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FIBER-OPTIC TECHNOLOGY AND STRUCTURAL CONDITION MONITORING OF MECHANICAL CABLES

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1. INTRODUCTION

Cables and ropes are, next to the wheel, some of man's most important and oldest inventions.† Some situations where cable systems are employed and where a high degree of efficiency and reliability is required are: suspension and cable-stayed bridges; high-speed sensor towing; towing and lifting of an object from either the ground or the sea by a helicopter, which is common practice in civilian and military operations; one of the most spectacular applications of ropes is in a gold mine in South Africa, which runs over several sheaves, is 9·3 long and weighs 110 t. [1]; wire strands are used as cords to strengthen rubber tyres, etc.

Proof of the importance of the subject matter is given by rather recent publications which deal with the following problems: stress analysis in power conductors predicting low cycle fatigue life and static overload conditions under handling and installation conditions [2]; bending of spiral strands in the case of large radii of curvature analyzing bending stiffness and overall hysteresis, both being amplitude dependent [3]; prediction of the bending resistance of cables by means of an acoustic emission method [4]. Performing tests of the integrity of such fundamental structural elements and even better: monitoring their condition, is certainly of the utmost importance.

Available techniques of various degrees of sophistication for evaluating the integrity of cables and ropes are: thorough visual examination and measurement of the external rope diameter; X-rays; induced wave propagation; magnetostrictive sensors; electromagnetic (EM) field; acoustic emission (AE).

Discussions on these methods and their relative advantages and disadvantages have appeared recently in the open literature [5–8], and they will not be treated here.‡ A new method which employs a commercial optical fiber for detecting the breakage of individual wires in a rope has recently been proposed [12]. Since Kao and Hockman [13] discovered that silica-index glass surrounded by a cladding with a lower refractive index offered a practical way to transmit light by total internal reflection, fiber-optic cables have been used

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† A cable made out of copper wires was found in the ruins of Nínive near Babylon, it was probably manufactured about 700 BC. The earliest wheels found in graves at Kish and Susa date from the second half of the 4th millennium B.C. (Encyclopaedia Britannica, 1971).

‡ Important findings on the use of the acoustic emission method for monitoring the structural health of mechanical cables have taken place at the National Engineering Laboratory (NEL, Glasgow, U.K.) [9, 10]. They were inadvertently omitted in the survey papers which have been previously quoted. On the other hand, the use of an infrared sensor has also been proposed [11].

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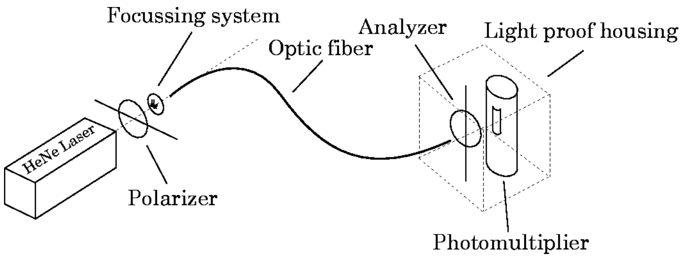

Figure 1. Essential elements of the laser-photomultiplier set-up used in phase A of the investigation [12].

extensively to solve complicated optical problems. In spite of glass vulnerability to damage and stress-accelerated corrosion, the application of protective polymer-coating techniques generated low-cost fibers with reduced losses almost to the theoretical limit and excellent long-term mechanical and chemical stability. For example, the fiber employed by Cortázar and coworkers [12] is typical, satisfying communication standards; it has a silica core with a silicon primary coating and it supports severe atmospheric conditions, immersion in water and a maximal stress of 700 $\mathrm{N/mm^2}$.

As is well known, glass or some other translucid material becomes double refracting as stresses are applied to it. This property has found extensive use in the field of mechanical stress analysis, and in the present specific application, advantage is taken of this photoelastic property of the glass.

Any incident plane-polarized beam, after travelling through the fiber, will emerge in a state of general elliptic polarization. The size and shape of the ellipse will depend critically on the total path travelled inside the fiber, which in turn is related to the stresses applied to it. By analyzing the emerging light with a polarizer, Figure 1, one can detect even tiny variations in the fiber length. Using this method in a commercial fiber (a typical component of a bundle for telephone applications) together with inexpensive equipment, the breaking of individual wires in a multiwired steel rope is detected. It is important to emphasize the fact that the fiber must be adequately attached to the mechanical cable† (see Figures 1, 2 and 3). The measured quantity is the mean intensity of the transmitted light through the analyzer which, as stated above, is affected by the stresses caused, in the optic fiber, by the vibratory phenomenon induced by fracture of wires of the rope. A comparison of the results obtained using this optical method with those obtained using the well-known acoustic emission method was also presented in reference [12]. Very good agreement was found in the case of experiments performed in air.

