Mech. Adv. Technol. Vol. 6, No. 1, 2022, pp. 31–40

DOI: 10.20535/2521-1943.2022.6.1.250801

UDC 622.673

The dependence of the internal electrical resistance of the cable rubber rope on the presence of a cable rupture

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Received: 5 January 2022 / Accepted: 30 May 2022

Problems. *The introduction of steel reinforced concrete coatings of structures, in our opinion, is preceded by the development of methods for monitoring the state of cable-stayed ropes - creating safe conditions for long-term operation of structures.*

The aim of the study. *Analytical determination of the dependence of the internal electrical resistance of a cable-stayed rubber cable rope on the presence of a cable rupture.*

Methods of implementation. *To control all cables, the system must provide alternate monitoring of the electrical resistances of the circuits formed by the cables, compare them with reference values, and issue a signal regarding the condition of the rope. It should be designed on the basis of the following data: the type and design of the cable-stayed rope, its length, the number and layout of the cables in the rope, the ability to access one or both of its ends, the electrical properties of the cables and rubber, the resistance values of the cables for all schemes of their determination.*

Research results. *Requirements for the automatic control system of the cable-stayed rubber cord rope. The regularity of the dependence of the electrical resistance of the cable-stayed rope on the burst of an arbitrary cable. Possibility of automatic control of the state of the rubber-cable cable-stayed rope.*

Conclusions. *The results obtained can be considered quite reliable, since the equations obtained on the basis of the fundamental provisions of electrical engineering are obtained analytically in a closed form. Experimental studies have established that the internal electrical resistance of the rope cables depends on its properties and the presence or absence of damage to the cables. The rope includes a number of cables. Any cable can be damaged.*

Keywords: *rubber rope, electrical resistance, control, cable rope, cable, mathematical model, signal.*

Introduction

One of the main tasks of modern capital construction is to reduce the production time of construction products and reduce the cost of its manufacture. This can be achieved by introducing steel-reinforced concrete coatings [1, 2]. Ropes are one of the components of such coatings. Ropes are used in various fields of technology: cableways, mine and elevator equipment, cranes, etc. The safety of people depends on their technical condition [3]. So. in 2017 in the shaft of the mine JSC “Novo-Shirokinsky mine” [4] the skip fell into the sump of the trunk. In March 2011 at the mine “17-17” bis, in 2006 at OJSC “Kola MMC”, OJSC “MMC” Norilsk Nickel”, at the mine” Skipova “OJSC” Uchalinsky GOK”. In 2006 Uchalinsky underground mine, in 2000 at Mine № 2, Excel Mining LLC there were breaks in the ropes.

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Tasks performed in the work

The proposed cable rope design can be considered as several flat rubber ropes connected as several layers. The design of a two-layer rubber rope is substantiated in [5].

The issue of substantiation of control of ruptures of ropes of rubber ropes and tapes, on the basis of change of electric resistance of ropes, was considered in a number of works [6–9]. A number of technical solutions for the control of rubber ropes and tapes have been proposed [10, 11]. According to the first of these solutions, it is proposed to lay a current conductor in the form of a spiral in a flat rubber band tape and control its electrical resistance. Cutting the tape is accompanied by the destruction of the embedded

ISSN 2521-1943 Mechanics and Advanced Technologies

spiral, which leads to an infinite increase in electrical resistance. This growth is recorded by the control system. The cable rope is stationary. There is no danger of cutting it. Its strength depends on the condition of the cables. The device monitors the condition of the cables [12]. The device works on the basis of control of magnetic conductivity of cables. The destruction of the cable leads to a change in its properties to form a magnetic field. This control allows you to control the cables located in the surface layers of the cable rope. It is acceptable for a two-layer cable rope. It also involves moving the control device along the rope, which complicates the control process. The most effective methods of control of steel ropes are electromagnetic methods [13, 14], which allow to control damage to almost all types of steel ropes. Longitudinal magnetization of a section of steel rope is used to identify local defects, which leads to an increase in the intensity of scattering fluxes over the location of the defect due to the redistribution of the magnetizing flux [15]. To control the geometric parameters of metal objects, it is advisable to use the eddy current control method [16]. Its advantage is that the examination can be performed in the absence of contact between the sensor and the rope - contactless. However, the cable rubber rope consists of a system of cables. The method is acceptable for cables of outer layers. The above shows that for a stationary rope is more appropriate method of controlling the change in electrical resistance of the cable due to the rupture of its continuity. Substantiation of requirements for the control system requires the following work:

– Build a mathematical model of current and voltage distribution in the cable rope as an electrical system with a parallel connection of discrete current conductors connected by distributed current conductors with significant electrical resistances.

– To build a solution of the mathematical model of current and voltage distribution in the cable rope as an electrical system with a parallel connection of discrete current conductors connected by distributed current conductors with significant electrical resistances.

– Investigate the voltage distributions between the cables of the cable rope as in an electrical system with a parallel connection of discrete current conductors connected by distributed current conductors with significant electrical resistances.

– Define the requirements for the control system.

In the rope due to the accuracy of manufacturing deviations of the axes of the cable from the design locations. We ignore the errors of manufacturing technology. Random uneven electrical parameters of cables and elastic shell. Consider a rope as a regular structure with electrical parameters that remain unchanged along the coordinate axes. In such a rope in three orthogonal directions - in the coordinate system (x, i, j) the cables are arranged regularly - in rows and in rows, this is shown in the scheme of control of the internal resistance of the cable rope (Fig. 1).

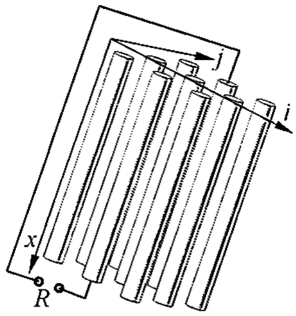


Fig. 1. The scheme of control of internal resistance of a cable rope

Core material and results

Consider the distribution of potentials in a rope of length L in which the cables are located in N rows, and each row consists of M ropes. The specific resistance of the cable is denoted by r. Let us denote the specific electrical conductivity of rubber between the cables by q. The electrical conductivity of the cables is much higher than the corresponding value of the rubber located between the cables. This allows you to neglect the stream directed along the cables. Consider the potential distributions between the i, j-th cable and adjacent cables and + 1, j; i-1, j; i, j + 1; i, j-1 of length Δx as done in [5].

