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A novel sensor to measure the biased pulse magnetic response in steel stay cable for the detection of surface and internal flaws

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ABSTRACT

A new type of sensor is designed to measure the biased pulse magnetic response in a large-diameter steel stay cable for the assessment of both surface and internal flaws. The sensor deploys two parallel-connected flexible flat coils (FFC) fed with a biased pulse current as the electromagnet for cable magnetization. A tunnel magneto-resistive (TMR) device and two series-connected sensing coils are used to measure the surface magnetic flux leakage (MFL) and the main-flux variation in the defective cable, respectively. A comparative study between the weak and near-saturated magnetization states of a defective cable is performed by finite element simulation tools to investigate the flaw detection ability of both the surface MFL and main-flux measurement methods With the optimized implementation plan and installation locations of the magnetic sensing elements, a prototype of the sensor and a biased pulse current supply is developed for proof-of-concept experiments. The MFL induced by a surface wire notch with the minimal size of 2 mm in width and 1 mm in depth can be detected by the TMR device with a lift-off distance of 8 mm to the notch. To achieve the quantitative evaluation of multiple internal broken wires (MIBW), main-flux measurements are applied to reveal the effect of the MIBW flaws on the estimated magnetic induction intensity of the cable. The approximate linear dependency of the magnetic induction intensity on the loss rate of the cross-section area can be concluded at the rising and falling edges of the pulsed current. The maximum magnetic induction intensity may act as the feature parameter to characterize the extent of the MIBW flaws with the high accuracy. Compared with the traditional yoke magnetizing sensor, the novel sensor utilizing the FFCs improves the detection flexibility and decreases the weight. The application of the biased pulse current not only reduces the power consumption for coil heating during long-term inspection but also allows the sensor to detect both the surface and internal flaws in the cables.

1. Introduction

Flaw assessment of the steel cables or wire ropes in the long-term service life is an attractive study topic in the field of nondestructive-testing (NDT) in the last decade [1–3]. The magnetic flux leakage (MFL) technique has been regarded as one of the most important ways to detect the flaws in steel cables or wire ropes [4–6]. Many successful application cases of MFL in the detection of surface or subsurface flaws in steel wire ropes have been reported [7–9]. Beneficial attempts are made on MFL sensor design to improve the sensitivity and practicability of the MFL technique. Sun et al. [10] used ring-shaped magnets to construct a new open magnetizing MFL sensor for the inspection of hoist wire ropes. Experimental comparisons between the open and traditional yoke magnetizing MFL sensors show that the new one has the smaller magnetic interaction force and simpler architectures in contrast to the traditional sensors. To achieve the flexible and lightweight sensor structure, Singh et al. [11] utilized the electromagnet with saddle coils to magnetize the tested steel track ropes and developed a flexible GMR sensor array for detecting the MFL signal induced by surface flaws. The authors of this work employed the advanced tunnel magneto-resistive (TMR) sensor array in the MFL method and identified slight surface wear and multiple single broken wires in steel wire ropes based on the MFL scanning image results [12,13].

Compared to the situation of steel wire ropes, the applications of MFL in large-diameter cables, such as the parallel wire cables which are commonly employed as load-bearing components in long-span cable-stayed bridges, are limited due to the difficulties in several aspects. First, to detect the subsurface even internal flaws in the cable with the MFL technique, the ultra-strong magnetic field is

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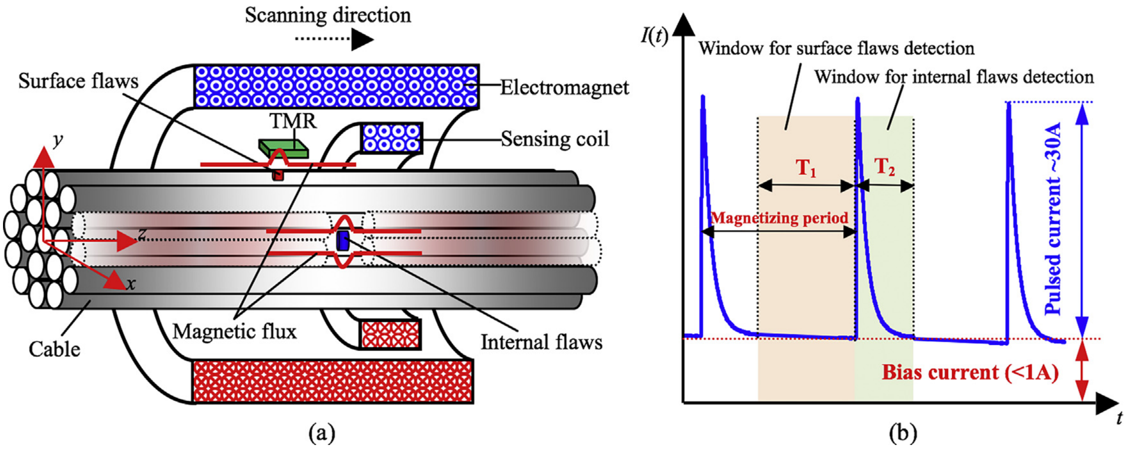

Fig. 1. Conceptual design of the new type sensor. a) Schematic diagram of the sensor configuration and b) Biased pulsed current for the excitation of the electromagnet.

required. Second, the characters of flexibility, light weight and low power consumption are preferred for the MFL sensor. It is necessary to develop a new MFL sensor structure and the improvement of the operation mode is required for steel stay cable inspections.

