637. Experimental research of steel rope integrity problem

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Abstract. This paper is dedicated to treatment of a problem of a steel rope diagnostics. Research was carried out in order to reveal possibilities of diagnostics of steel rope integrity by virtue of dynamical properties of tensed steel rope in a special test rig, which was designed and fabricated for this particular research work. Excitation of the considered system was accomplished by means of a special shaker, which was connected to the rope body. Vibration measurements were performed with respect to the test rig frame for the whole rope to detect the broken wire. During experimental research the efforts were made to excite the broken wire of the rope through the whole rope. Another series of experiments were conducted in order to determine the dynamic response of the wire to forced vibration of the rope with the constant amplitude of rope vibrations. In addition, attempts were made to define the influence of rope tension onto resonant frequency of the broken wire. Results of research are presented as spectrums of forced vibrations in a frequency range of interest. Major experimental findings are summarized by the conclusions.

Keywords: rope, integrity, defects, diagnostics, dynamical properties.

Introduction

Steel ropes are widely used in technical design and frequently implemented as flexible link in various machines, installations and equipment. Flexibility and one sided force transmitting makes them common in many applications, but mostly they are used for lifting devices and load carrying. There are some installations, where ropes are critical elements – like lifts, rope trains, funiculars, etc. Ropes are widely used for static load transmission – tensing towers, bridges, electric lines [1, 4] as well as ropes compensating motion of truss elements, sharing structure loads in the case of dynamic of structures and so on.

Due to extensive application of ropes as important linkage, a problem of proper care and early quality diagnostics became a key for safe and efficient exploitation of the machinery. Defect localization in the rope is complicated because of wire dimensions in length – for example, 5 storage house lift is equipped with a minimum of 2 sets of ropes with length of ca. 60 m. Recent tendencies are to use ropes of smaller diameter due to smaller dimensions of the equipment and smaller pulleys increases extent of diagnostics even more.

Modern rope consists from 3 parts (Fig. 1): core, strand, strand center and the wire [1, 3].

Steel rope strands and wires have unified shape and are produced from high quality steel. Strands are wired in the same or in the contrariwise direction to wire rotation, depending on type of rope. Core of rope is produced from the synthetic fiber and is filled with lubricant, which lubricates wires of the rope during tension and rope operation.

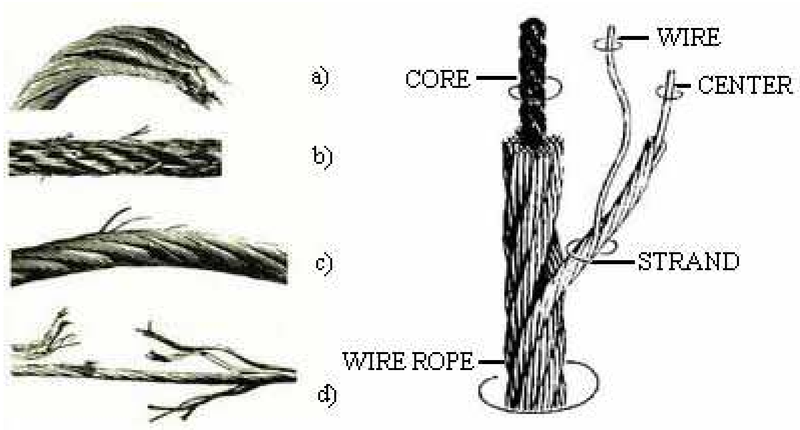

Fig. 1. Structure of a modern steel wire rope and rope defects: a) – broken rope due to the overload, b) – corrosion damage of rope with loss of integrity, c) – wire fracture due to radius of pulley or fatigue of metal, d) – disintegrated rope strands due to static overload

Steel ropes are produced applying high technology, but nevertheless during their lifetime the influence of mechanical impacts, chemical surrounding and temperature changes causes deterioration of rope material and defect formation.

Defect detection is a sophisticated process and a multitude of methods are available. The most popular and simple approach is based on the optical observation [2, 3], when experts evaluate quality of a rope by visual inspection. However this method is costly and is fairly inefficient. Furthermore it is not applicable to mounted ropes where access is not possible.

An electromagnetic method of rope condition monitoring, which is presented in Fig. 3 [5], is also used. It is based on detection of rope defect by evaluating electric signal from the sensor system. Such methods use permanent magnets, which create permanent magnetic fields in the rope and measuring process registers magnetic field variations around the rope outer surface.

