REAL-TIME NDE OF STEEL CABLE USING ELASTO-MAGNETIC SENSORS INSTALLED IN A CABLE CLIMBING ROBOT

Seunghee Park[1]*, Ju Won Kim[2], Jong Jae Lee[3], and Jin Suk Lim[4]

[1] *Department of Civil and Environmental Engineering, Sungkyunkwan University, Suwon, Korea*
[2] *Department of U-City Design and Engineering, Sungkyunkwan University, Suwon, Korea*
[3] *Department of Civil and Environmental Engineering, Sejong University, Seoul, Korea*
[4] *Intelligent Instrument System, USA*
* *Corresponding author (shparkpc@skku.edu)*

ABSTRACT: Recently, the steel cable used infrastructures are improved with progress in construction technology. In particular, the steel cable in long span bridges such as cable stayed bridges and suspension bridges are critical members which suspend dead load due to the main girders and bridge floor slabs. Damage at cable members can occur in the form of cross-sectional loss caused by corrosion and fracture, and it can lead structural failure due to concentrated stress of the cable. Therefore, nondestructive examination for steel cables is necessary so that the cross-sectional loss can be detected. This study proposes a steel cable health monitoring technique using an elasto-magnetic (E/M) sensor installed in a cable climbing robot. The E/M sensor is applied to detect the cross-sectional loss in this study while it was originally developed for measuring the tensile force in the previous works. To verify the feasibility of the proposed damage detection technique, steel bars which have 4-different diameters were fabricated and the output voltage value was measured at each diameter by the E/M sensor. Optimal input voltage and working point are chosen so that the linearity and resolution of results can ensure through repeated experiments, and then the E/M sensor scans the output voltage of the specimens based on the selected optimal condition. This E/M sensor based monitoring technique will be incorporated into the cable climbing robot in the further research. This proposed approach can be an effective automated tool for steel cable health monitoring.

Keywords: *Elasto-magnetic Sensor, Permeability, Steel Cable, Cable Climbing Robot, Non-destructive Examination, Structural Health Monitoring*

1. INTRODUCTION

Recently, the steel cable used infrastructures are improved with progress in construction technology. In particular, the steel cable in long span bridges such as cable stayed bridges and suspension bridges are critical members which suspend dead load due to the main girders and bridge floor slabs. Damage at cable members can occur in the form of cross-sectional loss caused by corrosion and fracture, and it can lead structural failure due to concentrated stress of the cable. Therefore, nondestructive examination (NDE) for steel cables is necessary so that the cross-sectional loss can be detected. However it's difficult to monitor their condition because most of cables are located at inaccessible locations.

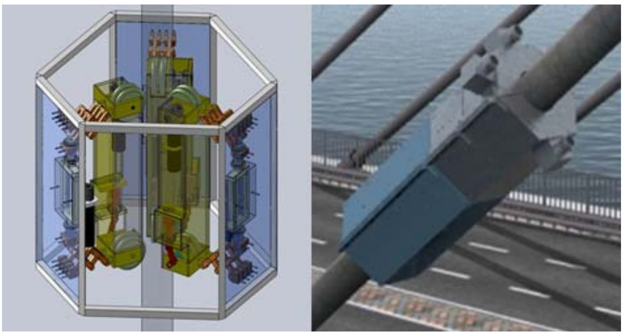

Fig. 1 The concept of cable climbing robot

To overcome this drawback, the cable climbing robot that can be approach to damage point has been developed [1], as shown in figure 1. Hence the available NDE technique for the cable climbing robot has been researched widely also.

In this study, magnetic sensor to detect the loss of cross-section area was applied for incorporating the cable climbing robot. The magnetic sensors are widely used to monitor the structure including aircraft and ship, because of its excellent reliability and reproducibility. There are various kinds of magnetic sensors, and the optimal magnetic properties can be utilized according to kind of target structure. Recently the elasto-magnetic sensor (E/M sensor) that can estimate the tensile force of cable by measuring the permeability was developed [2-4], and the researches about the usability of it have been performed.

