Crawler Robot Equipped with MFL Devices for Detecting Internal and Surface Flaws in Large-Diameter Steel Stay Cable

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ABSTRACT
In previous work, considering the complementarities of the classic magnetic flux leakage (MFL) and elasto-magnetic (EM) techniques, we proposed a novel sensor to measure the biased pulse magnetic response in steel stay cable for the detection of surface and internal flaws. In this study, a crawler robot is developed to carry the novel sensor for large-diameter steel stay cable inspection. The entire robot system consists of a drive mechanism, pre-loading mechanism, power supply and motor control module. The load capacity and the maximum climbing speed of the robot are experimentally evaluated. Finally, the proposed crawler robot equipped with MFL devices is applied for inspecting defective steel stay cable in laboratory. The testing results show that the crawler robot-based system can successfully detect both surface and internal defects in large-diameter steel stay cable.

1. Introduction

There are a large number of cable-stayed bridges and suspension bridges in China. In order to ensure the safety and reliability of the bridges, it is necessary to regularly inspect and maintain the steel cables of the bridges. Defect detection in large-diameter steel stay cable is one of the popular research topics [1,2]. In the past decays, the health condition of the stay cable was mainly evaluated by visual inspection methods. It is very time consuming to check the entire cable and also the defect inside the stay cable, which is commonly covered by polyethylene sheath, cannot be identified within visual inspection method. Therefore, advanced non-destructive testing techniques are increasingly developed for flaws detection in steel cables. For instance, some researchers attempt to apply ultrasonic guided waves (UGWs) for detecting flaws in the cable in a long distance [3,4]. However, so far, the exact behaviour of the UGWs in the large-diameter steel stay cable is still unclear to the community. The UGWs signal reflected from the flaws and the interfaces among the steel rods in the cable is very complicated to understand.

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Magnetic flux leakage (MFL) is another promising pathway for evaluating the flaws in the steel wire ropes and cables. There are many successful applications of MFL in small-diameter steel wire ropes \(^5^-^9\). However, the applications of MFL in large-diameter steel stay cable are rarely reported. This is because the classic MFL device is hard to provide strong enough magnetic field to fully magnetize the cable and the leakage field induced by the inside flaws is too weak to detect by the sensor near the outer surface of the cable. Magnetic circuit with large-size and strong permanent magnets may solve the limitations facing the classic MFL device at the expense of bulky in the device and difficulty in moving the device along the cable for inspection.

Elasto-magnetic (EM) technique is traditionally applied for monitoring the cable force by analyzing the variation in main magnetic flux in the cable \(^1^0\). In the EM application, pulse current is fed into the primary solenoid coil which is wrapped around and fixed to the cable to provide pulse magnetic field for cable magnetization. Sensing coils embedded inside the primary coil is used to detect the magnetic response in the cable. Due to the applied pulse magnetic field has ultra-low frequency and high peak amplitude, the EM technique is capable to fully magnetize the cable. If the fixed coil sensor becomes movable, then the EM technique can be employed for locating the corrosions or the site of diameter reduction in the cable \(^1^1\). More importantly, the EM technique is capable to detect the flaws deep in the central of the large-diameter steel stay cable.

The MFL technique has advantages of ease in operation and high sensitivity to the surface flaws, while the improved EM technique is tailor made for detecting flaws inside the cable. Considering the complementarities of the two techniques, the authors of this study proposed a novel sensor to measure the biased pulse magnetic response in steel stay cable for the detection of surface and internal flaws \(^1^2\). The electromagnet in the sensor only deploys two parallel-connected flexible flat coils (FFC). A tunnel magneto-resistive (TMR) device is used to measure the MFL signal induced by surface flaws and two series-connected sensing coils is employed to sensing the main-flux variation mainly caused by the internal defects. Compared with the traditional MFL sensor, the novel sensor has advantages in lightweight and functions of detecting both the surface and internal flaws in the cables.

In this study, we focus on developing a crawler robot to carry the prototype of the novel sensor reported in \(^1^2\) to scan along a large-diameter steel stay cable. The configurations of the crawler robot together with the inspection instrument are given in Section 2. Climbing tests results are discussed in Section 3 to evaluate the maximum climbing speed and load capacity of the robot. Inspection for both surface and internal defects using the crawler robot equipped with MFL devices is performed in Section 4. Finally the conclusion is given in Section 5.

### 2. Crawler Robot-based Inspection System

The crawler robot-based inspection system is shown in Fig.1. Two symmetrical track-type modules are employed in drive mechanism, and two DC motors connecting with worm gear speed reducers are used to provide driving force to the robot. The utilization of worm gear speed reducers can realize self-locking of the drive mechanism while the drag force is less than the resistance to avoid failure of the motor. Each track-type module is guided by a straight rail of the pre-loading mechanism so that the central distance between the two track-type modules can be adjusted to meet cables within a certain diameter range. In this study, the structure can be adaptive to the cables with different
diameters ranging from 85mm to 110mm. The screw thread pair in the pre-loading mechanism is designed to adjust the static friction force between the rubber track and the cable.

