{1+\cos\gamma} \right)^{\frac{r_c}{r}} \cdot \left(\frac{\sin\gamma_o}{\sin\gamma} \right)^{1-\frac{r_c}{r}} \cdot k + \frac{\mu \cdot v^2 \cdot {r_n}^2}{2 \cdot 10^6 \cdot {r_c}^2} + \\ + \frac{v^2 \cdot l}{1.08 \cdot 10^6} \cdot \sqrt{\frac{\mu}{\delta}} + \left(\frac{h}{P_m (r - r_c)} \right)^{12} . \tag{22}$$

3. THE EXPERIMENTAL PART

3.1. Characteristics of yarn testing

Measuring yarn tensile force during the transportation has been made on the automatic unwinding machine by "SAVIO" - firm, type RAS.15. Measuring has been done in the' factory NITEX - Niš and speed of unwinding was 930 m/min during regular production. Worsted cotton yarn, raw material 100% cotton, fineness 14 [*tex*] has been used for measuring. The yarn has been made in worsted spinning process. In the spinning factory of the cotton-mill-Belgrade and it has been winded-up on the spinal windings. Table 3.1. gives characteristics of these windings.

Table 3.1: Characteristics of the spinal windings.

characteristic of the winding	value
The mean diameter	40 mm
The height of a lower cone	30 mm
The height of upper cone	60 mm
The height of winding body	105 mm
The total height of empty pipe	240 mm
The diameter of empty pipe in lower part	30 mm
The diameter of empty pipe in upper part	22 mm
Volume density of winded-up yarn	$0.518\ g\cdot cm^{-3}$
Total length of wind-up yarn	3770 m
Number of windings in a layer	30
Number of windings in inter layer	15
Length of yarn in layer	3.97 m
Length of yarn in interlayer	1.35 m

3.2. Measuring of yarn force

Measuring of tensile force has been done at the top of the balloon at the first yarn guide. The distance between the measuring place and the top of the pipe was 100 mm.

The scheme of the measuring has been presented in the Fig. 4.

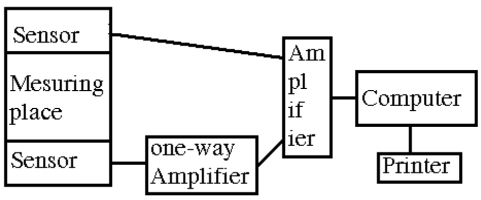


Fig. 4. The scheme of measuring equipment

We have chosen measuring principle for measuring the force at three points and this principle has been mainly used for measuring in operating conditions that's in contrast to measuring yarn tensile force in one point which characterizes the laboratory conditions. We always use measuring of tensile force by turning yarn in three items [1-5] when yarn moves for example like unwinding process.

The induction force sensor by "HBM" has been used for measuring . The type of sensor which we have used - Q11 + 100.

We have measured the machine vibrations with piezoelectrical sensor of vibrations by B&K ("Bruel & Kjaer") firm simultaneously on this sensor and also on the usher cleaner. Type of the sensor is 4873. The signals from this sensor have been amplified in one-way amplifier type 2635 by B&K firm and after that they have been taken in main amplifier together with the signals which have been obtained during the measuring of yarn tensile. This amplifier is by "HBM" firm, digital with memory for 24000 data. Type of amplifier is DMC 9012A. The electrical signals from both sensors have been amplified in this amplifier to appropriate value suitable for computer data processing. This signal is memorized and processed in the computer. The computer type 520C by Mekintosh firm has been used. The signals have been treated in program package Software BEAM 3. 1 (Bedienergefuhrte Erfassung und Auswertung von Messdaten). We have used exponential filter in this program package for cleaning the signal from the machine noise. Using this program package computer has opportunity to clean the signal from the noise which have been the result of machine influence on the sensor. That means that signal which comes into the computer includes, in spite of signals which we have obtained during the measuring of yarn tension, also signals of register murmurs. This noise results from the machine vibration influence on the force sensor which we have used for measuring of yarn tension.

