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REMOVABLE ACTUAL-STRESS SENSOR

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Abstract

Stress measurements of steel reinforcement for reinforced concrete member, strands for pre-stressing concrete, and cables for suspension bridges are the most important parameters for assessing the health of existing structures with cables. Elasto-magnetic (EM) sensors have been used extensively in measuring actual stresses of strands and cables of many types of constructions such as ground anchors, cable-stayed bridge cables, pre-stressed concrete tendons, spatial dome bracing rebars, and steel of reinforced concrete members. It has achieved accuracies of less than 1% for sizes of up to 20mm and 5% of up to 250mm in diameter, respectively, for new construction and with solenoid geometry. However, it is not practical for cable force measurements of existing steels and cables. In order to address this problem a new U-shaped EM sensor has been developed to directly measure the stresses in steel cables of existing structures. The sensor is removable and reusable. Small U-shaped EM sensor has proven to be accurate of within 3% for strand sizes of up to 20mm in diameter. Large U-shape sensor was also developed and manufactured for a bundle of twisted strands of up to 61mm in diameter. The calibrations and experiments were carried out to measure the stresses of hanger ropes during hanger rope replacement of an existing suspension bridge in Japan. The capability and advantage of a portable U-shaped EM sensor is confirmed and accepted.

INTRODUCTION

Sensing the change of magnetic properties, as one of the Non Destructive Evaluation (NDE) tools, has been applied in monitoring the rigidity of steel structures. Elastomagnetic (EM) sensory technology adopted the knowledge of "the magnetic properties of the ferromagnetic material vary with stress" [1,2]. The predominant EM technology in non-contact stress stressing of infrastructures is the solenoid system by utilizing two coils wound on the steel sample, i.e., primary coil and secondary coil. The primary coil provides variable magnetic flux to the measured object while the sensing coil picks up the induced electromotive force that is directly proportional to the change rate of the applied magnetic flux [4,5].

There are several limitations for the solenoid EM stress sensors. Firstly, the solenoid sensors are only suitable for the ready-to-be-built structures and needs to be installed before the cables are anchored [6,7]. Although the solenoid sensors can be wound on existing structures by field-manufactured process, the reliable calibration is a troublesome procedure [8]. Secondly, the solenoid EM sensors are permanent sensing devices and are not able to be re-used. Therefore, it is highly required to develop portable and reusable sensors for directly monitoring the actual stress of steel wire, cable and tendons. As a breakthrough in sensory technology, U-shape EM sensors were developed.

The U-shape EM stress sensory system is a magnetic circuit composed of the steel rod to be monitored and a ferrite yoke [9,10]. The U-shape yoke made of grain-oriented silicon steel laminations can magnetically saturate the steel cable [11].

In this paper, the test results of the large U-shape EM sensor for 61mm cable were presented. The tests were conducted in laboratory and on a bridge construction field in Japan in December of 2005. The objective is to monitor the tension of the hanger ropes during the hanger ropes replacement of Ohnaruto Bridge, on the long-span bridges along Kobe-Naruto Route of Honshu-Shikoku Expressway. This bridge was completed in 1985 with a mid-span of 876m. Due to corrosion damage and a subsequent reduction in load-carrying capacity, the existing hanger ropes were projected to have a limited service life. Consequently, they were planned to be replaced with new hanger ropes.

Each set of hanger ropes consists of four twisted pedal-like stranded wires. The diameter of the stranded wire is 61mm. In a suspension bridge, a set of hanger ropes is a critical structural member to suspend stiffening girder from main cables. The replacement was conducted by replacing each of the stranded wire one by one. When one wire is released, the stress distribution of the other three wires is a considerable factor to maintain the traffic convenience and structural safety. The stresses of hanger ropes were measured at every stage of loading such as before releasing, lift-off, wire pulling and after wire installation.

The field calibration was performed during wire pulling process and the U-shape sensor data was compared with a hydraulic jack. An accuracy of better than 7% is obtained through this field test.

THEORETICAL BACKGROUND

U-shape EM sensors with pick-up coils on the yoke foot are not designed to measure the magnetic flux variation through the coil wound on the yoke foot. The primary magnetizing coil are wound at the handle of the sensor. The schematic description of the U-shape EM sensor is shown in Figure. 1.

