

Modelling of the Winding Process on Rewinding Machines

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Abstract— This paper presents a simulation of the rewinding process using SolidWorks Motion. The study focuses on the interaction between various rolling-in rollers and accumulated packages, comparing simulation results with analytical calculations. It includes determining the package stiffness experimentally and modelling the winding dynamics, considering factors like friction, roller radius, rewinding speed, and other parameters. Simulations were performed for four roller types and different package body thicknesses. The results demonstrated the model's accuracy, showing a 95% approximation to analytical calculations. Key findings include the reduction of slipping with element rollers and the effect of package body thickness on contact length. These results can help optimise rewinding processes and improve the design of rewinding machines and friction gears. Further research is needed to analyse the rebound or loss of contact between the roller and the package.

Index Terms — Computer simulation modelling, packaging, bobbin, bobbin holder, rolling-in roller, geometric slipping, winding mechanism

I. INTRODUCTION

COMPUTER modelling of technological processes in machinery and the developing technologies for producing high-quality materials, including threads and yarns, is one of the promising directions in modern mechanical engineering. In studies [1, 2], rational choices of technologies are proposed, substantiated by their extensive application and relevance depending on specific technological tasks.

The study [3] examines an approach to effective quality

control of the winding processes on cylindrical forms with rounded ends, which is proposed to ensure the stability of the winding body geometry and uniform tension of textile materials made from composite fibres. The authors investigated the impact of winding angles on the fibre tension distribution depending on the packaging body. They also considered the conditions for the equilibrium of forces acting on the fibre, which ensure the maximum static friction to prevent slipping between the fibre and the surface of the package. The proposed discrete approach to analysing the influence of the packaging diameter allows for modelling the winding process, which will be used in this study.

Similarly, the study [4] aims to improve the quality of rewinding processes. It proposed algorithms and a device for measuring yarn tension, enabling the determination of thread tension and the displacement of the guide ring. This allows for real-time analysis of the dynamics of twisting and winding processes, enhancing production stability and improving the quality of the yarn formation process by twisting multiple fibres (threads).

In [5], the influence of filament thickness, used as the base for composite yarn, on the residual torque of the yarn, which significantly affects its quality, was studied. The results confirmed a statistically significant relationship between filament thickness and the residual torque of composite yarns, allowing for more precise optimisation of their production processes.

The findings from studies [4, 5] can only be applied to twisting machines and do not allow for a qualitative evaluation of technological parameters while rewinding finished yarns (threads) using methods based on frictional principles.

The degree of yarn hairiness after winding is a critical quality indicator affecting equipment productivity and the final fabric quality. Study [6] investigated the combined effect of four winding parameters (speed, tensioner load, distance to the guide, and packaging compression force) on yarn hairiness. Developed regression models for optimising rewinding process parameters, enabling effective optimisation of these parameters, considering the physical properties of materials directly influencing the quality of finished yarn.

Another factor impacting the quality of the final product is the influence of the guiding surfaces of working elements and the yarn (thread) properties on its tension in technological processes. Study [7] examines the mechanism of tension increase when yarn passes through a guide with

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significant curvature, enabling the optimisation of the guiding surfaces' geometry to minimise tension and improve the quality of technological processes. The findings from studies [6] and [7] indicate that the curvature of surfaces and thread tension forces significantly impact other rewinding parameters.

Parallel to this, studies in [8-10] are dedicated to modelling the rewinding process on winding machines, particularly investigating the sliding effect in the friction pair between the conical packaging and the cylindrical winding drum (pressing roller). However, the proposed methods consider only the rolling centre position without accounting for the elastic properties of materials. Similarly, the mathematical model of geometric sliding presented in [11] provides dependencies of relative sliding speeds and evaluates the friction moment during sliding. However, in calculations, the rolling pole is chosen as the geometric centre of the distance between the wheels without considering contact parameters with the surface.

The application of mathematical models [3-11] does not always guarantee high accuracy, as transitional kinematic and dynamic processes, such as rotational frequency changes, loss of contact between bodies, 3D body contact, changes in force factors, the physical and mechanical properties of materials, are often not considered. Accounting for these parameters is a complex engineering task and economically unjustified due to significant time expenditures. Thus, researching technological processes using computer modelling is a progressive and relevant method.

The study of technological processes using computer modelling is an important engineering task, ensuring the high adequacy of computer models to real-world conditions. This is confirmed by the results of analysing rotational mechanical systems using computer modelling in [12], which correlate with analogous results obtained analytically and experimentally in [13], demonstrating the high accuracy of mathematical models (on average, 0.95). The relevance of applying computer analysis and modelling methods for lever mechanisms is confirmed by studies [14-16], which show high precision of the obtained results.

Using computer technologies accelerates research results, optimising processes and mechanism parameters depending on their design and the physical and mechanical properties of the material. Furthermore, applying automated design systems eliminates the need to produce prototypes in the early stages of development, enabling the creation of virtual prototypes for comparison and ensuring high calculation accuracy [12-16].

