Tension control adaptive system synthesis used in winding of products made of “dry” composite material

A Mikitinsky
Platov South-Russian State Polytechnic University (NPI), str. Prosvesheniya 132, Novocherkassk 346428, Russia
E-mail: kolpahchyan@mail.ru, mialexp@mail.ru

Abstract. Products made by winding are widely used in many industries. The winding control systems requires synthesis of tension control regulators taking into account the specific features of this process. They determine the requirements for the synthesis of control regulators made of modern materials. Synthesis methods do not take into account the peculiarities of the “wet” composite tape. This article deals with the tension control adaptive system used in winding.

1. Introduction
The protective cover of the contact electrical bollards (CEB) is not hermetrical and that is why the moisture, dust, gaseous substances and other deleterious matter can get in it. The CEB’s consists of a multicomponent mixture consists of a multicomponent mixture circulating in a turbulent air stream. Destructive factors play a substantial role in the electric contacts’ wear, fundamentally change the idea of contact wear processes and make the results make unfair the results based on the deterministic models [1-3,6]. The studies of the electrical contacts wear in seaports confirm this conclusion.

Gradual failure of high-current electrical contacts under the influence of high-entropy destabilizing factors consist of two processes. The first one characterizes the impact of internal destabilizing factors (mechanical abrasion, temperature). The second one is connected with external high-entropy destabilizing factors described above. The first process needs the use of deterministic model; the second one needs the probabilistic approach.

Products made of composite materials by the winding have found application due to its unique chemical and mechanical characteristics in many industries such as chemical industry, spacecraft and rocket production [1]. There are “dry” and “wet” methods of winding, both methods are widely used.

Figure 1 shows the scheme of the “wet” winding.

Bobbins with material 2 are installed on the creel 1. The number of bobbins depends on the technological process and can change from 6 to 1200. Dry material 3 passes through tensioners 4 and the string (ровница) is formed on the special comb 5. The string passes through the bath 6 with the binder. A special sensor 7 controls the amount of binder.
Figure 1. The “wet” winding method

The squeezing rollers 8 remove the excess of binder. The electric drive 9 changes the gap between the rollers. The tension device 10 consists of a fixed roller 11 and a roller 12 that moves along the tensioner using an electric drive 13. By this way, the “wet” tape coverage angle changes. The measurer 14 measures the tape tension. The roller 15 lays the tape on the product 16 along a special path. For this purpose, it is equipped with stacking mechanisms, which is not shown on the figure. The drive 17 rotates the product 16. Several interconnected systems control the winding.

The change of the movable roller 12 position maintains the winding tension at a predetermined level.

The improvement of the winding technology imposes stringent requirements for the drive speed and their adaptation to changing operation modes. This article is devoted to the development of such a system. The experience of using the tension control systems allowed us to determine the basic requirements for the developed systems. In particular, the transition time must not exceed the period of 0.1 second and the excessive correction must not be more than 10%.

2. Terms of reference

It is necessary to develop a modern control system for the high-quality composite production using the “wet” winding method. The analysis showed that such a system should have three control loops (the inner loop of drive moment, the central loop of tensioner roller position, the external loop of tape tension). To create and study such a system we need a mathematical description of tape path taking into account the main elastic wound material features. This description must allow the control system synthesis and the analysis of static, dynamic and energy performance of system.

3. Literary sources overview

A lot of researches for ferrous metallurgy, pulp and paper, textile, chemical and electrical industries deal with the mathematical description of elastic tape. Differential equations obtained by a number of authors [2–8] describe the behavior of textile materials, metal tape and ropes when their winding or rewinding. There is a mathematical description of the "dry" and "wet" elastic tape [9–14].