A method of magnetic flux is based on measurements of three parameters: a) magnetic flux change about the broken wire (LF) and defects of strand, b) magnetic flux change in cross direction of the rope (LMA), c) magnetic flux change in longitudinal direction. The last method is usable in whole rope testing and uses permanent magnets and is applicable in broken wire or corrosion spot detection by magnetic flux or flux change detection.

This method locates the defect when the damaged rope passes magnetic head and induces signal change. Various types of sensors are used for the task [2, 4, 5].

Dynamic method of rope diagnostics

Implementation of the dynamic method of rope diagnostics relies on some assumptions. In this research work it is attempted to use as diagnostic parameters for rope integrity assessment the detectable vibration of broken wire in relation to a rope body. Therefore the initially broken wire is treated as a cantilever fixed to the rope body.

In this case it is possible to define natural frequency of the wire analytically. It is logical to analyze the 1st natural frequency and the corresponding vibration mode shape because then the desired amplitude is the highest and frequency – the lowest.

Fundamental frequency of the wire in cantilever configuration is evaluated according to the following formula [7]:

$$\omega = \frac{\mu}{l^2}\sqrt{\frac{EI}{\rho F}}, \quad (1)$$

where ω - angular frequency of a cantilever, $\mu = 3{,}52$ - coefficient for the 1st natural frequency, *l* - wire length, *E* - Young's modulus, *I* - moment of inertia, *ρ* - specific weight of the material, *F* - area of wire cross-section.

Length of wire is defined by length of wire in strand (Fig. 1). In our case one revolution of wire in strand is 22 mm, while rope diameter is 4 mm. Then mostly probable length of the broken wire is one half of strand pitch, i.e. 11 mm. Tests indicate that all broken wires in 4 mm length are from 8 to 12 mm. The results of calculations are provided in Table 1.

Frequencies from Table 1 initially were used to detect resonant frequencies during experimental research.

Table 1. Natural frequencies of the broken wire

Length *l*, 10-3 m	Angular frequency ω, 1/s	Frequency *f*, Hz
1	$1{,}18 \cdot 10^6$	$1{,}88 \cdot 10^5$
2	$2{,}95 \cdot 10^6$	$4{,}70 \cdot 10^5$
3	$1{,}31 \cdot 10^5$	$2{,}09 \cdot 10^4$
4	$7{,}38 \cdot 10^4$	$1{,}18 \cdot 10^4$
5	$4{,}72 \cdot 10^4$	$7{,}52 \cdot 10^3$
6	$3{,}28 \cdot 10^4$	$5{,}22 \cdot 10^3$
7	$2{,}41 \cdot 10^4$	$3{,}84 \cdot 10^3$
8	$1{,}84 \cdot 10^4$	$2{,}93 \cdot 10^3$
9	$1{,}46 \cdot 10^4$	$2{,}32 \cdot 10^3$
10	$1{,}18 \cdot 10^4$	$1{,}88 \cdot 10^3$
11	$9{,}78 \cdot 10^3$	$1{,}56 \cdot 10^3$
12	$8{,}22 \cdot 10^3$	$1{,}31 \cdot 10^3$

Values in this table are calculated for straight cantilever beam for the 1st natural frequency.

Test rig and the methodology of research

Fig. 2 presents a custom-built test rig that was used for rope testing and evaluation of dynamic behavior of the broken wire. Frame of the test rig weights about 250 kg and is fabricated from the cast iron. Frame is placed on a solid concrete floor through four vibration insulating supports, isolating the setup from the floor and building vibrations.

Rope supports 2, 3 are fixed tightly to the frame [10, 13] and used to hold rope tightened.

Research was performed on a 4 mm rope, which was tensed with a force of 200 N between two supports 2, 3. Rope was excited by a mini-shaker 11, which was tightly fixed to the test rig frame 1 and with hinge connected to rope 4. This vibrator was driven by power amplifier "2706" 8, which gets signal from the signal generator "1027" 10.

Measuring system of the test rig consists from two parts – linear transducer „Hottiger Tr102" 6, which measures vibration of the whole rope and linear transducer „Hottiger Tr4" 7, which registers vibration of broken wire in a specified position. Linear transducer „Hottiger Tr102" 6 was hold in own holder 12, which was fixed to the test rig frame 1. Linear transducer „Hottiger Tr4" 7 was hold by holder 5, also fixed to frame 1. Signals from sensors 6 and 7 were transmitted to signal amplifier 9 to diagnostic measuring portable station „Machine Diagnostics Toolbox Type 9727", equipped computer with a special software.