In this study, the E/M sensor was applied to detect the cross-sectional loss of steel cable by capturing the output voltage values while it was usually used for measuring the tensile force in the previous works. To verify the feasibility of the proposed damage detection technique, steel bars which have 4-different diameters were fabricated and the output voltage value was measured at each diameter by the E/M sensor. Optimal input voltage and working point are chosen so that the linearity and resolution of results can ensure through repeated experiments, and then the E/M sensor scans the output voltage of the specimens based on the selected optimal condition.

2. THEORICAL BACKGROUNDS

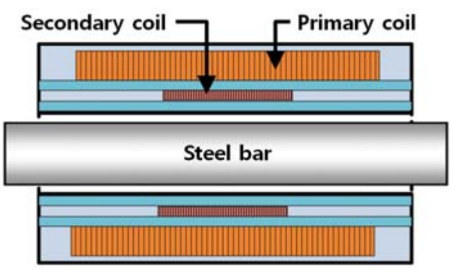

Fig. 2 The concept of elasto-magnetic sensor

An E/M sensor, as shown in figure 2, consists of a primary coil and a secondary coil, which work cooperatively to measure the apparent relative permeability and formalize the elasto-magnetic characterization of the material. As shown in figure 3, when pulsed current pass the primary coil, the ferromagnetic material is being magnetized and pulsed magnetic field is introduced along the steel rod.

Initially a gentle upward trend of the B-H hysteresis curve is produced. Then, as H field reaches the maximal value and decreases, B field follows a gentle return too. The relative permeability (μ_r) is measured in the descending section of the hysteresis curve, as equation (1).

$$\mu_r = \mu_0 \Delta B / \Delta H \qquad (1)$$

Where $\triangle B$ and $\triangle H$ respectively signified the variation in induction and magnetic field, and μ_0 is the permeability of the free space.

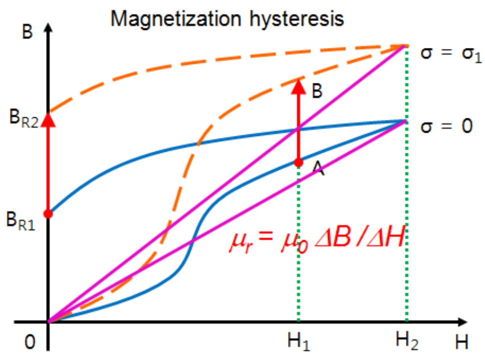

Fig. 3 The variation of magnetization hysteresis curve

The magnetic properties of ferromagnetic materials can be changed by stress [5-7]. This discovery began with the conception of magnetostriction, which indicates the magnetization of a magnetic material leads to shape variation. The magnetization is increased when tensile force was applied to ferromagnetic materials on magnetized condition. Therefore B-H hysteresis curve is changed as shown in figure 3 [8]. By using this property, the stress of steel cable can be monitor by capturing variation of relative permeability. In case of using the E/M sensor, the relative permeability is measured by equation (2) [9].

$$\mu_r = 1 + \frac{A_0}{A_f}\left[\frac{V_{out}(\sigma, T)}{V_0} - 1\right] \qquad (2)$$

Where μ_r is relative permeability, σ tensile stress, T temperature, V_{out} the integrated voltage with the rod in the solenoid, and V_0 is the integrated voltage without the rod in the solenoid.

Originally, E/M sensor was based on concept that the relative permeability is changed, as following the equation (2), when the stress is increasing.

Since the goal of this study is to monitor the decrease of cross-sectional area (A_f), the equation (2) was rewritten as equation (3).

$$V_{out} = [\frac{A_f}{A_0}(\mu_r - 1) + 1]V_0 \tag{3}$$

The relative permeability of ferromagnetic materials was over the 1, if A_0 and V_0 was fixed, output voltage (V_{out}) is decreased as the reduction of cross-sectional area, as following equation (3). Therefore the cross-sectional damage can be detected by monitoring the variation of output voltage value.