The graphic representation of yarn tension values is obtained on the printer in form of a diagram. This diagram of tensile force has been presented in the Fig. 5 at unwinding speed of 930 (m/min).The values of tensile forces in cN have been given at the ordinate and value of spinal winding K has been expressed in percentages on the abscissa. Yarn tensile force moves in a wide interval from o to 80 cN for around 70% of the winding and from o to 140 cN for around 30% of the winding and we can see this on the diagram. This wide interval of showing tensile force is a result of the influence on the sensor, beside yarn tensile force and also the influence of other unwinding parameters, for example: machine vibration during the unwinding process.

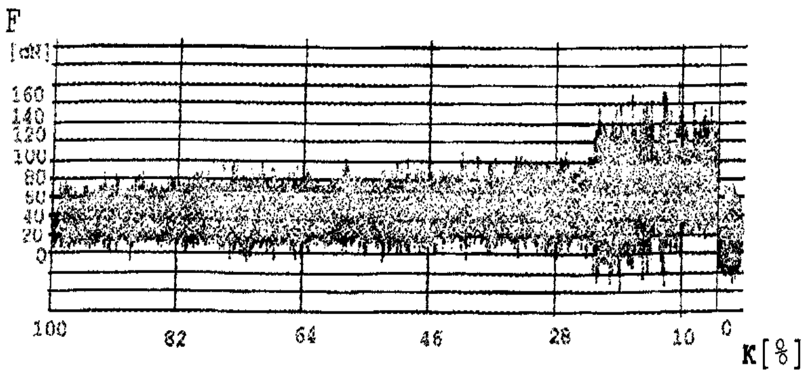


Fig. 5. Nonfiltered diagram of yarn tensile force at the unwinding speed of 930 (m/min).

Filtered diagram of yarn tensile force from the Fig. 5 has been presented in the figure

6. This diagram has been cleaned from influence of machine parameters on the sensor. Interval of yarn tension moves on the diagram at the begining of unwinding process from 26 to 32 cN, in the first zone which has value of 18% it is from 28 to 33 cN. This size is from 30 to 38 cN in the second zone. The value is from 33 to 41 cN in the third zone. The value is from 38 to 48 cN in the fourth zone, from 58 to 72 cN in the fifth zone and from 62 to 81 cN at the end of unwinding process. The increasing of yarn tensile force at the top of balloon is consequence of removing the position of yarn winding-off item. Namely, the height of balloon increases during the unwinding process and length of yarn in balloon increases also so that result is increasing yarn tensile force.

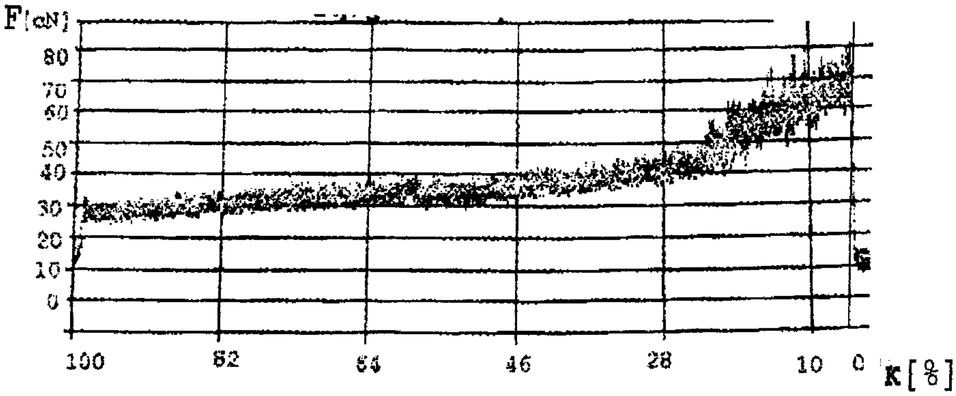


Fig. 6. Filtered diagram of yarn tensile force at the unwinding speed of 930 (m/min).

4. THE COMPARISON OF RESULTS OBTAINED BY THEORETICAL AND EXPERIMENTAL WAYS

Because of clear presentation of measuring results in the Fig. 5 and 6 diagram has been divided into six parts K, sizes of these parts have been expressed in percentanges from 100% - this is winding at the beginning of unwinding process to 0% - this is empty winding.

We have taken the greatest height of balloon in certain zones and according to it have calculated the length of yarn in balloon. According to presented mathematical model (22), we have presented values of balloon height and yarn length at these heights in the Fig. 7. The values expressed in mm.

