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TENSION OPTIMIZATION OF THE CONDUCTOR-AND-SUPPORT CABLE ELEMENTS DURING STRANDING PROCESS

І.М. Чаюн, *О.В. Непомнящий*. **Оптимізація натягнення елементів кабель-канатів при звивці.** Сталеві підйомні канати, кабелі та інші подібні вироби є стрижневими статично невизначуваними попередньо напруженими конструкціями. Попередні деформації їх елементів (дротів) обумовлені технологією їх виготовлення. Дроти відчувають розтягнення, вигин з крученням в стадії пружно-пластичної деформації. Пропонується механіко-математична модель визначення залишкових зусиль в дротах поліметалевого кабель-каната. ***Мета:*** Метою роботи є дослідження механіко-математичної моделі, що визначає залишкові зусилля в дротах кабель-каната, а також оптимізація параметрів звивки за критерієм відсутності залишкових зусиль після виготовлення. ***Матеріали і методи:*** Для оцінки впливу наближеного значення поздовжньої жорсткості виробу застосовано розроблений авторами раніше метод дослідження деформовано-напруженого стану розвантаження витих дротяних виробів від технологічних внутрішніх зусиль. В роботі елементом виробу розглядається кожен дріт окремо – це необхідно для дослідження впливу нерівномірності натягу дротів на дефекти кабель-каната (непрямолінійність у вільному стані і розкручуваність). ***Результати:*** На основі проведеного дослідження деформування кабель-каната в процесі розвантаження від звивального натягу його елементів встановлено залежності залишкових зусиль від рівня і співвідношень натягу елементів. Сформульовано умову забезпечення нульових залишкових зусиль в дротах кабель-каната після виготовлення. Встановлено, що розрахункові значення залишкових зусиль практично однакові при використанні наближеного і точного значень поздовжньої жорсткості кабель-каната.

Ключові слова: кабель-канат, деформація, напруження, залишкові зусилля.

I.M. Chayun, *A.V. Nepomnyashchyi*. **Tension optimization of the conductor-and-support cable elements during stranding process.** Steel lifting ropes, cables and other similar products are rod statically undeterminable prestressed structures. Preliminary deformations of their elements (wires) are caused by their manufacturing technology. Wires suffer stretching, bending with torsion in a stage of elastoplastic deformation. In this work the mechanic-mathematical model of residual forces determination in the wires of polymetallic conductor-and-support cable is offered. ***Aim:*** The aim of the work is studying of the mechanical and mathematical model defining residual forces in the wires of conductor-and-support cable and also the optimization of parameters of a twist by the criterion of residual forces lack after production process finishing. ***Materials and Methods:*** The method developed by the authors earlier to the study the strain-stressed state of twisted wire products off-loading from technological internal forces has been applied to assess the impact of the approximate value of the longitudinal stiffness of the product. In this paper, each wire is considered as an element of the product individually. This is necessary to investigate the impact of uneven wire tensions on defects of conductor-and-support cable (out-of-straight in a free state and stripping-down). ***Results:*** On the basis of the conducted deformation studies of conductor-and-support cable during off-loading process from twist tension of its elements the dependencies of residual forces on the level and interrelation of elements tension has been determined. The condition of ensuring of zero residual forces in the wires of conductor-and-support cable after production is formulated. It was found that calculated values of residual forces are almost identical when using of the approximate and exact values of longitudinal stiffness of conductor-and-support cable.

Keywords: conductor-and-support cable, deformation, strain, residual forces.

Introduction. Steel lifting ropes, cables and other similar products are the rod statically indeterminate prestressed constructions. The deformations of their elements (wires) are caused by their manufacturing method. Wires test a stretching, a bend with torsion in a stage of elastoplastic deformation. At unary twist and backtwist and a preformation are designed to provide lack of torsion and bend deformation of wires [1…5]. Therefore, it is expedient to investigate only influence of wires stretching on residual forces which is created by brake mechanisms on the section between pay-off spools and crimp terminals of closing machine.

According to steel-wire ropes which consist of wires of the identical module of elasticity, the link between a twist tension of elements (wires) and the further strain-stress state is considered in [6]. In the work [7] the residual forces in products, consisting of wires with different tension modulus, are

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explored. In these work, the approximate value of its longitudinal stiffness was used in determining the aggregate deformation of the developed twisted-wires product.