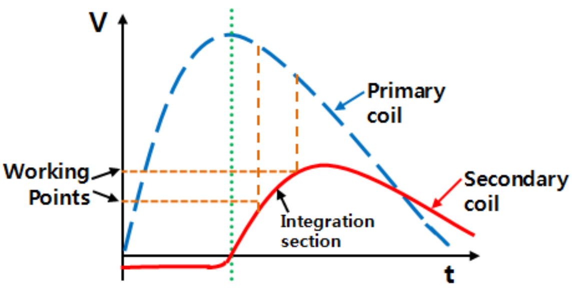

Fig. 4 The variations of output voltage value.

Figure 4 presents the variation of output voltage value measured at primary and secondary coil with time. It shows that the voltage value of secondary coil increases since voltage value of primary coil decreases.

At that time, actual measured value through equipment was the value to integrate the output voltage values of secondary coil in working point range. Hence it's important to choose optimal working point range which can represent clearly the variation of output voltage and features according to changes of specimen condition.

3. EXPERIMENTAL STUDY

3.1 Experimental procedure

A series of experimental studies were carried out to examine the capabilities of the elasto-magnetic sensor based cable health monitoring system to detect the cross-sectional loss. As shown in figure 5, a steel bar of 1610 mm long was prepared. It was fabricated 4 nodes of 400mm long which has 4-different diameters which decrease 1mm by each step; each diameter is 30mm, 29mm, 28mm, and 27mm. Fabricated steel bar specimen was inserted into a PVC pipe of 40mm outer diameter, thickness of 5mm to move the sensor head smoothly. This study applied a Cylindrical POWER EM^{TM} elasto-magnetic sensor head of 40mm Inner diameter, 170mm width to measure the output voltage according to the diameters of specimen, as shown in figure 6. Measured output voltage values are displayed by a Power-stress controller equipment of Intelligent Instrument System Corporation which is connected with the E/M sensor head by a cable, as shown in figure 7.

