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A PASSIVE WIRELESS DISPLACEMENT SENSOR FOR MONITORING CRACKS IN CIVIL STRUCTURES

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Abstract

A passive wireless crack width sensor suitable for use in civil structural health monitoring applications is presented. The sensor is based on a resonant electromagnetic cavity with one end of the cavity formed by a flexible membrane. A rod attached to the membrane causes the dimensions of the cavity to change when the rod is displaced. The change in dimensions causes a shift in the resonant frequency of the cavity that is directly related to the displacement of the rod. In the example shown, the shift is ~ 4-5 MHz per mm for a cavity with a resonant frequency of 2410 MHz. Using a pulse echo interrogation technique resonant shifts of 100 kHz or 0.022 mm are resolvable. Sensors were mounted onto concrete test prisms and cycled from 20C to -20C. Over this temperature range thermally induced changes of 0.0045 mm/C were observed.

INTRODUCTION

Cracks form in civil structures due to many factors including load, shrinkage displacement, restraint of temperature movements, and deterioration or fatigue. Therefore the existence and magnitude of cracks provides and important tool for the evaluation of the condition and performance of civil structures. For example, crack growth can be used as an indicator of fatigue in bridge decks [1]. Fiber optic [2,3] , cable impedance [4], robotic image collection [5] and image processing [6] based techniques have been developed for the measurement of cracks in civil structures. However these existing sensing technologies have a serious deficiency in that they require some type of permanent connection to the outside world or the requirement to bring imaging equipment into close proximity to the cracks. Recent cases have shown that the cost of installation and preparation of a site for monitoring equipment with wires or fibers can easily equal the cost of sensors and interrogation equipment. For example, the cost of installing a monitoring system in the Tsing Ma suspension bridge in Hong Kong was reported to be over $27,000 per sensor channel [7]. The cost of installation and maintenance of a permanent site will not be justified in all cases. The sensors reported in this work are going to be used in the field monitoring of cracks in a highway bridge. At present the cracks are measured manually, approximately once per year. Each time the cracks are measured a crew is required to set up ladders and safety harnesses, climb up, and manually measure the width of the cracks using various gauges (see figure 1). Wireless technology would make this type of monitoring more rapid, less costly, and potentially more repeatable. Most wireless sensors, however, still require some form of power for the transmission of information. To address this issue there is now considerable effort to develop passive wireless sensors for application in civil structural health monitoring [8-10]. As part of this effort we have developed a new type of wireless displacement sensor that requires no battery or electrical power. The displacement sensor is a passive device that can be easily attached to civil structures. In this paper we will be discussing the basic operating principles, interrogation technique, the results of laboratory testing of this sensor for the measurement of crack width in civil structures. The tests include temperature sensitivity testing as the sensors will be used outdoors.

Figure 1. Crew setting up to measure cracks in bridge deck.

In a displacement sensor, displacement must be converted into a signal format that can be used for observation or measurement. The sensor presented in this work uses the resonant behavior of electromagnetic cavities to covert displacement to frequency. The frequency can be measured wirelessly and the displacement easily calculated from the frequency. Any hollow conducting cavity can theoretically have an infinite number of resonant electromagnetic modes. In this work we have chosen to use a cylindrical cavity for reason of ease of fabrication. The sensor is shown in figure 2. A rod is attached to the cavity diaphragm and, as the rod is linearly displaced, it causes the diaphragm to deflect. This changes the dimensions of the cylindrical cavity and results in a shift in the cavity resonant frequency (~ 4-5 MHz/mm). The cavity is fabricated from copper tubing and copper plate with a wall thickness of 2.5 mm. The corrugated diaphragm was fabricated from brass sheet and hydraulically formed using machined dies.

When the rod in Figure 2 is displaced there is a shift of the cavity resonant frequency. The sensor is interrogated using a system designed for resonant RF cavity type sensors.

