1) Names and surnames of authors of the solution

Mirjana Filipovic,

Mihailo Pupin Institute, University of Belgrade, Volgina 15, 11060 Belgrade, Serbia. mirjana.filipovic@pupin.rs

Ljubinko Kevac,

[a]School of Electrical Engineering, University of Belgrade,
[b]Innovation center of School of Electrical Engineering, University of Belgrade,
Bulevar kralja Aleksandra 73, 11000, Belgrade, Serbia
ljubinko.kevac@ic.etf.rs

2) Name of the technical solution

Program package **CWUSOFT**, (**C**able **W**inding/**U**nwinding **SOFT**wer)

3) Key Words

winding/unwinding, winch, kinematics, dynamics.

4) For whom the solution was done (legal entity or industries)

Scientific Research for the purpose of validation of theoretical assumptions

5) The year when the solution was completed

2016.

6) Year when it began to be implemented and by whom

The program package **CWUSOFT** was implemented in published paper [1], in Journal of Mechanic, 2017, appropriate category M23.
We present the confirmation of theoretical contributions in the subtitle 4. "THE PROGRAM PACKAGE CWUSOFT" and subtitle 5. "TESTING THE CWU SYSTEM – SIMULATION RESULTS" using software package **CWUSOFT** in paper [1]. On this basis the software package CWUSOFT acquires the right to be ranked in the category M83.

7) The area and the scientific field, which the technical solution refers to

One of areas where this solution can be used is robotics CPR (Cable-suspended Parallel Robot). However, robotics is not the only scientific area where program package **CWUSOFT** can be used. There are a lot of these systems in different areas of science and engineering. Some of these systems are: measuring mechanism, machines in textile industry, cable logging systems in civil engineering and forestry, cranes, systems in shipping industry, and other complex cable driven systems.

8) Problem solved by technical solution

Validation of the general form of mathematical model of cable winding/unwinding system, defined for several different constructions was made. This model was presented in [1] and in this paper simulation results were achieved by using the program package **CWUSOFT**. Simulation results were confirmed through experimental validation.

9) State of the problem solution in the world

The general form of mathematical model of cable winding/unwinding system defined for several different constructions was not analysed in available world literature. This phenomenon was first analysed in detail in [1].

10) Description of the technical solution

This program system **CWUSOFT,** (**C**able **W**inding/**U**nwinding **SOFT**wer) was generated in MATLAB. The general mathematical model of cable winding/unwinding (CWU) system is confirmed by program system **CWUSOFT**. CWU system includes motor, gear and the winch for CWU process. This model is defined in general form for CWU systems.

The purpose of this research is pointing out the complexity of CWU systems. Even at these simple constructions one can see the influence of winding radius R and length lw on system's dynamics of response.

For the verification of the defined mathematical model, a novel program package **CWUSOFT** was defined. In [1], simulation results are shown through relevant dynamic variables of CWU system: angular position θ, radius R, length lw and angle γ. Simulation results were performed for one novel type of CWU system, see Figs. 2b) and 3. Simulation results were achieved by using the program package **CWUSOFT**. These simulation results as well as theoretical definitions were confirmed through the experimental analysis.

CWU systems can be sub-systems of more complex mechatronic systems and in that case the mathematical model of this complex system is much more complicated and one of the reasons is mutual coupling of several CWU sub-systems. Because of that, it is very important that dynamic characteristics which are indicated in [1] are included in the analysis and synthesis of these complex mechatronic

Volgina 15, 11060 Belgrade, Serbia
Phone: (+381 11) 2771-398, 2772-876
Fax: (+381 11) 2776-583
WWW.INSTITUTEPUPIN.COM
email: info@institutepupin.com

systems.

The several types of CWU systems will be presented. Their constructive differences will be indicated. The CWU system consists of: motor, gear, winch, pulley and cable that is wound/unwound on the winch. This construction of CWU system has a circular shape of the winch and it is shown in Fig. 1.