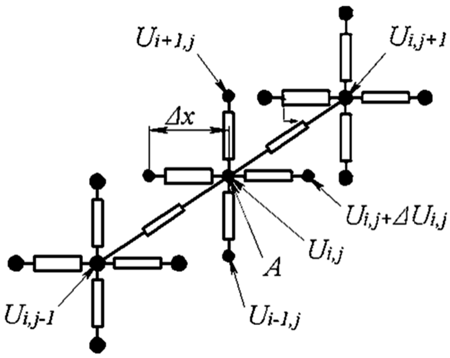


Fig. 2. Shows a diagram of the interaction of the segment i, j – that cable with adjacent cables as current conductors

According to Kirchhoff's law, the condition of equality of zero currents at point A, provided that $\Delta x \to 0$

$$\frac{dU_{i,j}}{rdx} + q\left(U_{i,j+1} + U_{i+1,j} - 4U_{i,j} + U_{i-1,j} + U_{i,j-1}\right) = 0 \qquad (2.1)$$

Consider Ohm's law. We obtain a linear homogeneous system of differential equations describing the potential distribution in a humotross multilayer (cable) rope:

$$\frac{d^2U_{i,j}}{dx^2} + rq\left(U_{i,j+1} + U_{i+1,j} - 4U_{i,j} + U_{i-1,j} + U_{i,j-1}\right) = 0$$
$$1 < i < M, \quad 1 < j < N. \qquad (2.2)$$

Note that system (2.2) is not acceptable for extreme cables. for them it has the following forms.

$$\frac{d^2U_{1,j}}{dx^2}+rq\left(U_{2,j}-U_{1,j}\right)=0\ , \tag{2.3}$$

$$\frac{d^2U_{i,1}}{dx^2}+rq\left(U_{i,2}-U_{i,1}\right)=0\ , \tag{2.4}$$

$$\frac{d^2U_{M,j}}{dx^2}+rq\left(U_{M-1,j}-U_{M,j}\right)=0\ , \tag{2.5}$$

$$\frac{d^2U_{i,N}}{dx^2}+rq\left(U_{i,N-1}-U_{i,N}\right)=0\ , \tag{2.6}$$

where $U_{i,j}$ is the distribution along the tape (x-axis) of potentials in and, j is the cable.

The obtained expressions (2.1)–(2.6), supplemented by the conditions of distribution of potentials and currents at the ends of the cables constitute a mathematical model of the cable rope as an electrical system with discrete conductors electrically connected elements with continuous parameters. The solution of homogeneous equation (2.1) will be sought in the following form.

$$U_{i,j}=\sum_{n-1}^{N-1}\begin{matrix}\sum\limits_{m=1}^{M-1}e^{\beta_{m,n}x+\sqrt{-1}\mu_m i+\sqrt{-1}\chi_n j}+\\ +\sum\limits_{m=1}^{M-1}e^{\beta_m^M x+\sqrt{-1}\mu_m i}+\sum\limits_{n-1}^{N-1}e^{\beta_n^N x+\sqrt{-1}\chi_n j}\end{matrix} \tag{2.7}$$

where $\beta_{m,n}$, β_m^M, β_n^N μ_m χ_n – characteristic indicators.

Values μ_m χ_n we find taking into account the forms of equations (2.1), (2.2), (2.4), (2.5), (2.6).

$$\mu_m=\frac{\pi m}{M}\ , \tag{2.8}$$

$$\chi_n=\frac{\pi n}{N} \tag{2.9}$$

Substitute (2.8), (2.9) into (2.7). Consider the possibility of zero numbers of rows and numbers of cables in rows. Given the sum of exponents with imaginary arguments of trigonometric functions, we obtain the expression for determining the characteristic *NM* of homogeneous equations (2.7).

$$\beta_{m,n}=\sqrt{2rq\left(2-\cos(\mu_m)-\cos(\chi_n)\right)}\ , \tag{2.10}$$

$$\beta_m^M=\sqrt{2rq\left(1-\cos(\mu_m)\right)}\ , \tag{2.11}$$

$$\beta_n^N=\sqrt{2rq\left(1-\cos(\chi_n)\right)}\ . \tag{2.12}$$

Taking into account expressions (2.8)–(2.12), solution (2.7) takes the following form.

$$\begin{aligned}U_{i,j}=&\sum_{n-1}^{N-1}\sum_{m=1}^{M-1}\left(A_{m,n}e^{\beta_{m,n}x}+B_{m,n}e^{-\beta_{m,n}x}\right)\times\\ &\times\cos\left(\mu_m(i-0{,}5)\right)\cos\left(\chi_n(j-0{,}5)\right)+\\ &+\sum_{m=1}^{M-1}\left(A_m^M e^{\beta_m^M x}+B_m^M e^{-\beta_m^M x}\right)\times\\ &\times\cos\left(\mu_m(i-0{,}5)\right)+\\ &+\sum_{n=1}^{N-1}\left(A_n^N e^{\beta_n^N x}+B_n^N e^{-\beta_n^N x}\right)\cos\left(\chi_n(j-0{,}5)\right)+\\ &+\frac{I_0}{MN}rx,\ (1\le i\le M),(1\le j\le N),\end{aligned} \tag{2.13}$$

where $A_{m,n}$, $B_{m,n}$, μ_m, χ_n A_m^M, B_m^M, A_n^N, B_n^N - vectors of constant values, I_0 - the amount of current passing through the rope.

We will use the accepted decision, Ohm’s law, we will define distributions of currents in cables.

$$\begin{aligned}I_{i,j}=r^{-1}&\left(\sum_{n-1}^{N-1}\sum_{m=1}^{M-1}\left(A_{m,n}e^{\beta_{m,n}x}-B_{m,n}e^{-\beta_{m,n}x}\right)\beta_{m,n}\times\right.\\ &\times\cos\left(\mu_m(i-0{,}5)\right)\cos\left(\chi_n(j-0{,}5)\right)+\\ &+\sum_{m=1}^{M-1}\left(A_m^M e^{\beta_m^M x}-B_m^M e^{-\beta_m^M x}\right)\beta_m^M\cos\left(\mu_m(i-0{,}5)\right)+\\ &\left.+\sum_{n=1}^{N-1}\left(A_n^N e^{\beta_n^N x}-B_n^N e^{-\beta_n^N x}\right)\beta_n^N\cos\left(\chi_n(j-0{,}5)\right)\right)+\\ &+\frac{I_0}{MN},\ (1\le i\le M),(1\le j\le N)\end{aligned} \tag{2.14}$$

The control system is aimed at establishing the rupture of the cable in the rope. The change in the electrical parameters of the rope and will be considered as a diagnostic parameter of the control system. Consider the distributions for two cases of rope without cable damage and rope with damaged cable.

