Assessing the Integrity of Steel Ropes for Lifting Machines Based on Testing Data

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Abstract. Factors affecting the integrity of steel ropes for lifting machines are considered; a brief review of existing approaches to assessment is made. The dependence of the intensity of the decrease in the area of the metal section of the ropes on the number of loading cycles is obtained. A method for determining the integrity of steel ropes is proposed.

1. Introduction
Lifting machines are an important link in the transport process. The effectiveness of their use is determined by the absence of downtime and incidents and accidents. One of the causes of accidents of a lifting machine is the fall of cargo as a result of breaks in cargo or of boom ropes. Therefore, special attention is paid to assessing the condition of steel ropes during the operation of lifting machines. The requirements for ensuring the safe operation of ropes are identified in the Federal Standards and Regulations \cite{6, 7}. In particular, the Standards set the evaluation criteria for a rope should be rejected and replaced with a new one \cite{7}.

Due to certain difficulties, there are no reliable scientific and regulatory methods for evaluating the life of steel ropes. This paper attempts to suggest such a method. The use of this technique will allow us to evaluate in practice both the expected and actual remaining life of the steel rope for the specific conditions of its operation.

2. Factors affecting the life of steel rope and limit condition criteria
The integrity of a steel rope is determined by the following factors:
- the design of the rope (the shape of cross-section, sizes, the stacking order of the wires in the strands); the quantity and order of stacking of the strands in the general structure of the rope; the type and material of the core; the presence of material filling the empty space between the strands; the design scheme of how strands lay in the ropes and the way wires are tightened in locks; the technological operations.

Marking group: the tensile strength of steel a wire rope is made of:
- Design and operating conditions of the cable-block system of the lifting machine.
- Cyclic (fatigue) strength of the rope – the number of bends on the block (roller) at a given tensile force until the specified limit state criterion appears.

In Russia, tests of steel ropes for endurance are regulated by the Federal Standards and Regulations 2387-80 \cite{5}.
Depending on the requirements of standards for ropes the test is carried out until the following signs of the limit state appear: breakage of wire in the sample; the specified number of wire breaks on the length of one section of the sample; the specified number of turns of the sample around the replacement roller; complete destruction of the rope sample.

Similar tests are carried out by foreign manufacturers of steel ropes. For example, the “Vero AG” rope catalog provides the information about the resources (including bending cycles) obtained during tests on blocks of a running machine for some rope brands [12].

The current standards set the main criteria for the limit state of the rope, when reaching the values at which the rope should be rejected [7]: reducing the outer diameter of the rope by the maximum number of percent; reducing the size of the outer wire of the rope by the maximum number of percent; limiting the number of wire breaks on the length of one step of the rope.

3. The practice of appointing the diameter of the rope

Historically, the practice of assigning the rope diameter is based on determining the calculated maximum breaking force

\[ F_0 = F_{\text{MAX}} Z_P, \]

where \( F_{\text{MAX}} \) is the calculated maximum force in the rope; \( Z_P \) is the safety coefficient.

In modern regulatory documents, the safety coefficient \( Z_P \) is officially referred to as the coefficient of working conditions and is assigned in conjunction with the planned intensity of the operation of the machine in which the rope is used [6,11]. The higher the intensity of the operation, the greater the value of the \( Z_P \) coefficient.

The rope diameter is assigned from the condition \( [F_0] \geq F_0 \). It is assumed that during the operation, the strength characteristics of the rope decrease, and the actual value of the safety coefficient \( Z_P \) decreases after \( N \) cycles.

In the past, this approach has been repeatedly criticized by scientists who have studied the impact of the rope operating conditions on their integrity [8, 10, 17]. However, a complete theory and methodology that allows you to determine the resource of the rope with the help of calculation has not been developed yet.