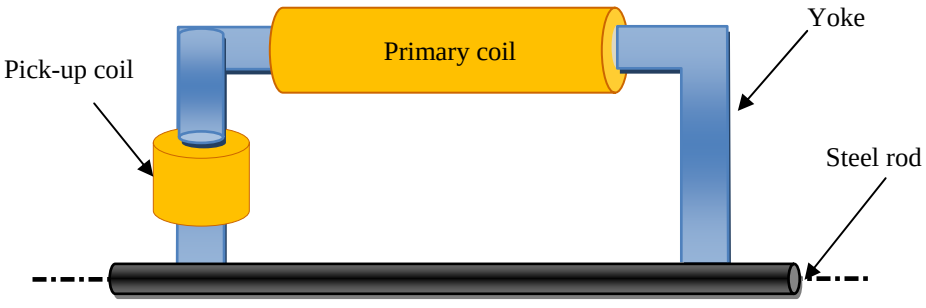

Figure. 1. The schematic description of U-shape EM sensor

The following equation governs an ideal closed magnetic circuit as:

$$\sum NI - \sum R_m\phi_m = 0 \quad (1)$$

Where N is the number of turns of the primary coil, and I is the primary current,

$$R_m = \int_C \frac{dl}{\mu A} \quad (2)$$

which is called the magnetic resistance of each section of the magnetic circuit, where l is the length of the integration route C, μ is the permeability of each material, and A is the cross area [3].

Theoretically, at any node of the magnetic circuit,

$$\sum \Phi = 0 \quad (3)$$

In the circuit composed of a U-shape sensor and steel rod, if the permeability of the steel rod changes, the magnetic resistance of the steel rod changes accordingly, leading to magnetic flux variations along the circuit. Under the ideal condition, the absolute flux variation at any node along the circuit should be the same. However, in the magnetic circuit of ferrite yoke and steel rod, due to the magnetic leakage through the air and the steel rod beyond the circuit, the absolute magnetic flux varies from node to node. As a result, the flux along the rod is less than that along the yoke foot, as given in the following equation:

$$\phi_{yoke} = p\phi_{rod} \quad (4)$$

where ϕ_{yoke} and ϕ_{rod} are respectively the flux along the yoke foot and the rod, p is a function of magnetic parameters of the rod and yoke, and the primary voltages, as well as the geometric characters of the magnetic circuit.

For a certain yoke (steel rod magnetic circuit as shown in Figure. 1), we also have

$$\phi_{rod}=f(V_{Primary}, F, A_{rod}) \quad (5)$$

where F and A_{rod} are the axial load and cross area of the rod, respectively. ϕ_{rod} is also related to some other factors such as the permeability of the rod. From Eq. (4) and (5), it is obtained that

$$\phi_{yoke} = p \bullet f(V_{Primary}, F, A_{rod}) = g(V_{Primary}, F, A_{rod}) \quad (6)$$

With pulsed current in the primary coil, the induced integrated pick-up voltage is proportional to the magnetic flux variation. Therefore, Eq. (6) can be rewritten as

$$V_{integrated} = \varphi(F, V_{pulsed\text{-}Primary}, A_{rod}) \quad (7)$$

Where $V_{integrated}$ is the integrated voltage from the pick-up coil wound on the yoke foot, and $V_{pulsed\text{-}Primary}$ is the pulsed primary voltage indicating the primary current according to Ohm's Law.

STRESS ESTIMATION, ACCURACY AND RELIABILITY

Through a laboratory experimental test, the correlation of load F and integrated pick-up voltage, $V_{integrated}$, is obtained and the results are shown in Figure 2. Figure 2(a) shows the results from different working points, WP

(presumed applied electric currents for an optimum measurement result), i.e., WP = 1.0V-2.5V and WP = 1.0V-3.0V. The load is applied up to about 65% of the 7mm piano wire yield strength of 53.5KN/A.

