SIMULATION AND ANALYSIS OF THE LOOP SPINNING SYSTEM

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Abstract
In this paper, the theory of the ballooning yarn has been adapted to the loop spinning process. The aim of a numerical simulation of high-speed winding process consists in establishing the shape of the curve of rotating yarn in the section between the gripping line of drafting motion rollers and the place where the yarn is wound upon a tube, and in determining the tensile force in the yarn in the said section. The compiled mathematical model serves for analysis and optimisation of boundary conditions of the examined winding process. The method of the determination of the ballooning yarn curve with usage of high speed cameras is used for the verification of the mathematical model. Shape of the ballooning yarn is defined by image analysis from video files.
Key words: loop spinning system, mathematical model, high- speed camera

1. Introduction

Nowadays, the world pays much attention to the research of new spindle systems of formation of yarn with permanent twist at high spinning velocities. In these systems, the yarn twisting and the winding of yarn upon the bobbin constitute an inseparable process. The aim of numerical simulation of the high-speed winding process consists in establishing the shape of the curve of rotating yarn in the section between the gripping line of drafting motion rollers and the place where the yarn is wound upon a tube, and in determining the course of tensile force in the yarn in the said section.

The loop spinning system ranks among systems where friction shear forces and resistance of air play an important role. The process of yarn formation is related with the rotation of yarn round a fixed axis, generating a phenomenon which is called yarn ballooning. The results presented up to now demonstrate non-linear character of the physical phenomenon of yarn ballooning. The compiled mathematical model will be employed for simulation of the complete process of yarn winding under determined boundary conditions. Attention is paid to the solution of movement of the yarn on the yarn carrier (separator).

The examined process is described by a system of non-linear differential equations of 2nd order. As an analytic solution can be obtained under a series of very simplifying assumptions only, there have been employed suitable numerical algorithms and methods for establishing the shape of the curve of rotating yarn and the course of tensile forces.

2. The mathematical model

2.1 Constructional arrangement of the winding and spinning system

The twisting of yarn is provided by means of a rotating hollow body (carrier, separator), through the hollow of which the produced yarn is passing, lying on its inner wall (see Fig.1). The rotating inner wall carries the yarn, and at the same time, it functions as separator of the yarn balloon, which would be generated by the rotating yarn. The angular velocity of carrying rotational movement of the yarn with respect to the carrier changes in dependence on the winding diameter, and the yarn is dragged along the inner wall of the carrier. After leaving the hollow of the carrier, the yarn passes upon a fixed ring, serving for reduction of outer diameter of the rotating loop. From the ring, the yarn passes into a loose balloon, it creates a loop and it is wound upon a bobbin. The loop of ballooning yarn participates considerably in the magnitude of the tensile force in the winding process. The loop spinning ranks among the systems of yarn formation with a constant balloon height.

The Fig. 2 shows the shape of the separator of the examined loop spinning system. In the past, its design was more complicated 1, however, the practice has shown that even a simpler configuration makes the system functional.

The simplified diagram in the Fig. 1 consists of the following components:

carrier 1,
rotating peg of the spindle 2,
tube of the carrier 4,
gripping line of output rollers of the drafting motion 5,
place of winding 6,
support ring 7,
guide eye (not shown).

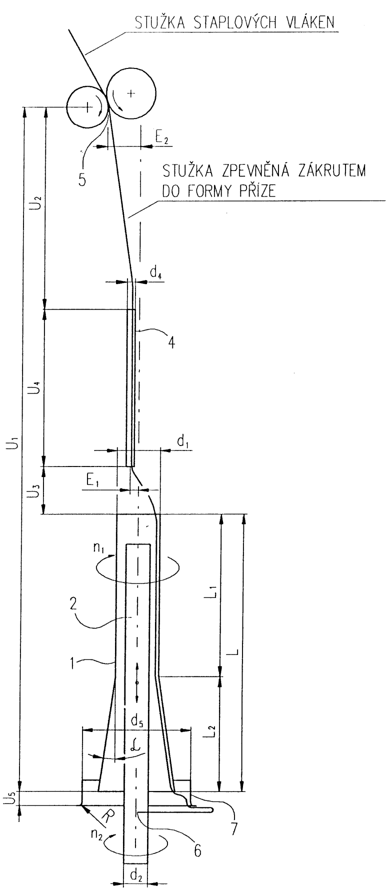

Fig. 1: Alternate diagram of loop spinning
(In the fig.: BAND OF STAPLE FIBRES // BAND STRENGHTENED BY TWISTING TO THE FORM OF YARN)

2.2 Assumptions defining the mathematical model

An exact solution of the shape of the yarn curve in general three-dimensional case results very difficult. It is practically impossible to get a simple analytic expression of the shape of this curve. Under certain simplifying assumptions, it is possible to establish the curve of the moving yarn by numerical solution of the given boundary problem.