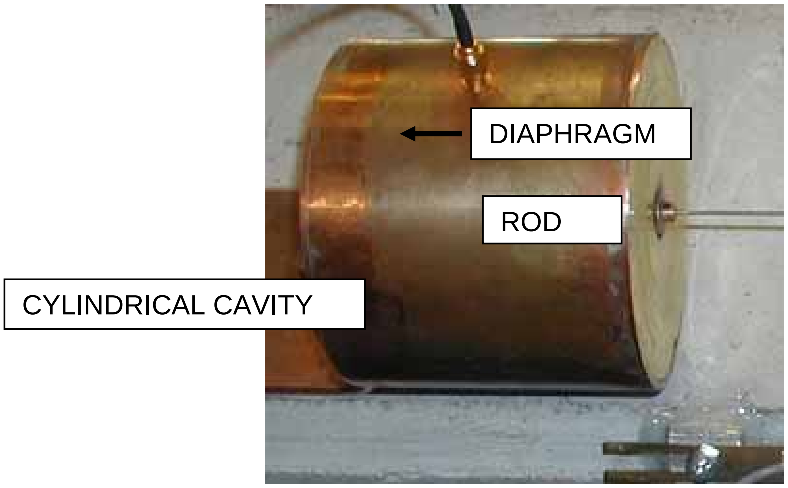

Figure 2 The displacement sensor has corrugated diaphragm on one end with a rod attached. As the rod is displaced the diaphragm is displaced causing the cavity to change dimension and hence shift the resonant frequency. The cavity is 100 mm in diameter.

INTERROGATION SYSTEM FOR WIRELESS SENSING

A block diagram of the sensing system is shown below (Fig. 3). The interrogation process starts with the transmission of an RF signal from the source (National Semiconductor LMX2470). This signal is passed from the signal generator to the transmitting antenna via a switch (Minicircuits ZASWA-2-50 RF switch). The transmitted signal then energies the sensing cavity, for this resonator with a frequency of approximately 2.41 GHz and Q approximately 1000, equilibrium of the excited field will occur in approximately 400 ns. Sometime after equilibrium is reached (~500 ns), the interrogation unit switches from send to receive (position b). The energy stored in the resonator will re-radiate out from the resonator and out of the attached antenna in the form of a decaying RF signal (Fig. 3, response signal). The received signal is directed into an RF detector (Analog Devices AD8347 evaluation board), which produces a voltage proportional to the incoming signal power. This voltage is then digitized using an A/D and downloaded to a laptop for processing. A second switch (switch #2) was used in the interrogation system to reduce the effects of environmental reflections and noise on the detected signal [5]. This switch inserts a time delay between transmission of the RF signal, and detection of the returned signal, this effectively discards the first part of the detected signal. Typically the first 50 nanoseconds of the signal is discarded. This eliminates signals reflecting from objects up to 15 m from the transmitting antenna. This technique has been employed successfully in the past with SAW based sensors in reducing environmental reflections [10].

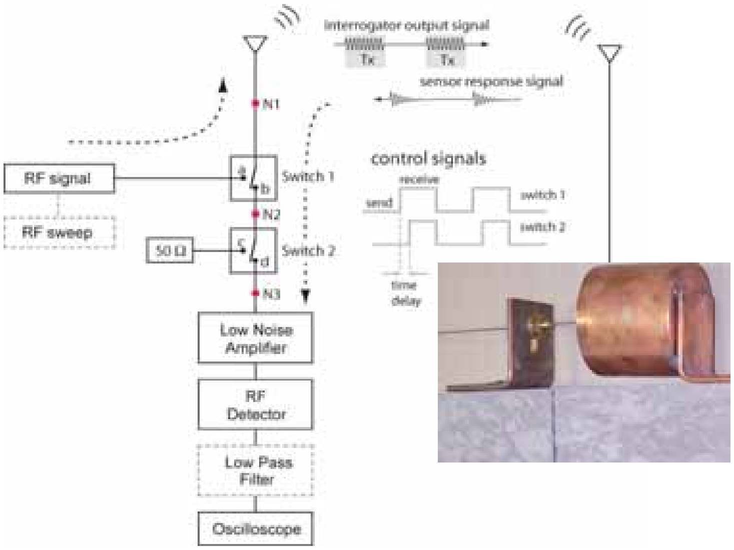

Figure 3. Schematic of the interrogation system, including a second gate used to gate out environmental reflections. The oscilloscope can also be replaced by a data acquisition system.