4. Theoretical part

The following expression shows the winding tension [12, 13]:

\[
\frac{dS_1}{dt} = \frac{1}{l_1(t)} \cdot \frac{dl_1(t)}{dt} \cdot S_1 - \frac{(E \cdot F_s - S_0)^2}{l_1(t) \cdot E \cdot F_s} \cdot v_1 + \frac{E \cdot F_s - S_0}{l_1(t) \cdot E \cdot F_s} \cdot v_2 - \frac{2 \cdot (E \cdot F_s - S_0)}{l_1(t) \cdot E \cdot F_s} \cdot v_1 \cdot S_1 + \frac{1}{l_1(t)} \cdot v_2 \cdot S_1 - \frac{1}{l_1(t) \cdot E \cdot F_s} \cdot v_1 \cdot S_1^2 + \frac{E \cdot F_s - S_0 \cdot \frac{dl_1(t)}{dt} + dS_0}{l_1(t)} \cdot \frac{dS_0}{dt},
\]

where, \(S_1\) is the winding tape tension; \(l_1(t)\) is the length of the material warp zone at the moment of time \(t\); \(v_1\) is the linear velocity of the material entrance in the winding zone; \(v_2\) is the winding linear velocity; \(S_0\) is the tape tension in the previous section; \(E\) is the elastic modulus; \(F_s\) is the tape cross-section area.
This expression is non-linear and its use for the regulatory systems analysis and synthesis is difficult. Therefore, the expressions are linearized [12, 13], and we can see that the linearized mathematical model accurately describes the elastic tape transition processes.

There is the linearized inequation below:

\[
\Delta S(t) + \left( \frac{\partial F}{\partial S_1} \right) \cdot \Delta S_1(t) + \left( \frac{\partial F}{\partial S_2} \right) \cdot \Delta S_2(t) + \left( \frac{\partial F}{\partial \alpha} \right) \cdot \Delta \alpha(t) + \\
+ \left( \frac{\partial F}{\partial S_0} \right) \cdot \Delta S_0(t) + \left( \frac{\partial F}{\partial \alpha} \right) \cdot \Delta \alpha(t) - \Delta S_0 = 0.
\]  (2)

The dependence of “wet” tape coverage angle of the tension roller \( \alpha \) on the rolling roller moving along the x-axis is also non-linear function [12, 13]. After its linearizing, we receives the following expression:

\[
\Delta \alpha(t) = k_s \cdot \Delta x(t),
\]  (3)

where, \( k_s = \left( \frac{\partial \alpha}{\partial x} \right)^0 \). \( x^0 \) is the rolling roller position.

Figure 2 shows the block diagram of the linearized generalized mathematical model of the tensioner mechanical part.

Figure 2. Block diagram of the linearized mathematical model of the tensioner mechanical part with the “wet” tape

Where, \( \Delta M_1 \) is the tensioner drive moment, Hm; \( \Delta \Omega_1 \) is the motor shaft rotation frequency, rad/s; \( J_\Omega \) is the equivalent moment of inertia, kg/m2; \( k_7 \) is the reduction gear ratio.

We use the following formulas to calculate the coefficients:

\[
k_1 = -\left( \frac{\partial F}{\partial S_1} \right)^0; k_2 = -\left( \frac{\partial F}{\partial S_2} \right)^0; k_3 = -\left( \frac{\partial F}{\partial \alpha} \right)^0; k_4 = -\left( \frac{\partial F}{\partial S_0} \right)^0; T_i = 1
\]  (4)

The carried out studies justify that the linearization coefficients depend on the winding speed, the tape tension during the winding and the tape tension in the previous section, the rolling roller position (tension roller coverage angle):

\[
T_i = f(v_2); k_1 = f(\alpha, S_0); k_2 = 1; k_3 = f(\alpha, S_0); k_4 = f(v_2).
\]  (5)

We think that the use of brushless DC motor [14-16] or synchronous electric motor with permanent magnets [17] is the most appropriate as an electromechanical chopper in tension device electric motor.