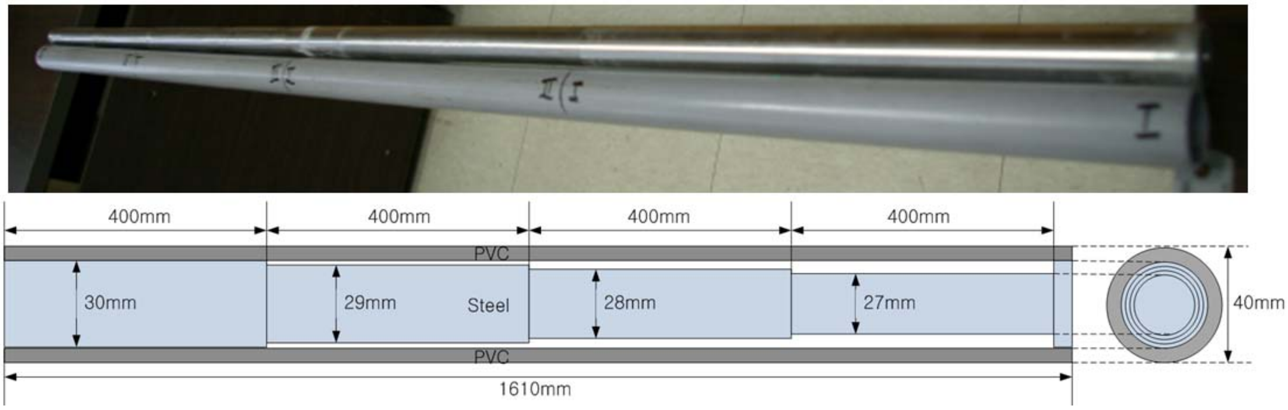

Fig. 5 A used steel bar specimen

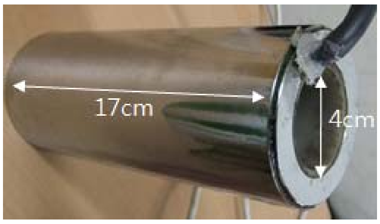

Fig. 6 A elasto-magnetic sensor head

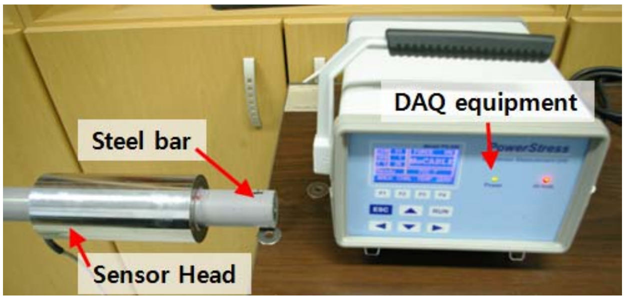

Fig. 7 The experimental setup

The experiment was divided into two categories. First, experiment was performed to choose the optimal experimental condition, input voltage, and working point, by observing the variations of output voltages as diameters of specimen under the various conditions. Next, the steel bar was scanned to detect the cross-sectional loss of specimen on selected optimal experimental condition.

In case of the first experiment, the sensor head was located at the center of each node of steel bar which is displayed in figure 8 (A, B, C, D) and measured output voltage values. This experiment was repeated five times in each condition while the input voltage and working point change for reproducibility.

In the second experiment, output voltage values were measured at the points from a to k including the cross-sectional change points ‘c, f, i’ while the sensor head moved at the same interval, as shown in figure 9.

3.1 Experimental results

First experiment was performed with changing input voltage and working point. Output voltage measurement was repeated 5 times at each condition, and its mean values were displayed in table 1 and figure 10.

Table. 1 The output voltage values measured from the first experiment

No	D(mm)	Test #1	Test #2	Test #3	Test #4	Test #5
Input voltage		450V	450V	300V	400V	400V
Working point		1.3-2V	1.3-1.8V	1.7-2.4V	1.7-2.4V	1.4-2.1V
A	30	1,118.3	864.5	982.4	984.0	1,064.8
B	29	1,078.5	831.7	970.1	971.8	1,039.5
C	28	1,063.8	819.0	963.8	964.8	1,028.9
D	27	1,055.4	815.1	955.9	958.0	1,020.3

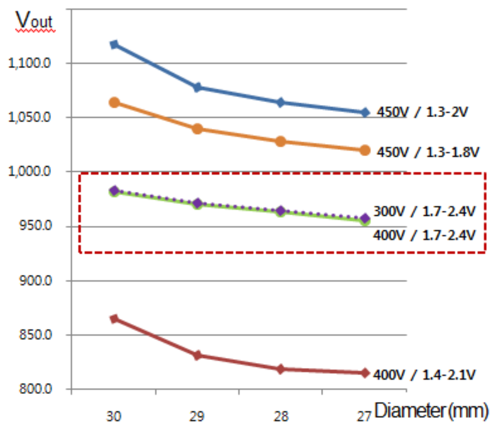

Fig. 10 The variation of output voltage value according to diameter of specimen

All of input voltage and working point conditions have changed as, output voltage decreased according to the decrease of diameter of the steel bar.

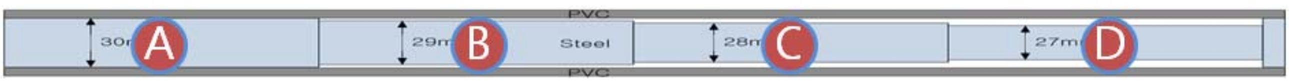

Fig. 8 The measurement points of the first experiment

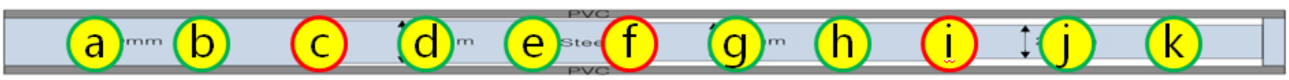

Fig. 9 The measurement points of the second experiment

When the input voltage which magnetizes the primary coil was changed from 300V to 400V at the same working point, the measured output voltages were the same in both conditions. It represents that the input voltage of 300V was enough to magnetize the primary coil of E/M sensor fully. Meanwhile, the measured output voltage values at the working point of 1.7V-2.4V were shown best linearity and resolution as decreasing the diameter when the experiments perform with changing working point condition. Then the input voltage and the end point of working point were fixed to 400V and 2.4V, the same experiment was performed while the starting point of working point change to 1.7V, 1.9V, and 2.1V. Its result represent that the working point of 1.9V-2.4V was the best range which shows the best linearity and difference of output voltage according to reduction of diameter, as displayed in figure 11.

