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ORIGINAL ARTICLE

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# Electromagnetic testing of multi-strand stay cables: novel technique and instrumentation

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**Abstract**

Steel stay cables are widely applied in various civil constructions. In recent decades, the so-called multi-strand stay cables have become widely used, particularly in the construction of cable-stayed bridges. Conventional method of stay-cable diagnostics utilizes magnetic rope testing instruments. However, because of the large diameter of multi-strand stay cables, the appropriate magnetic instrument should have an inappropriate high mass and create a significant force of attraction between the magnetic head and the stay cable, which likely would cause damage to the cable's outer protective shell. Alternatively, the eddy current method can be used for testing of stay cables. The special probe was developed that provides equal sensitivity to surface and subsurface breaks of the strands and reduces a disturbance of irregularity of magnetic properties along the cable. On the basis of this probe, a specific electromagnetic instrument was designed for nondestructive testing of multi-strand stay cables. The instrument was tested on a multi-strand mock-up and applied for inspection of the stay cables of bridges. Results of this are discussed in the article.

**Keywords**

Multi-strand stay cables, eddy current, rope testing

## 1 Introduction

Steel stay cables are widely used in various technical and structural applications [1]. In recent decades, the so-called multi-strand stay cables have become widespread, particularly in the construction of cable-stayed bridges [2, 3]. This paper describes the results of eddy current inspection of such stay cables.

## 2 Multi-strand stay cables

Multi-strand stay cables consist of parallel strands, each made of 7 wires in an insulating PET coating. The diameter of individual strands, excluding the coating, is usually 15.7 mm. A bundle of strands is encapsulated into the shell, which protects the strands from harmful environmental influences. The outer diameter of the shell depends on the number of strands, which can reach 169. The diameter of the shell in this case comes up to 355 mm. However, most cables used in real constructions don't have more than 100 strands and a diameter of the shell do not exceed 300 mm. The ends of individual strands are clamped in anchors, which in turn are fixed in the roadbed or pylon. Cable-stayed bridges, including those based on multi-strand cables, have become very popular in recent decades all over the world. A typical bridge contains hundreds or even thousands of meters of strands. Strands in such bridges play a role of one of the main load-bearing elements of the structure, which makes supervision of their technical condition very important.

The main criteria of the technical condition of stay cables is the residual load-bearing capacity. However, it is not possible to estimate it directly, so some indirect indicators must be used. The experience of inspection of conventional steel wire ropes on many bridges shows that the guy cables are subject to the following deterioration factors: corrosion, which causes the loss of metallic cross-section area, and wire breaks [2]. Multi-strand stay cables have a multi-level system of corrosion protection [3, 4], which includes a zinc coating of the wires, filling voids with compounds, a strand shell and the outer shell of the stay cable. Thus, breaks of individual wires and strands should be considered as the most likely defect type. Considering the high number of strands in a multi-strand stay cable (up to 165 strands), a reliable detection of one strand breakage should be acceptable from the point of reduction of load capacity. Calculations show that due to the long length of strands in the multi-strand stay cables (usually hundreds of meters) and no mechanical connection with neighbouring strands, a breakage of one strand will result in a large gap between broken ends. Thus, in real conditions, it is enough to detect the end of the broken strand.



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## 3 Non-destructive testing methods

Steel wire ropes are usually tested with instruments, based on a magnetic method of non-destructive testing, with a magnetic head (MH) to be placed on the rope. A magnetic system of MH magnetizes the rope and a measuring system records the magnetic flux leakage caused by defects and by reduction of the metallic cross-section of the rope. The main problem, which appears while applying the magnetic method for large-diameter stay cables, consists in the considerable increase of the instrument mass as the diameter of the rope under the test increases. The approximately estimated mass of the magnetic head for inspection of stay cables with a diameter of 300 mm should be about 700 kg. Additionally, the magnetic head causes a significant attraction force, which compounds the MH installation on the rope, and can cause damage to the outer protective shell of the stay cable. It should also be considered that installation of MH on a rope should be performed at a height.

All these difficulties make it almost impossible to use the magnetic method to inspect large-diameter stay cables [5, 6] and make it necessary to look for alternative methods. Other methods of non-destructive testing are described to be applied for large-diameter multi-strand stay cables [6]: visual method, x-ray method, ultrasonic method, method of estimation of stay cable tension using measured natural vibration frequencies, acoustic emission method. However, each method has serious disadvantages [6].