During thread rewinding, the primary task of the pressing roller is to ensure the required density and structure of the packaging (bobbin) [2, 3]. The winding process leads to changes in packaging thickness, affecting the rotational speed of the pressing roller and contact conditions (magnitude and force of pressing, contact zone, thread tension, and force constancy), as confirmed in studies [6-10]. The findings from studies [8-11] allow for the determination of slippage parameters of working elements and confirm that the reliable operation of the friction-pressing roller depends on the balance of friction forces (moments) and other factors influencing the nature and

magnitude of the roller slippage on the packaging [9, 10].

The reduction of slippage and the use of element rollers with uniform load distribution have been proposed [17], and the study of this design forms the basis of this work.

In [10], the design of the element roller [17] is analysed, and the slip dependences of the Rolling-in roller on the package are obtained, determining the relative slip rates v_s . However, the calculations take into account only the geometric feature of the design, but do not take into account the physical parameters and 3D contact of the package and the Rolling-in roller (material, mass of elements of the Rolling-in roller, pressing forces (F_n), friction coefficients (f), material elasticity, roller elasticity (C), etc.). In addition, in the calculations of the slip value of the Rolling-in roller [10], assumptions were made that determine the mechanism's operation under boundary conditions. For example, when the coupling margin coefficient $\beta=1$ [10], when the Rolling pole P_i is located on the geometric middle of the generating rolling-in roller (or its element) – $0.5 \times b_i$, and the values of the angular velocity of the elements of the Rolling-in roller were assumed to be constant [8, 9].

The obtained calculation results are approximate and valuable for objectively evaluating various mechanism designs that work on a similar principle under the same conditions.

In actual (physical) friction mechanisms, the position of the pole P_i depends on the pressing force (F_n) of the leading and trailing rollers. The rollers interact with a constant separation from the bobbin surface, which causes the appearance of different values of torsional moments at different ends of the rolling-in roller [10] or its elements. At the same time, these factors affect the qualitative formation of the package, the value of the coupling margin coefficient (β) and the choice of the optimal clamping force (F_n).

For an in-depth study of the operation of the Rolling-in roller in the winding mechanism of the rewinding machine, there is a need for experimental (physical study) [5, 6] or computer modelling [1, 12, 13]. At the same time, the application of a multi-pronged approach to the complex analysis of mechanisms and machines allows you to compare the results of similar calculations obtained by different methods, determine the amount of deviation and the specific influence of model factors on the calculation result, and evaluate the accuracy of calculations.

In addition, a comprehensive analysis will allow you to identify the causes of slipping of the Rolling-in roller and evaluate the effectiveness of the proposed methods for its elimination. Computer modelling will provide an opportunity to study various operating modes and roller design options, significantly reducing Experimental Research's cost. This approach to studying the winding mechanism of the rewinding machine will allow you to get more accurate and reliable results. It will contribute to further improvement of production technologies and increase their efficiency.

The paper proposes to conduct a comprehensive analysis of the slip value of a rolling-in roller on a conical package, using the example of a machine of the "Polycon" type, by computer modelling, considering a complex of factors of a physical machine.

II. EXPERIMENTAL SUBSTANTIATION

To consider the rigidity of the bobbin packaging in the computer model, its value was determined experimentally. For this purpose, an experimental setup was used (Fig. 1, a), which includes a tripod 1, in which the indicator of the clock type is fixed (with a division price of 1 micron), a set of weights 3 (100 and 150 grams), a package 4 and a rocker arm 5 with a rod 6.

Each series of measurements was performed in the following sequence:

- The rod 6 of the rocker arm 5, by moving the tripod 1, was installed at points P₁, P₂, and P₃ (Fig. 1, a) located at different radii of the package along the forming Package 4;

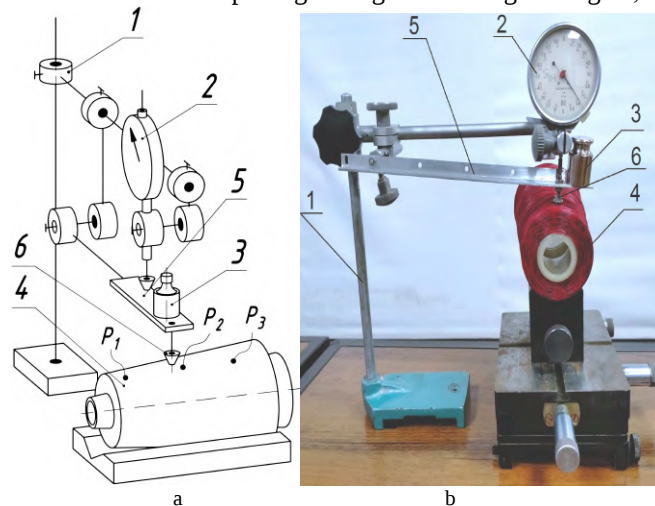


Fig. 1. Installation for measuring package stiffness: a-Experimental load diagram; b - experimental installation

- Rocker arm 5 was loaded with a heavy 3 weighing 100 gr. and the data of indicator 2 were recorded;
- After that, a weight 3 with a weight of 150 g was installed on the rocker arm 5, and the indicators of indicator 2 were removed;
- At each point, 10 measurements were made by turning the package for each heavy value. The measurement results are shown in Table 1.