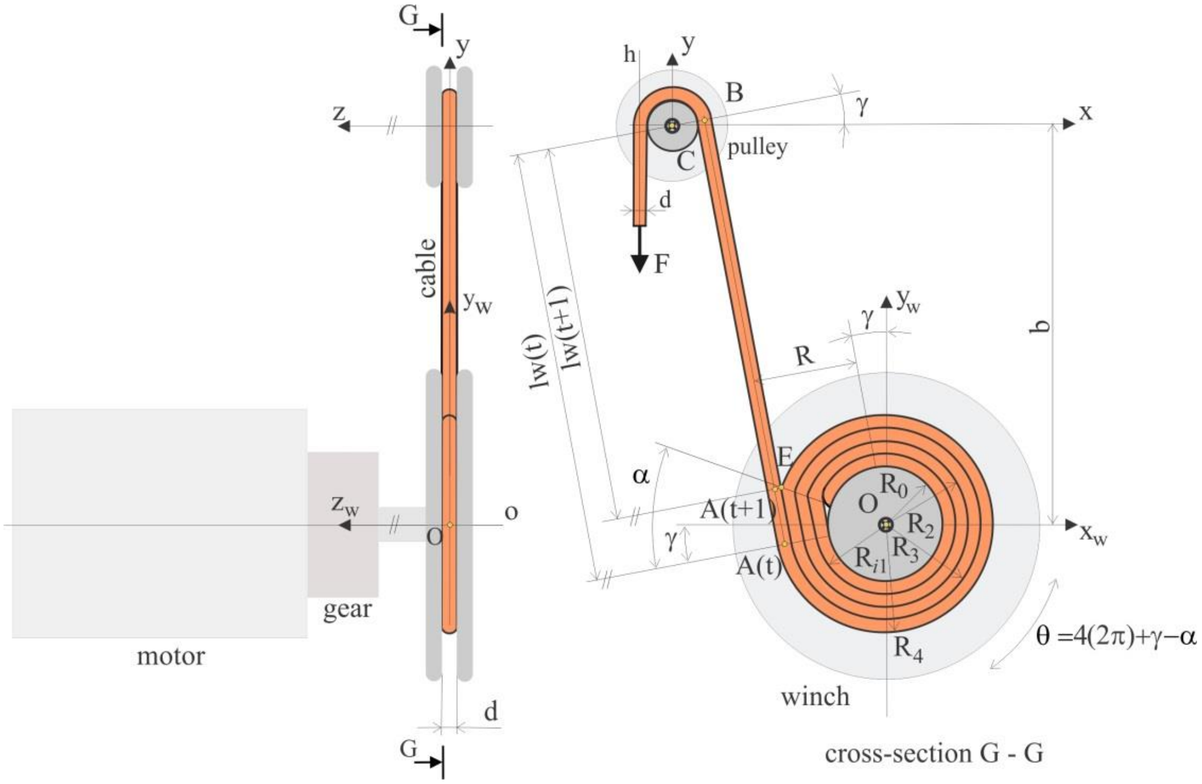

Fig. 1 Standard system for single – row radial multi-layered CWU process.

Detailed description of this system is presented in [2]. It was shown that this solution of the winch has adverse effects on the system's dynamic response and it causes instability and oscillations of the system. This structural instability of the winch from Fig. 1 has inspired the authors of this paper to design a new form of the winch for performing the smooth process of CWU. This novel solution of CWU system for smooth winding/unwinding in two variants in one part solved and presented in patent [3]. The new constructive solution of the system intended for performing smooth CWU process is presented in Fig. 2. Figs. 2b) and 2c) presented two new constructive solutions of the winch which can be used to avoid the constructively generated unstable and oscillatory behaviour of the system from Fig. 1:

1. The first constructive solution consists of two semicylindrical bodies of different radii and it is presented in Fig. 2b). Because of the characteristics of this winch, it has been named the two – cylinder winch.
2. The second constructive solution has a spiral shape and this winch is shown in Fig. 2c). It has

Volgina 15, 11060 Belgrade, Serbia
Phone: (+381 11) 2771-398, 2772-876
Fax: (+381 11) 2776-583
WWW.INSTITUTEPUPIN.COM
email: info@institutepupin.com

been named the spiral winch.