## 4 Electromagnetic testing

As an alternative to the magnetic method, a non-destructive testing by means of alternating electromagnetic fields of a small magnitude (not enough for magnetic saturation) has been proposed. One coil is being used as the source of the excitation field, and the other coils — as the signal receiver (see Figure 1). The frequency of the excitation current does not exceed a hundred Hz. So this method can be classified as the eddy current method of non-destructive testing.

One of the main problems of the eddy current method applied to ferromagnetic objects consists in significant noise levels, which results from inhomogeneity of magnetic properties of the material along the object under the test. For example, Figure 2 shows signals of absolute and differential probes when scanning the same defect-free section of the stay cable. The two upper diagrams (channel 1 and channel 2) refer to the real and imaginary components of voltage of the differential probe. The two lower diagrams (channel 3 and channel 4) refer to the real and imaginary components of voltage of the absolute probe. The horizontal axis of the diagrams corresponds to the spatial coordinate along the stay cable. The image overlays the results of two different scans (different scans in different colours) performed at different times. It can be seen that the curve does not change much from one run to another; so far, it is caused by variation of magnetic properties along the stay cable. Such an interference is difficult to suppress and it compounds the task of defect detection.

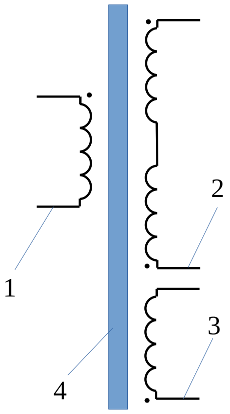


**Figure 1** ECT probe. 1 - Exciting coil; 2 - Pick-up coils (differential probe); 3 – Pick-up coil (absolute probe); 4 - Stay cable

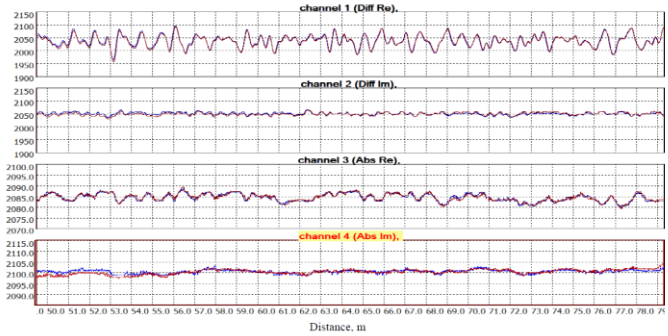


**Figure 2** Signals of repeated inspection (red and blue) of the same section of the stay cable (first and second traces – differential probe, third and fourth traces – absolute probe)

Noise can be reduced by magnetizing the object with a strong permanent magnetic field. However, in the case of large diameter stay cables, magnetization by a strong magnetic field leads to the same problems as described above for the MFL method. Thus, the rope testing instrument should provide reliable test results without magnetic saturation.

## 5 Intros MH 120-300 instrument

Typically, pass-through outer probes (encircling coils) with a uniform field are used to test such elongated objects as cables, that provides for reduction of the influence of the object's position inside the coil. However, numerical simulation [7, 8] and experiments with mock-up [9] have shown low efficiency of this approach for multi-layer cables, since it does not enable detection of defects in inner cable layers. This results from a higher sensitivity to noise from external layers than to the defects from internal layers. Figure 3 shows the signals from local defects in the outer (blue curve) and inner layers (red curve) of strand bundle. It can be seen that the signal of defect in the inner layer is comparable with the magnitude of the noise from the outer layer. Variation of geometric parameters of the test coil does not solve this problem: Figure 4 shows the influence of the base of a test probe with a long excitation coil on the relative variation of the signals caused by local defects (results of numerical simulation).

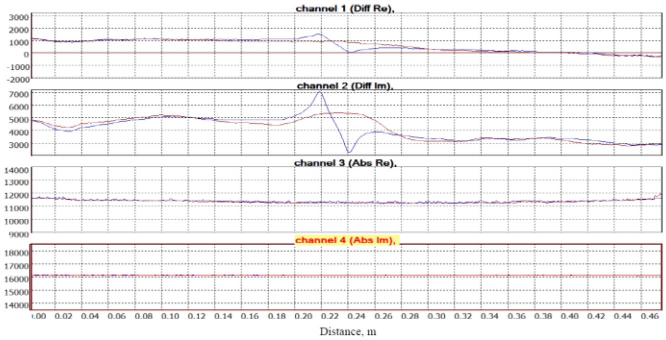


**Figure 3** Signals of the section of the stay cable simulator including 72 stands with imitated strand breakage in the outer layer (blue) and in the inner layer (red). (First and second traces – differential probe, third and fourth traces – absolute probe)