The first case. We will assume that to the end of the cable, denoted as K_0, J_0, in the cross section $x = 0$ the electric signal in 1A is brought. Note that the values of the indices in the cable numbers for convenience correspond to the coordinate of the section for which they are considered. The signal from the opposite end can be recorded according to various schemes. The extreme circuits are the circuit of signal removal from one cable (shown in Fig. 1) and the circuit of signal removal from all cables connected (electrically) to one node. We will take their potential equal to zero.

In both cases, in the cross section $x = 0$, the signal is applied to one cable. We write down the accepted in the form of boundary conditions.

When x=0 $$I_{i,j}=\begin{pmatrix}1 & i=K_0\wedge j=J_0\\ 0 & i\ne K_0\wedge j\ne J_0\end{pmatrix}. \tag{2.15}$$

Boundary condition (2.15) is a discontinuous δ-Dirac function on the discrete axes of genus numbers and rope numbers in rows at intervals M and N. We set the δ-Dirac function by the product of Fourier series.

$$I_{i,j}=\frac{4}{MN}\sum_{n=1}^{N-1}\cos\left(\chi_n\left(J_0-0,5\right)\right)\cos\left(\chi_n\left(j-0,5\right)\right)\times\times\sum_{m=1}^{M-1}\cos\left(\mu_m\left(K_0-0,5\right)\right)\cos\left(\mu_m\left(i-0,5\right)\right)++\frac{2}{N}\sum_{n=1}^{N-1}\cos\left(\chi_n\left(J_0-0,5\right)\right)\cos\left(\chi_n\left(j-0,5\right)\right)++\frac{2}{M}\sum_{m=1}^{M-1}\cos\left(\mu_m\left(K_0-0,5\right)\right)\cos\left(\mu_m\left(i-0,5\right)\right)++\frac{1}{MN},\ \left(1\le i\le M\right),\left(1\le j\le N\right). \quad (2.16)$$

We equate the values of currents with (2.16) to currents with (2.14) when $x = 0$.

$$I_{i,j}=\sum_{n-1}^{N-1}\sum_{m=1}^{M-1}\left(A_{m,n}-B_{m,n}\right)\beta_{m,n}\begin{pmatrix}\cos\left(\mu_m\left(i-0,5\right)\right)\times\\ \times\cos\left(\chi_n\left(j-0,5\right)\right)\end{pmatrix}++\sum_{m=1}^{M-1}\left(A_m^M-B_m^M\right)\beta_m^M\cos\left(\mu_m\left(i-0,5\right)\right)++\sum_{n=1}^{N-1}\left(A_n^N-B_n^N\right)\beta_n^N\left(\chi_n\left(j-0,5\right)\right)+\frac{I}{MN},\left(1\le i\le M\right),\left(1\le j\le N\right) \quad (2.17)$$

Determine the relationship between the constant values.

$$A_{m,n}-B_{m,n}=\frac{4}{MN\beta_{m,n}}\sum_{n=1}^{N-1}\cos\left(\chi_n\left(J_0-0,5\right)\right)\times\times\sum_{m=1}^{M-1}\cos\left(\mu_m\left(K_0-0,5\right)\right), \quad (2.18)$$

$$A_m^M-B_m^M=\frac{2}{M\beta_m^M}\sum_{m=1}^{M-1}\cos\left(\mu_m\left(K_0-0,5\right)\right), \quad (2.19)$$

$$A_n^N-B_n^N=\frac{2}{N\beta_n^N}\sum_{n=1}^{N-1}\cos\left(\chi_n\left(J_0-0,5\right)\right). \quad (2.20)$$

For the section $x = L$, consider the two possible cases listed above. Let when $x = L$.

$$I_{i,j}=\begin{pmatrix}-1 & i=K_L\wedge j=J_L\\ 0 & i\ne K_L\wedge j\ne J_L\end{pmatrix}. \quad (2.21)$$

Then.

$$I_{i,j}=\sum_{n-1}^{N-1}\sum_{m=1}^{M-1}\begin{pmatrix}\left(A_{m,n}e^{\beta_{m,n}L}-B_{m,n}e^{-\beta_{m,n}L}\right)\beta_{m,n}\times\\ \times\begin{pmatrix}\cos\left(\mu_m\left(i-0,5\right)\right)\times\\ \times\cos\left(\chi_n\left(j-0,5\right)\right)\end{pmatrix}\end{pmatrix}++\sum_{m=1}^{M-1}\left(A_m^M e^{\beta_m^M L}-B_m^M e^{-\beta_m^M L}\right)\beta_m^M\cos\left(\mu_m\left(i-0,5\right)\right)++\sum_{n=1}^{N-1}\left(A_n^N e^{\beta_n^N L}-B_n^N e^{-\beta_n^N L}\right)\beta_n^N\left(\chi_n\left(j-0,5\right)\right)+\frac{I}{MN},\left(1\le i\le M\right),\left(1\le j\le N\right) \quad (2.22)$$

and

$$-A_{m,n}+B_{m,n}e^{-2\beta_{m,n}L}=\frac{4}{MN\beta_{m,n}e^{\beta_{m,n}L}}\times\times\sum_{n=1}^{N-1}\cos\left(\chi_n\left(J_L-0,5\right)\right)\sum_{m=1}^{M-1}\cos\left(\mu_m\left(K_L-0,5\right)\right), \quad (2.23)$$

$$-A_m^M+B_m^M e^{-2\beta_m^M L}=\frac{2}{M\beta_m^M e^{\beta_m^M L}}\times\times\sum_{m=1}^{M-1}\cos\left(\mu_m\left(K_L-0,5\right)\right), \quad (2.24)$$

$$-A_n^N+B_n^N e^{-2\beta_n^N L}=\frac{2}{N\beta_n^N e^{\beta_n^N L}}\times\times\sum_{n=1}^{N-1}\cos\left(\chi_n\left(J_L-0,5\right)\right). \quad (2.25)$$

From expressions (2.18)–(2.20) and (2.23)–(2.25) we have the following values of vectors of constant quantities.

