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LOW-COST RESONANT SENSORS FOR CIVIL INFRASTRUCTURES

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Abstract

A class of low-cost, wireless sensor has been developed at the University of Texas at Austin to monitor civil infrastructure systems. The sensors are designed to be interrogated wirelessly sporadically over the life of the structure as part of a routine inspection. The sensors do not require batteries or connections to external power supplies. As such, the sensors are intended to be maintenance-free over the life of the infrastructure system.

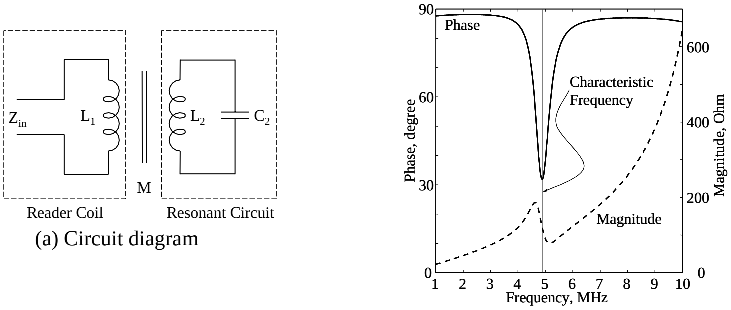
Research efforts to date have focused on detecting the onset of corrosion in reinforced concrete structures. It is envisioned that the sensors would be attached to the reinforcement before placement of the concrete. A sacrificial steel sensing wire extends from the sensor into the concrete and is exposed to the same levels of oxygen, moisture, and chlorides as the surrounding reinforcement. Corrosion of the sensing wire is designed to occur before the onset of structural damage. Therefore, the owner will have sufficient time to take corrective action to extend the service life of the structure.

Eighteen prototype sensors were embedded in two reinforced concrete slabs. Corrosion was induced by exposing the slabs to wet-dry cycles using salt water over an 18-month period. The sensors were interrogated every two weeks and the results of long-term accelerated corrosion test are discussed in this paper.

INTRODUCTION

The buildings, bridges, dams, and lifelines that comprise the civil infrastructure present unique challenges for sensor development due to their large size, unique designs, and continuous exposure to the environment, infrequent inspections, and long design life. Real-time health monitoring systems have been developed to address some of these concerns, but the costs associated with installation, maintenance, and interpreting the data are prohibitively expensive for all but a few, select infrastructure systems. In stark contrast to comprehensive, real-time sensor networks, the wireless sensors discussed in this paper provide a cost-effective option for enhancing the type and quality of information that can be obtained during a routine inspection of common structures. The sensors were designed to satisfy the following three objectives: low cost, long life, and reliable output. It is envisioned that the sensors will be embedded in a structure during construction (see Fig. 1) and interrogated sporadically over the service life of the structure.

A wireless mode of communication with the sensor was selected to reduce disruption of normal construction activities and to minimize the cost of the sensors. Because the sensors do not include any onboard processing capabilities, the fabrication costs are quite low. The costs for materials used to assemble a prototype sensor are less



(a) Circuit diagram

(b) Impedance response

Figure 2. Resonant sensor.

than $2.00 USD. The service life of the sensors is not limited by batteries, and the basic electrical components are not expected to deteriorate with time. Therefore, the expected life of the sensors is at least as long as the design life of the structure and the maintenance costs for the sensors are expected to be zero. The sensors have proven to be sufficiently robust to survive normal construction activities (see Fig. 1).

An external reader coil is used to both interrogate and power the embedded sensors using inductively-coupled magnetic fields. In this manner, the sensors may be considered to be passive elements within the structure – the sensors provide information about the condition of the structure only when interrogated. The output from the prototype sensors is characterized by a high signal to noise ratio. Conditions within the structure can be easily determined based on the presence or absence of resonant frequencies.

To date, the research team has focused on detecting the initiation of corrosion in reinforced concrete structures[1-5]. A prototype resonant corrosion sensor has been designed to detect a threshold level of corrosion, which occurs well before the onset of structural damage. The results of accelerated corrosion tests are used in this paper to demonstrate the potential and reliability of the threshold corrosion sensors.