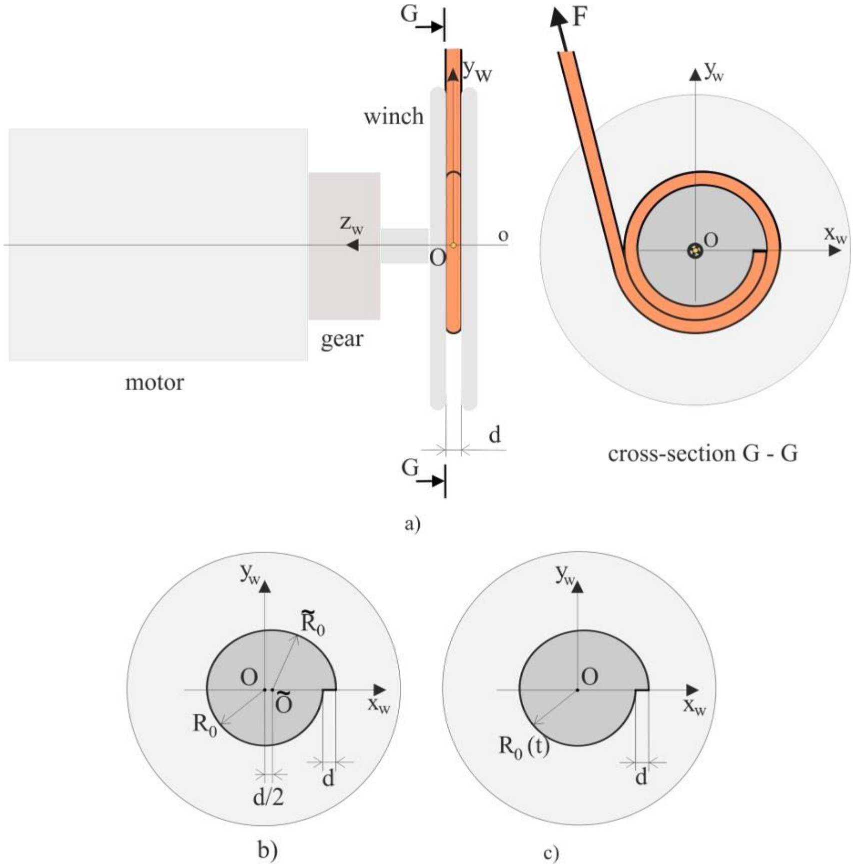

Fig. 2 The new winch for performing a smooth CWU process: a) the winding/unwinding system, b) the two – cylinder winch, c) the spiral winch.

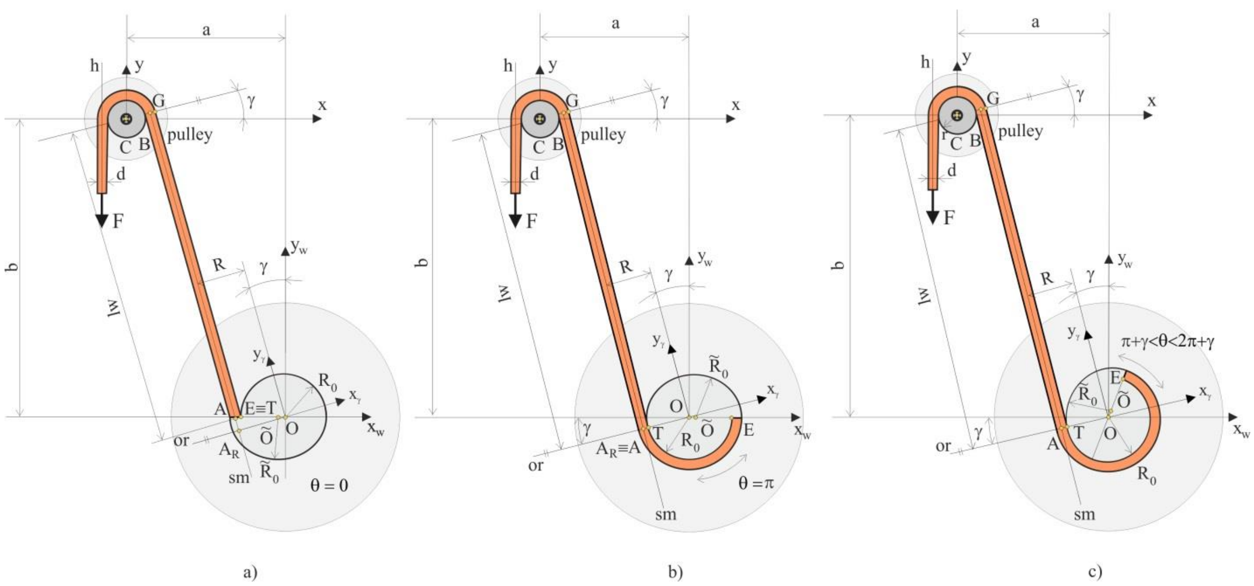

Fig. 3 The positions of the smooth CWU system for: a) $\theta = 0$ b) $\gamma < \theta < \pi + \gamma$, c) $\pi + \gamma < \theta < 2\pi + \gamma$.

