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To cite this version:

Ju-Won Kim, Seunghee Park, Dae-Joong Moon. Hidden Damage Detection for Main Cables of Suspension Bridges Incorporating DC Magnetization with a Search Coil-Based B-H Loop Measurement. Le Cam, Vincent and Mevel, Laurent and Schoefs, Franck. EWSHM - 7th European Workshop on Structural Health Monitoring, Jul 2014, Nantes, France. 2014. <hal-01022028>

HAL Id: hal-01022028

https://hal.inria.fr/hal-01022028

Submitted on 10 Jul 2014

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HIDDEN DAMAGE DETECTION FOR MAIN CABLES OF SUSPENSION BRIDGES INCORPORATING DC MAGNETIZATION WITH A SEARCH COIL-BASED B-H LOOP MEASUREMENT

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ABSTRACT

Recently, there have been lots of research and development activities to confirm the reliability in terms of the healthy condition for hanger cables of suspension bridges. However, little research about non-destructive evaluation (NDE) techniques for main cable of the suspension bridges has been carried out. In this context, this study proposes a new methodology incorporating DC magnetization with a search coil-based total flux measurement to investigate the loss of the cross section of the main cable due to corrosion damage. From the hysteresis curve of the magnetized main cable measured at the search coil of the proposed NDE equipment, a quantification algorithm to estimate the loss rate of the main cables' cross section is induced. The feasibility of the proposed NDE methodology is verified throughout an experimental study using a real scaled cable specimen with artificially inflicted broken wires.

KEYWORDS : *Cable NDE, Search coil, Total flux, DC magnetization, Damage quantification*

INTRODUCTION

In a steel cable, cross-sectional damage can occur due to corrosion and fracture, which can lead to stress concentrations. Furthermore, the cross-sectional damage can be a direct cause of structural failure. Therefore, nondestructive examination (NDE) to detect the initial stages of cross-sectional damage in a cable is strongly required.

However, it is difficult to monitor the condition of most cables, as the damage can be invisible and inaccessibly located. In particular, in case of main cables of suspension bridges, there have been no research and development activities yet other than direct visual inspections.

To overcome this limitation, this study proposes a noncontact cable inspection system incorporating the magnetic sensor by using the cable's ferromagnetic characteristic. Magnetic sensors are widely used to monitor structures, including aircrafts and ships, due to their excellent reliability and reproducibility [1-3]. Various kinds of magnetic sensors exist, and optimal magnetic properties can be utilized according to the kind of target structure [4-7]. However, it has been not widely applied to monitor the large scale civil infrastructures. Application of the magnetic sensor technique for infrastructure, such as suspension bridge, has been researched recently [8-10].

The magnetic flux leakage (MFL) method is most suitable for continuous structures which have constant cross-sections such as cables and pipes, and has been applied for the inspection of steel cables for ski lifts, elevators, and for other applications [11-14]. However, MFL method can only detect the local fault near the surface. So, hidden damages at the inside of large cable could not be detected.

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To supplement the limitation, this study proposes a new methodology incorporating the direct current (DC) magnetization with a search coil-based total flux measurement to investigate the loss of the cross section of the main cable due to corrosion damage. From the hysteresis curve of the magnetized main cable measured at the search coil of the proposed NDE equipment, a quantification algorithm to estimate the loss rate of the main cables' cross section is induced. The feasibility of the proposed NDE methodology is verified throughout an experimental study using a real scaled cable specimen with artificially inflicted broken wires.

1 THEORETICAL BACKGROUNDS

1.1 Magnetization using electromagnet

1.1.1 Magnetization of ferromagnetic material

Ferromagnetic materials become magnetized when the magnetic domains within the material are aligned [15]. This can be done by placing the material in a strong external magnetic field or by passing electrical current through the material. Some or all of the domains can become aligned. The more domains that are aligned, the stronger the magnetic field in the material. When all of the domains are aligned, the material is said to be magnetically saturated. When a material is magnetically saturated, no additional amount of external magnetization force will cause an increase in its internal level of magnetization.

1.1.2 Electromagnet using coil solenoid

When a current carrying conductor is formed into a loop or several loops to form a coil, a magnetic field develops that flows through the center of the loop or coil along its longitudinal axis and circles back around the outside of the loop or coil as shown in Figure 1. The magnetic field circling each loop of wire combines with the fields from the other loops to produce a concentrated field down the center of the coil. A loosely wound coil is illustrated below to show the interaction of the magnetic field. The magnetic field is essentially uniform down the length of the coil when it is wound tighter (Cullity & Graham 2011).