Assumptions defining a simplified model of the ballooning yarn:

- the yarn is elastic ideally,
- the yarn is uniform in mass,
- the deformation of the yarn is not influenced either by relaxation or creeping phenomena, and it does not depend upon temperature,
- the carrying angular velocity of the yarn is constant,
- the relative velocity of the yarn feeding is constant,
- the boundary conditions are independent on the time,
- the high-frequency phenomena, bringing about the vibration of yarn round the quasi-stationary position, are not considered in the model,
- the effect of air resistance in the direction of a tangent to the curve of ballooning yarn is disregarded.

2.3 Equations of motion of loosely ballooning yarn

For the case of ballooning yarn according to Fig. 3, we shall introduce a system of cylindrical co-ordinates $Or\varphi z$, revolving round the co-ordinate axis z at an angular velocity ω. The beginning O of the co-ordinate system is in the centre of the guide eye 4 and the axis z is identical with the axis of the spindle 2. The angular velocity of rotating loop is ω and the relative velocity of yarn is w.

The equation of equilibrium of the yarn element of the length ds is of the following form:

$$\mathbf{F}_V + \frac{d(T\mathbf{t})}{ds} = \mathbf{0}\,, \qquad (1)$$

where F_V is the resulting outside force acting upon the element ds, referred to the unit of yarn length, t is the unit vector of the tangent to the curve of ballooning yarn and T is the yarn tension. The equation (1) can be broken down into the following component equations according to Migushov [3]:

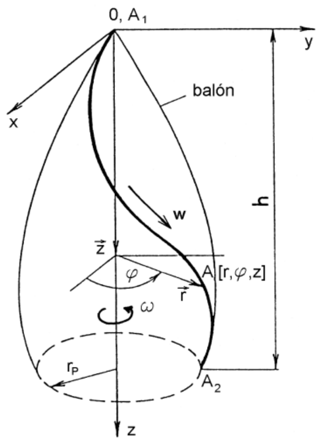

Fig. 2: Yarn balloon

$$\frac{d}{ds}\left(T_a\frac{dr}{ds}\right) - T_a r\left(\frac{d\varphi}{ds}\right)^2 + \frac{\mu_0}{f(T)}\omega^2 r + 2\frac{\mu_0}{f(T)}w\boldsymbol{\omega}r\frac{d\varphi}{ds} + F_{or} = 0$$

$$\frac{1}{r}\frac{d}{ds}\left(T_a r^2\frac{d\varphi}{ds}\right) - 2\frac{\mu_0}{f(T)}w\omega\frac{dr}{ds} + F_{o\varphi} = 0 \qquad (2)$$

$$\frac{d}{ds}\left(T_a\frac{dz}{ds}\right) + \frac{\mu_0}{f(T)}g + F_{oz} = 0$$

$$T_a = T - \frac{\mu_0}{f(T)}w^2\,, \qquad \frac{ds}{dl} = f(T), \qquad \left(\frac{dr}{ds}\right)^2 + r^2\left(\frac{d\varphi}{ds}\right)^2 + \left(\frac{dz}{ds}\right)^2 = 1\,,$$

where μ_o is the fineness of yarn, l is the length of not loaded yarn, F_{or} , $F_{o\varphi}$, F_{oz} are the components of the air resistance when by-passing the yarn referred to the unit of yarn length, g is the gravity acceleration.

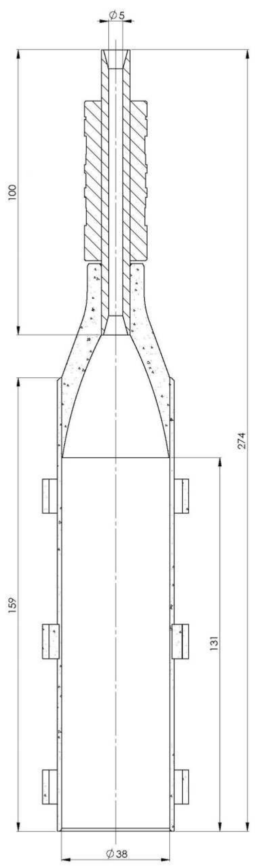

Fig. 3: Diagram of the separator

2.4 Equations of motion of the yarn on balloon separator

During its movement on the separator, the yarn is influenced – in addition to forces produced in loose ballooning – by the reaction from the separator. The same can be broken into the normal component and into the shear one

