Calibration of Elasto-Magnetic Sensors for Bridge-Stay Cable Monitoring

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ABSTRACT

We report on the calibration of built-on-site elastomagnetic (EM) sensors for monitoring the tension in bridge-stay cables. The stays being monitored were 116 mm and 128 mm full locked cables, supporting a 260 m long bridge deck, with design load from 5000 to 8000 kN. The EM sensing principle is based on the variation under stress of the magnetic permeability in a ferromagnetic material. The calibration included two test phases, one in the laboratory and the other on site. In the laboratory, the sensor was built around a segment of cable, identical to that under monitoring, loaded up to 9000 kN with a tension testing machine; the response of the sensor at different load levels was then compared with the load applied by the machine. The calibration shows that: the experimental load-to-permeability relationship is non linear but its slope is independent of the fabrication process; the permeability is very sensitive to temperature and the thermal compensation coefficient varies with load; the sensor is repeatable except for an offset, which must be identified at site by comparing the sensor response with the cable under known load and temperature. To record independently the load on site, we carried out vibration tests, estimating the tension by analyzing the harmonic sequence of the cable frequency response function.

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INTRODUCTION

In this paper we report on the calibration of site-fabricated elastomagnetic (EM) sensors used to monitor the tension in bridge-stay cables. An EM sensor measures the magnetic permeability of the steel cable and we use this quantity to estimate the cable stress status. The working principle of the sensor, that the magnetic permeability of a ferromagnetic material varies with the stress applied, was first suggested by Jarosevic [1] in 1998, and later developed by Sumitro et al. [2] into an industrial prototype. The structure monitored (Figure1) is a new cable-stayed bridge spanning the Adige River 10 km north of the town of Trento, Italy. This is a statically indeterminate structure, having a composite steel-concrete deck of length 260 m overall, supported by 12 stay cables, 6 per deck side, as shown in Figure 1(a) and (b). The deck cross section consists of 4 "I" section steel beams of depth 2m with variable flange dimensions along the span, carrying a 25cm thick concrete deck slab. The deck bears on the abutments and is anchored every 30 m to the cable stays. The bridge tower has 4 pylons of height 45m, and is located at the centre of the bridge span. The stays are full locked steel cables of diameters 116 mm and 128 mm, designed for operational loads between 5000 and 8000 kN. Structural redundancy, possible relaxation losses and an as-built condition differing from design, suggest that long-term load redistribution between cables can be expected [3].

In this paper we illustrate the EM sensors used in this project and their calibration procedure. First we introduce the physical principle of the sensor and we clarify the need for calibration. The calibration includes two test phases, one in the laboratory and the other on site. In the laboratory the sensor is built around a segment of cable, identical to that under monitoring, loaded up to 9000kN tension on a test machine; the response of the sensor at various load levels is then compared with the load applied by the machine. To record independently the baseline load level on site, we carried out vibration tests, estimating the tension level by analyzing the harmonic sequence of the cable frequency response function. Lastly, we provide an estimate of the sensor accuracy.

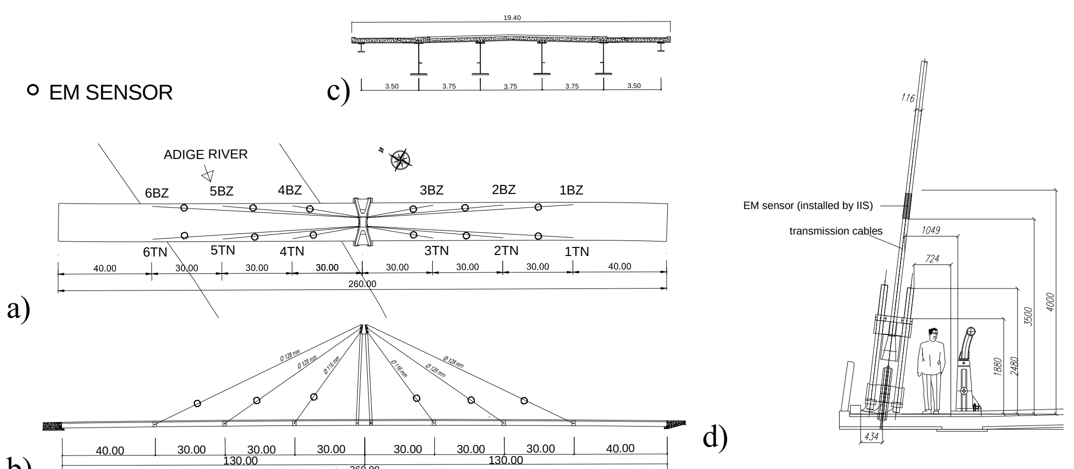


Figure 1. Plan view (a) and elevation (b) of the bridge; cross-section of the deck (c); view of a lower anchorage with the location of the EM sensor (d).