Figure 1. Prototype sensors attached to reinforcement in bridge deck.

THRESHOLD CORROSION SENSOR

The threshold corrosion sensor relies on the resonant characteristics of LC circuits to transmit information about the likelihood of corrosion within the reinforced concrete structure. The frequency response of an LC circuit can be determined by measuring the vector impedance across the terminals of an external reader coil that is magnetically coupled to the LC circuit (see Fig. 2a). The characteristic frequency of the circuit corresponds to an inflection point in the magnitude and a minimum in the phase of the impedance (see Fig. 2b). The phase response is used to identify the characteristic frequencies of the sensors throughout this paper. The value of the characteristic frequency depends on the inductance, L_2, and capacitance, C_2, of the resonant circuit:

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{L_2 \cdot C_2}}$$

The prototype threshold corrosion sensor includes two resonant circuits. The sensing circuit includes a transducer mechanism (in this case a steel wire that corrodes), while the second circuit serves only as a reference. The circuit diagram for the complete sensor and a photograph of the prototype corrosion sensor are shown in Figure 3.

In the prototype sensor, the circuit components were encapsulated in marine epoxy to protect the sensor from damage during construction of the reinforced concrete structure and to minimize exposure of the circuit components to the high pH environment in the concrete. A steel sensing wire extends into the concrete and is exposed to the same levels of oxygen, moisture, and chlorides as the adjacent reinforcement. Therefore, the steel sensing wire represents a mechanism for detecting threshold amounts of corrosion at the location of the sensor. Because the wire is much smaller in diameter than the reinforcement, the wire breaks due to corrosion before appreciable structural damage occurs.

The phase response of the two resonant circuits is shown in Figure 4. The characteristic frequencies are well separated: 0.5 MHz for the sensing circuit and 1.4 MHz for the reference circuit. The presence of the steel sensing wire increases the resistance of the sensing circuit compared with the reference circuit. Therefore, the characteristic frequency is more pronounced for the reference circuit when the circuits are interrogated separately.

As shown in Figure 3, the two inductive coils are positioned concentrically in the prototype corrosion sensor. The larger (5-cm) diameter coil is connected to the sensing circuit, while the smaller (3.2-cm) diameter coil is connected to the reference coil.

When the two circuits are interrogated together, the sensor circuit shields

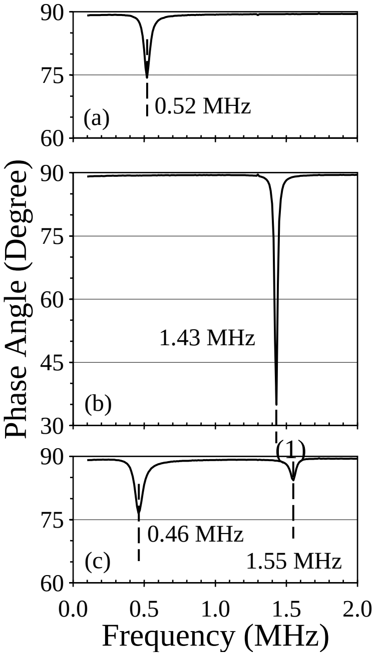


Figure 4. Phase response of concentric sensor:
(a) sensing circuit alone,
(b) reference circuit alone,
(c) both sensing and reference circuits.

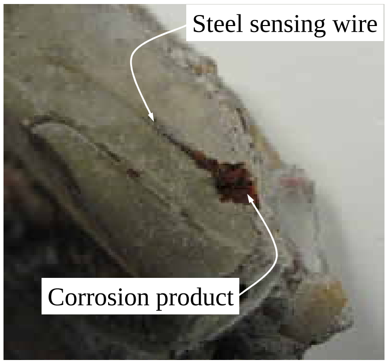


Figure 5. Corrosion of steel sensing wire.