This work proposes a mechanics-mathematical model for determining residual forces in the wires of polymetallic conductor-and-support cable, and a study of the impact of residual forces on defects of conductor-and-support cable (out-of-straight in a free state and stripping-down). The optimization of tension of elements by criterion of lack of residual forces after unloading is also executed. At the same time the influence of use of the approximate longitudinal stiffness value of a product on the accuracy of expected residual forces in comparison with exact value is estimated. Synthesis of earlier developed design pattern [6, 7] for a case of any quantity of twisting operations is also performed.

The aim of the work is studying of the mechanical and mathematical model defining residual forces in the wires of conductor-and-support cable and also the optimization of parameters of a twist by the criterion of residual forces lack after production process finishing.

Materials and Methods. The design pattern, that is similar to offered in work [7], has been applied to assess the influence of approximate value of longitudinal stiffness of a product (Fig. 1). In this work we will not consider wires layers as elements of a product, as it was in [7], but each separate wire. It is necessary to study the influence of unevenness of wires tension on defects of conductor-and-support cable (out-of-straight in a free state and stripping-down).

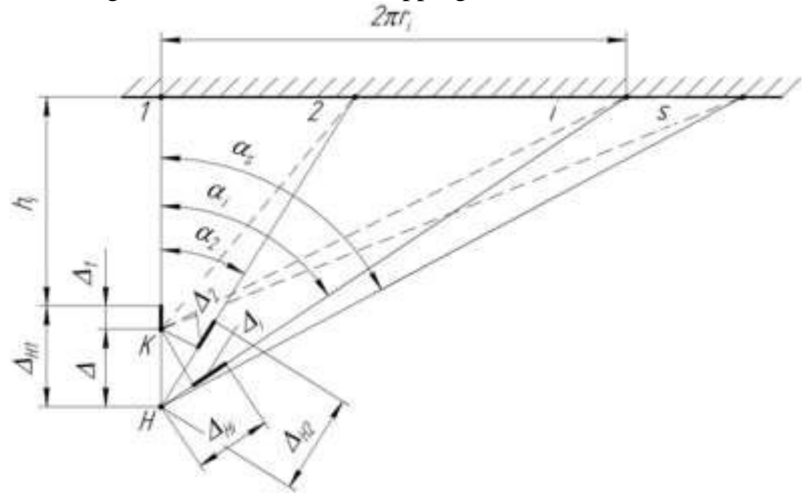

Fig. 1. Off-loading design scheme

The equation of static within the state after off-loading based on theorem about off-loading [8] will look the next way:

$$\sum_{i=1}^{s} \tilde{N}_i \cos\alpha_i = \sum_{i=1}^{s} \varepsilon_i E_i A_i \cos\alpha_i = 0, \tag{1}$$

where s – quantity of elements, that equals to sum of all wires in product, including insulating layer;

N_i and α_i – the residual force in the element (wire) and angle of its twisting accordingly;

ε_i and $E_i A_i$ – residual elastic deformation of *i-th* element in state after off-loading, to which the residual force $\tilde{N}_i$ and its longitudinal stiffness are accordingly proportionally).

Let calculate the residual elastic deformation of *i-th* element in state after off-loading using formula:

$$\varepsilon_i = \varepsilon_{Hi} - \varepsilon \cos^2 \alpha_i, \tag{2}$$

where ε_{Hi} and ε – are deformation of twist tension of *i-th* element and off-loading deformation of conductor-and-support cable accordingly.

The manufacturing process of conductor-and-support cable may comprise one or more twist operations depending on the design [9]. In one operation the products with linear wires contact are woven. This applies mainly to the spiral cables with linear touch of the wires between the concentric layers.

It will be performed at least three twisting operations for the hoist cable with a conductive element of the single twisting and two layers of armor, twisted in the opposite direction. Off-loading is performed after every operation. Thus, the methodology for determination of residual forces after first and further operations are slightly different from each other.

Tension of twisting and further off-loading in elements within every operation leads to a discrete accumulation (algebraic sum) of residual forces.

Conventionally, the elements can be divided into two categories. The first category consists of elements that are part of the part of conductor-and-support cable, twisted during previous operation. The second category includes elements that wove at this operation, i.e. entwine the part twisted at the previous operations. In certain elements the residual forces (tensions) will be stretching, in the other – compressing ones.