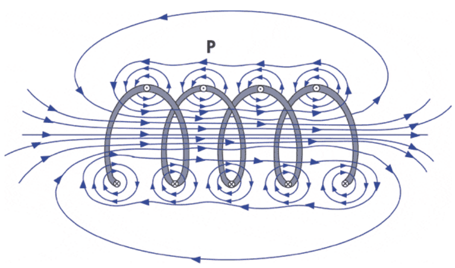

Figure 1: Magnetic field from a coil

The strength of a coil's magnetic field increases not only with increasing current but also with each loop that is added to the coil. A long, straight coil of wire is called a solenoid and can be used to generate a nearly uniform magnetic field similar to that of a bar magnet. The concentrated magnetic field inside a coil is very useful in magnetizing ferromagnetic materials for inspection using the magnetic testing method.

1.1.3 Yoke type electromagnet for magnetization

Electromagnets in the form of an adjustable horseshoe magnet (called a yoke) eliminate the problems associated with permanent magnets and are used extensively. Electromagnets only exhibit a magnetic flux when electric current is flowing around the soft iron core. When the magnet is placed on the component, a magnetic field is established between the north and south poles of the magnet as shown in Figure 2. A way of indirectly inducting a magnetic field in a material is by using the magnetic field of a current carrying conductor. A circular magnetic field can be established in cylindrical components by using a central conductor. Typically, one or more cylindrical components are hung from a solid steel bar running through the inside diameter. Current is passed through the steel bar and the resulting circular magnetic field establishes a magnetic field within the test components.

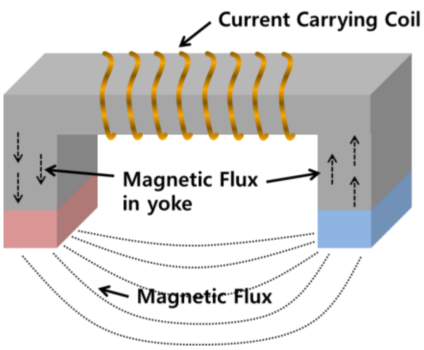

Figure 2: Yoke type electromagnet

1.1.4 Direct current magnetization

The direct current is applied to magnetize the entire cross-section of main cable in this study. DC flows continuously in one direction at a constant voltage. Current is said to flow from the positive to the negative terminal. In actuality, the electrons flow in the opposite direction. DC is very desirable when inspecting for subsurface defects because DC generates a magnetic field that penetrates deeper into the material. In ferromagnetic materials, the magnetic field produced by DC generally penetrates the entire cross-section of the component. Conversely, the field produced using alternating current is concentrated in a thin layer at the surface of the component.

1.2 Total magnetic flux measurement *using search-Coil sensor*

1.2.1 Search-Coil Magnetometer [4]

The principle behind the search-coil magnetometer is Faraday's law of induction. If the magnetic flux through a coiled conductor changes, a voltage proportional to the rate of change of the flux is generated between its leads. The flux through the coil will change if the coil is in a magnetic field that varies with time, if the coil is rotated in a uniform field, or if the coil is moved through a nonuniform field. Typically, a rod of a ferromagnetic material with a high magnetic permeability is inserted inside the coil to gather the surrounding magnetic field and increase the flux density.
The signal detected by a search-coil magnetometer depends on the permeability of the core material, the area of the coil, the number of turns, and the rate of change of the magnetic flux through the coil. The frequency response of the sensor may be limited by the ratio of the coil's inductance to its

resistance, which determines the time it takes the induced current to dissipate when the external magnetic field is removed.

1.2.2 Total magnetic flux measurement

The total flux is the integral of flux density times area over the area of the coil. The output of the fluxmeter is proportional to the number of turns on the coil as well. The fluxmeter uses a coil of electri-cally conductive wire which is often chosen by the user for the particular purpose at hand.
For a coil circling a flux path, the Faraday Induc-tion Law states that:

$$E = nd\phi / dt \tag{1}$$

Therefore, the total flux (ϕ is proportional to the integral of the voltage over time and inversely proportional to the number of turns in the coil [4, 16]:

$$\phi = 1/n\int Edt + \phi_0 \tag{1}$$

1.3 The Hysteresis Loop and Magnetic Properties

A hysteresis loop, as shown in Figure 3, shows the relationship between the induced magnetic flux density (B) and the magnetizing force (H) [17]. It is often referred to as the B-H loop. An example hysteresis loop is shown as figure 3.