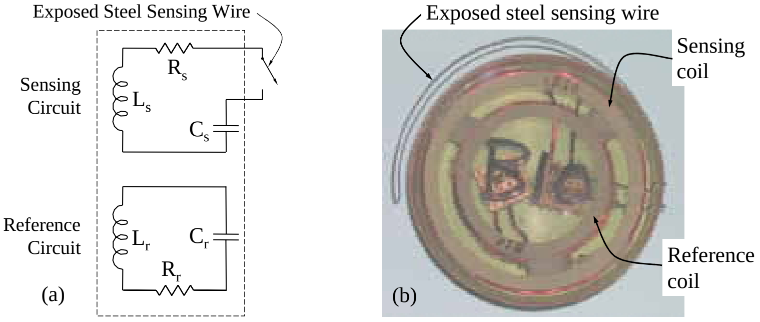


Figure 3. Threshold corrosion sensor: (a) circuit diagram, (b) prototype sensor.

the reference circuit and the amplitude of the phase response is reduced for both circuits (see Fig. 4c). In addition, the characteristic frequency of the sensing circuit shifts below 0.5 MHz and the characteristic frequency of the reference circuit shifts above 1.5 MHz. Despite these changes in the response of the circuits, both characteristic frequencies are still clearly visible from the measured phase response.

The state of the idealized switch shown in the circuit diagram of the sensor (see Fig. 3a) depends on the condition of the steel sensing wire. If the steel wire is intact (switch is closed), the characteristic frequencies of both the sensing and reference circuits will be present when the sensor is interrogated (see Fig. 4c). However, after the steel sensing wire has corroded (switch open) (see Fig. 5), only the characteristic frequency of the reference circuit will be detected (see Fig. 4b). Therefore, the prototype threshold sensor provides a simple means of determining the state of the switch, and therefore, the likelihood of corrosion within the reinforced concrete structure.

ACCLERATED CORROSION TESTS

Accelerated corrosion tests were used to monitor the long-term performance of the prototype corrosion sensors. Eighteen concentric sensors were embedded in two reinforced concrete slabs, which were designed to represent sections of a bridge deck. The slabs were 20 cm deep, 45 cm wide, and 3 m long (Fig. 6) and reinforced with two layers of deformed reinforcement, which were supported independently on plastic chairs to minimize the likelihood of macrocell corrosion.

Nine concentric sensors were attached to the top layer of reinforcement in each slab. The sensors in Slab 1 were fabricated using 26-gauge steel wire (0.40 mm diameter) and the sensors in Slab 2 were fabricated using 21-gauge steel wire (0.72 mm diameter). All other aspects of the two slabs were nominally identical. The concrete cover was approximately 3 cm.

The slabs were subjected to concentrated loads near the ends, creating a 0.9-m region of constant negative moment between the supports. The specimens were cracked in flexure before beginning the exposure tests. Average crack widths were 0.5 mm between the supports and extended across the entire width of the top surface of the slab.

A plastic reservoir was positioned at midspan of each slab and the slabs were subjected to alternating wet/dry cycles. The reservoir was filled with salt water for two weeks, and the concrete surface was allowed to dry for the next two weeks. The sensors are interrogated at the end of each two-week period between January 2005 and June 2006. The slabs were stored in an unheated building and experienced temperature fluctuations of more than 40 ºC during the tests. The salt water reservoirs provided the only source of moisture for the slabs, other than humidity in the atmosphere.

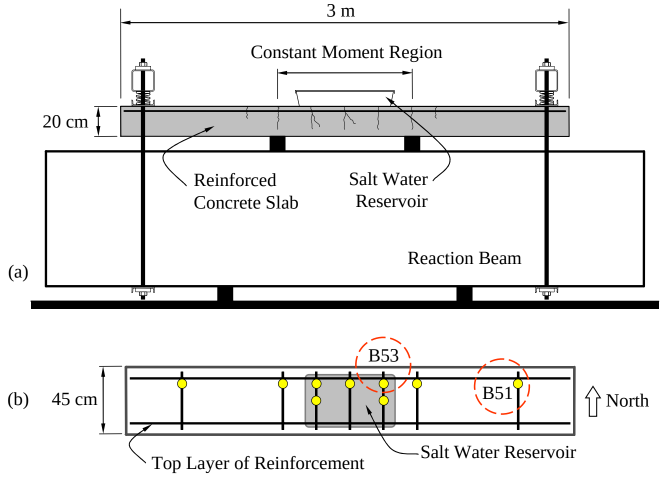


Figure 6. Slab specimens for accelerated corrosion tests: (a) elevation, (b) plan of Slab 2.

