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HEALTH MONITORING OF THE STEEL CABLES USING THE ELASTO-MAGNETIC METHOD

Fabo, P.
Department of Radiophysics
Comenius University, Faculty of Mathematics,
Physics and Informatics, Mlynska dolina F2, 84248
Bratislava, Slovakia
Tel: +421 905 575 817
fabo@fmph.uniba.sk

Jarosevic, A.
Department of Radiophysics
Comenius University, Faculty of Mathematics,
Physics and Informatics, Mlynska dolina F2, 84248
Bratislava, Slovakia
Tel: +421 905 917 440
jarosevic@fmph.uniba.sk

Chandoga, M.
PROJSTAR PK Ltd.
Nad Dunajom 50,
84104 Bratislava, Slovakia
Tel/fax: +412 2 654 22 432
projstar@nextra.sk

ABSTRACT

The EM method is a valuable tool for Civil Engineering for estimation of the real stress in the prestressing tendons, quality control during construction period, calculating the stress loss due to friction and relaxation, long-time monitoring of stress changes due to concrete creep, temperature changes, traffic load etc. Overview of EM technique with practical applications in the Civil Engineering is presented. The new generation of EM measuring devices is based on more than 15 years experience, including health monitoring systems for the nuclear power plant and a large span cable stayed and suspension bridges. Examples of laboratory and field tests are presented, including uncertainty of stress measurement, long-time stability, resolution and reliability.

Keywords: stress measurement, steel cable, stress sensor

INTRODUCTION

No accurate and simple method is available for direct measuring stress in steel cables of cable stayed and suspension bridges. These cables are often very large and long, containing hundreds wires or strands sheathed in a plastic or steel protective cover filled by cement grout or grease. For these reasons invasive methods such as strain gauges are inapplicable. The Elasto-Magnetic technology [1], [2] is a non-destructive method for stress monitoring in the steel cables. The cylindrical EM sensor is slipped over the cable during the construction period or wound in-situ on the existing cable, it can not be overloaded and its lifetime is practically unlimited. It is sensitive to the inner stress, not to the strain as the strain gauge. The EM technology is also applicable for dynamic load measurement. At the free length of the cable EM sensor moved along the steel cable can monitor the changes in the cross-sectional area of the steel and thus detect the damages - like a broken wire or corrosion

EM MEASURING METHOD

Magnetic properties of the steel depend on actual stress and temperature. In the simplest case relationship is linear and the main magnetic characteristics of the steel - permeability equals:

$$\mu(\sigma,T)=\mu(0,0)+m.\sigma+\alpha.T$$

where

σ	is the actual stress in MPa
T	is the temperature of the steel in °C
$\mu(0,0)$	is the initial permeability of the steel at zero stress and zero temperature
m	is the elasto – magnetic coefficient in MPa^{-1}
α	is the temperature coefficient of the permeability in $°C^{-1}$

From the known steel permeability $\mu(\sigma,T)$ and temperature T we are able to estimate the actual stress σ. Typical values for high stress steel are:

$\mu(0,0) = 5$, $m = 5.10^{-3}$ MPa^{-1} and $\alpha = -0.012$ °C^{-1}.

Important characteristics are the stress sensitivity $S\sigma=1/\mu(0,0).\partial\mu/\partial\sigma= 10^{-3}$ MPa^{-1} and the stress-temperature sensitivity $S\sigma T = \partial\sigma/\partial T = -2.4$ MPa °C^{-1}.

THE EM SENSORS AND THE MEASURING UNIT

The precise permeability measurement is a difficult task even in the laboratory conditions [3], [4], [5]. The EM sensor enables easily to measure changes of permeability with regard to the known load state, in the most cases the zero stress state. The primary winding magnetizes the cable and the change of the magnetic flux induces voltage in the secondary coil. The real sensor is the steel structure itself.

PSS (Precise Smart Sensor) is a new generation of very reliable and accurate cylindrical EM sensors for determining of stresses in all kinds of prestressing steel (wires, cables, bars) and prestressing tendons or cables up to 15 MN capacity.

Construction of the EM sensor is very simple and reliable. On a plastic bobbin primary and secondary coils are wound. Direct measurement of temperature is provided through the precise temperature sensor. The non-volatile ROM contains the unique sensor number and enables automatic communication with the measuring unit and utilization of calibration data. The steel cover protects sensor against any damage and poured polyurethane resin against moisture and even salt water. It can be embedded into the concrete and its lifetime is practically unlimited. The first EM sensors were installed in 1986 and have been working.