The experimental set-up has been considerably optimized and experiments in water are hereby presented.

2. DISCUSSION OF THE EXPERIMENTAL PHASES OF THE RESEARCH PROGRAM

2.1. *Previous experimental program* (*phase A*, *experiments performed in air*)

This phase of the investigation has been described in reference [12] but it will be briefly reviewed here for the sake of completeness. Figures 1 and 2 show the experimental arrangement and a detail of the attachment, respectively. A 40 cm long, 1·36 mm diameter steel cable, composed of seven wires, 0·45 mm diameter each, is stretched by means of a

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† This fact was easily accomplished in controlled laboratory experiments. Admittedly certain difficulties must be overcome in real operational systems [14].

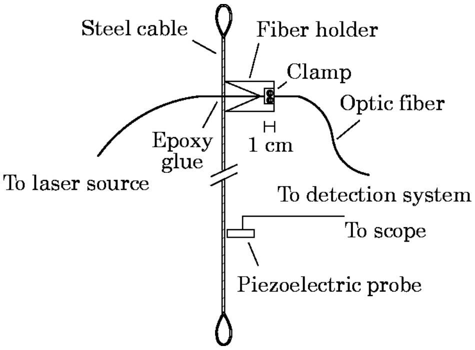

Figure 2. Details of the optic fiber-mechanical cable attachment [12].

hydraulic system. The interest is in detection of the breaking of an individual wire inside the cable. A monomode fiber 125 μm in diameter (jacket included) is attached to the steel multiwire cable using a holder designed to detect the transverse perturbation generated when individual wires break up during the stretching procedure (see Figure 2). The light source is a 0·5 mW HeNe non-polarized laser (type: Spectra Physics model 155) and two polaroid sheets are used as polarizer and analyzer, respectively. In the receiving end a standard photomultiplier tube (type: Hamamatsu IP28A) amplifies the light and transforms it to an electrical signal. This sign is sent to one channel of a digital scope (type: Tektronix 7612D with two plug-in units 7A16P) controlled by a PC with a standard IEEE488.2 board.

A notch was made on one of the wires to identify exactly the position of the failure, and a piezoelectric detector was installed symmetrically from the breaking point in order to contrast the optical detection with results obtained by the well-known acoustic emission method [15].

2.2. *Present experimental program* (*phase B*, *experiments performed in water*)

Figure 3 shows the second experimental arrangement in order to obtain data about individual wires breaking on a cable submerged in water. In this set-up, the same kind of rope used in the first phase of the program and with the same dimensions is tested. An acrylic box with a couple of feedthroughs placed at opposite faces of a container was designed and built for keeping the cable and fiber sensor under water. The light source utilized in this test was a 5 mW GaAs diode laser and the photodetector at the end of the fiber consists of a photodiode; see Figure 3. A couple of polaroid sheets were used as polarizer analyzer in order to detect variations of the light intensity due to the stress applied on the optic fiber as individual wires break.

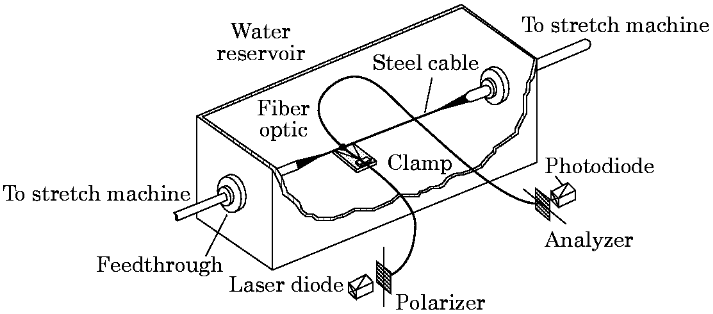

Figure 3. Experimental set-up developed for phase B of the investigation: tests performed in water medium.