SENSOR PHYSICAL PRINCIPLE

When we apply a magnetic field H to a medium, the resulting magnetic flux density B is proportional to a constant μ which is a characteristic of the medium and is referred to as the magnetic permeability. In the case of ferromagnetic materials the relationship between the B-field and the H-field is non linear and hysteretic, thus we normally refer to an incremental permeability which is the ratio between the incremental changes in the two fields.

$$\mu = \frac{\Delta B}{\Delta H} \tag{1}$$

The magnetic properties of a ferromagnetic material are altered when stress is applied, because the stress changes the configuration of the ferromagnetic domains in the medium: so by experimentally measuring the magnetic permeability of a cable we can understand the cable stress state. In essence, an EM sensor consists of two coils wound round the cable, as depicted in Figure 2 (a) and (b). To make the measurement, the interrogation unit charges the primary coil, applying a magnetic field H to the cable. The resulting B-field produces a current in the secondary or sensor coil, which in turn is recorded by the interrogation unit. In general, the voltage ε_{out} induced in the secondary is given by Faraday's law [2]:

$$\varepsilon_{out} = -\left[NA_f \frac{dB(t)}{dt} + N\left(A_0 - A_f\right)\mu_0 \frac{dH(t)}{dt} \right] \tag{2}$$

where N is the number of turns of the secondary; μ_0 is the magnetic permeability of the secondary coil alone; A_0 and A_f are the cross sections of the secondary and the steel, respectively. For an increment of magnetic field ΔH the resulting voltage on the secondary circuit is:

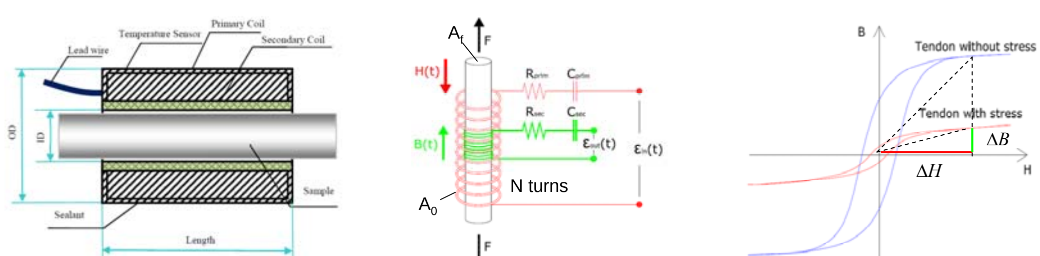
$$\left|\varepsilon_{out}\right| = \frac{1}{RC} NA_f \left[\Delta B + \left(\frac{A_0}{A_f} - 1 \right) \mu_0 \Delta H \right] \tag{3}$$

where R and C are the resistance and capacitance of the secondary circuit. If we take the same measurement without the ferromagnetic material, the resulting voltage is:

$$\left|\varepsilon_0\right| = \frac{1}{RC} NA_0 \mu_0 \Delta H \tag{4}$$

Therefore, the ratio of the two quantities reads:

$$\frac{\varepsilon_{out}}{\varepsilon_0} = \frac{1}{\mu_0} \frac{A_f}{A_0} \frac{\Delta B}{\Delta H} + \left(1 - \frac{A_f}{A_0}\right) = \bar{\mu} \frac{A_f}{A_0} + \left(1 - \frac{A_f}{A_0}\right) \tag{5}$$



a) b) c)

Figure 2. Schematic (a) and concept (b) of an EM sensor; theoretical relationship between magnetic field H and magnetic flux B for ferromagnetic materials.