We have enhanced the block diagram of the tensioning device mechanical part with the description of the electric part of electric drive and we’ve got a functional diagram of the tension control system (figure 3). There is a three-loop control system and it includes the internal current loop, the rotor speed control loop and the external loop of tension winding control.
The calculations of current control and subordinate control systems speed are well described [16,17] and therefore, we did not consider them in this paper. It should be noted that first-order aperiodic link [17,18] with transfer function \[ W(p) = \frac{1}{T_p p + 1} \] (where, \( k_{OCC} \) is the feedback sensor gain; \( T_P \) is the converter time constant) can replace two internal loops.

There are legends on figure 3: \( PS \) is the tension controller; \( PC \) is the engine rotation speed controller; \( PT \) is the motor current controller; \( ТП \) is the transistor transducer; \( НУ \) is the tensioner; \( ОУ \) is the controlled object (elastic tape).

Figure 4 shows the simplified structural diagram of a tension control system.

The transfer function of the tension regulator is as follows:
\[
W_{PS} = \frac{T_p + 1}{k_1 \cdot (1/k_{OCC}) \cdot k_{OCS} \cdot 8 \cdot T_H \cdot p} = \frac{T_p + 1}{k_1 \cdot k_{CSS} \cdot p}.
\]  
where, \( k_1 \) is the coefficient of tension control feedback sensor gain loop; \( k_{CSS} = 8 \cdot k_{OCS} / k_{OCC} \cdot T_H \).

In the resulting function, the values of \( T_1 \) and \( k_1 \) change in wide range. It negatively affects the tension control quality during the winding process. The study was realized using the MatLab Simulink software. Tension regulator does not provide satisfactory quality of tension control when changing the parameters of the controlled object. In previously developed tension control systems, the regulator was set up to the most optimal parameters combination of the controlled object [10, 11, 22, 23]. But the tension control quality worsened when the controlled object parameters was changed.

To reduce the influence of parameters on the regulatory system it is advisable to introduce a tension regulator correction.

Obviously, we can use expression (3) to do it. However, they are quite complex and the calculations require a lot of time.

We simplify these expressions. For this purpose, we used the approaches that are described in the theory of experiment planning [19-21].

In order to build a standard matrix of the experiment we converted the factor level values to natural numbers. Table 2 shows calculation data.

### Table 1. Variable parameters

| Parameter | from | to    | Unit   |
|-----------|------|-------|--------|
| \( \alpha \) | 2    | 6     | rad    |
| \( S_0 \)  | 100  | 500   | H      |
| \( v_2 \)  | 0.1  | 0.3   | m/s    |
First, we considered the varied parameters that change during the winding. They are variable parameters. Table 1 shows variable parameters.

The regression coefficients values allow us to estimate factors and their interactions influence on the model parameter. The coefficient value corresponds to this factor influence on the model parameter value when the factor value moves from zero to upper or lower level.

We use the first-order model to assess the influence of these factors and the mathematical description of the process:

\[ y = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_4 X_4 + b_{12} X_1 X_2 + b_{13} X_1 X_3 + b_{14} X_1 X_4 + b_{23} X_2 X_3 + b_{24} X_2 X_4 + b_{34} X_3 X_4 + b_{123} X_1 X_2 X_3 + b_{124} X_1 X_2 X_4 + b_{134} X_1 X_3 X_4, \]

(7)

where, \( b_0 = \frac{\sum_{i=1}^{N} y_i}{N}; b_1 = \frac{\sum_{i=1}^{N} X_{1i} y_i}{N}; b_2 = \frac{\sum_{i=1}^{N} X_{2i} y_i}{N}; \)

We have the following results for \( k_1 \) coefficient:

\[ b_0 = 71,89; b_1 = -52,79; b_2 = 43,3; \quad b_3 = -0,01; \quad b_{12} = -34,6; \quad b_{23} = 0,012; \quad b_{13} = 0,012; \quad b_{123} = -0,012; \]

We have the following results for \( k_3 \) coefficient:

\[ b_0 = -525,89; \quad b_1 = -126,46; \quad b_2 = -360,29; \quad b_3 = 0; \]

\[ b_{12} = -82,31; \quad b_{23} = 0; \quad b_{13} = 0; \quad b_{123} = 0; \]