$$B_{m,n}=\frac{4\beta_{m,n}^{-1}}{MN\left(e^{-2\beta_{m,n}L}-1\right)}\times\times\sum_{m=1}^{M-1}\begin{pmatrix}\dfrac{\sum_{n=1}^{N-1}\cos\left(\chi_n\left(J_L-0,5\right)\right)\cos\left(\mu_m\left(K_L-0,5\right)\right)}{e^{\beta_{m,n}L}}+\\ +\cos\left(\chi_n\left(J_0-0,5\right)\right)\cos\left(\mu_m\left(K_0-0,5\right)\right)\end{pmatrix} \quad (2.26)$$

$$B_m^M=\frac{2}{M\beta_m^M\left(e^{-2\beta_m^M L}-1\right)}\times\sum_{m=1}^{M-1}\frac{\cos\left(\mu_m\left(K_L-0,5\right)\right)}{e^{\beta_m^M L}}++\cos\left(\mu_m\left(K_0-0,5\right)\right), \quad (2.27)$$

$$B_n^N=\frac{2}{N\beta_n^N\left(e^{-2\beta_n^N L}-1\right)}\sum_{n=1}^{N-1}\frac{\cos\left(\chi_n\left(J_L-0,5\right)\right)}{e^{\beta_n^N L}}++\cos\left(\chi_n\left(J_0-0,5\right)\right). \quad (2.28)$$

$$A_{m,n}=\frac{4}{MN\beta_{m,n}}\sum_{n=1}^{N-1}cos\left(\chi_n\left(J_0-0,5\right)\right)\times\times\sum_{m=1}^{M-1}\cos\left(\mu_m\left(K_0-0,5\right)\right)+B_{m,n}, \quad (2.29)$$

$$A_m^M = \frac{2}{M\beta_m^M} \sum_{m=1}^{M-1} \cos\left(\mu_m \left(K_0 - 0,5\right)\right) + B_m^M , \quad (2.30)$$

$$A_n^N = \frac{2}{N\beta_n^N} \sum_{n=1}^{N-1} \cos\left(\chi_n \left(J_0 - 0,5\right)\right) + B_n^N . \quad (2.31)$$

The found vectors of constants allow to determine the distributions of potentials and currents in the rope cables. A simpler scheme is one in which the ends of all cables are electrically connected. Accordingly, the potential of the connection point can be considered equal to zero.

When $$x = L.\ U_{i,j} = 0 \quad (2.32)$$

According to condition (2.32) we equate to zero the values of potentials (2.13) in the section $x = L$.

$$A_{m,n}e^{\beta_{m,n}L} + B_{m,n}e^{-\beta_{m,n}L} = 0 , \quad (2.33)$$

$$A_m^M e^{\beta_m^M L} + B_m^M e^{-\beta_m^M L} = 0 , \quad (2.34)$$

$$A_n^N e^{\beta_n^N L} + B_n^N e^{-\beta_n^N L} = 0 . \quad (2.35)$$

From expressions (2.18)–(2.20) and (2.34)–(2.35) we have.

$$B_{m,n} = -\frac{4e^{\beta_{m,n}L} \cos\left(\chi_n \left(J - 0,5\right)\right)\cos\left(\mu_m \left(K - 0,5\right)\right)}{M\,N\left(e^{\beta_{m,n}L} + e^{-\beta_{m,n}L}\right)\beta_{m,n}} \quad (2.36)$$

$$B_m^M = -\frac{2e^{\beta_m^M L} \cos\left(\mu_m \left(K - 0,5\right)\right)}{M\left(e^{\beta_m^M L} + e^{-\beta_m^M L}\right)\beta_m^M} , \quad (2.37)$$

$$B_n^N = -\frac{2e^{\beta_n^N L}}{N\left(e^{\beta_n^N L} + e^{-\beta_n^N L}\right)\beta_n^N} \cos\left(\chi_n \left(J - 0,5\right)\right). \quad (2.38)$$

$$A_{m,n} = \frac{4}{M\,N\beta_{m,n}} \cos\left(\chi_n \left(J - 0,5\right)\right)\cos\left(\mu_m\left(K - 0,5\right)\right) + B_{m,n} , \quad (2.39)$$

$$A_m^M = \frac{2}{M\beta_m^M} \cos\left(\mu_m \left(K - 0,5\right)\right) + B_m^M , \quad (2.40)$$

$$A_n^N = \frac{2}{N\beta_n^N} \cos\left(\chi_n \left(J - 0,5\right)\right) + B_n^N . \quad (2.41)$$

The found vectors of constants allow to determine the distributions of potentials, currents in the cables of the cable rope without damage. Analysis of the results showed that the signal removal scheme does not significantly affect the potential distribution in the cross section $x = 0$. Applying the potential difference to the opposite ends of the cables of the cable rope, to create a smooth signal, you need to sum up the greater potential difference. The relative difference in the values of the supplied potentials depends on the number of cables of the cable rope. It increases with the number of cables and the length of the rope and depends on the location of the cable in the cross section. For the corner it is larger than for the average.

Consider a cable rubber rope with a damaged cable. The current distributions (2.14) do not depend on the presence of cable breaks. The latter locally change the structure of the rope makes it impossible to use expressions (2.13), (2.14) for such a rope. Conditionally in the section $x = \xi$ divide the rope into two parts. We will give numbers one and two to the parts. Part numbers will be introduced into the lower indices of notation of electrical parameters and coefficients in expressions to determine them. In the section $x = 0$ the boundary conditions (2.15) are unchanged. This allows us to use expressions for the ratios of unknown constants (2.18)–(2.20). and record them as for the first part of the rope in the following forms.

$$A_{m,n,1} - B_{m,n,1} = \frac{4}{M\,N\beta_{m,n}} \sum_{n=1}^{N-1} \cos\left(\chi_n \left(J_0 - 0,5\right)\right)\times$$
$$\times \sum_{m=1}^{M-1} \cos\left(\mu_m \left(K_0 - 0,5\right)\right) , \quad (2.42)$$

$$A_{m,1}^M - B_{m,1}^M = \frac{2}{M\beta_m^M} \sum_{m=1}^{M-1} \cos\left(\mu_m \left(K_0 - 0,5\right)\right) , \quad (2.43)$$

$$A_{n,1}^N - B_{n,1}^N = \frac{2}{N\beta_n^N} \sum_{n=1}^{N-1} \cos\left(\chi_n \left(J_0 - 0,5\right)\right) . \quad (2.44)$$

In the cross section of the cable break by number K_ξ, located in a row by number J_ξ, the following conditions must be met:

When $x = \xi$

$$I_{i,j,1} = I_{i,j,2} , \quad (2.45)$$

$$I_{K_L,J_L} = 0 , \quad (2.46)$$

$$U_{i,j,2} - U_{i,j,1} = u\begin{pmatrix} 1 & i = K_\xi \wedge j = J_\xi \\ 0 & i \neq K_\xi \vee j \neq J_\xi \end{pmatrix} , \quad (2.47)$$

where u is an unknown value of the potential difference between the ends of the damaged cable in the cross section of its rupture.