where we indicate with $\bar{\mu}$ the relative permeability of the ferromagnetic material to vacuum:

$$\bar{\mu} = \frac{1}{\mu_0}\frac{\Delta B}{\Delta H} \tag{6}$$

Manipulating Equation (5) we eventually obtain the following expression:

$$\bar{\mu} = 1 + \frac{A_0}{A_f}\left(\frac{\varepsilon_{out}}{\varepsilon_0} - 1\right) \tag{7}$$

which directly correlates the relative permeability $\bar{\mu}$ to the sensor output ε_{out}. The permeability of a cable of ferromagnetic material is also sensitive to temperature T and stress σ. To account for temperature and load changes, [2] suggest modification of Equation (5) to:

$$\bar{\mu} = \frac{A_0}{A_f}\left(\frac{\varepsilon_{out}(\sigma,T) - \varepsilon_{out}(0,T_0)}{\varepsilon_0}\right) + \alpha(T_0 - T) \tag{8}$$

where $\alpha = \mathrm{d}\bar{\mu}/\mathrm{d}T$ is the temperature sensitivity and T_0 is the baseline temperature, used to calibrate constant ε_0. A suggested value for α is 0.012 °C^{-1}, according to [1]. Equation (8) implies that the relationship between temperature and permeability can be assumed linear, while in general the relationship between voltage and stress should be calibrated experimentally on the specific cable and sensor.

LABORATORY CALIBRATION

The EM sensor used in this project is a site-fabricated device supplied by Intelligent Instrument Systems Inc. [4]. The device has two coils wound on-site around the cable, separated by plastic shells, and protected by an epoxy and metal cover. The output of the interrogation unit is a voltage proportional to the magnetic flux B and, for H constant, to the magnetic permeability of the cable. Therefore, the measurement of magnetic permeability is indirect, derived from a voltage measurement.

The response of an EM sensor is based on the elasto-magnetic properties of the specific steel of the cables, and is also sensitive to the cable cross-section and size, to the temperature and to the sensor manufacturing process. Therefore, these sensors require calibration before use. Site-fabricated sensors, as in this case, should ideally be calibrated on-site, for example loading and unloading the cable while simultaneously comparing the response of the EM sensor with a reference gauge (e.g. a load cell). However these sensors were installed two years after opening the bridge and the owner could not allow the cables to be unloaded to perform tests. Therefore calibration was under laboratory conditions on site-fabricated prototype sensors and on segments of cable identical to those of the bridge.

Scope of the calibration procedure is to provide the laws relating the sensor measurements to temperature and stress. To do this the sample cable, on which the calibration sensor is built, is subjected separately to load and temperature gradients.

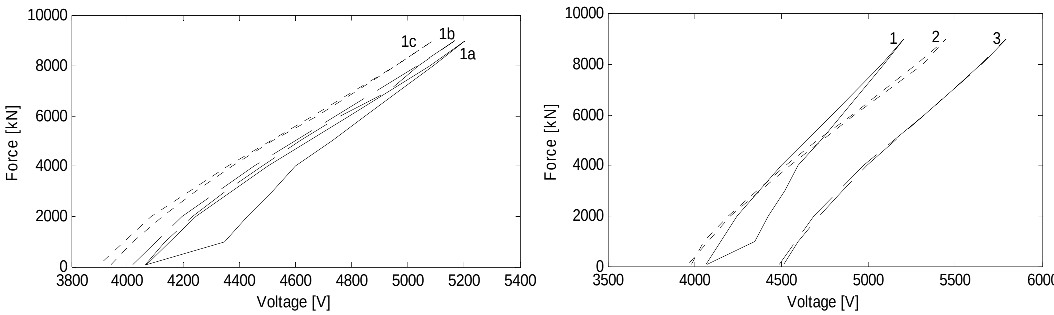


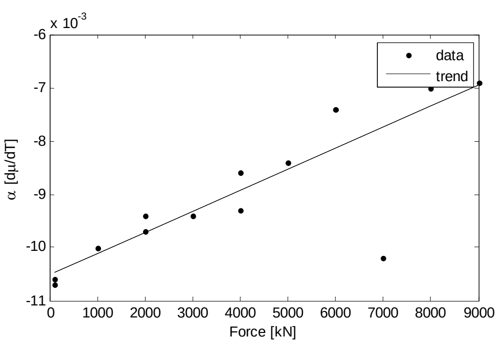
Figure 3 - Left: different load-voltage calibration curves of the same sensor: the uninterrupted (1a) and interrupted (1b) lines are different load cycles at temperature T=27.2 °C, while the dotted (1c) line is the same sensor at temperature T=37.7°C. Right: force to voltage ratio for three different sensors (after temperature compensation).