By sweeping through a range of frequencies and monitoring the signal after low pass filtering, the resonant peak can be easily located. Figure 4 shows a typical result obtained by sweeping through the resonant peak of the displacement sensor. The antennas were separated by approximately 0.5 m in this case. Two peaks are shown in figure 4. One is for 0 displacement and a second is for a displacement of 2 mm. Clearly, the peaks can be easily identified and the background signal is low and relatively constant. Once the swept-frequency data is obtained, one then has to determine the location of the peak in the presence of electronic and other forms of noise. In this work, a servo peak location algorithm was employed [11].

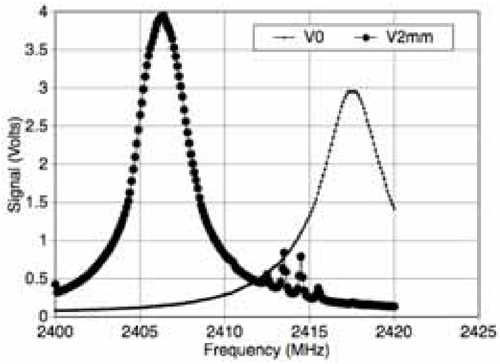

Figure 4 A plot of the response of displacement sensor with diaphragm at 0 mm and 2 mm displacements. The small peaks from 2413 to 2415 MHz in the 2mm displacement spectra are parasitic resonances of the cylindrical cavity. These do not effect the measurement as they are below the threshold where the peak location algorithm operates.

The servo algorithm uses a frequency sweep to find a coarse estimate for the peak position and peak magnitude [11]. Then the signal is sampled at frequency above and below the estimated peak frequency by a difference frequency (1

MHz for example). The difference between the two samples is calculated. If the peak is exactly half way between the two samples and the peak is symmetric then the difference will be 0. If the difference is not zero it is used to find a better estimate of the peak. The process repeated for a certain number of cycles or until peak position is determined to the required repeatability [11]. This algorithm has been found to yield estimates of peak position that are significantly less than the width of the peak (less than 100 kHz in the present case) [11]. For a sensitivity of 4.5 MHz/mm (see below) this corresponds to a displacement resolution of 0.022 mm.

CHARACTERIZATION OF THE DISPLACEMENT SENSOR

The displacement sensor was characterized using a precision micrometer to displace the diaphragm and hold it in a fixed position while measurements were taken. (see figure 5). The diaphragm was slightly preloaded to avoid having a dead band. The sensor was displaced in approximately 0.06 mm increments up to a maximum displacement of 1.27 mm. The uncertainly in the displacement is estimated to be less than 0.01 mm. For each increment the measurement takes about 10 seconds. The measurements were then written to a file. These measurements are presented in Figure 6. For a total displacement of 1.27 mm the resonant frequency shifted by 5.46 MHz. The shift is close to linear and the proportionality constant is 4.3 MHz/mm. The maximum deviation from linearity was 0.06 mm over the 1.27 mm range.

Figure 5. The displacement sensor was mounted on a test jig and a wire was attached to the diaphragm. Using the micrometer the diaphragm was translated in 0.1 mm increments. At each increment the resonant frequency of the cavity was determined using the servo method outlined above.