**Figure.1 (a) and (b) show the model and the picture of the crawler robot, respectively.**

The bias pulse magnetic response detection system is shown in Fig.2. The detail information of the system can be found from [12]. DC power supply 1# provides a current (with amplitude less than 1A) superposed with a pulse current (with amplitude up to 25A) which is generated by a charging and discharging circuit. The operations of the solid state relay (SSR) is issued by the MCU. The command sent by the MCU is transferred to an Amega 2560 control board to drive the motors of the crawler robot. The MCU and the digital acquisition card communication with the PC (LabVIEW platform) through RS232 and USB interface, respectively.

**Figure.2 (a) the picture and (b) the diagram of the bias pulse magnetic response detection system.**

### 3. Climbing Tests

First, the relationship between the climbing speed of the robot at the cable with different tilt angle is studied. During the tests, the preload applied by the screw thread pair is fixed and measured by a pressure sensor to be around 520N. The climbing speed and the required motor torque are estimated when the tilt angle of the cable with respect to the direction varies from 0 degree to 90 degree. The results are separately shown in Fig.3a and Fig.3b.
When the robot climbs horizontally, its climbing speed can reach to around 3.18 m/s. As the increasing of the tilt angle of the stay cable, the climbing speed demonstrates approximately linear decreasing trend. In contrast, the motor torque linearly increases from 0.3 N·m to around 0.46 N·m.

The load capacity of the robot is tested under the condition that the maximum driven voltage is selected for motors control. The load of the robot is simulated by hanging several pieces of steel blocks to the robot body. During the tests, the robot climbed vertically and the robot's climbing speed is first investigated. Please note that when the load increases it is definitely a must to adjust the pre-tightening force applied by the pre-loading mechanism to increase the static friction force between the robot wheel and the cable sheath. As shown in Fig.4, both the climbing speed of the robot and the required pre-tightening force almost linearly depends on the applied load. As the load increases, the climbing speed decreases while the required pre-tightening force increases. According to the results in Fig.4, the maximum load capacity of the robot is estimated around 52.76 kg (the self-weight of the robot is around 25 kg) when the pre-tightening force is selected around 529.2 N. Since the weight of the novel MFL sensor is less than 1 kg, the load capacity of the robot is quite enough for carrying the MFL sensor to inspect the cable.

Figure 3: the estimated (a) climbing speed and (b) motor torque when the tilt angle of the cable changes.

Figure 4: the estimated (a) climbing speed and (b) pre-tightening force at different load cases.
4. Defect detection experiment

The tested steel cable is composed of 107 parallel steel wires with a diameter of 7 mm. The polyethylene protective layer of the steel cable is simulated with a plexiglass tube (7mm in thickness and 99 mm in outer diameter). Two broken wire defects (see Fig.5) were manually made on the steel stay cable. The surface flaw has a single broken wire and the air gap of the flaw has a width of 5mm. The loss of cross-sectional area at the internal multiple broken wire flaws is estimated as 15% and the air gap of the flaw is around 10mm.

![Figure 5: The diagram of the surface and internal defects.](image)

The crawler robot moves along the cable at a speed of 1.7 m/min and the duty cycle of the biased pulse is around 10%. Fig.6a and Fig.6b show the output signal obtained by the sensing coil and the TMR device, respectively. It is difficult to directly distinguish the defect information from the raw signals representing the variation of main flux (Fig.6a). The induced voltage by each pulse magnetic field is extracted from Fig.6a and then digital integral is applied to the voltage to estimate the maximum magnetic induction intensity ($B_{\text{max}}$). The dependency of the estimated value of $B$ on the inspection locations is sketched as the bathtub curve in Fig.7a. The middle concave range of the bathtub curve indicates the location of the internal defect. The diffusion effect of the leakage field in the space may cause the concave range is larger than the actual width of the defect.

![Figure 6: The output signal obtained by (a) the sensing coil and (b) the TMR device, respectively.](image)

As for the results in Fig.6b, the bottom envelop of the output voltage ($U_b$) clearly reflect the changes of MFL signal when the robot passing by the surface defect. The bottom envelop of the output voltage is extracted and plotted in Fig.7b. The single peak can be treated as an indicator of surface defect and the defect locates around the location of the peak voltage.
Seen from the results in Fig. 7, it is found that the value of the featured parameter $B_{\text{max}}$ (or $U_b$) at the defect location is quite lower (or larger) than the results obtained from the health cable. As a consequent, the proposed crawler robot equipped with MFL devices is successful in the application of detecting both surface and internal defects in large-diameter steel stay cable.

5. Conclusions

To apply the previously reported novel MFL sensor and instrument for large-diameter steel stay cable inspection, a crawler robot is designed to carry the MFL devices moving along the inspected cable. The maximum load capacity of the robot (with own weight of 25kg) was experimentally evaluated to be around 52.76kg. Linear dependency of the climbing speed on both the load and the climb angle are concluded based on the experimental results. In the MFL inspections, two parallel-connected flexible flat coils (FFC) fed with a biased pulse current is employed as the electromagnet for cable magnetization. A tunnel magneto-resistive (TMR) array and two series-connected sensing coils are used to measure the surface MFL and the main-flux variation in the defective cable, respectively. The experimental results show that the proposed crawler robot equipped with the MFL devices successfully detects both the surface and internal flaws in the cables.

Future work will focus on the improvement of the climbing robot and MFL device to make the entire system more compact and stable for in situ applications.

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References