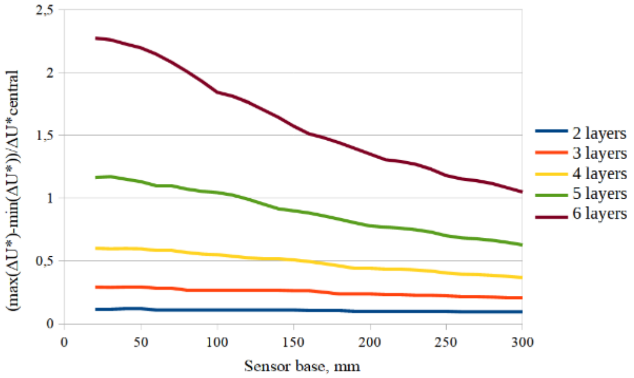


**Figure 4** Signals of the section of the stay cable simulator including 72 stands with imitated strand breakage in the outer layer (blue) and in the inner layer (red). (First and second traces – differential probe, third and fourth traces

Application of a non-uniform excitation field enables us to reduce the noise from the external layers relatively to defect signal from internal layers. Numerical simulation has shown that by applying a narrow excitation coil it is possible to find such geometrical parameters of the test coil, which makes signals from external and internal defects approximately the same magnitude, see Figure 5.

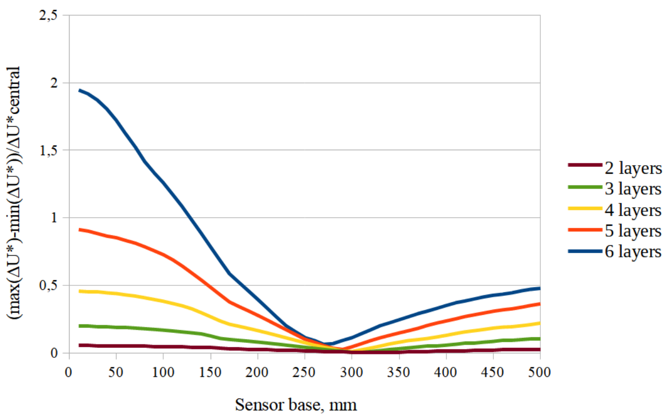


**Figure 5** Influence of the base of a differential probe with an «narrow» excitation coil on the relative variation of the signals caused be local defects

Based on results of numerical simulation, a probe was developed that provides equal sensitivity to surface and subsurface breaks of the strands [10]. This probe was used with a special rope test instrument, Intros MH 120-300 (see Figure 6). The instrument consists of two halves, which are to be put on the stay cable sequentially. The mass of the instrument, depending on the equipment, varies from 35 to 50 kg.

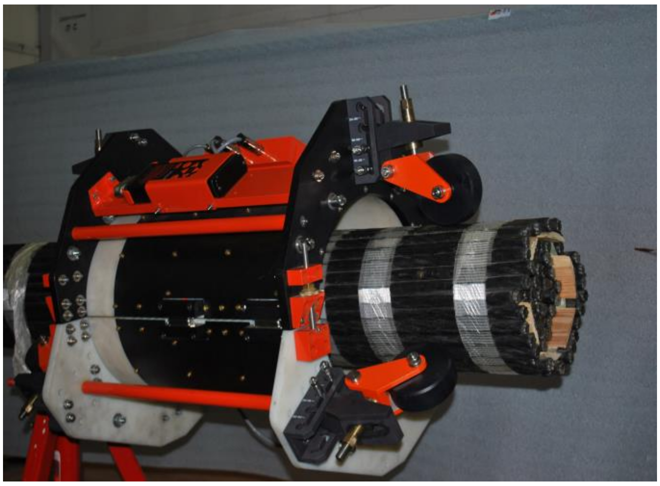

**Figure 6** The Intros MH 120-300 installed on the mock-up of multi-strand stay cable

The instrument was tested on mock-ups of multi-strand cables of different diameters and with different numbers of strands [9]. Experiments have confirmed that signals from defects in different layers are close in magnitude (see Figure 7). Thus, the disturbance caused by the external and internal layers must also be of approximately the same magnitude, which results in close sensitivity of the instrument to external and internal defects.