By using either of the two new constructive solutions of systems from Fig. 2: the two – cylinder winch

Volgina 15, 11060 Belgrade, Serbia
Phone: (+381 11) 2771-398, 2772-876
Fax: (+381 11) 2776-583
WWW.INSTITUTEPUPIN.COM
email: info@institutepupin.com

(Fig. 2b) or the spiral winch (Fig. 2c), a smooth process of CWU on the winch is achieved. For further discussion, only the constructive solution from Fig. 2b) will be used.

Fig. 3 presents three currently selected positions during the process of the CWU on the winch. Angle θ is measured as deflection between the line $\overline{OE}$ and negative part of the x_w axis, in positive mathematical direction, around point O. The process presented in Fig. 3 is named as: single – row radial multi-layered smooth CWU process on the winch or abbreviated smooth process of CWU on the winch. Dynamic variables which characterize the process shown in Fig. 3 are the following: winding/unwinding radius abbreviated R, length $lw = \overline{AB}$, and angle γ.

The change of these variables during the CWU process is smooth and nonlinear. Three phases of this process are to be observed:

a) in Fig. 3a) the starting position of the CWU system is presented. In this case angle θ is $\theta = 0$.

b) in Fig. 3b) the position of the smooth CWU process for the following values of angle θ is presented: $\gamma < \theta < \pi + \gamma$. In this period, dynamic variables R, $lw = \overline{AB}$, and γ, of this process are constant, so this area has been named the *con* area,

c) in Fig. 3c) the position of the smooth CWU process for the following values of angle θ is shown: $\pi + \gamma < \theta < 2\pi + \gamma$. In this period dynamic variables R, $lw = \overline{AB}$, and γ, of this process change their values, so this area has been named the *smvar* area. Changes of the characteristic variables are smooth and nonlinear, which is substantially different in comparison with the CWU process presented in Fig. 1. During the process of the smooth CWU on the winch, areas *con* and *smvar* alternate cyclically.

CWU system for multi-row radial and axial CWU process is shown in Fig. 4. This type of CWU system is characterized with one motor and two gears. One gear rotates the winch, while the other gear moves it translatory based on its rotation. It can be seen that this system has one DOF. The motor which drives the winch has a rotary motion around the winch's axis. This motion is labelled as θ. For successful and controllable winding/unwinding of the cable on the winch, this winch must have a translatory motion along its z_w axis as well. This motion is labelled as c_θ. It can be seen that these two motions have linear and ideal relation which are known in the literature. Many researchers, i.e. designers of CPR systems assume application of CWU systems which keep relation between these two motions linear.

In order to facilitate understanding of this system's functionality, the first winding/unwinding layer will be described first. This example is shown in Fig. 5

Volgina 15, 11060 Belgrade, Serbia
Phone: (+381 11) 2771-398, 2772-876
Fax: (+381 11) 2776-583
WWW.INSTITUTEPUPIN.COM
email: info@institutepupin.com

a) The first layer of winding

Fig. 5 presents only the first layer of CWU process from Fig. 4. Many authors use cable winding/unwinding on the first layer only, without the possibility and need for using the second layer, for implementation of their CWU system. The cable is only axially furled around the winch. Angular motion θ and translator motion c_θ must be coordinated for ideal cable furling to be achieved. Unlike examples from Figs. 1-3, this phase of CWU implies constant characteristics R, lw, and γ, so their first derivatives are zero. Radius of winding/unwinding is $R = R_0 + d/2$.