$$\mathbf{N} = R\mathbf{n}_0 \qquad\qquad \mathbf{F}_S = -Rf_1\frac{\mathbf{v}}{v}\,, \qquad (3)$$

where R is the reaction on the yarn from the separator referred to the unit of yarn length, n_o is the vector of the normal line to the plane constituting the surface of the separator, given by the equation $P(r,\varphi,z) = 0$, f_1 is the co-efficient of shear friction between the yarn and the separator.

For balloon separators that are symmetrical axially with respect to the axis of rotation z there holds that the normal component of the reaction lies in the meridian plane. The equations of motion of the yarn in loose balloon (2) can therefore be adapted for the movement of yarn on balloon separator into the following general form:

$$
\begin{aligned}
&\frac{d}{ds}\left(T_a\frac{dr}{ds}\right)-T_a r\left(\frac{d\varphi}{ds}\right)^2+\frac{\mu_0}{f\,(T)}\omega^2 r+2\frac{\mu_0}{f\,(T)}w\omega r\frac{d\varphi}{ds}+F_{or}+N_r+F_{Sr}=0\\
&\frac{1}{r}\frac{d}{ds}\left(T_a r^2\frac{d\varphi}{ds}\right)-2\frac{\mu_0}{f\,(T)}w\omega\frac{dr}{ds}+F_{o\varphi}+F_{S\varphi}=0\\
&\frac{d}{ds}\left(T_a\frac{dz}{ds}\right)+\frac{\mu_0}{f\,(T)}g+F_{oz}+N_z+F_{Sz}=0\\
&T_a=T-\frac{\mu_0}{f\,(T)}w^2,\qquad \frac{ds}{dl}=f\,(T),\qquad \left(\frac{dr}{ds}\right)^2+r^2\left(\frac{d\varphi}{ds}\right)^2+\left(\frac{dz}{ds}\right)^2=1
\end{aligned}
\tag{4}
$$

$P(r,\varphi,z) = 0$

where N_r and N_z are components of normal reaction, F_{Sr}, $F_{S\varphi}$, F_{Sz} are components of shear reaction. The general motion equations (4) are specified in the model for the chosen plane of the balloon separator. In case of the examined loop spinning system, it is a cylindrical, conical or toric plane.

2.5 Boundary conditions

From the point of view of acting forces, the curve of the twisting yarn in the spinning system can be divided into several sections, depending whether the yarn balloons loosely in the concerned section or the yarn balloon is limited in some manner. Furthermore, particular attention is paid to that section of the spinning system that is characterised by yarn ballooning, both with loose and with limited balloon. The proposed mathematical model simulates the process of yarn formation in the section between the guide eye 4 and the winding of the yarn upon the tube of rotating spindle 6 (Fig. 1). The part of the system between the output of fibre band from the drafting motion 5 and the guide eye 4 is not included in the model directly, because the change of forces acting upon the yarn in this section is not significant. The model includes the angle of embracement of the yarn on the guide eye and the increase of tensile force determined by the Euler's relation:

$$T_o = T_s.e^{f_0 \cdot \beta}, \tag{5}$$

where T_o is the value of tensile force in the place where the yarn leaves the guide eye 4, f_o is the co-efficient of shear friction between the yarn and the guide eye, T_s is the value of tensile force above the guide eye 4 and is equal to the value of the force in the area of the gripping line 5 practically, β is the total angle of embracement of yarn on the guide eye.

As has been stated already, during its formation in the spinning system in compliance with the Fig. 1 and Fig. 2, the yarn passes through several sections, differing in particular by their geometric shapes and different forces acting upon the yarn. Namely, they are the following eight sections:

- first section of loosely ballooning yarn between the guide eye and the input to the carrier tube, including the transfer of yarn upon its inner wall; the small cone on the input section is not considered,
- the section of yarn movement on the inner wall of the cylindrical part of the carrier tube, including the transfer upon its conical end section, considering the Euler's relation for the increase of tensile force,
- the section of yarn movement on the inner wall of the conical section of the carrier (angle 27°)
- the section of yarn movement on the toric plane including the transfer of the yarn upon the inner cylindrical wall of the carrier
- the section of the yarn movement on the inner wall of cylindrical section,

- the section of loosely ballooning yarn between the carrier and the static wall of the cylindrical ring, including the transfer of yarn upon its inner wall,
- the section of yarn movement on the inner wall of the static ring, including its transition into a loose balloon, considering the Euler's relation for the increase of tensile force,
- the section of loosely ballooning yarn between the bottom edge of the static ring and the place of winding on the bobbin.