During load calibration the temperature must be constant and the voltage measurements need to be redundant: with at least 3 voltage readings at each load step, as suggested by the sensor suppliers. A first set of tests was carried out to select the optimal acquisition parameters (in particular, the charge profile) in order to reach magnetic saturation in the cable and to obtain the highest sensitivity. The load permeability relationship can be seen as a load-voltage relationship, where calibration extended over a series of 1000kN load steps from 0kN to 9000kN with the corresponding voltage readings.

The left hand graph in Figure 3 shows the experimental relationship between the load F applied and the voltage V recorded by a sensor on a 128 mm cable. Curves (1a) and (1b) are the responses to the first and second load cycles at an ambient temperature of 27.2 °C. Although in general the relationship is non linear and changes with the load cycle, it was seen to be constant beyond the second cycle. Generally speaking, the load-permeability (F-μ) relationship is non-linear and can be approximated with a third degree equation of the type:

$$F = C_3\overline{\mu}^3 + C_2\overline{\mu}^2 + C_1\overline{\mu} + C_0 \tag{9}$$

where C_0 to C_4 are the equation coefficients. Although non linear, we saw that the relationship becomes virtually linear for loads above 4000kN.



a)

b)

Figure 4. (a) Coefficient α (permeability sensitivity to temperature) for the 128mm cable; the coefficient varies with the load level; (b) view of the sensor on a 116 mm cable during Laboratory calibration.

TABLE 1. MEAN AND STANDARD DEVIATION OF COEFFICIENTS α, a AND b IDENTIFIED BY LABORATORY CALIBRATION

Cable Diameter [mm]	α [1/°C]		a [kN/V]		b [V/°C]	
	μ	σ $\times 10^{-3}$	μ	σ	μ	σ
116	-8.79	1.40	6.35	0.34	-7.48	2.08
128	-9.27	2.42	6.20	0.66	-8.88	1.32

The temperature-voltage relationship was found by taking voltage readings from the sensors at two different temperatures, 27.2 °C and 37.7 °C, and at different loads. For example, curve (1c) shows the response of the same sensor at T=37.7 °C. Consistently with Equation (8), the effect of a temperature increase is to shift the F-V curve to the left. Unexpectedly, we found that coefficient α is not exactly constant, but changes slightly with the stress level: as shown in Figure 4(a) values from 0.011 to 0.007 have been identified at different load levels. The relationship is linear and can be taken into account in the calibration equation. The temperature sensitivity is also dependent on the cable diameter.

Based on these observations, the F-V relationship can be written as:

$$F = F_0 + a \cdot \left(\left(V - V_0 \right) - b \cdot \left(T - T_0 \right) \right) \tag{10}$$

where V_0 is the voltage recorded at known reference load F_0 and temperature T_0, T is the temperature, a=dF/dV is the force to voltage slope at reference temperature T_0 and b=dF/dT is the force to temperature sensitivity. In principle, this equation enables a force to be estimated, given the known coefficients a and b and given the interrogation unit response V_0 at single arbitrary values of force and temperature F_0 and T_0. Table 1 reports the mean and standard deviation of coefficients α, a and b identified during the laboratory calibration.

Further tests were carried out to verify the repeatability of the sensor. The right hand graph in Figure 3 shows the response of three different sensors manufactured in the laboratory on the same cable, using the same procedure. All curves are very similar in slope a, but exhibit a very different x-intercept, making the sensor non-repeatable. Additional tests showed that the voltage to temperature sensitivity dV/dT, and therefore the coefficient α, is virtually independent of the manufacturing process. While the scatter in the curve slope a is relatively small, and can be attributed to a bias error, the uncertainty in the x-intercept requires on-site calibration of the sensor, for at least one known value of tension and temperature.