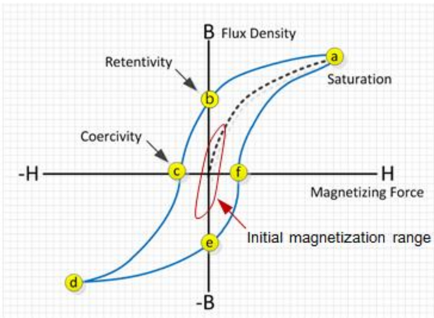

Figure 3: Magnetic hysteresis curve

The loop is generated by measuring the magnetic flux of a ferromagnetic material while the magnetizing force is changed. A ferromagnetic material that has never been previously magnetized or has been thoroughly demagnetized will follow the dashed line as H is increased. As the line demonstrates, the greater the amount of current applied (H+), the stronger the magnetic field in the component (B+). At point "a" almost all of the magnetic domains are aligned and an additional increase in the magnetizing force will produce very little increase in magnetic flux. The material has reached the point of magnetic saturation. When H is reduced to zero, the curve will move from point "a" to point "b." At this point, it can be seen that some magnetic flux remains in the material even though the magnetizing force is zero. This is referred to as the point of retentivity on the graph and indicates the remanence or level of residual magnetism in the material. As the magnetizing force is reversed, the curve moves to point "c", where the flux has been reduced to zero. This is called the point of coercivity on the curve. The force required to remove the residual magnetism from the material is called the coercive force or coercivity of the material.

From the hysteresis loop, a number of primary magnetic properties of a material can be determined.

1. Retentivity - A measure of the residual flux density corresponding to the saturation induction of a magnetic material. In other words, it is a material's ability to retain a certain amount of residual magnetic field when the magnetizing force is removed after achieving saturation. (The value of B at point b on the hysteresis curve)
2. Residual Magnetism or Residual Flux - the magnetic flux density that remains in a material when the magnetizing force is zero. Note that residual magnetism and retentivity are the same when the material has been magnetized to the saturation point. However, the level of residual magnetism may be lower than the retentivity value when the magnetizing force did not reach the saturation level.
3. Coercive Force - The amount of reverse magnetic field which must be applied to a magnetic material to make the magnetic flux return to zero. (The value of H at point c on the hysteresis curve)
4. Permeability - A property of a material that describes the ease with which a magnetic flux is established in the component.
5. Reluctance - Is the opposition that a ferromagnetic material shows to the establishment of a magnetic field. Reluctance is analogous to the resistance in an electrical circuit.

2 FABRICATION OF TOTAL FLUX BASED CABLE NDT SENSOR

Figure 4 shows the concept of total flux measurement sensor head that is being fabricated in this study.

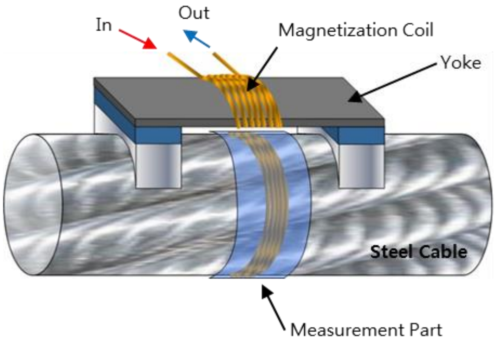

Figure 4: The concept of total flux sensor head

A yoke type electromagnet using the coil solenoid is used to magnetize the cable specimen. And a search coil is applied to measure the total magnetic flux. The search coil was configured to open-able type by two semicircular coils, as Figure 5, for convenient installation in-situ.

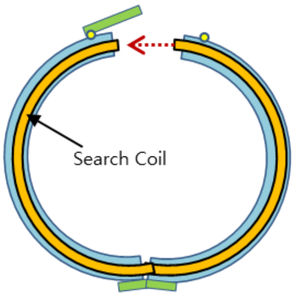

Figure 5: An open-able search coil sensor

Figure 6 displays a schemetic diagram of a NDT system for main cables of suspension bridges. In this system, direct current is used to magnetize the entire cross-section of the specimen. Stable direct current is generate by bipolar power supply, and it supply to the primary coil at the yoke to magnetize the cable specimen.