In the last section of loosely ballooning yarn, the compiled model considers the movement of the rotating loop in the plane perpendicular to the spindle axis only, i.e. the distributing motion of the spindle board has been disregarded.

2.6 Numerical solution of the mathematical model

The solution of the model of ballooning yarn leads generally to a boundary problem for a system of non-linear differential equations of 2nd order. These equations comprise the sought functions r(s), φ(s), z(s), T(s), and their first or second derivatives. The length of arc of the curve s figures here as an independent variable. The system of equations (2) or (4) can be resolved with respect to the highest derivatives of sought functions, and converted into a system of equations of 1st order. The boundary problem is resolved by the shooting method, where the character of the boundary conditions allows converting the solution into a problem with initial conditions.
The calculation of the yarn curve is carried out for each section of the spinning system separately, with some sections leading to a boundary problem. The system of differential equations is resolved by the Runge-Kutt method. For determining the approximations of the missing initial values, the iteration method of secants has been employed. As the basis of the calculation, there serves the outer iteration cycle for determination of the initial value T(0), and the iteration is ended if the boundary condition on the wound bobbin is fulfilled. The missing initial values of individual sections are determined by means of inner iteration cycles; for example, for the first section there is resolved the progression of initial problems with varied values r´(0), and the iteration is ended if the boundary conditions in the place of transfer of loosely ballooning yarn upon the cylindrical plane of the carrier tube are fulfilled.
For the resolution of the problem, there has been compiled a program in the environment MATLAB, allowing to obtain discrete values of the functions r(s), φ(s), z(s), T(s), from which it is possible to establish the shape of the curve of rotating yarn and the yarn tension in an arbitrary point of this curve, for all the sections of the spinning system.

3. Analysis of rotating curve of the yarn

There is examined the effect of extension of the static ring to the maximum radius and the tensile force in the produced yarn.

Chosen parameters:

Yarn fineness	16 tex
R. p.m. of the spindle	44.000
Package diameter	22 mm
Co-efficient of friction yarn - ring	0.2

Geometry of the separator according to Fig. 2

Results of the analysis of rotating curve of the yarn

The results of the analysis are presented in form of a table. From results follows, that the influence of the ring extension is insignificant. Differences between maximal radii are in the order of millimetre tithes. The uniformity of the real yarn influences on the maximal tension force in order of cN tithes, that’s why we can consider the differences of the maximal tensile forces to be insignificant.

Off-set of the ring [10^{-3}m]	r_{max} [m]	F_{max} [N]
0	0,044267	0,355200
5	0,043886	0,350819
10	0,043651	0,348105
15	0,043310	0,344208
20	0,043367	0,344630

4. Methodology for verification of the model of high-speed winding processes

For the verification of mathematical model of loop spinning, two methods have been proposed. The first one consists in comparison of the shape of curve of ballooning yarn, formed during the process of yarn winding on the bobbin. The second way is check of the course of the axial tensile force in the yarn in a convenient point of the spinning line. However, problems arise in obtaining the verification data. It is practically impossible to monitor the complete shape of the yarn in the process of its formation from the guide eye up to the point of its winding on a bobbin. The yarn passes inside of the rotating separator, which is housed in a fixed bush because of safety reasons. Because of this reason, there is monitored only the loop of the ballooning yarn in the place where the yarn leaves the separator and is wound upon a bobbin.

The monitoring of the course of axial tensile force results more complicated still, not because of structural reasons only, but also due to the fact that the twists are introduced into the yarn step by step from the point of winding and they proceed along the yarn tow[illegible] drafting motion. The separator (carrier) operates as a twist brake, and the result is a low number of twists and consequently, low strength of the yarn in the point of possible measuring of the tensile force. The only possible place of measuring is situated between the yarn eye and the drafting motion, where the yarn does not form a balloon.

As a rule, the tensile force in yarns is measured by introducing a feeler into the yarn path; in this way, another friction zone is created, and the yarn is exposed to a higher stress. In our case, any attempts to introduce a feeler of tensile force into the yarn path have resulted in yarn breaks; therefore, we have abandoned the measuring of axial tensile force for the time being.