Figure 2(b) shows that tension varies quadratically with the integrated pick-up voltage. Tests also indicate some parallel shifts in the curves from test at Location I to test at Location II under the same WP = 1.0V-3.0V. These shifts may be caused by the various leakage of the flux in the ferrite yoke-steel rod circuit and the magnetic remanence. Furthermore, it should be noted that to reduce the adverse effect of magnetic remanence in the rod, the transient primary current should be high enough to saturate the steel rod. Remanence is the magnetization left behind in a medium after an external magnetic field is removed.

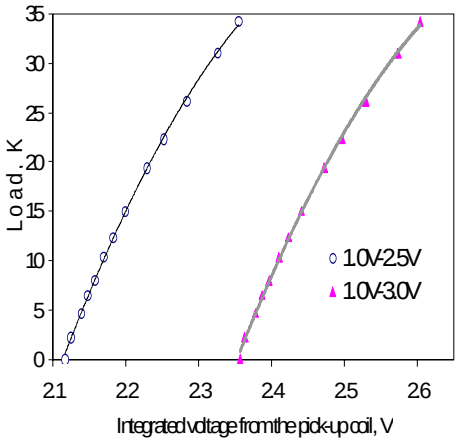

Figure. 2(a). Under different working points

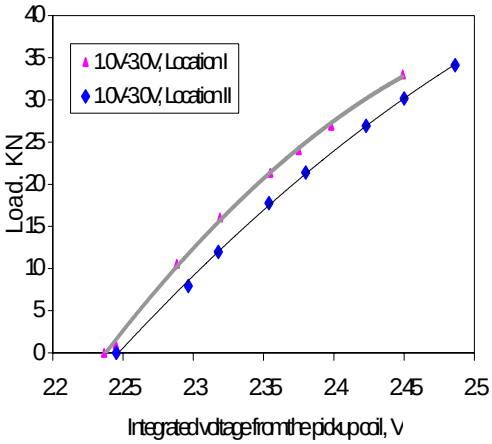

Figure. 2(b). For different test locations

Figure. 2. The integrated voltage and load relationship

Under certain pulsed primary current, if the initial (without load) integrated voltages are calibrated to the same value, the correlation of load and integrated voltage is almost fixed, as shown in Figure 3. It can be observed that a good calibration gives an error better than 5%. Figure 3 indicates that the higher the working point, the better the resolution becomes. From these tests, it is also shown that the measurement resolution is better than 200N(5.2Mpa) .

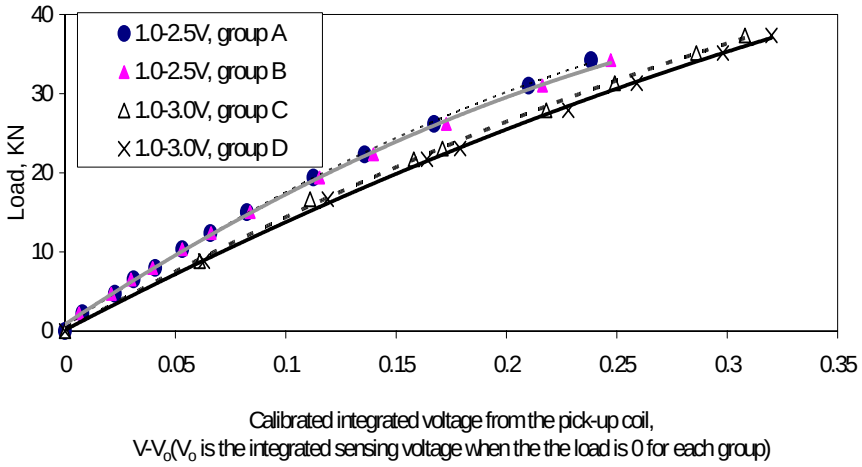

Figure. 3. The measurement tests for four group A,B,C and D

Figure 4 indicates that U shape EM sensor gives satisfactory repeatability, especially at higher loads, provided that the location of the U shape EM sensor remains the same. It is more efficient for the induction to be transferred from the yoke to the steel rod. In order to minimize the influence of magnetic remanence, we can either increase the turns of the primary coil or the current density.