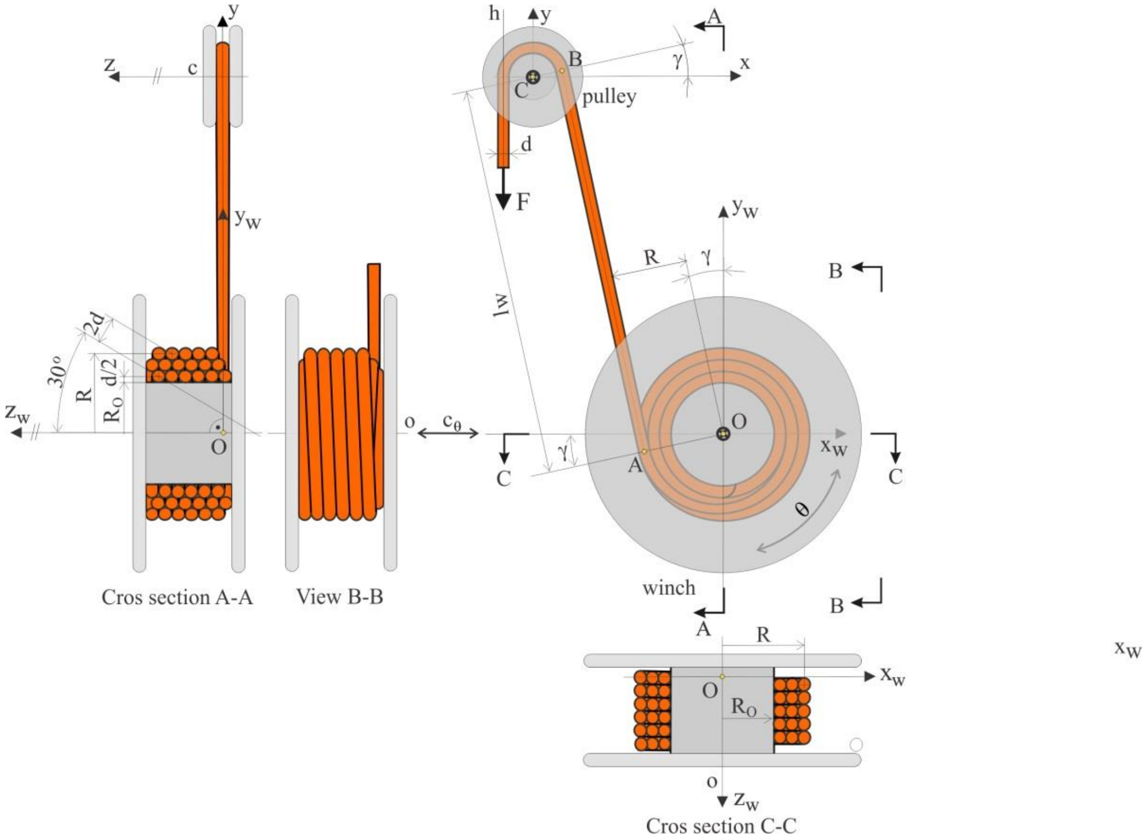

Fig. 4 The system for multi-row radial and axial CWU process.

b) The second and third layer of CWU process

Fig. 6 shows the second layer of CWU process, while Fig. 4 presents the third layer of CWU process. Both figures relate to the same system, but because of easier understanding two different situations are examined. Like it was stated before, this type of the system implies coordinated angular θ and translator c_θ motion. Unlike the CWU phase on the first layer from Fig. 5, at the moment when the cable starts winding/unwinding on the second/third layer, characteristic variables R, lw, and γ, become changeable, so their first derivatives are not zero. From Fig. 6 one can see that the winding/unwinding radius has a value of $R = R_0 + d/2 + 2d/2$ in the C-C cross-section, while this value is

Volgina 15, 11060 Belgrade, Serbia
Phone: (+381 11) 2771-398, 2772-876
Fax: (+381 11) 2776-583
WWW.INSTITUTEPUPIN.COM
email: info@institutepupin.com

$R = R_0 + d/2 + (2d/2)\cdot\cos(30^o)$ when system traverses the next 90^o, see the cross-section A-A. During the winding on the second layer, radius R continually increases and decreases each 90^o that causes the change of length lw and angle γ.