The measuring unit energizes the primary winding and processes the voltage induced in the secondary coil. The new generation of the measuring units use for permeability measurement the current pulse, obtained by discharging large capacitor through the primary coil. Typical duration of the pulse is 50-200ms and the peak current reaches 25A. This approach minimizes the heating of the measured steel.

The measuring unit suitable for all EM sensors is a portable, computer controlled and 24V battery powered. It works in the local or remote mode, it can be extended using multiplexor units up to 256 channels. After sensor installation and taking the zero reading it is possible at any time connect the portable measuring unit and measure the actual force and temperature or build the standalone measuring system. Such system is installed at the nuclear power plant Temelin in Czech Republic for monitoring the force in the prestressing tendons of the nuclear reactor envelope or at the suspension bridge Jiangyin over the Yangtze river in P. R. China.

At the Fig. 1 is shown possible arrangement of cylindrical PSS (Precise Smart Sensor) integral sensors for measuring the average stress in the single wire or strand, cable made from wires or strands (for large cross-sectional area of the cable more powerful measuring unit must be used) and the PMS13 (Precise Multi Strand) sensor for measuring the average stress / force and stress distribution between the strands in the cable made from 13 strands 0,6".

The result of the laboratory test of the sensor PMS13 is shown at the Fig. 2. At the major plot is shown the calibration curve of the sensor PMS13. The cable made from 13 strands 0,6" was loaded by hydraulic jack in the loading frame and the PROCEQ WIGA RING annular dynamometer was used as the reference. Uncertainty of the sensor after calibration is under 1%. The stress sensitivity is approximately $6,5.10^{-4}$ MPa^{-1}.

At the left minor plot is shown the temperature record during the stability test at zero stress.

At the right minor plot is shown stability of the zero reading for the temperature compensated sensor. Over 60 hours its stability is better than ± 0,1MPa. Difference in the temperature of the cable and temperature measured by the temperature sensor built inside the PMS sensor affects the accuracy. The very precise reading would be taken at the temperature steady state.