TABLE 1

Results of measurement of package stiffness

№ experiment	Results of measurement of package stiffness								distributed over the length of package stiffness, H/(м)
	indicator readings, microns								
	Load – 1,0 H				Load – 1,5 H				
	1 point	2 point	3 point	average	1 point	2 point	3 point	average	
1	36.0	35.0	42.0	37.7	75.0	85.0	103.0	87.7	$1.0 \cdot 10^4$
2	30.0	30.0	35.0	31.7	57.0	70.0	100.0	75.7	$1.1 \cdot 10^4$
3	25.0	30.0	40.0	31.7	58.0	65.0	69.0	64.0	$1.5 \cdot 10^4$
4	32.0	25.0	45.0	34.0	60.0	65.0	100.0	75.0	$1.2 \cdot 10^4$
5	25.0	25.0	35.0	28.3	75.0	85.0	102.0	87.3	$8.5 \cdot 10^3$
6	32.0	37.0	43.0	37.3	77.0	82.0	90.0	83.0	$1.1 \cdot 10^4$
7	30.0	33.0	45.0	36.0	60.0	70.0	100.0	76.7	$1.2 \cdot 10^4$
8	25.0	35.0	40.0	33.3	72.0	83.0	101.0	85.3	$9.6 \cdot 10^3$
9	30.0	35.0	42.0	35.7	60.0	70.0	100.0	76.7	$1.2 \cdot 10^4$
10	28.0	34.0	45.0	35.7	58.0	74.0	98.0	76.7	$1.2 \cdot 10^4$
Package stiffness value									$1.1 \cdot 10^4$

The distribution of the observation results follows a normal law.

The distribution of the observation results follows a normal distribution [18]. The mean square value and deviation were calculated according to the method [19], and the stiffness was determined by the formula:

$$C = \frac{\Delta P}{\Delta}, \quad (1)$$

where ΔP - is the difference in weight of the weights, N; Δ – is the difference in instrument readings, m.

III. PROBLEM SOLVING

When performing computer modelling of winding processes, it is necessary to achieve maximum compliance of the solid-state computer model of the rolling-in roller with physical models, which will allow comparing the results of a physical experiment on existing equipment with analytical calculations and determine the magnitude of the influence of factors that were taken arbitrarily or by recommendations.

The assumptions and description of the computer model factors are as follows:

1. The mass and geometric dimensions of the computer model's roller should correspond to the physical values of the roller (elements);
2. The resistance arising from friction in rolling bearings and inertial characteristics of the roller at the initial moment of start-up is neglected since its influence on the modelling result will be minimal when the speed is set;
3. The geometric 3D model of the package is a two-part model in which each element is assigned its material: the spool is STEV, and the package is the material of the yarn "Nylon". The thickness of the winding body was taken into account discretely with an interval of 10 mm and built in the form of model configurations developed according to the methodology [20, 21]. The outer surface of the package is smooth, and the thread winding structure is not considered.
4. The rolling-in roller is an assembly unit containing an axle and a rolling-in roller (solid or elemental) assembled with rolling bearings. Thus, the value of the mass of the rollers coincides with the values of the mass of the rollers of the physical model;

5. The force of pressing the rolling-in roller against the package (bobbin) depends on the thickness of the winding body (its value varies by about 10%), therefore, to bring the computer model closer to the physical (actual) mechanism and simplify calculations, $F = 3.6$ N is taken (obtained by measurement and corresponds to the average value for the Polycon machine);

6. Assume that the contact of the rolling-in roller with the package is carried out along the entire length of the generative cone of each configuration of the package (spool), the friction coefficients between the bodies correspond to the materials used, the stiffness at the contact of the package body with the rolling-in roller corresponds to the experimental values $C = 1.1 \cdot 10^4$ N/m. All parameters are considered by setting the "3D contact" option of the SolidWorks Motion calculation system [20, 21].

7. To simplify the computer model, the analysis excluded the mechanism parts that do not significantly affect the analysis results, such as fasteners and rolling bearing parts. Instead, their influence on the system was replaced by external forces, and bushings replaced the bearing supports with the appropriate coefficient of friction and stiffness [20, 21].

The assumptions made mainly take into account the actual physical properties of the materials of the winding mechanism during the winding of the package and the interaction force between the package and the rolling-in roller, the value of which depends on the current system parameters, as well as the physical properties of the parts.

The modelling of the package winding process took into account the actual physical properties of the winding mechanism materials and the forces of interaction between the package and the rolling-in roller. To create a 3D computer model of the winding mechanism, the contact of the rolling-in roller and the package along the cone face was used, where the position of the rotation axes of the rolling-in roller and the package were set using 3D contact. To carry out simulation modelling of the winding process, 20 variants of 3D models of winding mechanisms with different types of rollers (modifications M1, M2, M3, M4) and a package with a fixed instantaneous body thickness ($t=0, 10, 20, 30, 40$ mm) were created (Fig. 2).