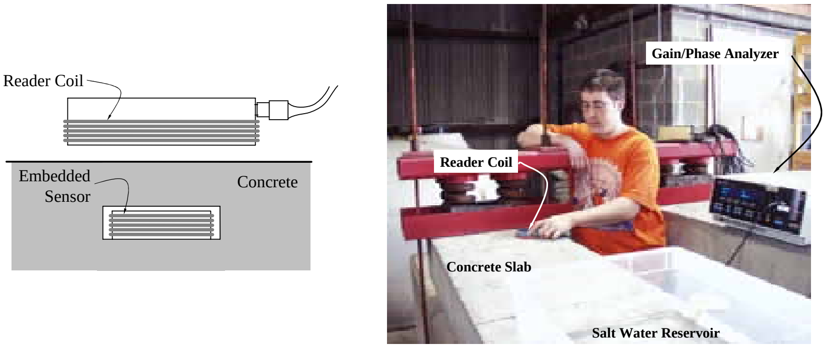


Figure 7. Method used to interrogate corrosion sensors.

MEASURED RESPONSE OF THRESHOLD SENSORS

The measured frequency response of two sensors is discussed in this section. Sensor B53 was located directly beneath the salt water reservoir and Sensor B51 was located at the east end of Slab 2 (see Fig. 6b). Each sensor was interrogated by placing the reader coil on the surface of the concrete above the sensor (see Fig. 7).

The frequency response of Sensor B51 is shown in Figure 8. The characteristic frequencies of both the sensing circuit and reference circuit are clearly visible in the phase response during each interrogation, indicating that the sensing wire was intact throughout the accelerated corrosion test. In contrast, the frequency response of Sensor B53 changed during the test (see Fig. 9). Two characteristic frequencies were observed in the phase response of Sensor B53 during the first 13 months; however, only the characteristic frequency of the reference circuit was detected during later interrogations. The change in the frequency signature indicates that the steel sensing wire fractured due to corrosion.

The trends in the response of Sensors B51 and B53 were representative of all 18 sensors. At the beginning of the accelerated corrosion test, all sensors exhibited two characteristic frequencies. With time, the characteristic frequency of the sensing circuit disappeared for some of the sensors, indicating the initiation of corrosion at those locations. It should be noted that if a sensor exhibited a single characteristic frequency during an interrogation (see

Fig. 9b), this response was repeated in all subsequent interrogations. The sensor response did not reverse due to changes in temperature or moisture content within the concrete.

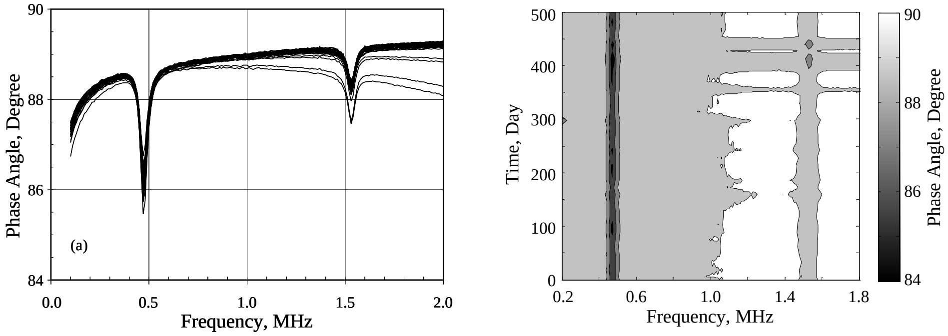


Figure 8. Measured response of Sensor B51: (a) 39 interrogations between January 2005 and June 2006, (2) contour plot (1.0-degree contour intervals).