For verification of stationary model of the winding process, there has been employed a high-speed camera I-speed 2, and subsequently, the method of picture analysis, developed recently 2.

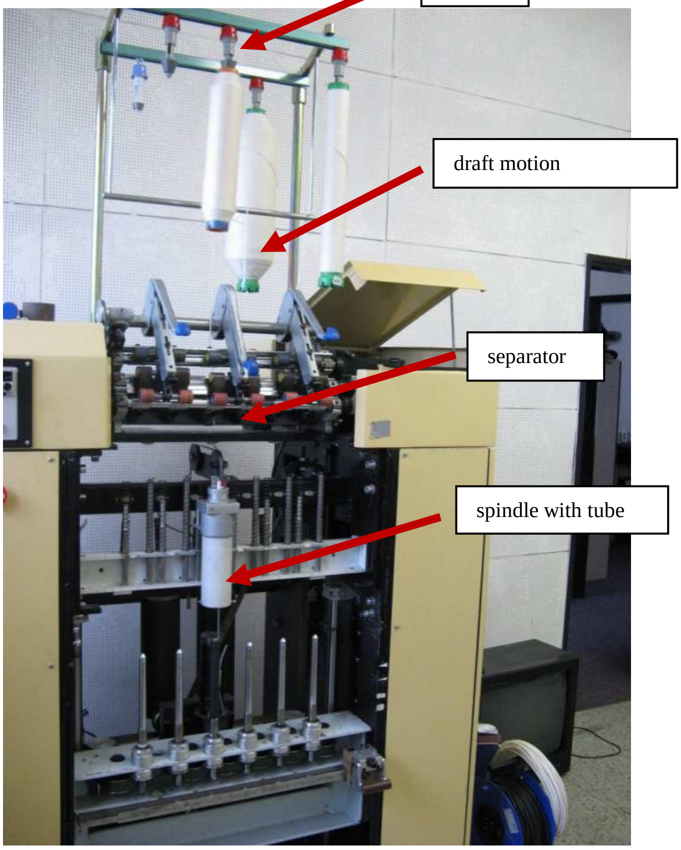

Fig. 4: Functional model of loop spinning

4.1 Experiment

The experiment has been carried out on the equipment displayed in the Fig. 4. The roving is unwound from the bobbin, brought to the drafting motion and afterwards, through the guide

eye. Subsequently, the fibre band is twisted by means of rotating separator, and wound upon a bobbin, fitted on the peg of the spindle. The ballooning yarn creates a practically planar curve, and the camera has recorded it in the axis of the spindle approximately. The installation of the camera directly in the axis of the spindle is not possible technically, and a certain distortion of results cannot be avoided.
The drive of the rotating separator is derived from the rotating spindle by means of a magnetic coupling. Consequently, only the r. p.m. of the spindle are eligible. The following table indicates the input values at which the measurings have been realised.

Yarn fineness [tex]	**R. p.m. of spindles**	**Feeding velocity [m/min]**	**α [ktex$^{2/3}$/m]**	**Twist [t/m]**
10	30000	24,9	56	1206
10	34000	28,2	56	1206
14,2	30000	29,7	60	1009
14,2	34000	33,7	60	1009
49	30100	42	96	717

The result of measurings has been a set of videos (*.avi) for various input values. The camera completes each video with a file with suffix *.uda, containing parameters of the record of individual measurings. The picture of the yarn loop has been taken with the frequency of 1.000 shots per second.

4.2 Picture analysis

An analysis of the taken photos can be carried out by means of the program supplied together with the camera, or employing other software. For our application it is more suitable to employ a program for determining the shape of ballooning yarn, developed in the past 2.
This algorithm consists in decomposing the video into individual snapshots, which in the first step are transformed from coloured ones to levels of grey. The Fig. 5 shows one of these shots.
According to the original algorithm, there followed an identification of the yarn in the picture by means of the program generated in the Matlab environment.