The diagram of calculated mean values deviation of yarn tensile force at the top of balloon from the measured values of this force has been shown in the Fig. 8. Values of winding size have been presented in percentages.

The error made during the calculation of this force is shown in Fig. 9.

We can see that the greatest error has been mode at the end of unwinding process because of difficulty of predicting the yarn behavior in that part of its moving. This is influenced by nonpredictable removing of a large number of yarn layers and increased surface of contact between yarn and bobbin at that moment). The error moves in interval until 15%.

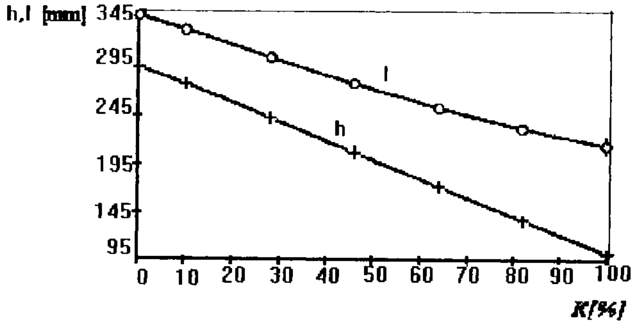


Fig. 7. Values of h and l depending on size of yarn winding on the automatic machine for unwinding
h - height of balloon expressed in mm,
l - length of yarn in balloon expresses in (mm).

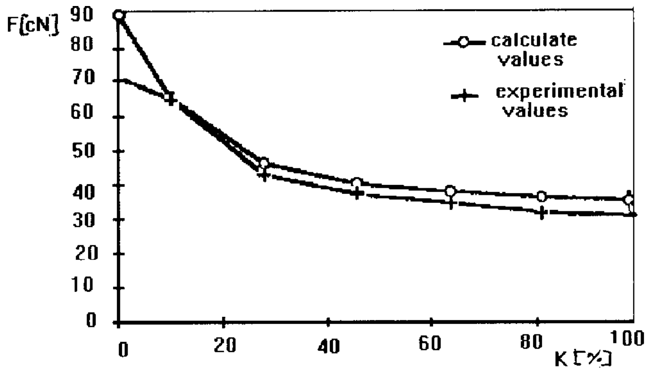
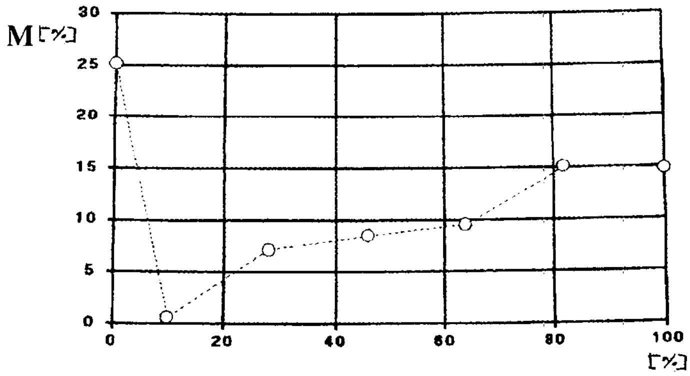


Figure 8. The diagram of experimental and calculated mean values of yarn tensile force



M (%) size of winding in (%)

Figure 9. Review of the error made during the calculation of yarn tensile force at unwinding speed of 930 m/min
M (%) - the error of calculating tensile force in (%)

5. THE CONCLUSION

We have presented the mathematical model of winding yarn off the spool and derived expression for determining initial force of yarn tension during the separation of yarn from the spool and expression for yarn tensile force during the winding-off process and forming the balloon. The expression which we have obtained on the basis of the theoretical research has been expanded with articles which take into consideration the conditions of measuring. The model which we have formulated in this way follows very well behavior of yarn during the unwinding process in experimental conditions.

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TEORIJSKA I EKSPERIMENTALNA ISTRAŽIVANJA ODMOTAVANJA PREĐE SA KALEMA

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U radu su izvršena teorijska i eksperimentalna istraživanja premotavanja pređe sa kalema. Matematički model, postavljen na osnovu teorijskih i eksperimentalnih istraživanja, dobro prati sam proces premotavanja što je utvrđeno upoređivanjem rezultata sile zatezanja dobijenih teorijskim i eksperimentalnim putem.