From condition (2.47) we find the following relations.

$$A_{m,n,2} - A_{m,n,1} + \left(B_{m,n,2} - B_{m,n,1}\right)e^{-2\beta_{m,n}\xi} =$$
$$= \frac{4u}{M\,Ne^{\beta_{m,n}\xi}} \sum_{n=1}^{N-1} \cos\left(\chi_n\left(J_\xi - 0,5\right)\right)\times$$
$$\times \sum_{m=1}^{M-1} \cos\left(\mu_m\left(K_\xi - 0,5\right)\right), \quad (2.48)$$

$$A_{m,2}^{M}-A_{m,1}^{M}+\left(B_{m,2}^{M}-B_{m,1}^{M}\right)e^{-2\beta_m^M\xi}=\frac{2u}{Me^{\beta_m^M\xi}}\times$$

$$\times\sum_{m=1}^{M-1}\cos\left(\mu_m\left(K_\xi-0,5\right)\right), \quad (2.49)$$

$$A_{n,2}^{N}-A_{n,2}^{N}+\left(B_{n,2}^{N}-B_{n,2}^{N}\right)e^{-2\beta_n^N\xi}=\frac{2u}{Ne^{\beta_n^N\xi}}\times$$

$$\times\sum_{n=1}^{N-1}\cos\left(\chi_n\left(J_\xi-0,5\right)\right). \quad (2.50)$$

Condition (2.44) provides the following relations.

$$A_{m,n,2}+A_{m,n,1}-\left(B_{m,n,2}-B_{m,n,1}\right)e^{-2\beta_{m,n}\xi}=0, \quad (2.51)$$

$$A_{m,2}^{M}+A_{m,2}^{M}-\left(B_{m,2}^{M}-B_{m,2}^{M}\right)e^{-2\beta_m^M\xi}=0, \quad (2.52)$$

$$A_{n,2}^{N}+A_{n,1}^{N}-\left(B_{n,2}^{N}-B_{n,1}^{N}\right)e^{-2\beta_n^N\xi}=0. \quad (2.53)$$

The ratios (2.42)–(2.44), (2.48)–(2.50), (2.51)–(2.53) determine the interdependence of the components of the three groups of vectors. Each of these groups includes four such vectors. We formulate three more expressions of the interdependence of vectors constant in the expressions of currents and potentials. We construct them from the condition of the nature of the current supply to the ends of the rope in the cross section $x = L$.

Consider two possible cases of signal removal from one cable and from all. In the first case, similar to the found expressions (2.23)–(2.25), we have.

$$-A_{m,n,2}+B_{m,n,2}e^{-2\beta_{m,n}L}=\frac{4e^{-\beta_{m,n}L}}{MN\beta_{m,n}}\times$$

$$\times\sum_{n=1}^{N-1}\cos\left(\chi_n\left(J_L-0,5\right)\right)\sum_{m=1}^{M-1}\cos\left(\mu_m\left(K_L-0,5\right)\right) \quad (2.54)$$

$$-A_{m,2}^{M}+B_{m,2}^{M}e^{-2\beta_m^M L}=\frac{2}{M\beta_m^M e^{\beta_m^M L}}\times\sum_{m=1}^{M-1}\cos\left(\mu_m\left(K_L-0,5\right)\right), \quad (2.55)$$

$$-A_{n,2}^{N}+B_{n,2}^{N}e^{-2\beta_n^N L}=\frac{2}{N\beta_n^N e^{\beta_n^N L}}\times\sum_{n=1}^{N-1}\cos\left(\chi_n\left(J_L-0,5\right)\right) \quad (2.56)$$

In the second case, the potential supply circuit to the ends of the rope is a circuit in which the ends of the cables are electrically connected. Take into account (2.33)–(2.35). We will receive.

$$A_{m,n,2}e^{\beta_{m,n}L}+B_{m,n,2}e^{-\beta_{m,n}L}=0, \quad (2.57)$$

$$A_{m,2}^{M}e^{\beta_m^M L}+B_{m,2}^{M}e^{-\beta_m^M L}=0, \quad (2.58)$$

$$A_{n,2}^{N}e^{\beta_n^N L}+B_{n,2}^{N}e^{-\beta_n^N L}=0. \quad (2.59)$$

Expressions for the first circuit of current supply to cables and the second-potential expressions in the section $n\,x = L$ complement three groups of equations and create a number of algebraic linear systems. Each of the systems has four unknown - the required values in terms of currents and potentials. Omit the intermediate transformations. We present the final results in the form of linear functions of unknown magnitude – the potential difference between the ends of the damaged cable.

$$B_{m,n,2}=B_{m,n,20}+u\,Bu_{m,n,20}, \quad (2.60)$$

$$A_{m,n,2}=A_{m,n,20}+u\,Au_{m,n,20}, \quad (2.61)$$

$$B_{m,n,1}=B_{m,n,10}+u\,Bu_{m,n,10}, \quad (2.62)$$

$$A_{m,n,1}=A_{m,n,10}+u\,Au_{m,n,10}. \quad (2.63)$$

The given expressions include unknown coefficients. Their value depends on the scheme of signal removal in the cross section $x = L$. We give their values for the two cases. In case of removal of a signal according to fig. 1:

$$B_{m,n,20}=4\frac{e^{-2\beta_{m,n}L}\cos\left(\chi_n\left(J_L-0,5\right)\right)\cos\left(\mu_m\left(K_L-0,5\right)\right)-\cos\left(\chi_n\left(J_0-0,5\right)\right)\cos\left(\mu_m\left(K_0-0,5\right)\right)}{MN\left(1-e^{-2\beta_{m,n}L}\right)\beta_{m,n}}$$

$$Bu_{m,n,20}=-2\frac{\left(e^{\beta_{m,n}\xi}-e^{-\beta_{m,n}\xi}\right)\cos\left(\chi_n\left(J_\xi-0,5\right)\right)\times\cos\left(\mu_m\left(K_\xi-0,5\right)\right)}{MN\left(1-e^{-2\beta_{m,n}L}\right)}$$

$$A_{m,n,20}=4\frac{e^{-\beta_{m,n}\xi}\cos\left(\chi_n\left(J_L-0,5\right)\right)\cos\left(\mu_m\left(K_L-0,5\right)\right)}{MN\beta_{m,n}}+$$

$$+B_{m,n,20}e^{-2\beta_{m,n}L};$$

$$Au_{m,n,20}=-Bu_{m,n,20}e^{-2\beta_{m,n}L}; \quad B_{m,n,10}=B_{m,n,20};$$

$$Bu_{m,n,10}=\frac{2e^{\beta_{m,n}\xi}}{MN}\cos\left(\chi_n\left(J_\xi-0,5\right)\right)\cos\left(\mu_m\left(K_\xi-0,5\right)\right)+Bu_{m,n,20};$$