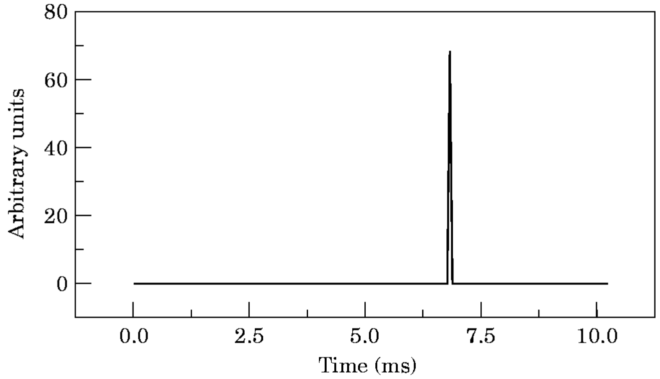

Figure 4. Signal corresponding to fracture of a single wire (cable immersed in water).

It was found that the laser diode-photodiode arrangement developed in this phase of the program was considerably more convenient than the experimental set-up described in section 2.1. The advantages are mainly of a practical nature since the diode laser and the photodiode are solid state devices and resist ill-treatment which may occur, inadvertently, during the normal laboratory procedures but which may be inevitable in real operational conditions. The laser diode is connected to a 9 V battery. On the other hand the photodiode did yield very neat and intense signals with a polarization voltage of 1·2 V while the photomultiplier used in section 2.1 needed a polarization voltage of 500 V.

3. EXPERIMENTAL RESULTS AND CONCLUDING REMARKS

Several experiments have been run on cable specimens of the same characteristics, using the set-up shown in Figure 3. Typical results obtained are those shown in Figure 4 (corresponds to rupture of a single wire) and Figure 5, where successive breakage of four wires is observed. One immediately concludes that the present set-up allows for the detection of breaking of wires with very clear signals. Practically no spurious signals or noise is observed.

On the other hand the experimental set-up depicted in Figure 1 and used in phase A of the present research program did not allow for the determination of failure of wires in such an eloquent, clear fashion; see Figure 6 [12]. The methodology under development

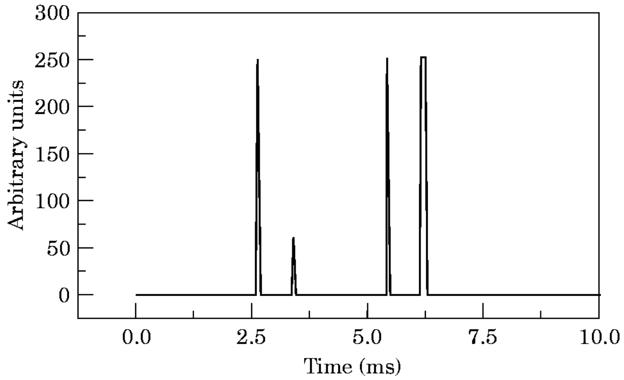

Figure 5. Signals corresponding to consecutive fracture of four wires (cable immersed in water).

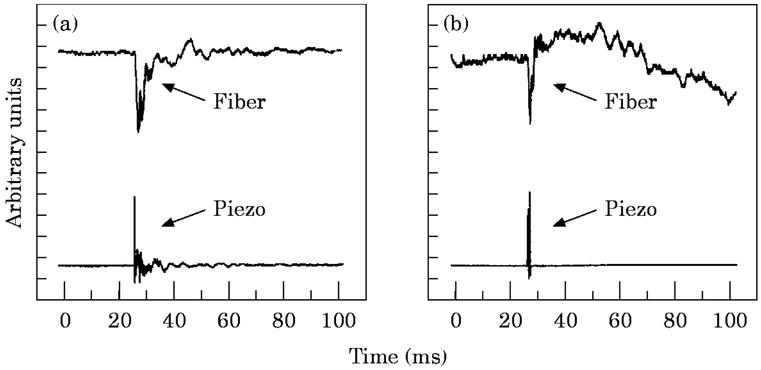

Figure 6. Breakage of two different wires: experiments performed in phase A of the research program [12]; (a) optical and mechanical pulses generated by breakage of the first wire; (b) optical and mechanical pulses generated by breakage of the second wire.

is also applicable in the case of synthetic ropes where, obviously, traditional electromagnetic techniques are of no use.

Man has learned quite a bit about wheels and cables in the last sixty and thirty centuries, respectively. Hopefully he will have learned more about cables in the next thirty centuries since quite a bit more is known, nowadays, about wheels.

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