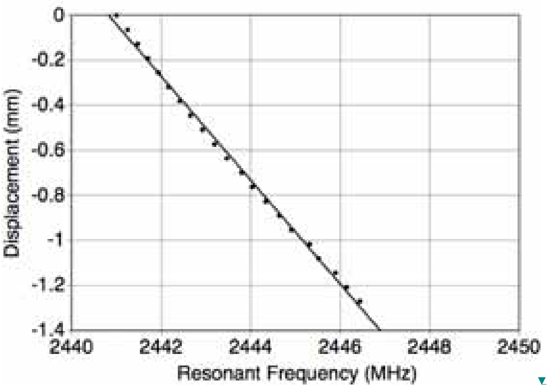

Figure 6. Characterization curve of resonant frequency shift versus displacement for a sensor. For a 1.27 mm displacement the resonant frequency of the cavity changed by 5.4 MHz yielding a proportionality constant of 4.3 MHz/mm.

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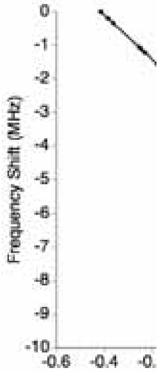

Since the intended use for these sensors is the monitoring of cracks in bridge decks on highway bridges measurements will have to be taken over a range of temperatures. In order to test for the effects of temperature, sensors were mounted onto concrete test prisms. The 100 x 100 x 350 mm prisms were prepared using a standard highway bridge deck concrete mix with a compressive strength of 40 MPa. The sensors were then mounted onto the prisms using predrilled holes and concrete screws. The sensor mounted onto a prism can be seen in figure 6. The sensors were then set inside a temperature controlled environmental chamber and temperature ramped from -20C to 20C. Measurements of displacement were taken at various temperatures. This procedure was repeated several times and for several sensors.

Figure 7 Wireless displacement sensor mounted onto concrete test prism for temperature sensitivity testing.

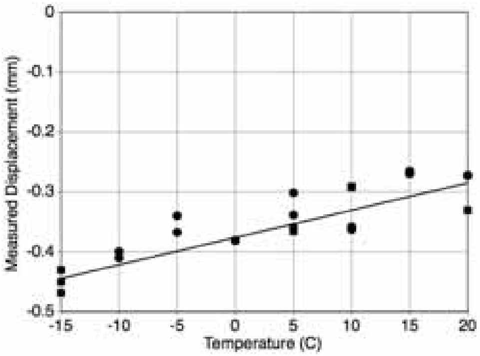

Figure 8 Displacement versus temperature for displacement sensor mounted to concrete prism. Line is linear fit to the results. The temperature sensitivity is approximately 0.0045 mm/C.

The round dots are from one temperature cycle test and the squares are from a second test cycle. Over the temperature range examined, the sensor measured a displacement of 0.158 mm or 0.0045 mm/C. This is consistent with the expected thermal expansion coefficients of the concrete and copper.

DISCUSSION

In field structures, where cracks already exist, the gauge can be used to monitor the stability or evolution of critical crack widths. It is anticipated that the field prototype gauge will be able to measure crack width changes from 0 to 1.5 mm with a repeatability of 0.05 mm. While the current rate of data acquisition is not suitable for crack movement under live loads, it can be used to monitor crack opening and closing due to shrinkage, thermal effects and residual crack widths from fatigue cycles. The latter application is of interest on the Salmon River Bridge project.

These wireless sensors use measurements based on the physical size of an electromagnetic cavity. Once the gauge has been properly calibrated and temperature sensitivity established, the gauge can be used for long-term measurements as it is not susceptible to long-term drift found in other measuring devices or adhesively bonded systems. In addition, the device is not sensitive to the instrument used to measure the resonant frequency of the cavity; therefore, in a long-term project new or upgraded units can be used without loss of calibration or initial reference values.

CONCLUSIONS

A new type of passive wireless crack width sensor has been presented. This sensor is based on resonant RF cavities and the changes in resonant frequency due to changes in the dimensions of the cavity. These sensors are passive and are interrogated with a pulse-echo technique. These sensors have a demonstrated sensitivity of less than 0.022 mm and a temperature sensitivity of less than 0.0045 mm/C when mounted to concrete. At present one reading can be acquired in approximately 10 seconds. This sensor should find application in civil structural health monitoring for crack width monitoring.

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