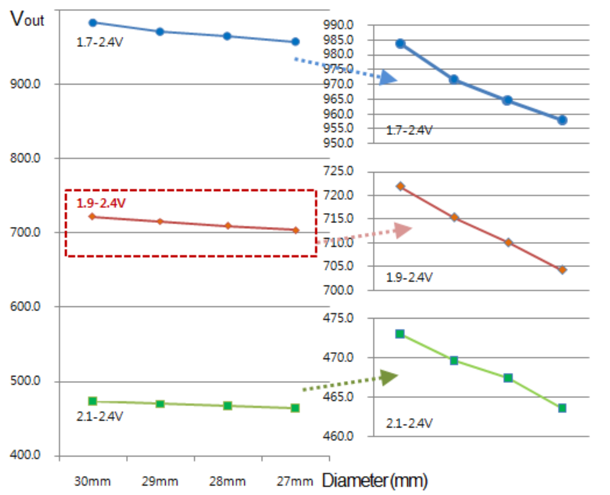

Fig. 11 The output voltage charts for choosing optimal experimental condition

Next, Second experiment was performed by scanning the output voltage while the sensor head was move at the same distance on the selected optimal conditions (input voltage: 400V, working point: 1.9V-2.4V). Second experiment repeated 3 times and its results are displayed in table 2 and figure 12.

Table. 2 The output voltage values measured from the second experiment

No.	Distance (mm)	Diameter (mm)	Test #1	Test #2	Test #3
a	133	30	721.7	721.8	722.7
b	267	30	719.7	719.2	720.3
c	400	Changing point	669.1	620.6	607.1
d	533	29	713.5	712.7	712.8
e	667	29	714.4	714.4	716.2
f	800	Changing point	578.0	659.1	669.5
g	933	28	710.1	710.5	710.5
h	1066	28	709.4	711.4	710.6
i	1200	Changing point	555.7	605.9	535.3
j	1333	27	705.7	704.6	705.7
k	1467	27	705.9	704.5	704.3

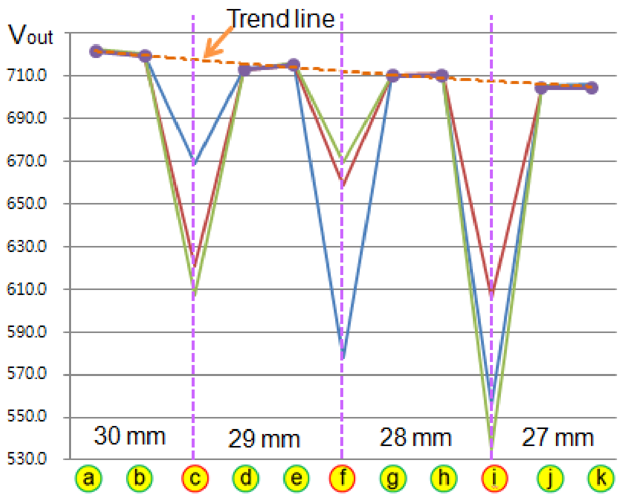

Fig. 12 The output voltage chart of second experiment

The output voltage decreases linearly according to decreasing the diameter of specimen as previous experiment. In addition, E/M sensor head was moved by slipping to the direction where it has a smaller diameter when the output voltage was measured at the diameter changing point, and measured output voltage values at that time were significantly less than the output voltage values of the trend line about the reduction of diameter. Based on these results, it confirmed the possibility of the E/M sensor based cross-sectional damages detection for steel cables.