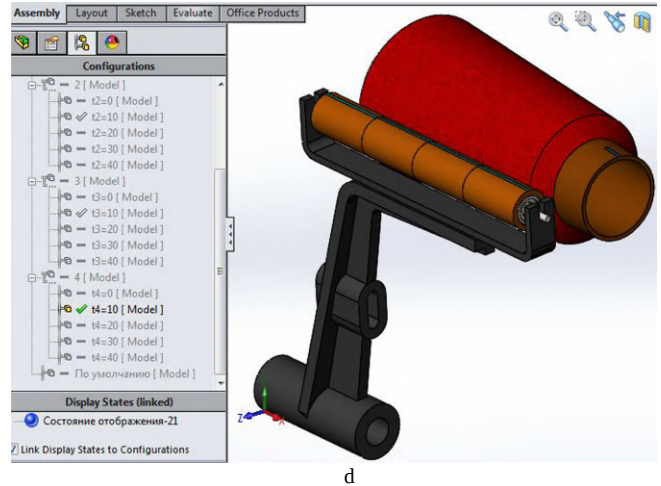
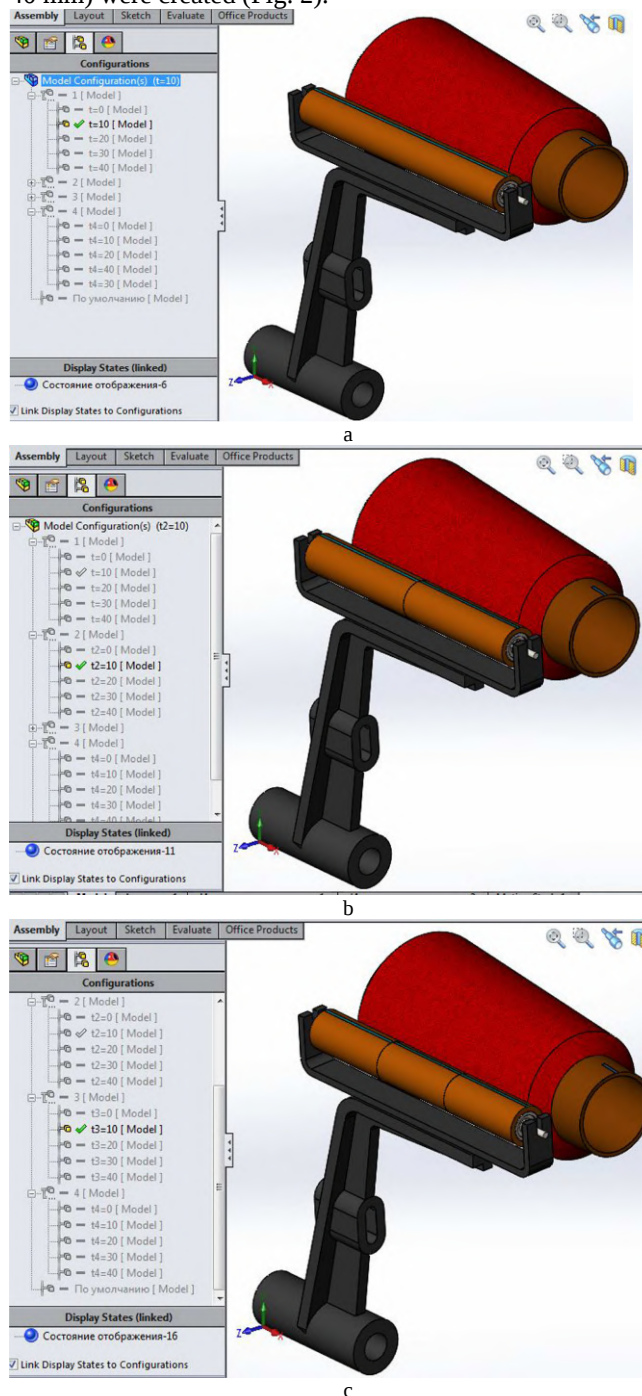


Fig. 2. Configurations of solid-state computer 3D models of the reeling mechanism for the machine "Polycon": a - with a single-element rolling-in roller (M1); b - with a two-element rolling-in roller (M2); c - with a three-element rolling-in roller (M3); d - with a four-element rolling-in roller (M4)

To verify the moving masses of the 3D models of the rolling-in rollers (elements) and the rocker (Fig. 3), the SolidWorks "Mass Properties" application was used, and the results are shown in Table 2.



Fig. 3 Design of the roller: a - physical models of the elements of the rollers; b - computer solid models of the elements of the rollers and their mass-inertial parameters

TABLE 2

Mass and inertial parameters of the links of the roller device

Modification of the rolling-in roller	Weight of the rolling-in roller assembly, kg	
	Physical model	computer model
M1	0,10	0,097
M2	0,090	0,083
M3	0,093	0,084
M4	0,091	0,083
rocker arm	0,860	0,845

As the measurement results show, the mass difference does not exceed (3÷7%) of the mass of the mechanism parts used in the "Polycon" machine. To implement the kinematic analysis, we used the configurations of the 3D model of the mechanisms (Fig. 2). As an example, Fig. 4a shows a computer model of a winding mechanism with specified material properties and imposed restrictions on the movement of elements for a three-element rolling-in roller (modification M3) with a winding body thickness of $t = 30$ mm.