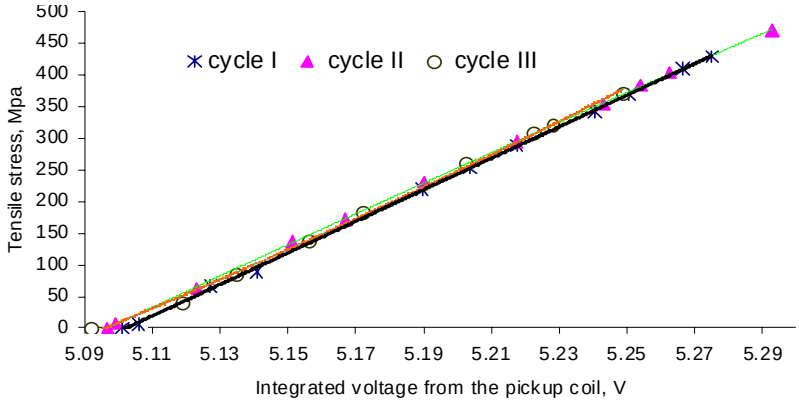

Figure. 4. The repeatability of U-shape EM sensor

APPLICATION

Large U-shape sensor was manufactured at the University of Illinois in Chicago (UIC). The material to be tested is the twisted steel bundle. The picture of the yoke and cross section of the cable are given in Figure 5 and Figure 6, respectively. Because the diameter of the bundle was larger than expected, the sensor was re-cut in Japan for a better fitting as shown in Figure 7.

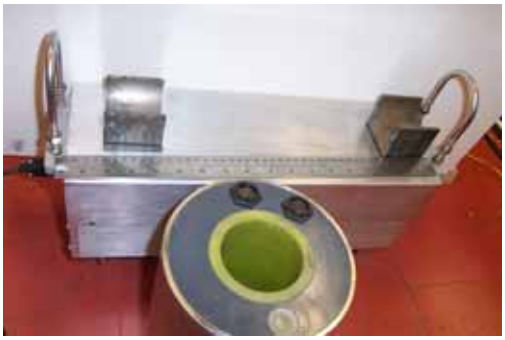

Figure. 5. Large U-shape sensor

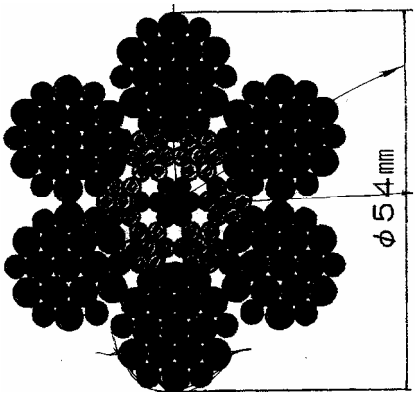

Figure. 6. Pedal-like strand

Figure. 7. Contact the yoke to the pedal-like strand with the real diameter of 61mm

The application of the large U-shape sensor was conducted during the replacement of hanger rope at one of the suspension bridges at Seto Naikai Japan. The hanger rope configuration is shown in Figure 8. Each hanger consists of four pedal-like strands, i.e., strands A,B,C and D.

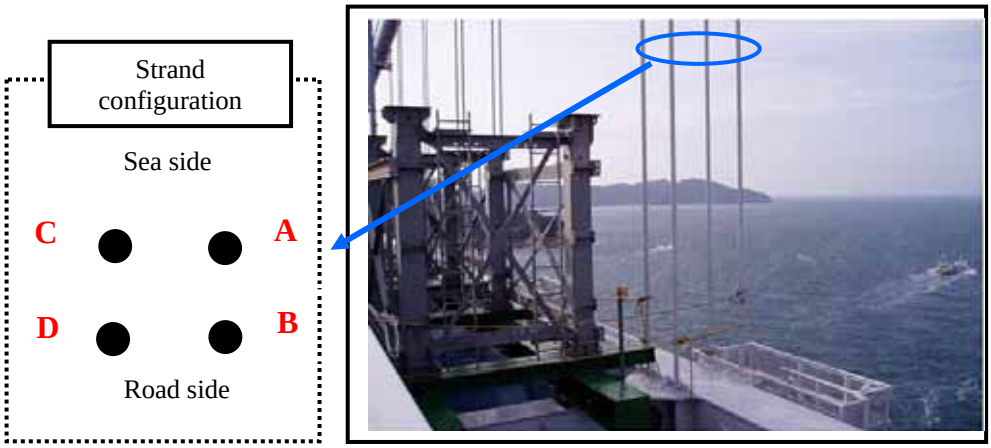

Figure. 8. The hanger rope configuration

The measurement set-up is shown in Figure 9. The U-shape sensor is attached at the measured pedal-like strand D at the height of 2600mm from the bridge deck. A temperature sensor is also attached at 500mm from the U-shape sensor.