Bergamini et al. [14] reported that the wires surrounding internal flaws had the shield effect on the weak MFL signal at the weak magnetization level. The leakage magnetic field induced by the internal flaws could propagate to the surface only if the tested structure was in the near-saturation magnetization state. For this purpose, Xu et al. [15] designed a traditional MFL sensor equipped with six bulky magnetic yokes for saturated magnetization of a cable with a diameter of 114 mm. Although the sensor could detect the subsurface flaws in the cable, the serious attraction of cables to the sensor and the large weight of the entire sensor restricted the applications. Christen et al. [16] provided a way to minimize the size and weight of the MFL inspection system. A single solenoid coil wound around a stay cable was fed with DC current up to 100 A to achieve saturated magnetization of the tested cable and dozens of independent pick-up coils formed a circular sensor array to detect the distribution of the MFL signal for three-dimensional localization of internal defects. However, inflexibility of the sensor, large power consumption, and the resulting coil heating problem remain to be resolved.

A flexible solenoid coil with circulating pulsed current acting as an electromagnet may allow saturated magnetization in the tested cable while suppressing the coil heating effect. Compared to Hall elements that are frequently used in MFL sensors, the TMR device has the higher sensitivity and is more suitable for detecting the weak MFL signal induced by surface flaws. The main-flux measurement method can be used to evaluate the cross-sectional area variation induced by the internal flaws in the cable [17]. In this study, a new type of flexible sensor integrating the surface MFL detection with main-flux measurement techniques is proposed to detect both the surface and internal flaws. To increase the flexibility of the sensor, the tested cable is wrapped with flexible flat coil (FFC) in multiple layers to act as the magnetizing coil. A specially designed biased pulse is fed into the magnetizing coil to provide strong magnetic field for saturated magnetization. A solenoid pick-up coil is used to measure the main flux variations of the cable under the pulsed magnetic field in order to evaluate the multiple internal broken wires. When exposed to a strong pulsed magnetic field, the TMR device tends to be in its saturated state and fails to detect the MFL signals. Hence, the TMR device works during the application period of the bias current with a low amplitude to detect the surface MFL signals.

The methodology of measuring the biased pulse magnetic response in cables for surface and internal flaws detection is investigated by finite element simulations in Section 2. Experimental performance tests are conducted in Section 3 to verify the feasibility of the prototype of the new sensor. In Section 4, the new sensor is used to detect the surface notches and assess the multiple broken wire flaws in the center of the cables. The conclusions are given in Section 5.

2. Methodology

The main configuration of the proposed new type sensor is shown in Fig. 1a. The electromagnet for cable magnetization deploys a multi-layer solenoid coil wound around the tested cable. The concept of the biased pulse excitation current is illustrated in Fig. 1b. The excitation current, $I(t)$, is superimposed by a sharp impulse with a peak current up to around 30 A and a DC current with an amplitude lower than 1 A. A magnetization period can be divided into two stages: the majority of the period (T_1) when the amplitude of the current is close to the bias value of the DC current and the rest time interval (T_2) for the sharp impulse.

The time interval of T_1 acts as a valid window for TMR devices to detect the MFL signal induced by surface flaws. Compared with the time interval of T_1, the magnetic field applied by the electromagnet during the time interval of T_2 is much stronger than that in the time interval of T_1 and can force the TMR to be in the saturated state. Therefore, in the period for sharp impulse, only the sensing coil inside the electromagnet senses the main flux variation, $d\Phi/\mathrm{d}t$, as output voltage signal of $U_o(t)$, which can be estimated from the following formula [18],

$$U_o(t) = -N\frac{\mathrm{d}\Phi(t)}{\mathrm{d}t} = -N\left[\frac{\mathrm{d}B(t)}{\mathrm{d}t}A_m + \mu_0(A_s - A_m)\frac{\mathrm{d}H(t)}{\mathrm{d}t}\right] \quad (1)$$

where N is the total number of coil turns of the electromagnet; A_m and A_s are the cross section areas of the tested cable and the sensing coil, respectively. The parameter of μ_0 is the permeability of air.

For a given electromagnet with a fixed excitation current, the term of $H(t)$ is almost unaffected by the flaws in the cables. However, the flaws increase the reluctance in the path of magnetic flux inside the cable, thus resulting in a reduction of the magnetic induction intensity, $B(t)$ [19]. The induced signal of $U_o(t)$, the value of $\Phi(t)$ or $B(t)$ estimated from Eq. (1) may allow the characterization of the deep flaws in the center of the cable.

Along with the tested cable being magnetized under the biased pulsed magnetic field provided by the proposed sensor, the TMR device and the sensing coil can separately detect the surface MFL signal and the main flux variation in the cable. By moving the sensor along the cable, both the surface and internal flaws can be assessed