The residual forces after the first twist operation. Let us consider the method for determining of residual forces for products made of multimodulus by elasticity elements (wires) when twisting for a single operation. In the case of manufacturing products in several steps – it will be a method of determination of residual forces after the first operation.

The off-loading force from total twisting tension can be represented as

$$P = \sum_{i=1}^{s} P_i \cos\alpha_i, \tag{3}$$

where P_i – tension of *i-th* element.

Off-loading deformation of conductor-and-support cable based on (1)…(3) is determined as

$$\varepsilon = \frac{P}{G}, \tag{4}$$

where G – longitudinal stiffness of conductor-and-support.

The approximate expression of conductor-and-support cable longitudinal stiffness according to [10] can be calculated in this way:

$$G = \sum_{i=1}^{s} E_i A_i \cos\alpha_i^3. \tag{5}$$

The exact value of conductor-and-support cable longitudinal stiffness according to [11] is determined as

$$G = \sum_{1}^{s} \mathrm{sc}\,\alpha\,(\Phi_p K_{e\varepsilon}^2 + \Phi_t K_{t\varepsilon}^2 + \Phi_u (K_{b\varepsilon}^2 + K_{n\varepsilon}^2)), \tag{6}$$

where $\Phi_p; \Phi_t; \Phi_u$ – longitudinal, torsional and flexural stiffness of wires section respectively;

$K_{e\varepsilon}; K_{t\varepsilon}; K_{b\varepsilon}; K_{n\varepsilon}$ – specific deformations of wires.

The residual force in *i-th* wire (element) is determined as

$$\tilde{N}_i = P_i - \frac{\sum_{i=1}^{s} P_i \cos\alpha_i}{G} E_i A_i \cos^2\alpha_i. \tag{7}$$

The residual forces after the second twist operation. At the second twisting operation the elements of conductor-and-support cable should be considered the part of the product, which has been twisted at the first operation and the layers of wires that wove in a second step. In accordance with twisting technology, at the second operation the tension of all selected elements is created. At this, let calculate the off-loading force of conductor-and-support cable by formula

$$P = P_1^* + \sum_{i=1}^{s_2} P_{i2} \cos\alpha_i, \tag{8}$$

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where P_1^* – tension of part, twisted during 1st operation;

s_2 – number of elements (wires) of conductor-and-support cable, twisted during 2nd operation;

P_{i2} – wire tension *i-th* element, twisted for 2nd operation.

As noted, off-load must be performed on each element (wire) separately and of conductor-and-support cable as a whole. In the first operation, the elements are off-loaded from the forces created by their twist tension. In the second operation the forces in elements, twisted during first operation, consist of residual forces after first operation and forces, linked with tension P_{i2} at the second operation, which can be expressed this way

$$P_{i2} = \tilde{N}_{i1} + \frac{P_2^*}{G_2^*} G_i \cos^2 \alpha_i , \tag{9}$$

where $\tilde{N}_{i1}$ – residual force in wire of i-*th* element from off-loading after 1st operation;

G_2^* – longitudinal stiffness of part, twisted during 1st operation;

G_i – stiffness of i-*th* element.

Wires tension, which twisted during second operation generate residual forces.

The amount of residual force after off-load related with the second twist operation can be defined as

$$\tilde{N}_{i2} = P_{i2} - G_i \frac{P_1^* + \sum_{i=1}^{s_2} P_{i2} \cos \alpha_1}{G} \cos^2 \alpha_i . \tag{10}$$

The residual forces after the third twist operation. For the third twisting operation should be considered that elements of conductor-and-support cable, which have been twisted during first and second operations and wires layers, which are twisted during third operation. The twisting process is accompanied by the tension of all marked elements. Thus the conductor-and-support cable off-load force is calculated according to the expression

$$P = P_3^* + \sum_{i=1}^{s_3} P_{i3} \cos \alpha_i , \tag{11}$$

where P_3^* – tension of part, twisted during 1st and 2nd operation;

s_3 – number of elements, twisted during 3rd operation;

P_{i3} – wires tension of *i-th* layer, twisted during 3rd operation.

At the third operation the forces in elements, twisted during first and second operations, consist of residual forces after second operation $\tilde{N}_{i2}$ and forces, linked with tension at third operation:

$$P_{i2} = \tilde{N}_{i2} + \frac{P_3^*}{G_3^*} G_i \cos^2 \alpha_i , \tag{12}$$

where G_3^* – longitudinal stiffness of part, twisted during 1st and 2nd operation.