The influence of different interference factors, such as the transverse displacement of the cable in the probe, rotation of the probe relative to the cable, local magnetization of the cable, and others. Tests have confirmed that signals from stand breaks can be confidently detected against the background of interference from the proved influencing factors.

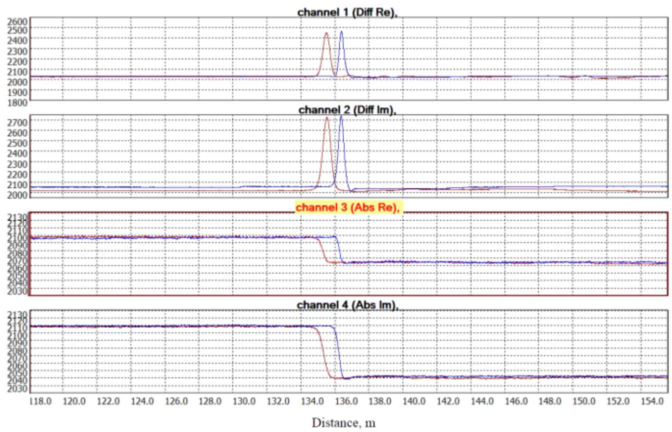


**Figure 7** Influence Signals from the end of the strand on the surface of the stay cable simulator (red) and in the central layer of the stay cable simulator (blue) are close in magnitude (first and second traces – differential probe, third and fourth traces – absolute probe)

The developed rope test instrument was applied for inspection of several bridges with multi-strand stay cables [4]. At the beginning of the inspection, a reference signal of a broken strand should be obtained. Part of one real strand of approximately 1 m length attached to the stay cable can be used for this purpose. Tests have shown that the level of interference is significantly lower than the signal from the broken strand in the outer layer (see Figure 8). It is not possible to imitate the break of the internal strand on a real stay cable, but laboratory tests have proved that the magnitude of the signal from the internal broken strand is close to the magnitude of the signal from the external broken strand. Figure 9 shows Intros MH 120-300 on the stay-cable of the bridge in Vladivostok.

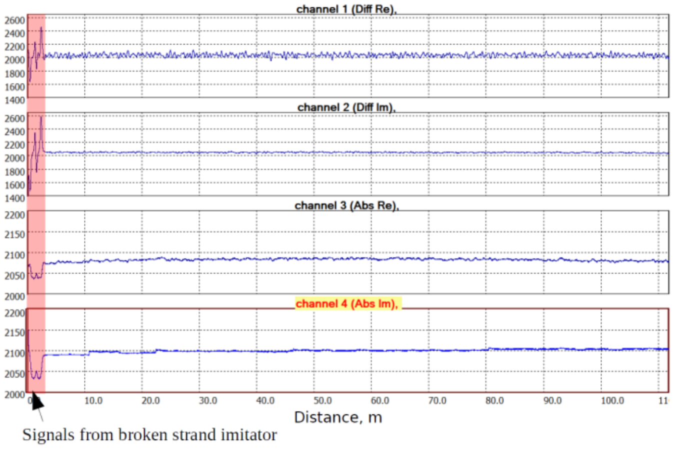


**Figure 8** The trace from the bridge multi-strand stay cable. At the beginning of the multi-strand stay cable, a defect simulator is attached to obtain a "reference" signal (first and second traces – differential probe, third and fourth traces – absolute probe)

**Figure 9** Intros MH 120-300 at the stay-cable of the bridge in Vladivostok (Far East)

## 6 Conclusion

The obtained results demonstrate the applicability of the eddy current method for non-destructive testing of multi-strand stay cables. The developed novel instrument allows inspecting multi-strand stay cables with a diameter from 120 to 310 mm with a sensitivity of one broken strand in any layer of the stay cable. The instrument also provides a measurement of relative the loss of metallic cross-section with an accuracy of 5%. The proposed method provides an ability to considerably reduce weight of the test instrument and avoid adverse attraction forces between the probe and the stay cable.

The developed instrument was used for non-destructive testing of stay cables of several bridges. This experience has shown that for multi-strand stay cables of large diameter the developed instrument provides a good alternative to conventional devices of magnetic rope testing.

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[10] Patent RU 2781153 C1 EDDY CURRENT TRANSDUCER FOR NON-DESTRUCTIVE TESTING OF STRAND ROPES / Semenov Aleksei Veniaminovich, Ulitin Iurii Mikhailovich; Proprietor: «INTRON PLUS»