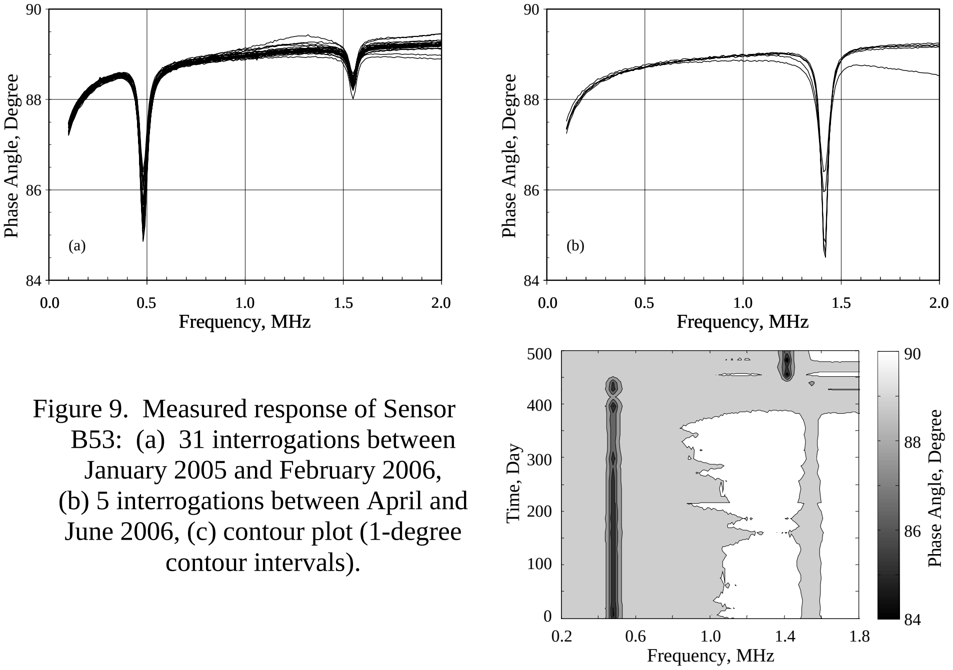


Figure 9. Measured response of Sensor B53: (a) 31 interrogations between January 2005 and February 2006, (b) 5 interrogations between April and June 2006, (c) contour plot (1-degree contour intervals).

Half-cell potentials were measured at 31 locations on the top surface of both slabs each time the sensors were interrogated. Contour plots of the half-cell potentials at the conclusion of the accelerated corrosion test are shown in Figure 10. The likelihood of corrosion exceeded 90 percent in the constant moment region of both slabs and was less than 10percent at the ends of the slabs.

The condition of each sensor at the conclusion of the accelerated corrosion test is also indicated in Figure 10. All four sensors positioned at the ends of the slabs indicated that corrosion had not occurred, while 10 of 14 sensors near the middle of the slabs indicated that corrosion was likely. Therefore, the sensor readings were consistent with the measured half-cell potentials. More sensors indicated the presence of corrosion in Slab 1 than Slab 2, although the environmental conditions were nominally identical in the two slabs. The sensors in Slab 1 were fabricated using smaller diameter steel sensing wire, and therefore, the sensing wires in Slab 1 corroded faster.

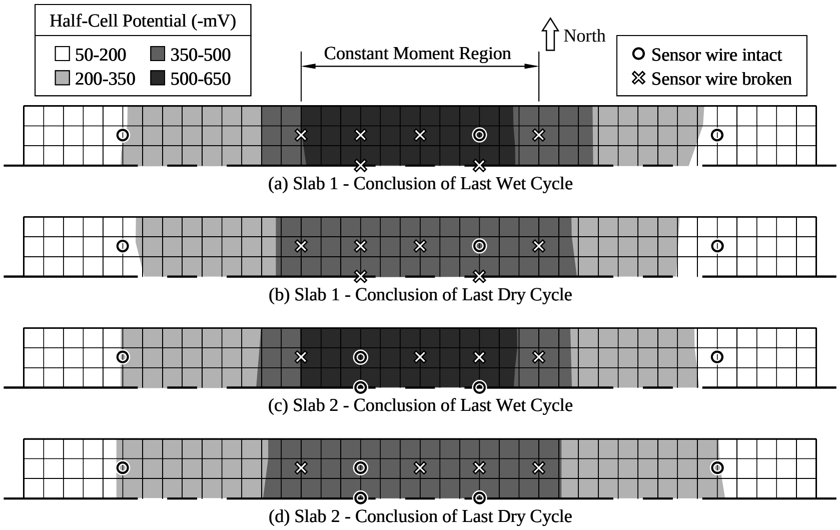


Figure 10. Half-cell potential zones and condition of sensors at conclusion of accelerated corrosion test.