In wires of elements, which are twisted third operation, the forces will be their tension during this operation. The residual forces after off-loading, linked with third operation, are determined in the same way (7) and (10), namely

$$\tilde{N}_{i3} = P_{i3} - G_i \frac{\sum_{i=1}^{s_3} P_{i3} \cos \alpha_1}{G} \cos^2 \alpha_i . \tag{13}$$

For a single-wire hoist cable, the third operation will be the last. For multilayer wires of power lines, individual constructs of twisted ropes, the third operation will be intermediate.

Results and Discussion. On the basis of the conducted researches it is possible to construct the generalized algorithm of determination of the residual forces linked with a twisted tension of elements. The offered algorithm consists of the following steps:

1) Calculation of own forces off-loading at *n-th* operation in elements, twisted during previous (*n*–1) operations, using formula:

$$P_{i\,n} = \sum_{i-1}^{n-1} \tilde{N}_{i\,j} + \frac{P_n^*}{G_n^*} G_i \cos^2 \alpha_i \,, \tag{14}$$

where $\tilde{N}_{i\,j}$ – residual force in i *-th* element after off-loading on *j-th* operation;

P_n^* – tension force of the part of product at *n-th* operation, twisted during previous (*n*–1) operations;

G_n^* – longitudinal stiffness of the part of product, twisted during previous (*n*–1) operations;

G_i – longitudinal stiffness of i *-th* element.

2) Determination of off-loading force of conductor-and-support cable at *n-th* operation using formula:

$$P_n = P_{n-1}^* + \sum_{i=1}^{s_n} P_{i\,n} \cos\alpha_i \ , \tag{15}$$

where P_{n-1}^* – tension of the part, twisted during (*n*–1) operations;

s_n – number of elements, which are twisted during *n-th* operation;

P_{in} – wires tension of i *-th* layer, which are twisted during *n-th* operation.

3) Calculation of residual forces from off-loading at *n-th* operation is determined by formula:

$$\tilde{N}_{i\,n} = P_{i\,n} - G_i \frac{\sum_{i=1}^{s_n} P_{i\,n} \cos\alpha_1}{G} \cos^2 \alpha_i \, . \tag{16}$$

4) Verification of the correctness of the residual forces determination: the sum of projections of residual forces on the axis of conductor-and-support cable must be zero, as shown in the following formula.

$$\tilde{N}_{in} \cos\alpha_i = 0. \tag{17}$$

Comment. The study shows that it is possible to determine residual forces from off-loading after each operation, taking into account only the tension of elements. Then, the total residual force in *i-th* element can be determined as

$$\tilde{N}_i = \sum_{j=1}^{n} \tilde{N}_{ij}, \tag{18}$$

where n – number of twisting operations with forthcoming off-loading;

$\tilde{N}_{i\,j}$ – force in *i-th* element at off-loading on *j-th* twisting operations.

The natural requirement is to require the same tension of wire within the layer. The preferable distribution of residual forces in all layers as on character, so and in their values it is possible to achieve by the choice of tension levels of wires layers. As for hoist cable, which consists of conducting core, twisted of copper wires and two layers of steel wires armor, favorable level of residual forces can be created by tension ratio. For example, in a core of a hoist cable (Fig. 2) it is important to prevent significant compression stress that can lead to buckling. This explains the situation of hoist cable insulation destruction due to bend of loop-shaped form of separate core wires that is shown in [12].

Dependence of residual forces $\bar{N}$ and relative tension $\bar{\sigma}$ ($\bar{\sigma} = \sigma / \sigma_T$, where σ_T – yield tensile strength of copper wires core) on twisting tension of the elements in the wires of core layer for the cable KOBDF-6 is shown in Fig. 3.