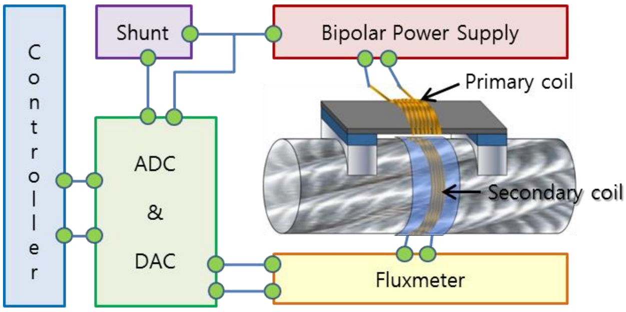

Figure 6: Schematic diagram of main cable NDT system

In this study, a cycle of DC power is supplied to gain a cycle of magnetization curve. Its amplitude range is ±18V and it input to primary coil for 30 seconds. Figure 7 shows the wave shape of an input voltage applied in the proposed magnetization system.

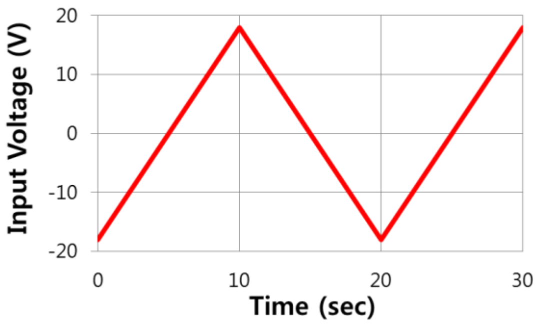

Figure 7: An input voltage shape for magnetization

After the magnetization process, the residual magnetic flux density is measured by search coil sensor (secondary coil) from the cross-section of magnetized specimen, and measured magnetic flux values are integrated by fluxmeter.
A cycle of magnetization loop is obtained through the mentioned process. Since too excessive system is required for saturation magnetization of large-size cross section of main cable, initial magnetization range, as the red line in Figure 2, is utilized in this study.
Among the characteristics of magnetization curve according to cross-sectional condition of cable specimen, retentivity, coercivity and permeability (as mentioned in chapter 2.3) are utilized to capture the change of cross sectional condition. In addition, the quantification and classification of cross sectional damage are studied by using the correlation between these characteristics.

Figure 8 shows the detail drawing of sensor head which is designed as previously mentioned. It is designed suitable to apply to the 50cm diameter cable. The detailed information for the proposed NDE system is described in Table 1.

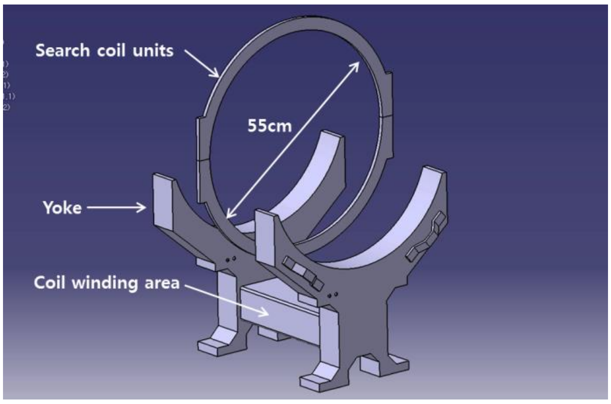

Figure 7: A detail drawing of the sensor head

Table 1: Specification of proposed NDE system

Search coil diameter	550 mm
Yoke size	L: 430 x W: 440 x H: 350 [mm]
Average magnetic path	290 mm
Coil winding	N1: 900 turns, N2: 20 turns
Max current	± 14 A
Total flux range	1×10^3 to 2×10^9 Maxwell-turns
Input voltage range	± 18 V
Examination time	< 30 sec
Magnetizing depth	Whole cross section area
Control program	LabVIEW based UI

The internal diameter of search coil is 550mm, and the yoke size is L: 430mm x W: 440mm x H: 350mm. Coil winding number of primary coil in the yoke is 900 turns and the winding number of search coil is 20 turns. The time for a cycle of test is 30 seconds. This system is controlled by using LabVIEW based user interface (UI).

CONCLUSION

In this study, a main cable NDE system incorporating DC magnetization with a search coil-based total flux measurement is proposed to investigate the loss of the cross section of the main cable at the suspension bridges. Currently, the proposed magnetic NDE system for main cable is being fabricated. After the fabrication, a series of experimental study using a real main cable specimen will be carried out. The authors would expect the proposed NDE system can be very efficiently utilized for the monitoring the hidden damage and quantification

ACKNOWLEDGEMENTS

This work is a part of a research project supported by Korea Ministry of Land, Transportation Maritime Affairs(MLTM) through Core Research Project of Super Long Span Bridge R&D Center(08 CTIP-E01) & Basic Science Research Program through the National Research

Foundation(NRF)funded by the Ministry of Education, Science and Technology of Korea (NO. 2010-0023404). The authors wish to express their gratitude for the financial support.

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