The rotation frequency of the package (spool) is $n=1650 \text{ min}^{-1}$ ($\omega=172.78 \text{ rad}^{-1}$), and the direction is counterclockwise, which corresponds to the operating speed of the machine "Polycon" (Fig. 4b).



Fig. 4. Kinematic parameters of the winding mechanism: a - setting the parameters of the spool speed and direction from the computer model of the mechanism; b - indicators of the operating speed on the "Polycon" machine

The relative value of sliding ε_{xi} of the cylinder on the cone is determined by the expression [10], taking into account the sign:

$$\varepsilon_{xi} = \frac{v_{si}}{v} = \frac{x - m_i}{l_{pi} - m_i}, \quad (2)$$

$$v_{si} = v_i^{\max} - v_i^{\min}, \quad v_i^{\max, \min} = \frac{l_{pi} \pm (x - m_i)}{l_{pi}} v_{pi}, \quad (3)$$

where v_s – sliding speed, m/s;

v_{pi} – speed in the rolling pole, m/s;

$v_i^{\max}, v_i^{\min}$ – are, respectively, the maximum and minimum speeds of the i -th roller, m/s.

l_{pi} – is the distance from the i -th rolling pole P_i of the i -th element of the rolling-in roller to the top of the packing cone;

m_i – is the value of the displacement of the i -th rolling pole P_i .

For the extreme case when $F_t = F_n \cdot f$ and $\beta = 1$ [10], coordinate m_i coincides with the geometric centre of the contact line of the i -th element of the rolling-in roller, while

the geometric slip rate v_s reaches its maximum at the value of:

$$x_i = \pm \frac{b_i}{2}, \quad (4)$$

where i – is the number of rolling elements; b_i – is the length of the contact line of the rolling element along the packer face, m. Obviously, for the outermost elements of the rolling-in roller, the length of the contact line along the tangent will depend on the thickness of the package body t and the number of elements in the rolling-in roller.

Taking into account (3) and (4), the sliding speed of the i -th element of the rolling-in roller:

$$v_{si} = \frac{2 \cdot (0.5b_i - m_i) \cdot v_{pi}}{l_{pi}}. \quad (5)$$

The geometric slip of the elemental roller will be equal to the sum of the geometric slips of each element and, according to [10], will be as follows:

$$\varepsilon_x = - \sum_{i=1}^n \frac{0.5b_i - m_i}{l_{pi} - m_i}. \quad (6)$$

The frequency of rotation of the i -th element is determined by taking into account the pure rolling and the value of the gear ratio:

$$n_i = \frac{l_{pi} \cdot \sin(a)}{r_2} n, \quad \omega_i = \frac{l_{pi} \cdot \sin(a)}{r_2} \omega, \quad (7)$$

where n_i, n – respectively rotational speeds of the i -th element of the rolling-in roller and the packer, min^{-1} ;

ω_i, ω – the angular frequencies of the i -th element of the rolling-in roller and the packer, s^{-1} ; r_2 – radius of the rolling-in roller ($r_2 = 11 \cdot 10^{-3} \text{ m}$);

a – the angle of inclination of the forming cone of the packaging ($a = 3.27$ degrees).

For the analytical calculation of the slippage rate, the geometric parameters of 3D models of the package (Figure 6) were determined according to the method [10], and the parameters of contact between the elements of the rollers and the package (Tables 3 and 4) were determined according to [20, 21]. The beginning of the numbering of the roller elements is from the larger diameter of the package cone.

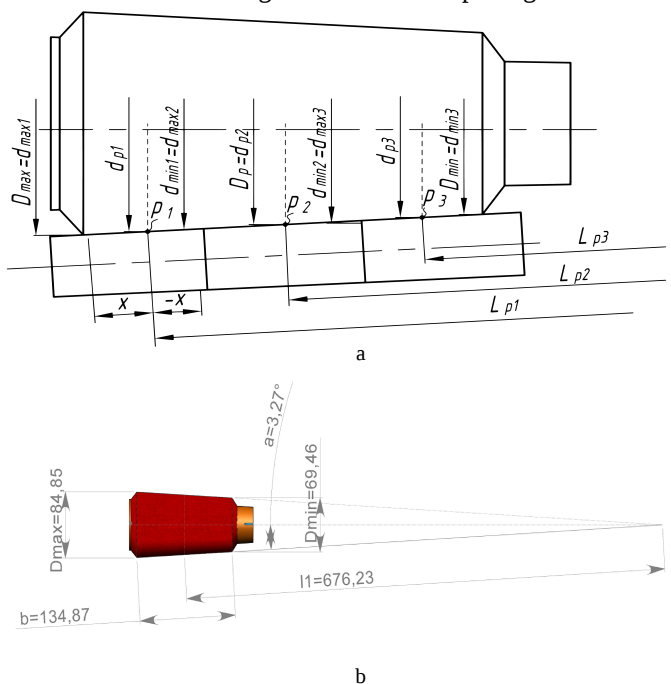


Fig. 6. Geometrical parameters: a - contact with the i -th element of the rolling-in roller and the packaging; b - the i -th package