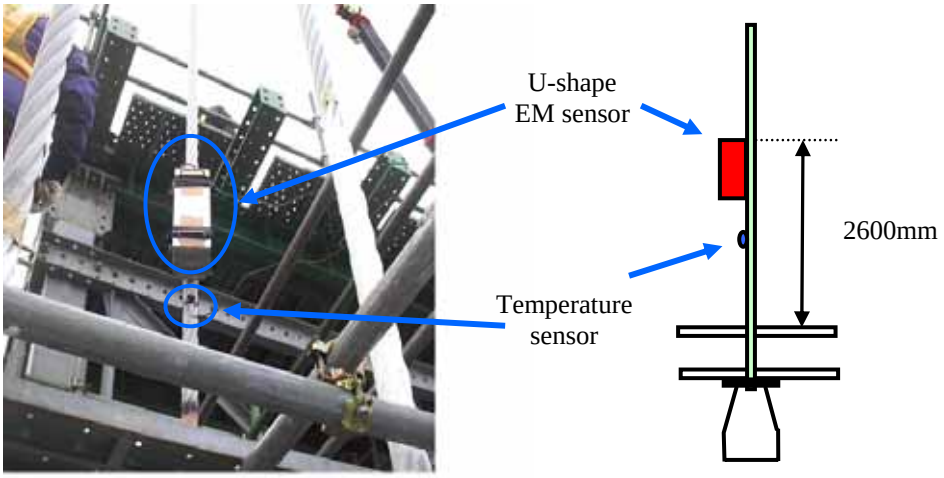

Figure. 9. Sensor setup during field test

Before conducting the field-measurement, a series of calibrations were performed in the Keisoku Research Consultant's Laboratory at Hiroshima, Japan. The pedal-like strand was pulled by a steel frame and the data from the U-shape sensor was recorded by a Power Stress Unit as shown Figure 10.

Figure. 10. Calibration test set up with the specimen to hanger rope in diameter of 61mm

Power stress unit

The calibration result is summarized in Figure 11. From the calibration, the actual stress, W, was obtained as expressed in the Eq. (8). An accuracy of better than 7% is obtained by comparing the field-tested result with the jack values.

$$W = 1.0319 \times V_{integrated} - 1574.5 \quad (8)$$

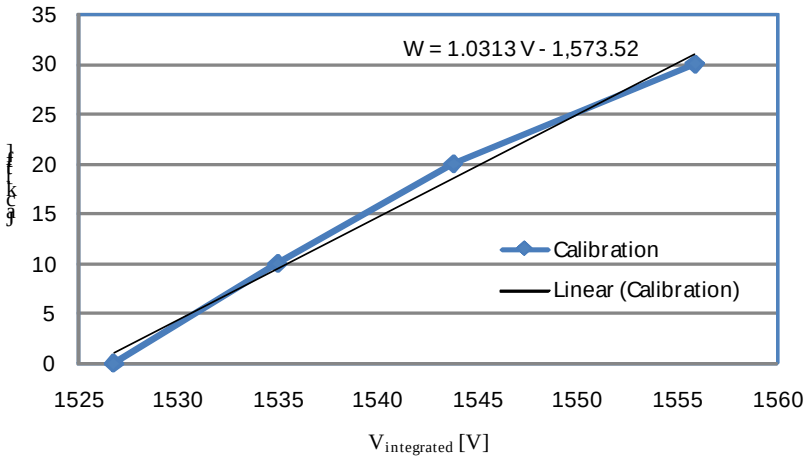

Figure. 11. Calibration test result

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