Fig. 2. Test rig for rope integrity diagnostics: 1. Frame; 2. Rope support; 3. Rope support; 4. Test rope; 5. Holder of transducer Tr4; 6. Linear transducer „Hottiger Tr102“; 7. Linear transducer „Hottiger Tr4“; 8. Power amplifier 2706; 9. Amplifier „Hottiger KWS 503 D“; 10. Signal generator 1027; 11. Electrodynamic mini-shaker 4810; 12. Holder of transducer Tr102; 13. Broken wire

Procedure of the experimental research is as follows. Signal generator 10 through power amplifier 9 drives mini-shaker 11 at the lowest possible frequency when harmonic oscillations are excited. In our case this occurred around 100 Hz. Then vibration amplitude was set to 50 μm by changing coefficient of amplification. Amplitude of rope vibration was measured by sensor 6. Then signal from the sensor 7, which measured broken wire vibrations, was registered. These vibrations are measured relatively to the test rig frame, so in order to determine relative wire vibration with respect to the whole rope it is necessary to calculate the difference of signals in respect of vibration phase.

During testing the frequency of forced vibrations was varied from 100 Hz to 2000 Hz in step of roughly 10 Hz. Frequency ranges with resonant areas were analyzed in frequency of 1 Hz in order to obtain more accurate amplitude results.

Wires of length 11 mm bind (resultant length 5,5 mm) ant straight wires from 8 mm to 11 mm with pitch 1 mm were used for the research. Diameter of this wire d = 0,26 mm.

Vibration data was processed with software Origin 6.1 and Pulse.

Results of experimental research

The first result of this experimental research was excitation of broken wire by exciting the whole rope in a cross-section that is significantly remote from broken wire. Excitation of the wire was observed in frequency ranges lower than the calculated ones and the oscillations had significant amplitude, noticed even by the naked eye.

Results of experimental research – resulting spectrum of broken wire vibration in broad range of frequencies was performed with the same amplitude of rope vibrations, therefore amplifier should be adjusted in every point of vibration to obtain the required amplitude. Results, provided in Fig. 4, represent dynamic response of a broken wire within range of considered frequencies. It is observed that low frequency vibrations around 190 Hz and 380 Hz were obtained with all the wire samples.

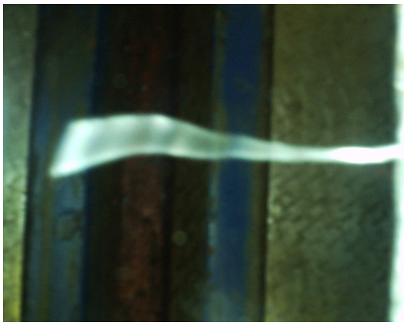

Fig. 3. Path of vibrating 11 mm wire of rope on 509 Hz, photo made by instrumental microscope x30, frame duration – 1/50 s

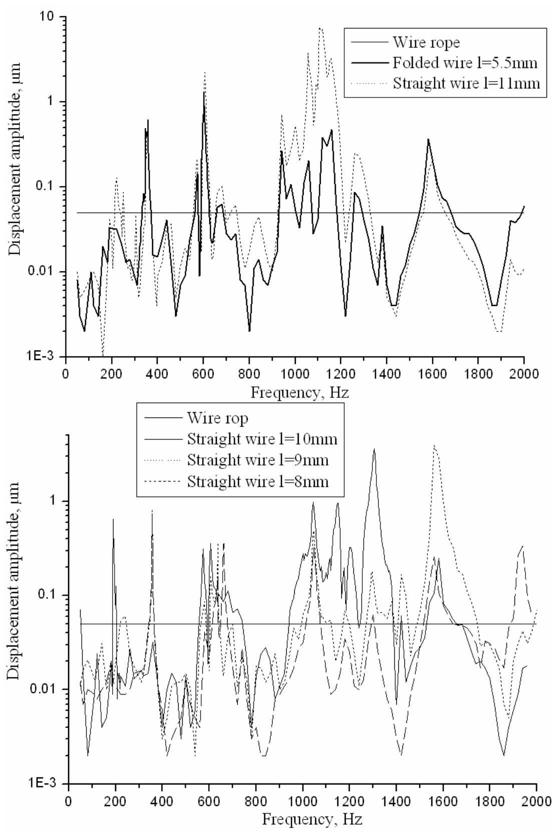

Fig. 4. Spectrum of frequencies of broken wire vibration for different length of wire; whole rope vibration amplitude – 50 µm

In order to obtain more detailed results, a research in narrow frequency range was performed. Here awe evidently observe (Fig. 5) that in some ranges of frequencies (especially around 600 Hz) experimental research with all wire length causes large amplitude of vibrations, and these are definitely nonresonant vibrations of the wire.