4. Well-known approaches to assessing the resource of a steel rope

Since the invention of steel wire ropes (1827), the problem of determining the integrity of ropes has been investigated. In 1915, one of the first researchers experimentally established two main factors that affect the resource of steel ropes [1]:

- the ratio of the diameter of the rope \( d \) to the diameter \( D \) of the envelope block or drum \( d/D \);
- the number of rope bends on the \( N \) block.

During the following almost 200-year period, the study of the influence of various factors on the integrity of ropes continued. Some findings from the research are reported in the technical literature. For example, the book of Professor Betman G. (1930), contains the results of research of other scientists which was carried out in 1915-1924 [2]. In Russia, such work was also actively carried out. For example, Prof. Zhitkov D. G. proposed to determine the integrity of steel ropes in domestic production [10]. The purpose of the research was to determine the limits of the rope integrity during the number of bends on blocks \( N \) on the tensile force \( F \) and the \( d/D \) ratio, as well as on the factors mentioned above. Such studies were carried out later, their results are given in the technical literature [3, 4, 8, 9, 12, 14, 17].

As a modern approach to assessing the integrity of steel ropes, special attention should be paid to the research carried out by the employees of “INTRON PLUS” (http://www.intron.ru). In this research [3] the main provisions of the approach for determining the integrity of steel ropes are based on the generalization of the results of long-term studies of the state of steel ropes by nondestructive testing. Measurements are made along the entire length of the rope, which allows one to determine the problem areas with the most intensive damage. To illustrate the data obtained as a result of the study, Fig. 1 represents the state of the rope, based on its length. [3].
Figure 1 shows the results of studies performed at certain intervals. The problem areas where the area of the metal cross-section of the rope decreases first, and then there are breaks in the wires – these areas are clearly defined.

Our research confirms that the ropes of lifting machines wear out unevenly, there are always problem areas in which the damage increases most intensively along the length of the ropes.

The authors of the research proposed to determine the remaining life of a steel rope by comparing the calculated safety coefficient $Z_N$, determined by the calculation based on the results of successive control evaluations of the rope condition, with a certain permissible safety coefficient $[Z_N^*]$, assigned for the reasons of static strength of the rope. The initial data used in the calculations are: parameters of a cable-block system, the area values of a metallic cross-section of the rope $A$, the number of loading cycles of a rope during the period $N$ and the effort in the rope $F$.

![Figure 1. Representation of the state of the rope, retrieved from the screen of the device.](image)

Close to the linear dependence of the intensity of the reduction of the area of the metal cross section of the ropes on the number of loading cycles $N$ is of great importance to the research which was carried out by the authors.

$$\Delta A = (A - A_N)/N,$$  \hspace{1cm} (1)

where $A; A_N$ – the areas of the metal cross-section of the rope on the problem area, determined in the period between studies; $N$ – the number of loading cycles of the rope for this period.

Thus, the obtained numerical value of the $\Delta A$ intensity allows us to predict the change in the area of the metal cross-section of the rope in the problem area for the subsequent period of its operation.

This important result was used by us while developing a method for the determining the resource of a steel rope in specific operational conditions and it was done with the help of calculation.

5. Method of calculating the resource of a steel rope
The method is based on the data from at least one control study of the rope condition performed by the non-destructive testing. The control results determine the problem section of the rope, its length, coordinates of the beginning and the end along the entire length of the rope, and the area of the metal section at the moment of the control.

During actual operation, two conditions must be met to obtain reliable results of the rope resource assessment.

The first condition is a stable maintenance of the rope operation intensity throughout the entire calculation period. The intensity of the exploitation of the rope is determined by the intensity of the use of the mechanism of a cable-block system and it depends on two parameters: the loading regime, characterized by the load-pattern multiplier $K_m$, and the class to use $T$ mechanism, which is...
characterized by the operating mechanism in a mechanical clock to the time of resource exhaustion [11]. These two parameters are used to determine the so called characteristic number $C = K_m T$.