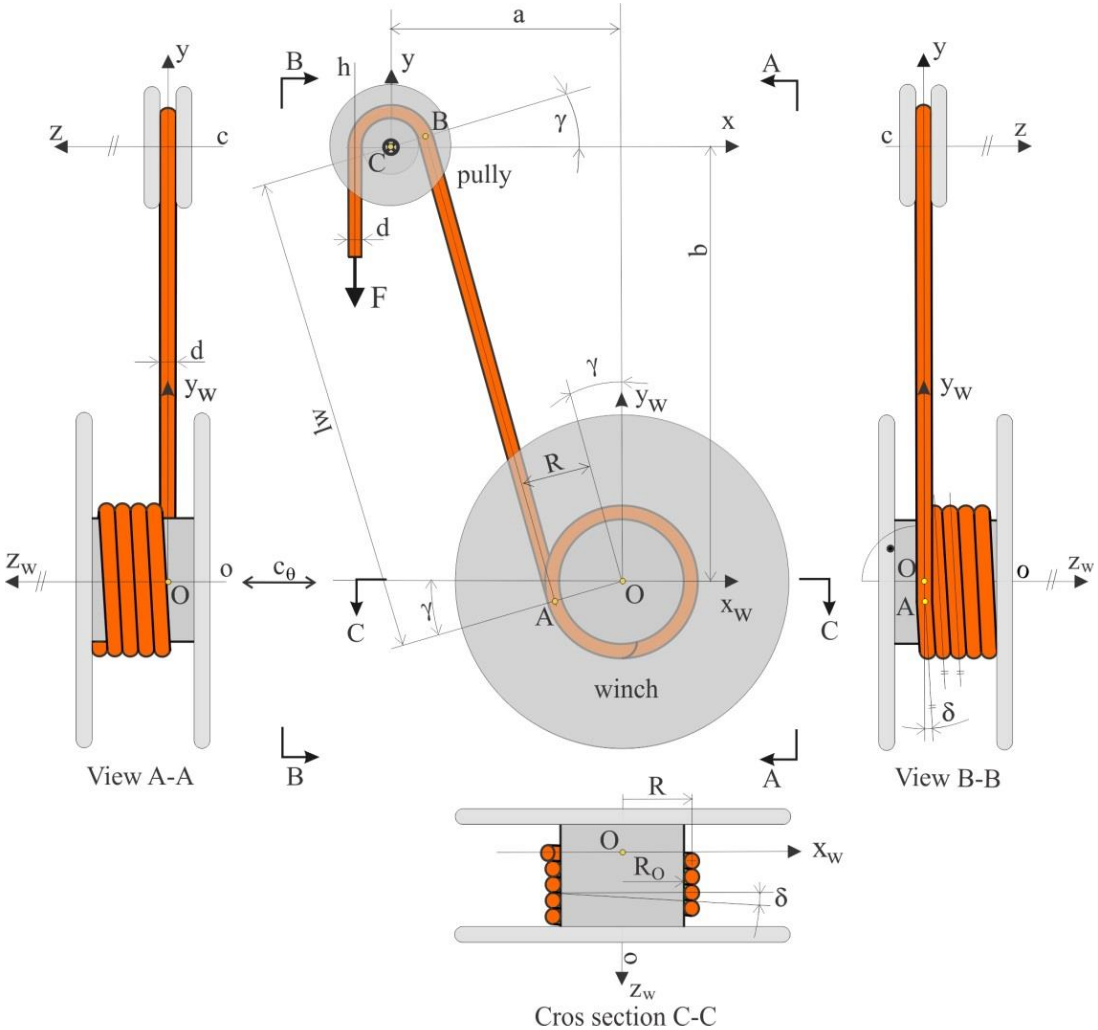

Fig. 5 The system for multi-row radial and axial CWU process – one layer.

In the case of CWU process on the third layer from Fig. 4, one can see that radius *R* has a value of $R = R_0 + d/2 + 4d/2$ in the cross-section C-C, while after system traverses next 90^o, the radius is $R = R_0 + d/2 + (4d/2)\cdot\cos(30^o)$. This can be seen in the cross-section A-A from Fig. 4. During the winding on the third layer, radius R continually increases and decreases each 90^o. This change of radius *R* causes the change of length lw and angle γ.

Following rule applies for CWU systems from Figs. 1-6: coordinate system x_w - y_w belongs to the plane defined by coordinate system x - y. This condition is constructively secured for systems from Figs. 1-3.

Volgina 15, 11060 Belgrade, Serbia
Phone: (+381 11) 2771-398, 2772-876
Fax: (+381 11) 2776-583
WWW.INSTITUTEPUPIN.COM
email: info@institutepupin.com

For CWU systems shown in Figs. 4-6, this is secured with coordinated translational motion of the winch c_θ along z_w axis in dependence of angular rotation θ. This condition is especially noticeable in cross-section A-A shown in Figs. 4 and 5.