ON-SITE CALIBRATION AND ACCURACY ESTIMATION

This calibration was carried out using the outcome of the vibration test as reference measurement. The choice of a vibration method to estimate the reference load, instead of using a load cell for example, was due once again to the owner refusing release of the cables. During the vibration test, an accelerometer was applied crosswise on the cable and its response to a hammer blow was recorded. An example is shown in Fig. 5(a). After extracting the harmonic series of the signal, the tension was estimated using the following expression [5][6]:

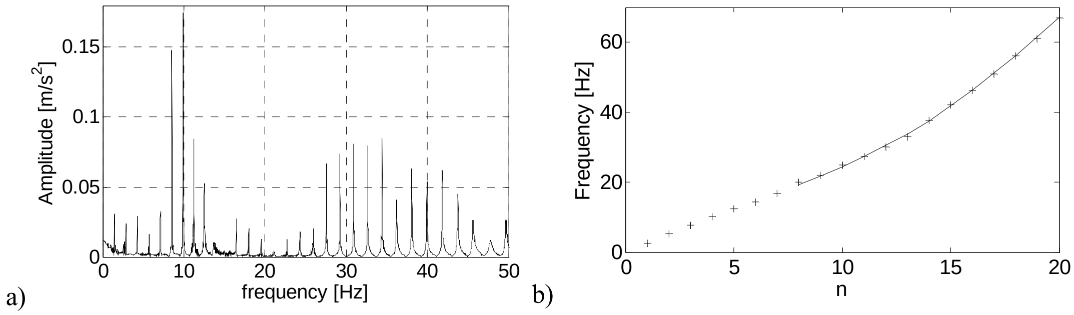


Figure 5. Fast Fourier Transform of the signal acquired on STR1TN (a) and comparison between frequencies measured (points) and the theoretical trend (continuous line) (b).

$$F = k\left(\frac{2L}{n}\right)^2 f_n^2 - \left(\frac{\pi n}{L}\right)^2 EJ \tag{11}$$

where k is the linear mass of the cable, L the cable length, f_n the frequency of the n-th harmonic, E the apparent Young's modulus of the cable steel and J the moment of inertia of the cable cross-section. More specifically, we fitted the relationship between experimental frequency f_n and harmonic order n using F as a parameter. The quality of the fitting is shown in the graph, Figure 5(b).

This method has limited accuracy in estimating loads, even where many harmonics are identified: the standard deviation of the baseline cable tension is 200-300kN (for cable tension varying from 4000 kN to 7000 kN). Also, due to uncertainties in coefficients a and b in Equation (10), the accuracy deteriorates with departure from the calibration load and temperature conditions.

Figure 6 shows the results of a Monte Carlo analysis [7], which simulates the standard deviation expected for different values of tension and temperature. Specifically, the graph refers to cable STR5TN (one of the intermediate bridge cables) with a 6500 kN ±198kN load at temperature 27±0.5°C. The graph shows that the most significant source of error is the inaccuracy of the baseline measurement; compared to this, the uncertainty in force sensitivity is not critical, while the temperature sensitivity can result in an additional error of 50 kN. Similar results were found for the other cables.

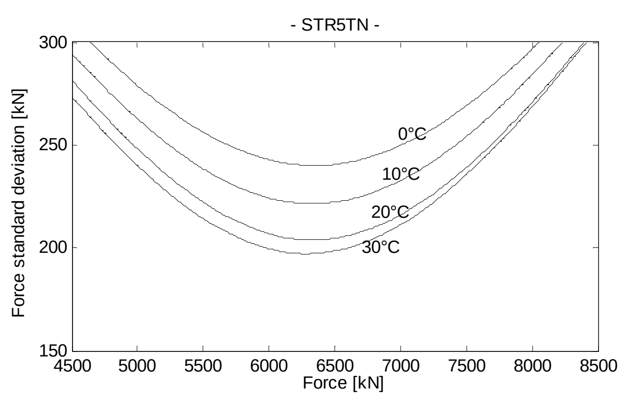


Figure 6. Standard deviation of load on cable STR5BZ estimated by Equation (10).

CONCLUSIONS

We report on the calibration of built-on-site elastomagnetic (EM) sensors for monitoring the tension in full locked bridge cables of diameter 116 mm and 128 mm. The calibration shows that: the experimental load-to-permeability relationship is non linear but its slope is independent of the fabrication process; the permeability is very sensitive to temperature and the thermal compensation coefficient varies with load, but is independent of the fabrication process; the sensor is repeatable except for an offset, which can only be identified on site by comparing the sensor response with the cable under a known load and temperature condition. To record independently the load level on site, we carried out vibration tests, estimating the tension level by analyzing the harmonic sequence of the cable frequency response. After calibration, EM sensors allow loads to be estimated directly, with an accuracy of 200kN and with some deterioration on departure from the calibration load and temperature conditions. Because the most significant source of error is inaccuracy of the baseline measurement, sensor precision could be improved by direct on-site calibration.

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