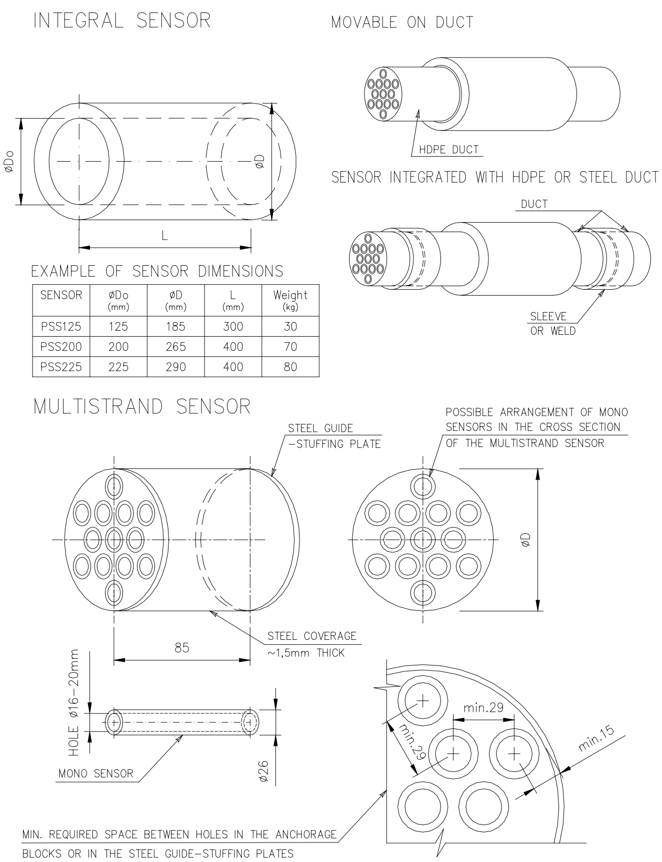

Fig. 1 Possible arrangement of EM sensors

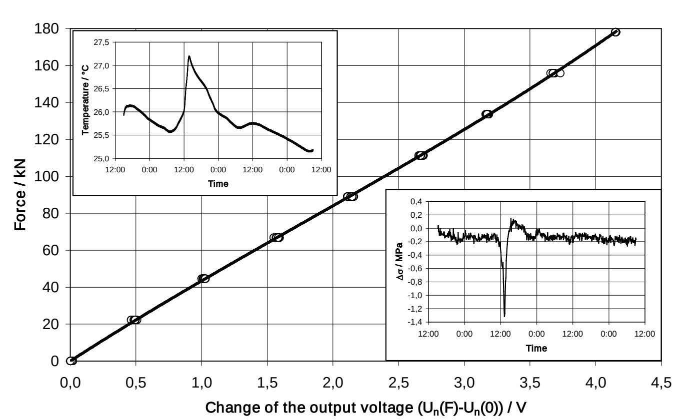

Fig. 2 Laboratory test of the sensor PMS13

THE SMART CABLES

For the health monitoring of the stay cable bridge it is very important to know the actual force in the all stay cables and stress distribution between the single strands in the whole cable. The EM sensor can be integrated as a part of the stay cable during its construction. The possible arrangement is shown at the Fig.3. It is possible to build it inside the active or dead anchor, as a single sensor over the whole cable for measuring the average stress or as MULTISTRAND sensor for measuring the stress distribution between the single strands or wires. Such arrangement enables to know the real stress in the cable at any time during cable prestressing, during the whole construction period and during all lifetime of the cable. The EM sensor can be calibrated directly during the cable prestressing, provided the prestressing force is known with the sufficient accuracy and the sensor is installed near the active anchor. This approach guarantees the uncertainty of force measurement under 1% and resolution under 1MPa. The easiest way how to exclude the temperature influence is to take readings at the same temperature or to estimate the temperature coefficient of the whole arrangement in the laboratory conditions (e.g. during the loading test of the anchor or cable).

EXAMPLES OF EM SENSORS APPLICATION

At figures Fig.4 – Fig.6 are given several examples of EM sensors application in the Civil Engineering

At the Fig.4 is shown the time history of the prestressing force in the elliptic unbounded tendons of the nuclear reactor envelope at Temelin, Czech Republic. Sensors V1, V4 are located near the anchor, V2, V5 in the middle of the both branches of the tendon and V3, V6 near the bottom deviator. Readings were taken every ten days after prestressing and then every month during the next five years.

At the Fig.5 is shown the result of continuous in-situ measurement during the replacement of the external tendons at the PC bridge. At the major plot is shown the time history of the force in the external tendon made from 13 monostrands 0.6" prestressed by the single-strand jack strand by strand. The minor plot shows the estimation of the friction loss using the readings of the EM sensor behind the deviator and EM sensor near the active anchor. The true value of the friction coefficient is affected by the group effect and can be reliably estimated only by in-situ measurement.

At the Fig.6a is shown the time history of the force in the cables 1WT (north tower, full square) and 16WB (south tower, open triangle) forming the main cable of the suspension bridge over the Yangtze river in Jiangyin, PRC, during March 2000. At the Fig.6b is shown time record of force on Sunday., March 19-th. Readings were taken every 10 minutes. This figures illustrate also the long term stability and the resolution of the EM sensor. The measuring system with the remote data transfer was installed by the company Strainstall Engineering Services, Ltd. [6].

The EM sensor enables to measure distribution of the stress along the cable without removing the cable sheath, even thin wall steel tube. The EM sensors should be installed from the both sides close to the deviator. Such arrangement guarantees the force ratio measurement with uncertainty less than 0,1% what is essential for precise estimation of the friction coefficient. No preliminary calibration is necessary in the case when only the ratio of forces is important.