In modern lifting machines the coefficient of the load distribution, operating mechanism for machine-hours and the number of cycles of the operation of the mechanism are fixed by the device check operating parameters of the crane and are determined by the transcript of the testimony of this device. Therefore, determining the actual characteristic number and the actual intensity of the operation is not difficult.

The second condition is a reliable determination of the number of loading cycles of the problem section of the rope.

Let's consider the definition of the calculated rope resource based on the following criteria:
- $[d]$ - the permissible minimum allowed value of the outer diameter of the rope;
- $[\delta]$ - the permissible minimum allowed size of the outer wire of the rope;
- $[Z_F]$ - the assigned minimum coefficient of the static strength of the rope.

The permissible minimum allowed value of the outer diameter of the rope ($d$).

According to the current regulations, this value is determined by the acceptable percentage $[P_d]$ of reducing the rope diameter, at which the rope must be rejected, [7, table 5]

$$[d] = d(1 - [P_d]/100),$$

where $d$ is the nominal diameter of the new rope.

The wear rate of the $\Delta A$ rope for $N$ cycles is determined by the formula (1).

The area of the metal section of the new rope is

$$A = k_3 \pi d^2 / 4,$$

where $k_3 < 1$ – is the rope cross-section filling coefficient.

From the moment of the installation of the new rope up to the moment of inspection after $N$ loading cycles, the loss of the metal cross section of the rope at a problem area which is done according to the method of study is specified in the $\%$ of $R_P$ reduction from the initial value of $A$ area.

The corresponding area of the metal cross section of the rope is

$$A_N = A(1 - P_N/100 ).$$

The diameter of the rope in $N$ cycles is

$$d_N = \sqrt{A_N / \pi},$$

The intensity of the rope diameter reduction is

$$\Delta d = (d - d_N)/N, \ \text{mm/cycle}.$$

Under the condition of maintaining the intensity of operation and maintaining the intensity of $\Delta d$ the diameter of the rope after $N$ loading cycles is

$$d_N = d - \Delta d \cdot N.$$

For the purposes of practical application of the given formula it is necessary to enter the reserve coefficient $kd > 1$, which takes into account the errors of the proposed method.

Then the formula for determining the resource by the outer diameter can be represented as

$$d_N = d - \Delta d \cdot N \cdot kd. \quad (2)$$

The condition for the rejection of the rope is

$$d_N \leq [d].$$

Let’s put it in the equation (2) $d_N = [d]

$$[d] = d - \Delta d \cdot N \cdot kd.$$

From this expression we get a formula for determining the resource by the outer diameter
\[ N_{Rd} = d - \lfloor d \rfloor / \Delta d k_d. \]  

(3)

If the operating time of the rope is known in the number of loading cycles for (3) the period of a year, the calculated service life of the rope before reaching the maximum state in the diameter is

\[ L_d = N_{Rd} / N_T , \] measured in years

The calculated residual life of the rope after \( N \) loading cycles is

\[ N_{do} = N_{Rd} - N. \]

The estimated remaining service life is

\[ L_{do} = N_{do} / N_T , \] measured in years

Fig. 2 gives a graphical interpretation of the resource definition based on the criterion for reaching the limit value of the outer diameter of the rope.

The graphs in Fig. 2 present the wear rate without taking into account the safety coefficient – line 1; with taking into account the safety coefficient - line 2.

**Figure 2.** To the resource definition of the rope by the criterion of the minimum limit of the outer diameter.

The permissible minimum allowed value of the size of the outer wire of the rope is \([\delta]\).

The current regulations define this value by the acceptable percentage \([p\delta]\) of reducing the size of the outer wire of the rope, at which the rope must be rejected, [7]

\[ [\delta] = \delta (1 - [p\delta]/100), \]

where \(\delta\) is the nominal size of the outer wire of the rope.

The determination of the rope resource with the help of this criterion is based on the algorithm for calculating the criterion for the allowed value of the outer diameter of the rope.