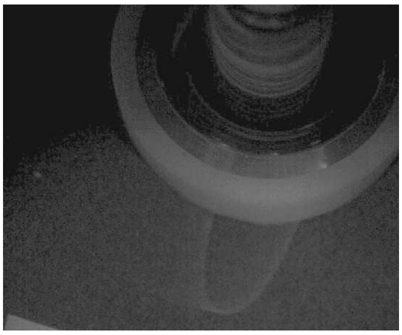

Fig. 5: The shot from the record taken by the high-speed camera I-Speed 2, yarn fineness 49tex

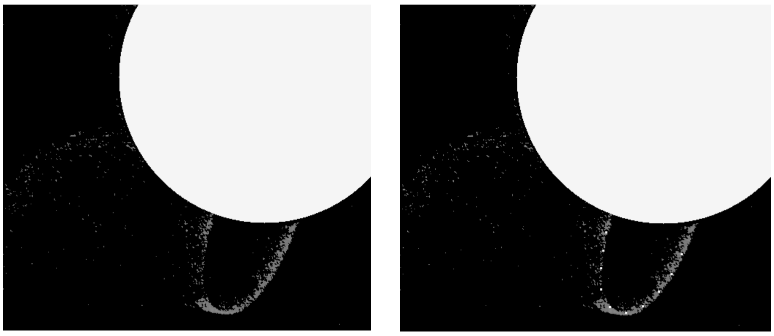

Fig. 6: On the left, the adjusted snapshot intended for the analysis, on the right, the established trajectory of the yarn

When working with the photos for yarn of the fineness 10 tex, it has been possible to identify a small part of the loop only, surpassing the edge of the separator. Due to the given lighting conditions, it is hardly possible to identify the yarn on the background of the separator. In this part of the loop, noise has been picked up only in the analysis of the picture.
Because of these reasons, we have concentrated on the analysis of shots for the yarn fineness 14.2 tex and 49tex only, where the radius of the loop reaches higher values, and a large part of the loop can be identified without problems. Better conditions for the analysis result from higher yarn fineness, too. The result of analyses is the determination of the maximum radius of the loop and of its shape. The shape of the loop is shown in the Fig. 7. The maximum radius is 48 mm.

4.3 Simulation by means of a computerized model

The above picture analysis will serve for verification of mathematical models of high-speed winding process, which are being developed. The simulation of the examined process has been carried out with the same input parameters as the measuring. The result is displayed in Fig. **8**. The maximum radius is 48.3 mm.

4.4 Comparison of results

In the Fig. 8, the result of the simulation has been planted into the diagram with elaborated results of the measuring. From this diagram there follows that in the section where it has been possible to identify the yarn, the shapes and radii of the loops obtained from the model and from the picture analysis show a very good level of agreement.

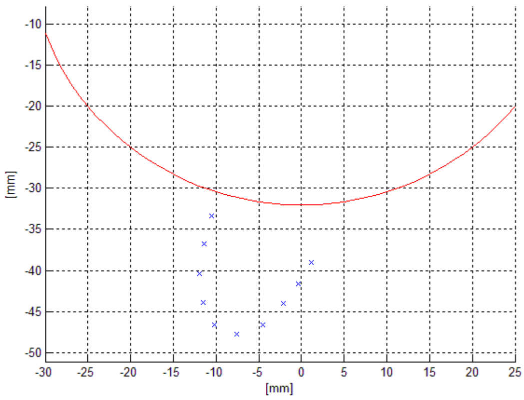

Fig. 7: Result of measuring

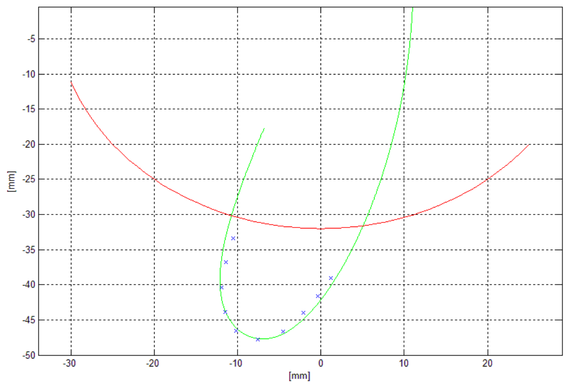

Fig. 8: Comparison of results of a simulation with measuring

5. Conclusion

The theory of the ballooning yarn has been adapted to the loop spinning process in this paper. There was described the mathematical model. From the analysis results, that the off- set of the ring does not have a big influence on the maximum tensile force and maximum radius. The method of the determination of the ballooning yarn curve with usage of high speed cameras was used for the verification of the mathematical model. Shape of the ballooning yarn is defined by image analysis from video files. From results follows that in the section where it has been possible to identify the yarn, the shapes and radii of the loops obtained from the model and from the picture analysis show a very good level of agreement.

Acknowledgements: The financial support of the Ministry of Education of the Czech Republic through research project MSM: 4674788501 is acknowledged.

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