Based on the mathematical model of CWU systems, defined in [1], a novel program package CWUSOFT has been synthesized. This program package contains several subroutines combined into one unit:

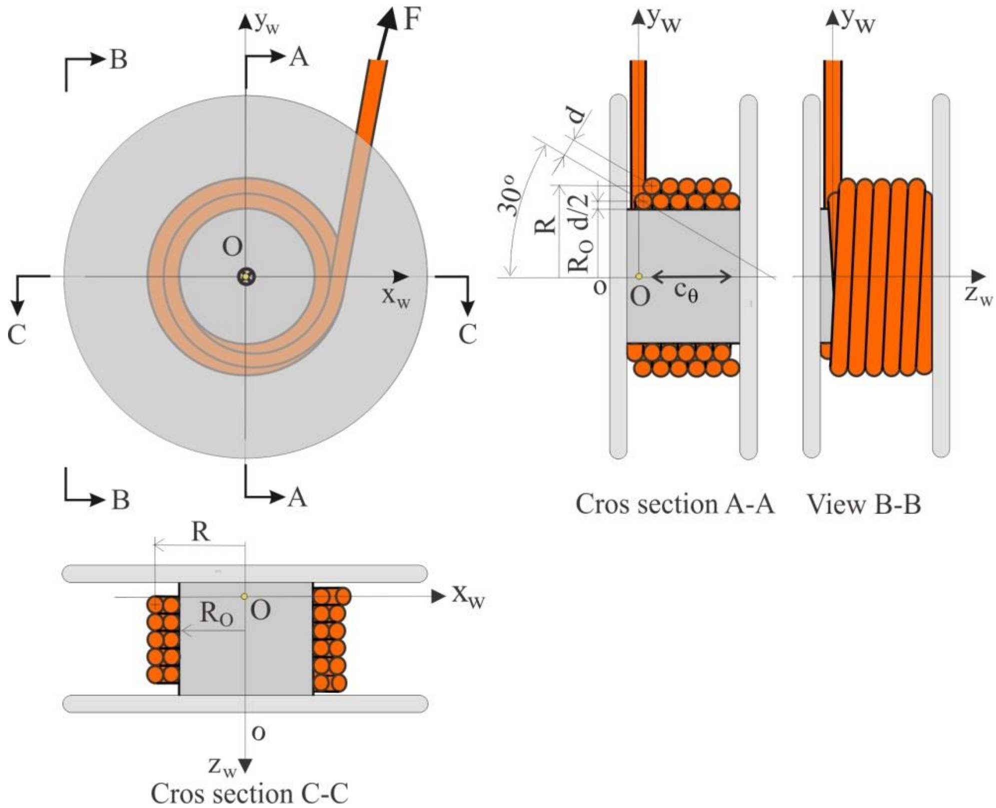

Fig. 6 The system for multi-row radial and axial CWU process – two layers.

1. Subroutine for generation of the reference trajectory. In this case, the reference trajectory of the load in x - y space along the line h is defined. From x - y space, the internal coordinate, angular position of CWU system θ, is calculated. It should be noted that for CWU system for multi-row radial and axial CWU process it is possible to calculate the translator motion c_θ of the winch as well. This procedure includes the kinematic model of the CWU system.

2. Subroutine for generation of the dynamic response of the CWU system. In this subroutine, the influence of the changes of radius R and length lw between the winch and hanging point is included. This is defined through the resultant torque M which includes the dynamics of load's motion (force F) via Lagrange virtual work principl, which includes the geometry of the

Volgina 15, 11060 Belgrade, Serbia
Phone: (+381 11) 2771-398, 2772-876
Fax: (+381 11) 2776-583
WWW.INSTITUTEPUPIN.COM
email: info@institutepupin.com

mechanism, i.e. its kinematic model, as well. It can be seen that now the relation between the resultant torque M and force F is related via the following variables $\dot{y}$, $\dot{R}$, $\dot{l}w$, θ, R.

3. Subroutine for control structure of the system. This routine assumes the creation of various control structures.

The software package **CWUSOFT** is used to verify the validity of the generated mathematical model. The experimental confirmation of simulation and theoretical results are given in [1].

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Volgina 15, 11060 Belgrade, Serbia
Phone: (+381 11) 2771-398, 2772-876
Fax: (+381 11) 2776-583
WWW.INSTITUTEPUPIN.COM
email: info@institutepupin.com