$$A_{m,n,10}=\frac{4e^{\beta_{m,n}\xi}}{MN\beta_{m,n}}\cos\left(\chi_n\left(J_0-0,5\right)\right)\cos\left(\mu_m\left(K_0-0,5\right)\right)+$$

$$+B_{m,n,20};$$

$$Au_{m,n,10}=\frac{2e^{\beta_{m,n}\xi}}{MN}\cos\left(\chi_n\left(J_\xi-0,5\right)\right)\cos\left(\mu_m\left(K_\xi-0,5\right)\right)+$$

$$+Bu_{m,n,20};$$

$$B_{m,20}^{M}=2\frac{e^{-2\beta_m^M L}\cos\left(\mu_m\left(K_L-0,5\right)\right)-\cos\left(\mu_m\left(K_0-0,5\right)\right)}{M\,N\left(1-e^{-2\beta_m^M L}\right)\beta_m^M};$$

$$Bu_{m,20}^{M}=\frac{\left(e^{\beta_m^M\xi}-e^{-\beta_m^M\xi}\right)\cos\left(\mu_m\left(K_\xi-0,5\right)\right)}{M\,N\left(e^{-2\beta_m^M L}-1\right)\beta_m^M};$$

$$A_{m,20}^{M}=\left(\frac{2\cos\left(\mu_m\left(K_L-0,5\right)\right)}{M\,N\beta_m^M}+B_{m,20}^{M}\right)e^{-2\beta_m^M L};$$

$$Au_{m,20}^{M}=Bu_{m,20}^{M}e^{-2\beta_m^M L};$$

$$A_{m,10}^{M}=2\frac{\cos\left(\mu_m\left(K_0-0,5\right)\right)}{M\,N\beta_m^M}+B_{m,20}^{M};$$

$$Au_{m,10}^{M}=\frac{e^{\beta_m^M\xi}\cos\left(\mu_m\left(K_\xi-0,5\right)\right)}{M\,N\beta_m^M}+Bu_{m,20}^{M};$$

$$B_{m,10}^{M}=B_{m,20}^{M};$$

$$Bu_{m,10}^{M}=\frac{e^{\beta_m^M\xi}\cos\left(\mu_m\left(K_\xi-0,5\right)\right)}{M\,N}+Bu_{m,20}^{M};$$

$$B_{n,20}^{N}=2\frac{e^{-2\beta_n^N L}\cos\left(\chi_n\left(J_L-0,5\right)\right)-\cos\left(\chi_n\left(J_0-0,5\right)\right)}{M\,N\left(1-e^{-2\beta_n^N L}\right)\beta_n^N};$$

$$Bu_{n,20}^{N}=2\frac{\left(e^{-\beta_n^N\xi}-e^{-\beta_n^N\xi}\right)\cos\left(\chi_n\left(J_\xi-0,5\right)\right)-\cos\left(\chi_n\left(J_\xi-0,5\right)\right)}{M\,N\left(1-e^{-2\beta_n^N L}\right)\beta_n^N};$$

$$A_{n,20}^{N}=\left(2\frac{\cos\left(\chi_n\left(J_L-0,5\right)\right)}{M\,N\beta_n^N}+B_{n,20}^{N}\right)e^{-2\beta_n^N L};$$

$$Au_{n,20}^{N}=Bu_{n,20}^{N}e^{-2\beta_n^N L};$$

$$A_{n,10}^{N}=2\frac{\cos\left(\chi_n\left(J_0-0,5\right)\right)}{M\,N\beta_n^N}+B_{n,20}^{N};$$

$$Au_{n,10}^{N}=\frac{e^{\beta_n^N\xi}\cos\left(\chi_n\left(J_\xi-0,5\right)\right)}{M\,N\beta_n^N}+Bu_{n,20}^{N}$$

$$B_{n,10}^{N}=B_{n,20}^{n};$$

$$Bu_{n,10}^{N}=\frac{e^{\beta_n^N\xi}\cos\left(\chi_n\left(J_\xi-0,5\right)\right)}{M\,N}+Bu_{n,20}^{N}.$$

In the case of electrical connection of cables in the cross section $x = L$, the coefficients acquire the following values:

$$B_{m,n,20}=-\frac{2\cos\left(\chi_n\left(J_0-0,5\right)\right)\cos\left(\mu_m\left(K_0-0,5\right)\right)}{M\,N\left(e^{-2\beta_{m,n}L}+1\right)\beta_{m,n}};$$

$$Bu_{m,n,20}=-2\frac{\left(e^{\beta_{m,n}\xi}-e^{-\beta_{m,n}\xi}\right)\cos\left(\chi_n\left(J_\xi-0,5\right)\right)\times\times\cos\left(\mu_m\left(K_\xi-0,5\right)\right)}{M\,N\left(e^{-2\beta_{m,n}L}+1\right)};$$

$$A_{m,n,20}=-B_{m,n,20}e^{-2\beta_{m,n}L};$$

$$Au_{m,n,20}=-Bu_{m,n,20}e^{-2\beta_{m,n}L};$$

$$B_{m,n,10}=B_{m,n,20}e^{-2\beta_{m,n}L};$$

$$Bu_{m,n,10}=\frac{2e^{\beta_{m,n}\xi}}{M\,N}\cos\left(\chi_n\left(J_\xi-0,5\right)\right)\times\times\cos\left(\mu_m\left(K_\xi-0,5\right)\right)+Bu_{m,n,20};$$

$$Au_{m,n,10}=\frac{2}{M\,Ne^{\beta_{m,n}\xi}}\cos\left(\chi_n\left(J_\xi-0,5\right)\right)\times\cos\left(\mu_m\left(K_\xi-0,5\right)\right)-Bu_{m,n,20}e^{-2\beta_{m,n}L};$$

$$A_{m,n,10}=-B_{m,n,20}e^{-2\beta_{m,n}L};$$

$$B_{m,20}^{M}=-\frac{2\cos\left(\mu_m\left(K_0-0,5\right)\right)}{M\,N\left(e^{-2\beta_m^M L}+1\right)\beta_m^M};$$

$$Bu_{m,20}^{M}=\frac{\left(e^{\beta_m^M\xi}-e^{-\beta_m^M\xi}\right)\cos\left(\mu_m\left(K_\xi-0,5\right)\right)}{M\,N\left(e^{-2\beta_m^M L}+1\right)\beta_m^M};$$