TABLE 3
Geometrical parameters of the package depending on the thickness of the winding body t

№	Thickness of the package body, t	Minimum cone diameter, $D_{\min}$	Maximum cone diameter, $D_{\max}$	The diameter of the package in the rolling pole, D_p	Length of the package cone, b	The angle of the package cone, a
	$\cdot 10^{-3} \text{ m}$					degree
1	0	48,8	65,9	57,0	150,1	3,27
2	10	69,5	84,8	77,0	134,9	
3	20	90,3	104,0	97,0	119,5	
4	30	111,2	123,1	117,0	104,1	
5	40	132,1	142,2	137,0	88,8	

TABLE 4
Geometrical parameters of the contact between the package and the first element of the rolling-in roller, mm

Modifications of the rolling-in roller	Body thickness of the package, t	b1	b2	b3	b4	lp1	dp1	lp2	dp2	lp3	dp3	Lp4	dp4
M1	t0	160	-	-	-	502,7	57,4	-	-	-	-	-	-
	t1	134,9	-	-	-	676,2	77,2	-	-	-	-	-	-
	t2	119,5	-	-	-	851,5	97,2	-	-	-	-	-	-
	t3	104,1	-	-	-	1036,8	117,16	-	-	-	-	-	-
	t4	88,8	-	-	-	1208,1	137,16	-	-	-	-	-	-
M2	t0	80	80	-	-	539,9	61,6	464,8	53,1	-	-	-	-
	t1	68,2	66,8	-	-	709,7	77,1	642,2	73,26	-	-	-	-
	t2	60,5	59,0	-	-	881	100,5	821,3	93,7	-	-	-	-
	t3	52,8	51,3	-	-	1052,4	120,1	1000,4	114,1	-	-	-	-
	t4	45,2	21,8	-	-	1223,9	139,6	1179,5	134,6	-	-	-	-
M3	t0	53,3	53,3	53,3	-	553,2	63,2	502,7	57,4	451,5	51,54	-	-
	t1	41,6	53,3	40,0	-	722,9	82,5	676,2	77,2	628,8	71,78	-	-
	t2	33,9	53,3	32,3	-	894,3	102,1	851,5	97,2	807,9	92,14	-	-
	t3	26,2	53,3	24,6	-	1065,8	121,6	1026,8	117,2	987,1	112,3	-	-
	t4	18,5	53,3	16,9	-	1237,2	141,2	1208,1	137,2	1166,2	132,02	-	-
M4	t0	40	40	40	40	559,8	63,9	521,9	59,6	481,9	55,0	444,8	50,8
	t1	28,2	40	40	26,7	729,6	83,2	695,5	79,4	655,5	74,8	622,1	71,0
	t2	20,5	40	40	19,1	901,0	52,8	870,7	99,4	830,7	94,74	801,3	91,4
	t3	12,8	40	40	11,8	1072,4	124,4	1046,0	119,4	1006,1	114,46	980,4	111,5
	t4	5,5	40	40	3,6	1243,9	141,9	1221,3	139,4	1181,3	133,76	1159,5	131,3

The position of the i -th rolling pole P_i of a particular element of the rolling roller relative to the apex of the packaging cone can be obtained based on its angular velocities $\omega_i^{Model.}$, using equation (7):

$$l_{pi}^{Model.} = \frac{\omega_i^{Model.}}{\omega} \cdot \frac{r_2}{\sin(a)}. \quad (8)$$

The coordinates m_i of the rolling pole P_i of the i -th element for the computer model are found as the difference between the values of its geometric distance to the top of the packing cone l_{pi} (Table 4) and the same value obtained from the expression (8):

$$m_i = l_{pi}^{Model.} - l_{pi}^{Theor.},$$

or

$$m_i = \frac{r_2 \cdot (\omega_i^{Model.} - \omega_i^{Theor.})}{\omega \cdot \sin(a)}. \quad (9)$$

Expression (10) shows how the parameters of the 3D contact, the force of the roller pressing against the package, and other factors affect it.

IV. RESULT

The computer experiment was carried out for different modifications of the rolling-in roller depending on the

winding body - t , a series of calculations was performed for 20 models in total. The results of the computer simulation of the modified M4 winding mechanism, taking into account the thickness of the package body $t=20$ mm, are shown in Fig. 7.

The curves in Fig. 7 show the rolling-in roller elements' maximum speed and acceleration time (acceleration $\varepsilon \neq s^{-2}$ at the moment of start-up). In addition, it was found that during the movement at the set speed, speed fluctuations occur ($\varepsilon \approx 0 s^{-2}$); these fluctuations can be caused by various factors, such as slipping of the roller elements, changes in bearing surfaces, or interaction between different parts of the mechanical system. The data obtained allow for a more detailed engineering analysis of the mechanical system, which can be used to improve its performance.

To compare the results of the computer experiment and maintain the integrity of the assumptions made and the adequacy of the comparison result, we take the value of the speed of the roller as the arithmetic mean at the set speed when the acceleration is $\varepsilon \approx 0 s^{-2}$. The calculation results and other values of the angular velocity of the roller elements depending on the thickness of the package body t are presented in Fig. 8.