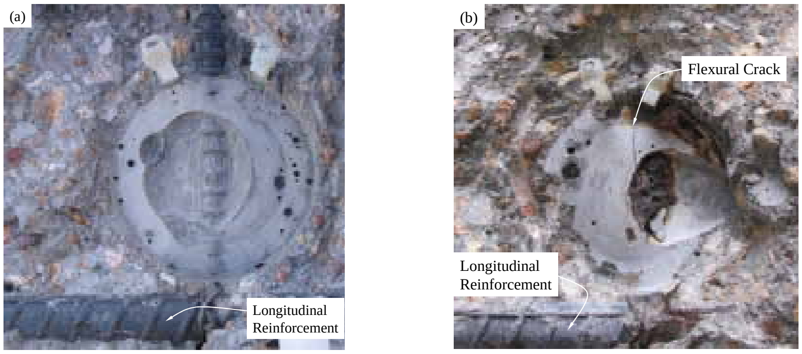


Figure 11. Condition of reinforcement in vicinity of sensors: (a) Sensor B51, (b) Sensor B53.

The concrete cover surrounding the sensors was removed at the conclusion of the accelerated corrosion test, and the observed corrosion was consistent with the half-cell readings. No evidence of corrosion was observed on the surface of the reinforcement at the end of the slabs (see Fig. 11a). In contrast, corrosion was observed on the longitudinal and transverse reinforcement in the vicinity of flexural cracks throughout the constant moment region (see Fig. 11b). No corrosion was observed between cracks.

The condition of the reinforcement, as determined during the autopsy, is compared with the readings from the threshold corrosion sensors in Table 1. All four sensors located at the ends of the slabs exhibited the expected response. Corrosion was not observed in these areas, and all sensors indicated that the threshold amount of corrosion had not occurred. No cases of false positive readings were recorded during the accelerated corrosion test.
The majority of the sensors in the constant moment region correctly indicated that a threshold amount of corrosion had occurred. However, four of the 14 sensors gave false negative readings. These sensors indicated the absence of corrosion, while corrosion was present on the surface of the adjacent reinforcement.

The observed corrosion occurred only where the reinforcement crossed the flexural cracks. Field measurements[6] of chloride levels in bridge decks indicate that chloride levels are several times higher at the location of a crack than in sound concrete away from the crack; therefore, the chloride levels were expected to vary within the constant moment region. The paths of the cracks did not cross the sensing wires for all sensors, which is one explanation for the false negative readings.

The possibility of false negative sensor readings represents a limitation of any type of point sensor because the sensor only monitors the environmental conditions at the location of the sensor. This is a particular concern for structures, such as the test slabs, where the presence of cracks accelerates the penetration of chlorides into the concrete. Had the duration of the accelerated corrosion test been extended, it is expected that more of the threshold sensors would have indicated the presence of corrosion due to additional transport of the chlorides through the concrete.

CONCLUSIONS

The sensors discussed in this paper were designed to detect the onset of corrosion in common reinforced concrete structures. The results from the accelerated corrosion test demonstrate that the threshold sensors provide an economic, nondestructive means of evaluating the environmental conditions with a reinforced concrete structure. The condition of the external sensing wire is easily determined from the characteristic frequencies of the resonant sensors. The presence of two dips in the phase response indicates that corrosion has not occurred at the location of the sensor, while a single dip indicates that a threshold amount of corrosion has occurred. Sensor output was not sensitive to environmental conditions, such as temperature, humidity, and the moisture content of the concrete. In addition, once corrosion was detected by a sensor, the readings did not reverse during a later interrogation. The only change in the sensor readings was caused by corrosion of the sensing wire.

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