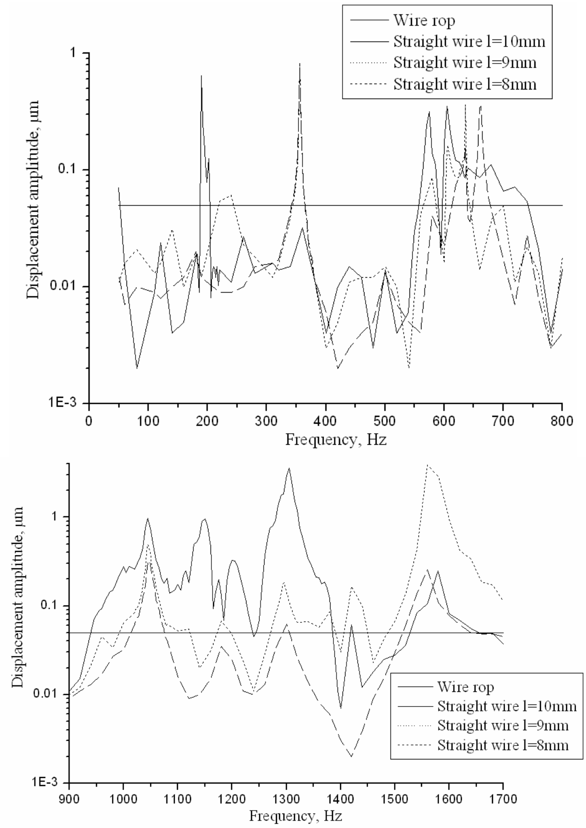

Fig. 5. Detailed frequency spectrum of broken wire vibrations in frequency ranges 50…800 Hz (upper graph) and 900…1700 Hz

In order to make sure that the broken wire of rope will not be influenced by internal movement of wires in the strands we performed separate experimental study of a single piece of rope of the same diameter, having broken wire of 11 mm, placed directly onto the mini-shaker and excited with a prescribed amplitude within the complete frequency range 50…2000 Hz. Results of this research are presented in Fig. 6 as spectrum of broken wire vibrations. In this case, when using the same equipment, no areas of spectrum with low frequency is obtained. Resonant frequency around 1000 Hz differs from theoretically calculated 1560 Hz, but the vibration mode shape as assumed as the 1st mode, so main difference can be in fixture of wire in the rope, i.e. it is different from the cantilevered fixture.

Presented results raises new tasks for further research and brings prospective to create new technical solution of rope integrity diagnostics using dynamic methods.

Conclusions

Performed experimental research provides some insight into diagnostics of wire rope integrity using dynamic properties of the tensed rope system. Successful excitation of the wire through relatively massive rope makes the idea of assessment of rope integrity possible.

Obtained results lead to the following conclusions:

1. Broken wire of the rope (as dynamic system) may be excited harmonically for the case of tensed wire rope.

2. Relative vibration of rope wire to rope body is fairly significant – excitation of rope permanently set to be 50 μm and wire vibration amplitude can reach up to 2 mm.
3. Theoretically calculated resonant frequencies of wire (treated as cantilever) are higher in comparison to the experimental values. This indicates special fixing conditions of the wire to rope body.

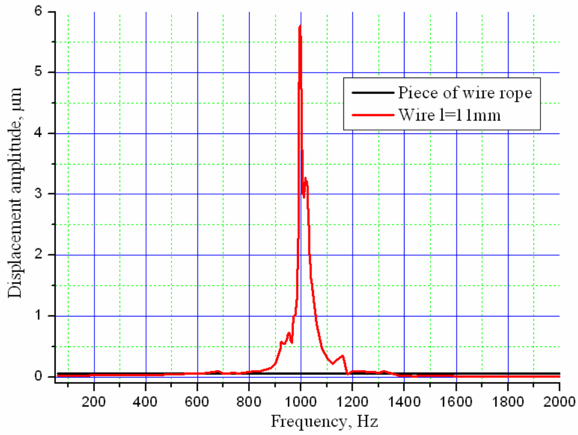

Fig. 6. Spectrum of separate sample of rope (50 mm length) with 11 mm broken wire in whole range of frequencies of experimental research

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