The values of the total sliding speed and relative slip were determined by expressions (4) and (5), taking into account (8) and (9). Diagrams of the average values of the sliding speeds of the rollers of modifications M1-M4 are shown in Fig. 9.

The angular velocity values obtained are used to determine the value of the rolling pole displacement m_i Fig. 10.

The results of solving the problem of computer modelling made it possible to determine the level and nature of the distribution of the rolling-in roller rotational speeds, as well as the value of the pole displacement - m_i of the rolling centre of a cylindrical roller on a conical package, which ultimately makes it possible to assess the effect of the rolling-in roller pressing force on the rolling centre displacement and determine the adhesion coefficient.

Fig. 7 shows the results of computer modelling of the roller (elements), namely, graphs of the values of the rotational speeds of the rollers and their oscillations arising from the difference in the linear speeds of the roller and the ends of the package. It should also be noted that the maximum value of the rotation speed is reached in different time intervals, which indicates a close acceleration of each roller in relation to the current value of the bale diameter.

Changing the diameter of the bobbin and increasing the number of rollers leads to a change in the frequency of their rotation. At the same time, the acceleration value will be different for different rollers, with a simultaneous increase in the diameter of the package for the outermost elements of the roller, the length of the contact line along the face decreases and, accordingly, the speed difference at its ends decreases (the value $v_s \rightarrow 0$). At the same time, the inner rollers have a constant value of the constituent's length; accordingly, the slip value is directly proportional to the value of the diameter of the package in the pole.

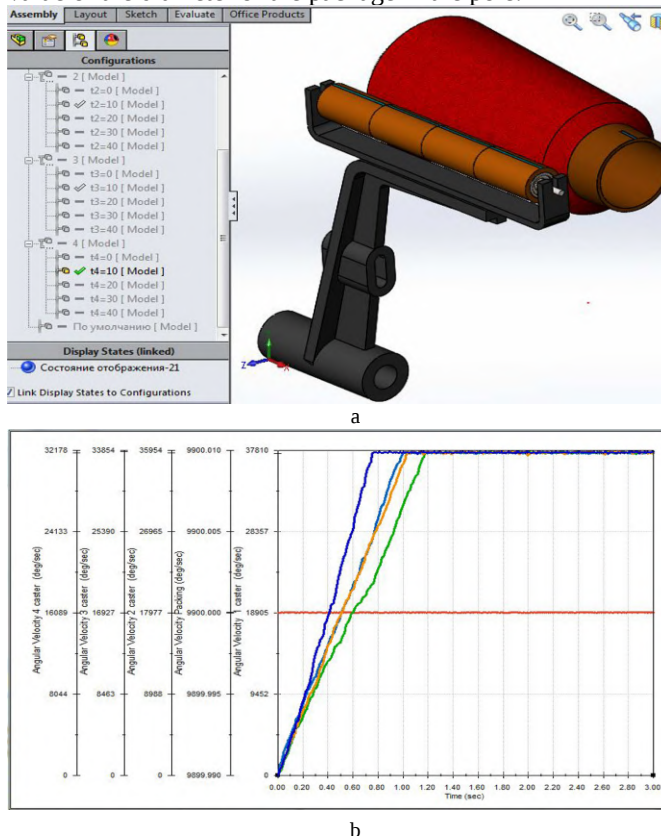


Fig. 7. Diagrams of the angular velocity of the rolling elements of the M4 modification roller at $t_2=20$ mm