$$A_{m,20}^{M}=-B_{m,20}^{M}e^{-2\beta_m^M L};$$

$$Au_{m,20}^{M}=-Bu_{m,20}^{M}e^{-2\beta_m^M L};$$

$$A_{m,10}^{M}=-B_{m,20}^{M}e^{-2\beta_m^M L};$$

$$Au_{m,10}^{M}=\frac{e^{-\beta_m^M\xi}\cos\left(\mu_m\left(K_\xi-0,5\right)\right)}{M\,N}-Bu_{m,20}^{M}e^{-2\beta_m^M L};$$

$$B_{m,10}^{M}=B_{m,20}^{M};$$

$$Bu_{m,10}^{M}=\frac{e^{\beta_m^M\xi}\cos\left(\mu_m\left(K_\xi-0{,}5\right)\right)}{M\,N}-Bu_{m,20}^{M};$$

$$B_{n,20}^{N}=-\frac{2\cos\left(\chi_n\left(J_L-0{,}5\right)\right)}{M\,N\left(e^{-2\beta_n^N L}+1\right)\beta_n^N};$$

$$Bu_{n,20}^{N}=\frac{\left(e^{\beta_n^N\xi}-e^{-\beta_n^N\xi}\right)\cos\left(\chi_n\left(J_\xi-0{,}5\right)\right)}{M\,N\left(e^{-2\beta_n^N L}+1\right)\beta_n^N};$$

$$A_{n,20}^{N}=-B_{n,20}^{N}e^{-2\beta_n^N L};\; Au_{n,20}^{N}=-Bu_{n,20}^{N}e^{-2\beta_n^N L};$$

$$A_{n,10}^{N}=B_{n,20}^{N}e^{-2\beta_n^N L};\; B_{n,10}^{N}=B_{n,20}^{N};$$

$$Bu_{n,10}^{N}=\frac{e^{\beta_n^N\xi}\cos\left(\chi_n\left(J_\xi-0{,}5\right)\right)}{M\,N}-Bu_{n,20}^{N}.$$

The obtained expressions allow to determine the distributions of currents and potentials between the ropes of the rope as a function of the unknown value of the potential difference between the ends of the damaged cable in the cross section of its rupture. From the condition of zero current between these ends (2.46) we find the value of the unknown potential difference.

$$u=-\frac{\begin{aligned}&\sum_{m=1}^{M-1}\sum_{n=1}^{N-1}\left(A_{m,n,2}e^{\beta_{m,n}\xi}-B_{m,n,2}e^{-\beta_{m,n}\xi}\right)\beta_{m,n}\psi\left(m,K_\xi\right)\omega\left(n,J_\xi\right)+\\&+\sum_{m=1}^{M-1}\left(A_{m,2}^{M}e^{\beta_m^M\xi}-B_{m,2}^{M}e^{-\beta_m^M\xi}\right)\beta_m^M\psi\left(m,K_\xi\right)+\\&+\sum_{n=1}^{N-1}\left(A_{n,2}^{N}e^{\beta_n^N\xi}-B_{n,2}^{N}e^{-\beta_n^N\xi}\right)\beta_n^N\omega\left(n,J_\xi\right)+\frac{1}{M\,N}\end{aligned}}{\begin{aligned}&\sum_{m=1}^{M-1}\sum_{n=1}^{N-1}\left(Au_{m,n,2}e^{\beta_{m,n}\xi}-Bu_{m,n,2}e^{-\beta_{m,n}\xi}\right)\beta_{m,n}\psi\left(m,K_\xi\right)\omega\left(n,J_\xi\right)+\\&+\sum_{m=1}^{M-1}\left(Au_{m,2}^{M}e^{\beta_m^M\xi}-Bu_{m,2}^{M}e^{-\beta_m^M\xi}\right)\beta_m^M\psi\left(m,K_\xi\right)+\\&+\sum_{n=1}^{N-1}\left(Au_{n,2}^{N}e^{\beta_n^N\xi}-Bu_{n,2}^{N}e^{-\beta_n^N\xi}\right)\beta_n^N\omega\left(n,J_\xi\right).\end{aligned}}$$

Where $\psi\left(m,i\right)=\cos\left(\mu_m\left(i-0{,}5\right)\right)$;

$\omega\left(n,j\right)=\cos\left(\chi_n\left(j-0,5\right)\right)$.

The found values of the potential difference allow to determine the desired distributions of currents and potentials.

We performed calculations of current and potential distributions for the rope with characteristics $r = 0.001$ Ohm / m $q = 0.01$ m / Ohm. The number of ropes in each row and the number of rows was taken to be five. The length of the rope was taken equal to $L = 100$ m. The distributions were determined for the cases of current supply of the middle ($K_0 = J_0 = 3$) cable and for the rope with a damaged cable surface ($K_0 = J_0 = 3$) – 1 and without damage – 2 cables.

General recommendations for the implementation of research of the railway rail for analysis of surface initiated rolling contact fatigue cracks

In fig. 3. 1–5 shows the distributions for the case of electrical connection of the ends of the rope in the section $x = L$.

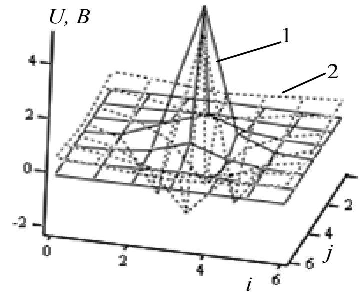


Fig. 3. Shows the distribution of potentials in the cross section $x = 0$

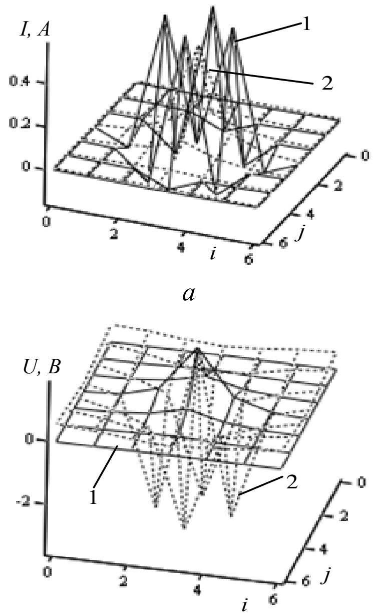


Fig. 4. *a*) shows the distributions of currents and potentials, *b*) in the cross section of the cable damage $x = \xi$

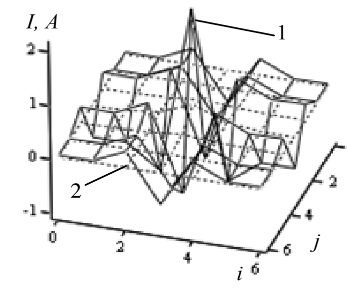


Fig. 5. Shows the current distributions in the cross section $x = L$

The graphs show a significant effect of cable bursts on the patterns of current and potential distributions in the rope.