The size of the outer wire after \( N \) rope loading cycles is

The condition for the rejection of the rope is

\[ \delta_N \leq [\delta]. \]

Then after successive substitutions and transformations we get a formula for the determining the rope integrity under the condition that the permissible minimum size of the outer wire of the rope is reached

\[ N_{Rd} = (\delta - [\delta]) / (\Delta \delta k_d) \]
The assigned minimum coefficient of the static strength of the rope is \([Z_F]\).

The breaking force of the new rope is determined by the strength limit \(\sigma_v\) of the wires and the metal area of its cross section is \(A\).

During the operation, after running for \(N\) cycles, the metal cross-section area of the rope is \(A_N\). Then the breaking force of the rope is

\[
F_N = \sigma_v A_N k_F k_Z,
\]

where \(k_F > 1\) is the static strength margin coefficient that takes into account the reliability of the data and calculation methods.

The maximum force in the rope is determined by the formula

\[
F_{\text{MAX}} = F_O / Z_F.
\]

The calculated coefficient of static strength margin is

\[
Z_F = F_N / F_{\text{MAX}}.
\]

Numerous studies have found that the operating time of steel ropes from the moment of testing a new rope to the moment of its complete destruction is distributed as follows: the operating time until the first wire breaks is 40-50\%, the operating time until complete destruction–50-60 % [4,8,10]. Therefore, the permissible minimum value of the reserve coefficient which is reached during the operation of the rope should be taken as \([Z_F]\) ≥ 0.75 \(Z_P\).

The conditions for achieving the limit state of the rope under the condition of the absence of wire breakage is given below \(Z_F \geq [Z_F]\).

Using the accepted approach, the rope resource for static strength is

\[
N_{RF} = N (Z_P - [Z_F]) / (Z_P - Z_F).
\]

The final rating of the steel rope resource is determined by the minimum value of the resource found by the criteria listed above (2), (3), (4), that is

\[N_R = \min\{N_{RF}, N_{RD}, N_{RF}\} .\]

In practice, it is important to determine the remaining life and service life of the rope. For a given rope running time with \(N\) cycles the remaining resource is

\[N_O = N_R - N .\]

If the intensity of the operation of the rope in the subsequent period does not change, then at the annual operating time \(N_t\) the remaining life of the rope is

\[L_O = N_O / N_t .\]

Thus, the method for determining the resource of steel ropes of lifting machines by means of calculation proposed here allows us to solve important problems in practice.

6. Verification of the proposed method

In order to assess the accuracy of the results obtained using the method proposed here, we have tested the static strength of four ropes to be disposed of, and the mechanisms of the outrigger berth of the oil and gas complex.

The calculated breaking forces of the \(F_n\) ropes were determined by the formula (4). The initial data for the calculations were taken on the bases of the certificates for the ropes. The adopted values of coefficients are \(k_3 = 0.8; k_F = 1.1\).

The tests were carried out on a certified breaking machine.

The comparison of the experimental \(F_0\) and calculated \(F_n\) values of the breaking force was performed using the formula (tabl.1)
\[(F_3 - F_N)/F_3\]

### Table 1. Experiment Results

| Rope diameter, мм | Test effort $F_3$, кН | The estimated effort, $F_N$, кН | Difference from the test effort , % |
|------------------|------------------------|----------------------------------|-------------------------------------|
| 38               | 1489                   | 1407                             | – 5,5                               |
| 32               | 960                    | 1308                             | + 36                                |
| 30               | 931                    | 933                              | – 0,2                               |
| 16               | 221                    | 262                              | + 18                                |

With the exception of the results obtained for the rope with the diameter of 32 mm, for other ropes, the differences in estimates are quite acceptable for the experimental and theoretical data.

### 7. Conclusions
1. The importance of the efficiency of lifting machines in the transport process is noted.
2. The factors affecting the resource of steel ropes for lifting equipment are listed.
3. A brief description of the method for the determining the resource of steel ropes with the help of calculation is given.
4. The data of experimental testing of the proposed method are presented.

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