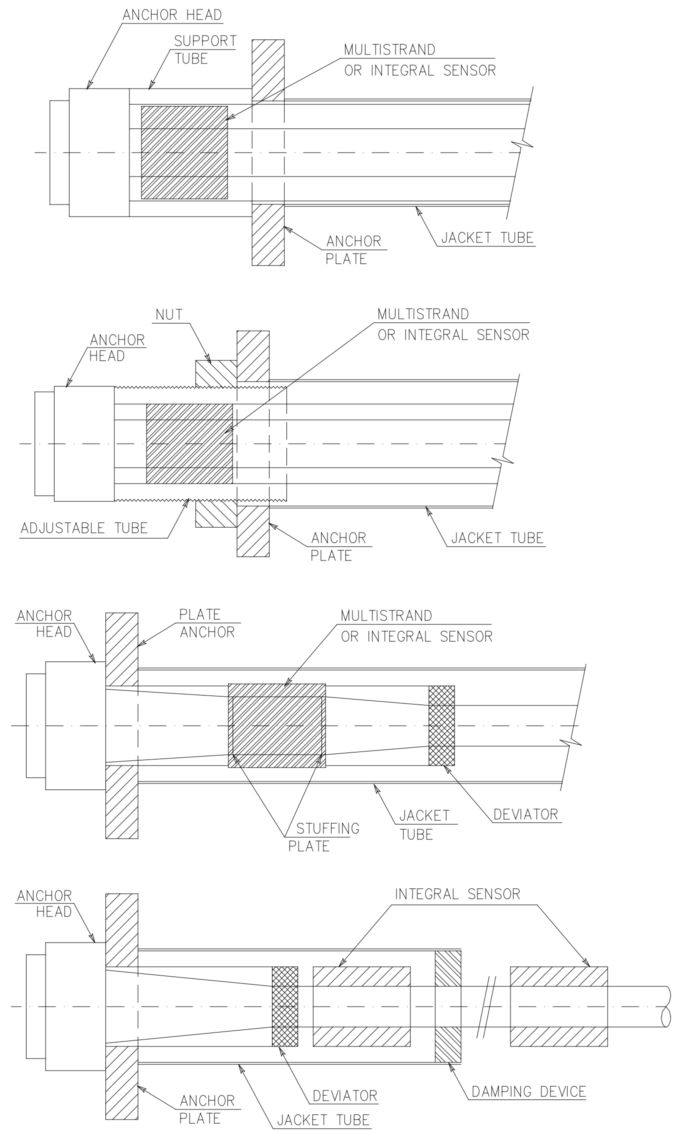

Fig.3 EM sensor integrated with the different stay cable anchoring systems.

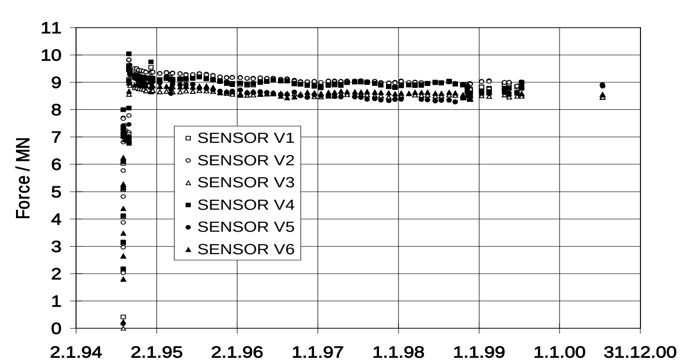

Fig.4 Time history of the prestressing force in the elliptic unbounded tendons of the nuclear reactor envelope during the construction period.

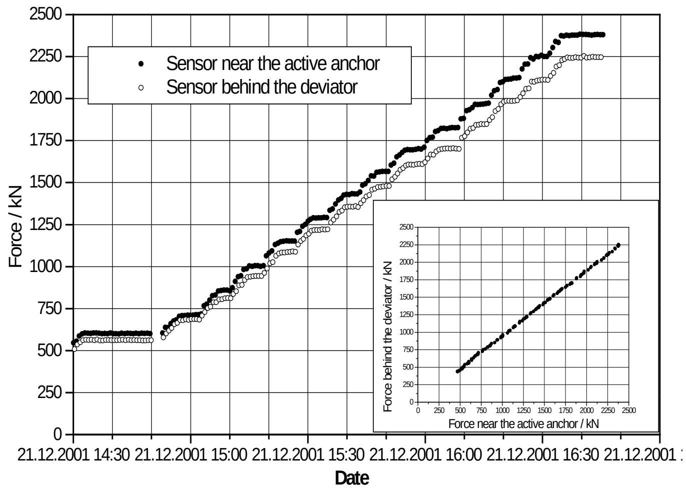

Fig.5 Continuous monitoring of the external tendon

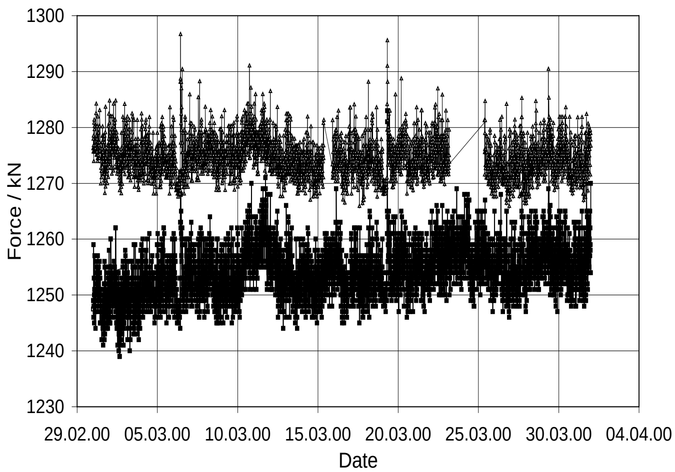

Fig.6a The Jiangyin Yangtze River Bridge - time history of the force during March 2000.