The results of calculations for the case of bringing the potential difference to the ends of one cable are shown in Fig. 6–8.

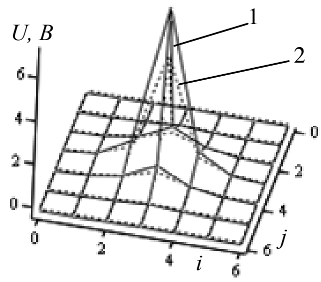
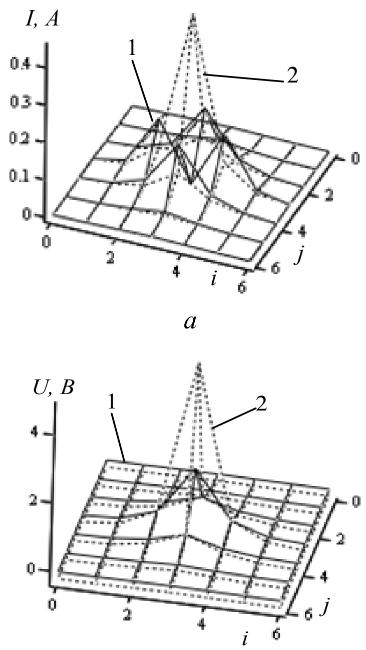


Fig. 6. Characterizes the potential distribution in the cross section $x = 0$



b

Fig. 7. *a*) shows the distributions of currents and potentials, *b*) in the cross section of the cable damage $x = \xi$

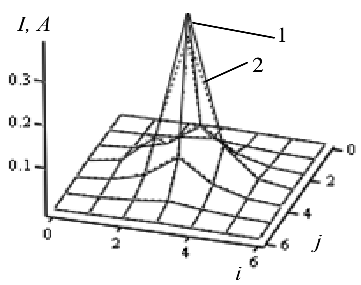


Fig. 8. Shows the current distributions in the cross section $x = L$

The potential difference between the supply points of a unit value determines the resistance of the system. The potential in the cross section $x = L$, respectively (32) is zero, and the potential difference is equal to the potential at the end of the cable number K, located in the row number J, in the section $x = 0$ and is the resistance in case of cable damage.

$$R = \sum_{n-1}^{N-1}\sum_{m=1}^{M-1}\left(A_{m,n,1} + B_{m,n,1} + u\left(Au_{m,n,1} + Bu_{m,n,1}\right)\right)\times \times\psi\left(m,K\right)\cos\left(\chi_n\left(J-0,5\right)\right) +$$

$$+\sum_{m=1}^{M-1}\left(A_{m,1}^{M} + B_{m,1}^{M} + u\left(Au_{m,1}^{M} + Bu_{m,1}^{M}\right)\right)\psi\left(m,K\right) +$$

$$+\sum_{n=1}^{N-1}\left(A_{n,1}^{N} + B_{n,1}^{N} + u\left(Au_{n,1}^{N} + Bu_{n,1}^{N}\right)\right)\cos\left(\chi_n\left(J-0,5\right)\right) + \frac{rL}{MN}$$

The obtained expressions allow to determine the distributions of currents and potentials between the ropes of the rope. We considered the case of bringing potentials to one arbitrary cable at one end of the rope. For the received unit current, the potential difference at the points of signal removal is a diagnostic parameter. Its values for the considered schemes of signal removal allow to define a condition of cables in a rope.

The problem of determining currents is linear. It allows the application of the principle of superposition. According to this principle, the distributions of potentials and currents can be made. The obtained dependences, by compiling the results, allow to determine the currents and potentials for any circuit of signal removal from the ends of the rope ropes.

The results of determining the changes in the electrical resistance of the rope in different schemes of signal removal allow you to control the gusts on this indicator.

Conclusions

To ensure the search for an unknown damaged cable, the system should be based on: identification of each pair of cable ropes; cyclic determination of electrical resistance of each pair of cables; comparison of a certain value with the "normative" established analytically by the above method; determining the result of the comparison.

The study of known works on the development of the method of continuous monitoring of the condition of the cables of the cable rope showed the possibility of applying the method of control of the internal resistance of the cable rope to control the condition of the cables of the cable rope of high reliability.

Using the methods of electrical engineering, a mathematical model is constructed, the method of its analytical solution in a closed form is formulated, the dependence of the distribution of stresses and currents in the rope on its parameters is investigated. The received decisions for a rope with the whole and damaged cable. They allowed to formulate requirements for the system of continuous automatic monitoring of the condition of the cable rope of increased reliability.

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Залежність внутрішнього електричного опору гумового троса кабелю від розриву кабелю

І.В. Бельмас, Е.І. Білоус, А.І. Танцура, А.В. Швачка

Проблематика. *Використання сталевих залізобетонних покриттів споруд, на нашу думку, передує розробка способів контролю стану вантових канатів - створення безпечних умов для довготривалої експлуатації споруд.*
Мета дослідження. *Аналітичне визначення залежності внутрішнього електричного опору гумотросового вантового каната від наявності розриву троса.*
Методика реалізації. *Для контролю всіх тросів система має забезпечувати послідовне контролювання електричних опорів ланцюгів утворених тросами, порівнювати їх із еталонними значеннями, видавати сигнал щодо стану каната. Вона повинна бути спроектована на основі наступних даних: тип і конструкція вантового каната, його довжина, кількість та схема розташування тросів у канаті, можливість доступу до одного або обох його кінців, електротехнічні властивості тросів та гуми, значення опорів тросів для всіх схем їх визначення.*
Результати дослідження. *Вимоги до системи автоматичного контролю гумового каната. Закономірність залежності електричного опору каната вантового від пориву довільного троса. Можливість автоматичного контролю стану гумотросового каната вантового.*
Висновки. *Отримані результати вважатимуться досить достовірними, оскільки отримані на основі фундаментальних положень електротехніки рівняння отримані аналітичним шляхом у замкнутому вигляді. Експериментальними дослідженнями встановлено, що внутрішній електричний опір тросів каната залежить від його властивостей та наявності чи відсутності пошкоджень тросів. До складу каната входять низка тросів. Пошкоджено можливо будь-який трос*

Ключові слова: *гумотросовий канат, електричний опір, керування, трос, математична модель, сигнал.*