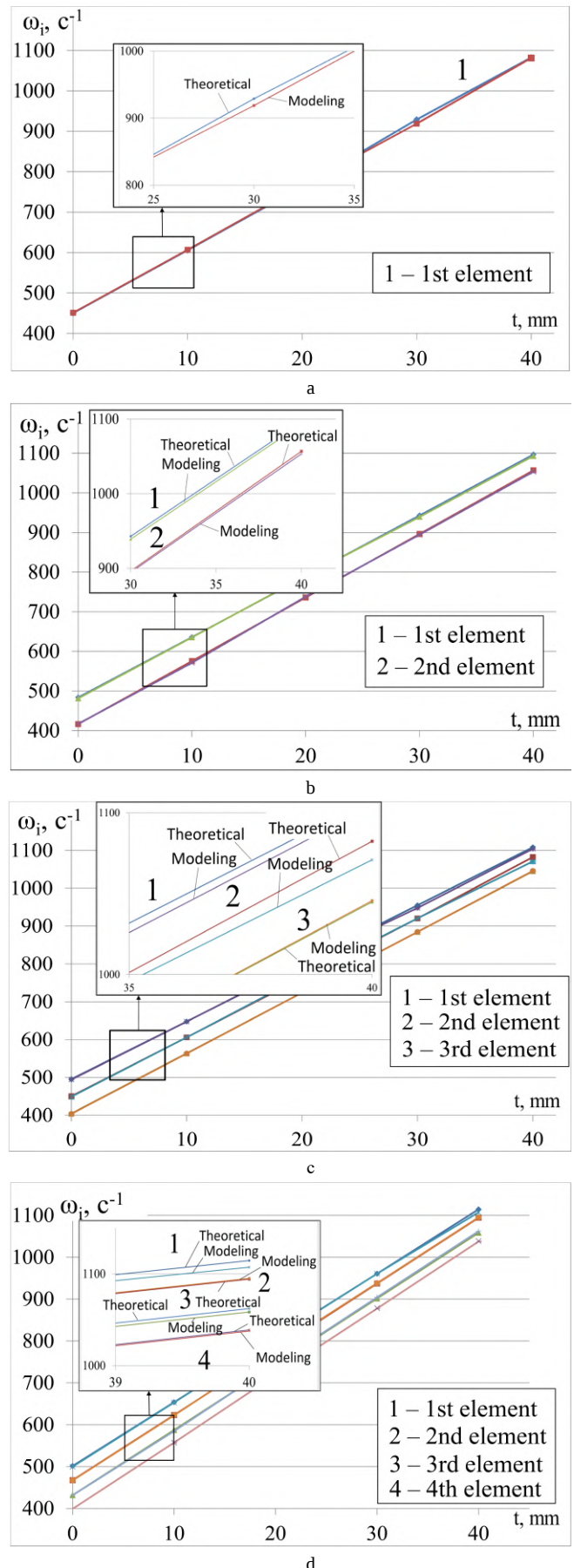
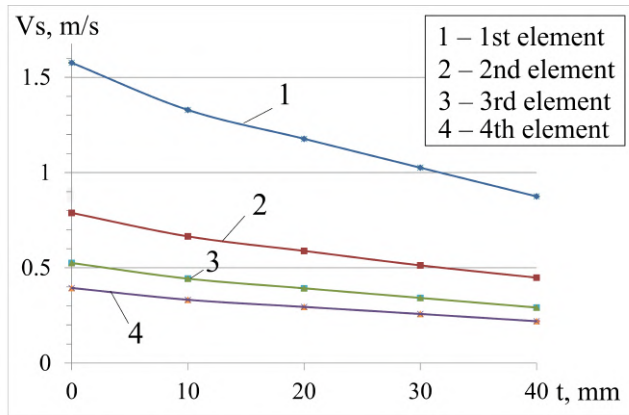


Fig. 8. Diagrams of the angular velocity of the rollers depending on the number of elements obtained theoretically and by computer modelling (c^{-1}): a - Diagram of the angular velocity of the M1 modification rolling-in roller; b - Diagram of the angular velocity of the elements of the rolling-in roller of the M2 modification; c - Diagram of the angular velocity of the elements of the rolling-in roller modification M3; d - Diagram of the angular velocity of the elements of the rolling-in roller of the M4 modification



1 - M1 modification rolling-in roller; 2 - M2 modification rolling-in roller; 3 - M3 modification rolling-in roller; 4 - M4 modification rolling-in roller
Fig. 9. Diagrams of the average sliding speed of the rollers

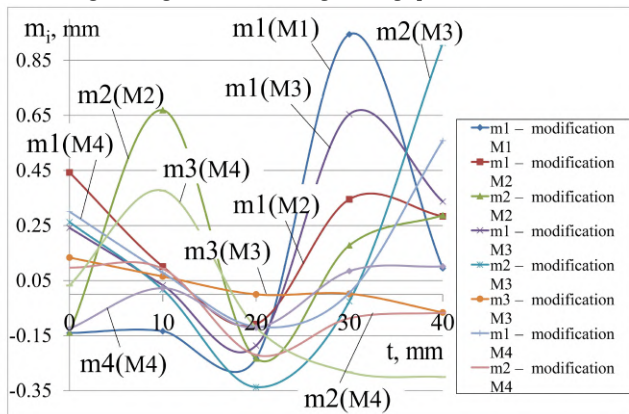


Fig. 10. Diagrams of the pole displacement m_i for the i -th rollers (mm)

The dependences of the rolling-in roller slip on the surface of a conical package were analytically determined. The calculation results show a decrease in slippage and friction energy consumption when using an improved four-element design of the roller. The analysis results make it possible to determine the optimal characteristics of winding mechanisms using a certain number of elemental rollers, depending on the package's parameters.

V. CONCLUSIONS

1. The conducted research showed that the values of the winding roller speed, obtained through computer modelling methods, confirm the reliability of the calculations and the high accuracy of the results (approximately 95%), which is an accepted standard for engineering calculations.

2. It was established that increasing the winding body from 0 to 0.04 m reduces the average sliding speed for all modifications of the mechanisms by approximately 43-45%.

3. Applying element rollers of modifications M2-M4 reduces the sliding speed by 48.0-75.3% compared to the solid roller of modification M1.

4. During a series of computer simulation experiments, it was found that the contact between the rolling-in roller and the package is not constant, and a rebound phenomenon (loss of physical contact) occurs, revealing opportunities for further in-depth research.

5. The obtained results allow the determination of the optimal characteristics of winding mechanisms, and the proposed computer experiment algorithms using computer simulation modelling can be applied to the design or study of typical rewinding machines or friction drives.

The modelling results can be successfully applied in further research on winding mechanisms and in the design and construction of new equipment

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