We have the following results for \( k_4 \) coefficient:

\[ b_0 = 22378,78; \quad b_1 = 2671,0; \quad b_2 = 2702,11; \quad b_3 = 3227,88; \]

\[ b_{12} = -3007,88; \quad b_{11} = -2339,88; \quad b_{23} = -2339,88; \quad b_{123} = 3227,88; \]

Table 2. Experiment planning matrix (calculations) and calculation results

|   | 2   | 3   | k1     | k3     | k4     | T1  |
|---|-----|-----|--------|--------|--------|-----|
| 1 | 1   | 1   | 45,99  | -133,30| 25400  | 10,05|
| 1 | 1   | 1   | 5,01   | -232,64| 25330  | 10,15|
| 1 | 1   | 1   | 221,2  | -637,27| 25400  | 10,05|
| 1 | 1   | 1   | 24,58  | -1107,00| 22644 | 10,15|
| 1 | 1   | 1   | 45,88  | -133,30| 25080  | 3,38 |
| 1 | 1   | 1   | 5,01   | -232,64| 25330  | 3,48 |
| 1 | 1   | 1   | 221,2  | -637,27| 25400  | 3,48 |
| 1 | 1   | 1   | 24,58  | -1107,00| 26640 | 3,48 |
| 1 | 1   | 1   | 53,59  | -512,59| 25560  | 5,1  |

We have the following results for \( T_1 \) time constant:

\[ b_0 = 6,59; \quad b_1 = 0,033; \quad b_2 = 0,011; \quad b_3 = -2,95; \quad b_{12} = -0,011; \]

\[ b_{13} = -0,011; \quad b_{23} = 0,011; \quad b_{123} = -0,011. \]

These results are obtained for coded variables, that are varying from -1 to +1.
Obviously, the lower the coefficient before the coded variable the less influence this variable has on the overall result. We think that the test significance is 5% of b0 coefficient.

We have the following result for k1 coefficient:

\[
k_1 = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 = 71.89 - 52,79 X_1 + 43.3 X_2 - 34.6 X_3;
\]

We have the following result for k3 coefficient:

\[
k_3 = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 = -525.89 - 126,46 X_1 - 306,29 X_2 - 82,31 X_3;
\]

We have the following result for k4 coefficient:

\[
k_4 = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_4 X_1 X_2 + b_5 X_1 X_3 + b_6 X_2 X_3 + b_7 X_1 X_2 X_3 =
\]

\[
22378,78 + 2671 X_1 + 2702,11 X_2 + 3227,88 X_3 - 3007,88 X_1 X_2 - 2339,88 X_1 X_3 -
\]

\[
-2339,88 X_1 X_3 + 3227,88 X_1 X_2 X_3;
\]

We have the following result for T1 coefficient:

\[
T_1 = b_0 + b_1 X_1 = 6.59 - 2,95 X_1.
\]

The obtained results show that the parameters vary in a wide range:

- k1 from 5.01 to 221.2, i.e. 44 times;
- k3 from -133.3 to -1107, i.e. 8.3 times;
- k4 from 25330 to 26640, i.e. 1.05 times;
- T1 from 3.38 to 10.15 i.e. 3 times.

Figure 4 shows the block diagram of tension control system with adaptive controller.

Block 2 converts the dimension value into dimensionless value. Block 1 counts the values of k1 and T1 coefficients.

Figure 6 shows the simulation results of the tension control system when the controlled object parameters are changed to a significant degree.

Adaptive system works well with wide changes of the controlled object parameters, the excessive correction in the system does not exceed 9%, and the transient time is 1.12 sec.

5. Conclusions
1. The block diagram and the tension control system of the products winding by “wet” composite tape with adaptive controller are developed.
2. Analytical expressions to calculate the tension control parameters are obtained. These expressions take into account the “wet” composite tape properties.
3. The synthesized adaptive controller takes into account the elastic properties of the tape.
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