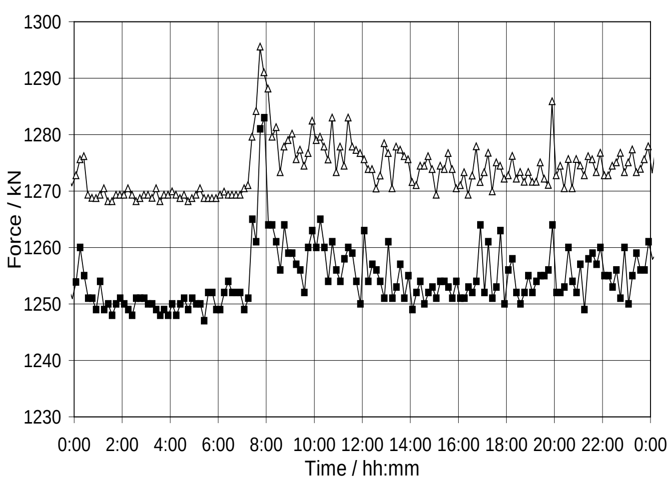

Fig.6b The Jiangyin Yangtze River Bridge - time history of the force during Sunday, March 19-th, 2000.

DYNAMIC LOAD MEASUREMENT AND DAMAGE MONITORING

EM method is also suitable for dynamic load measurement [7], [8]. Special type of the EM sensor is able to measure the dynamic stress changes inside the cable continuously. Monitoring of the traffic load, wind blows, earthquake is possible at any cross sectional area of the cable, even near the anchor wedges. Figure 7 shows comparison of EM sensor and the strain gauge.

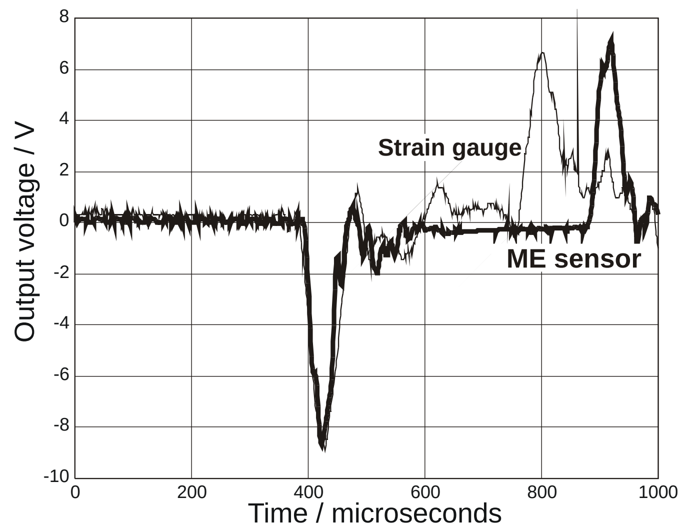

Fig.7 Comparison of EM sensor (thick line) and the strain gauge (hair line) used for percussion load measurement

EM sensor moved along the cable is able to detect the changes in the cross sectional area of the steel with the accuracy better than 1% [9]. It can be used for monitoring the damage of the cable (broken wires) or corrosion at the free length of the cable. Research in that field is still ongoing.

CONCLUSION

Our experience over the past 15 years confirms that the EM method is reliable, accurate and generally applicable for many structural monitoring situations when other methods of measuring force or stress in the steel are inapplicable. But do pay attention to that:

EM sensor is not a real sensor, it is only the input and output part of the sensor - sensor is the steel structure itself.

it is impossible to calibrate the EM sensor like the load cell. The best way is to calibrate the whole arrangement on site during prestressing when the prestressing force is known.

for successful application of the EM method it is essential to know the elasto-magnetic (EM) characteristics. Our experience with the low-carbon prestressing strands from different manufacturers has shown that scatter of their EM characteristics is within ±5%.

magnetic properties of the steel also change with temperature. The stress-temperature sensitivity is up to ±5MPa°C^{-1}. For the very precise measurement of the small stress changes (e.g. relaxation measurement) is the best solution the differential sensor (like a dummy gauge).

Information about stress in the cable is transferred to the sensing coils of the EM sensor by the changes of the magnetic flux. There are no problems with insulation resistance but ferromagnetic surrounding of the sensor affects the distribution of the magnetic flux. In cases, when ferromagnetic surrounding is not stable, the magnetic shielding of the sensor is necessary.

ACKNOWLEDGMENTS

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