4. CONCLUSIONS

The E/M sensor based cross sectional damage detection technique for the steel cable health monitoring which can be incorporated into the cable climbing robot was proposed in this study. Experimental study was performed to verify the feasibility of the proposed technique, and it can be confirmed through following facts.

1. Measured output voltage was decreased according to the decrease of diameter of the steel bar specimen.
2. The primary coil of E/M sensor was magnetized enough when the input voltage value exceeds the certain input voltage value, and the measured output voltage value was constant.
3. The Linearity and resolution of measurement result changed through changing working point.
4. The E/M sensor scans the output voltage of the specimens based on the selected optimal condition. Measured output voltage was decreased linearly according to the reduction of diameter and the output voltage values which measured at the diameter changing point were significantly less than the output voltage values of the trend line about the reduction of diameter.

Overall, these results demonstrate that the steel cable monitoring technique using the E/M sensors can be used effectively to detect the cross-sectional damage.

However, while these methods demonstrate feasibility, there are still several issues remaining before this method can be applied practically. Additional research under a variety of environmental factors, such as vibration and temperature should be considered. For that object, the experiments should be performed under an environment similar to the conditions that steel cables are constantly exposed. Furthermore, improvement of system such as lightweight and low power is needed to incorporate into the cable climbing robot. A more accurate and efficient steel cable monitoring system is expected through continuous studies.

ACKNOWLEDEMENT

This study was supported by the u-City Master and Doctor Support Project funded by Ministry of Land, Transport and Maritime Affairs (MLTM) and the research project supported by Korea Ministry of Land, Transportation Maritime Affairs(MLTM) through Core Research Project4 of Super Long Span Bridge R&D Center(08 CTIP-E01). This all-out support is greatly appreciated.

REFERENCES

[1] Nayyerloo, M., Chen, X.Q., Wang, W.H. and Chase, G., "Cable-Climbing Robots for Power Line Inspection" Mobile Robots – State of the Art in Land, Sea, Air, and Collaborative Missions, I-Tech Education and Publishing, Vienna, 2009, pp.63-84.

[2] M. L. Wang, G. Lloyd and O. Hovorka, "Development of a remote coil magneto-elastic stress sensor for steel cables", *SPIE 8th Annual International Symposium on Smart Structures and Material, Health Monitoring and Management of Civil Infrastructure Systems*, Newport Beach CA, Vol. 4337, 2001, pp. 122-128.

[3] S. Sumitro, A. Jarosevic, M. L. Wang, "Elasto-magnetic sensor utilization on steel cable stress measurement", *Proceedings of the 1st fib Congress, Concrete Structures in the 21st Century*, Osaka, 2002, pp.79–86

[4] M. L. Wang, G. Wang, and Y. Zhao, "Application of EM stress sensors in large steel cables, Sensing issues in civil structural health monitoring", Chapter III, 2005, pp.145-154.

[5] J. P. Joule, "On a new class of magnetic forces", Ann. Electr. Magn. Chem., Vol. 8, 1842, pp. 219-224.

[6] P. E. Mix, Introduction to nondestructive testing, John Wiley & Sons, Inc., Hoboken, NJ,1987.

[7] M. J. Stablik and D. Jiles, "Coupled magnetoelastic theory magnetic and magnetostrictive hysteresis", *IEEE Trans. Magn.*, Vol. 29, 1993, pp. 2113-2123.

[8] D. C. Jiles, C. C. H. Lo, "The role of new materials in the development of magnetic sensors and actuators", Sensors and Actuators A, Vol. 106, 2003, pp. 3-7.

[9] M. L. Wang, Z. Chen, S. S. Koontz and G. D. Lloyd, "Magneto-elastic permeability measurement for stress monitoring", *In Proceeding of the SPIE 7th Annual Symposium on Smart Structures and Materials, Health Monitoring of the Highway Transportation Infrastructure*, CA, Vol. 3995, 2000, pp. 492-500.