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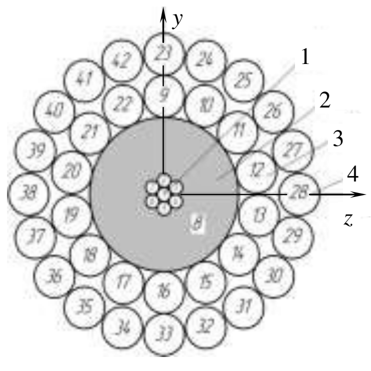

Fig. 2. Cable KOBDF-6 cross-section: 1 – conducting core; 2 – insulating layer; 3 – internal layer of armor; 4 – external layer of armor

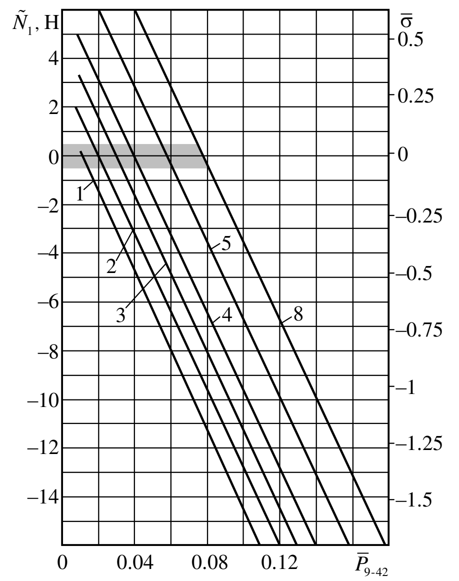

Fig. 3. Dependence of residual forces $\bar{N}_{2-7}$ and relative tension $\bar{\sigma}$ on twisting tension of the elements in the wires of core layer for cable KOBDF-6: $\bar{P}_{9\text{-}42}$ = 0.1 (1); 0.2 (2); 0.3 (3); 0.4 (4); 0.6 (5); 0.8 (6)

Tension of core wires $\bar{P}_{1-7}$ and armor $\bar{P}_{9-42}$ in relative dimensioning can be calculated using expression

$$\bar{P} = \frac{P}{P_T} = \frac{4P}{\pi\,\delta^2\,\sigma_T}, \qquad (19)$$

where P_T – force, corresponding to breaking elastic state.

The dependencies shown in Fig. 3 cover a wide range of tensioning core wires and armor wires. Let's notice, that calculations at which the relative tension $\bar{\sigma}>1$, being correct, are wrongful, because the value of such tensioning coincides to Hook's law. For other hoist cables the dependencies of residual forces in the wires can be illustrated with similar plots.

The considered cable KOBDF-6 has the following characteristics [13]: conducting core of construction 1+6; wires diameter δ=0.35 mm; angle of twist of layer α=19°; modulus of elasticity of wires E=1.3×10^5 MPa; yield stress σ_T=100 MPa. The core diameter is 4.25 mm, isolation material – fluoroplastic (modulus of elasticity E=840 MPa, yield stress σ_T=20 MPa). Internal armor layer consists of 14 wires, which twisting angle α_i=22°50′, twisting radius r_i=2.625 mm. External armor layer consists of 20 wires, twisting angle α_e=19°20′, twisting radius r_e=3.65 mm. Diameter of armor wires δ=1.1 mm, modulus of elasticity E=2.1×10^5 MPa.

Analysis of residual forces dependencies (7), (10), (13), (16) and dependencies presented in Fig. 3, show that there is such tension ratio, at which the residual forces in wires, linked with off-loading by twisting tension, will be zero. It is purely phenomenologically possible to claim that it is feasible on condition of simultaneity of own off-loading of all of conductor-and-support cable elements. Analytically such condition has an appearance

$$\varepsilon_{н_i} - \varepsilon\cos^2\alpha_i = 0, \qquad (20)$$

where $\varepsilon_{н_i}$ – tension deformation of *i-th* element:

$$\varepsilon_{н_i} = \frac{P_i}{G_i} = \frac{P_i}{E_i\dfrac{\pi\delta_i^2}{4}}, \qquad (21)$$

ε – off-loading deformation of conductor-and-support cable from axial force, linked with elements tension (6).

Conclusions. On the basis of the conducted deformation studies of conductor-and-support cable during a discharge process from twist tension of its elements the dependencies of residual forces on the level and interrelation of elements tension has been determined. The condition is formulated at which providing there will be no residual forces. An analytical description of this condition is provided. The condition is applicable for different types of developed wire products: twisted wire rope, armored hoist cable and so on. It was found that calculated values of residual forces are almost identical when using of the approximate and exact values of longitudinal stiffness of conductor-and-support cable.

For zero residual longitudinal forces, zero values are also associated with their integral internal force factors – torque and bending moments. The absence of these moments provides the essential requirement of quality on straightness of conductor-and-support cable after manufacture.

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