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Coupled coil sensor system with extended range for civil monitoring applications

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ABSTRACT: Wireless sensors are being explored for many SHM applications. Passive wireless sensors have the advantage of not requiring an electrical power source on the sensor, as the energy of the sensor is provided by the interrogation system. Coupled coil sensors are a class of passive wireless sensors with many possible applications. They work by using resonant coils coupled to a measurand that shifts the sensor coil resonant frequency. In this paper, we present a new interrogation method that enhances the accuracy and range of coupled coil sensors. This method uses time domain gating to produce measurements that are dominated by the response of the sensor coil. Using this method the resonant peak position can be determined within 1 part per thousand and at much greater distances than have been demonstrated in past work. In the case of a %RH sensor this translates into being able to detect changes in %RH of less than ~2%.

1 INTRODUCTION

Most existing sensing technologies used for the monitoring of large civil infrastructure have a serious deficiency in that they require a permanent connection between the sensor and the interrogation unit that collects, analyses, and stores data from the sensor. The cost of installation and preparation of structures for monitoring can easily exceed the cost of sensors and interrogation equipment. Wireless sensors are an attractive solution to this problem. However, transceiver based wireless sensors require battery or local power for electronics on the sensor. This negates many of the advantages of wireless sensors, as the batteries require frequent replacement. Most importantly, these sensors cannot be directly embedded within a structure as this does not afford a mechanism for battery replacement.

Passive wireless sensors are an emerging alternative, where the sensor is a passive device and hence there is no requirement for local power. These types of sensors have found applications in structural health monitoring including: corrosion detection (Andringa et al. (2005)), ion concentration measurement (Garcia-Canton et al. (2007)), strain measurement (Chuang et al. (2005)), and moisture detection (Harpster et al. (2002)). One passive wireless sensing system, coupled-coil sensors, operates by using resonant coils whose resonant frequency is a function of the sensed quantity. One coil is placed in the medium being monitored, with the other used as an external interrogation coil. Changes in the sensor coil's resonant frequency are most commonly detected by measuring the impedance of the interrogator coil. However, this interrogation technique is greatly affected by the dominating response of the interrogator coil. Furthermore, this technique requires a small separation distance between the sensor and the interrogator, and is sensitive to changes in the surrounding environment.

This paper discusses a new interrogation method, which uses time-domain gating to reduce the influence of the interrogator coil, resulting in a measurement that is dominated by the response of the sensor coil. In this paper, we present demonstrations of this sensing system being used for corrosion detection and relative humidity measurement.

2 PRINCIPLE OF OPERATION

2.1 Overview

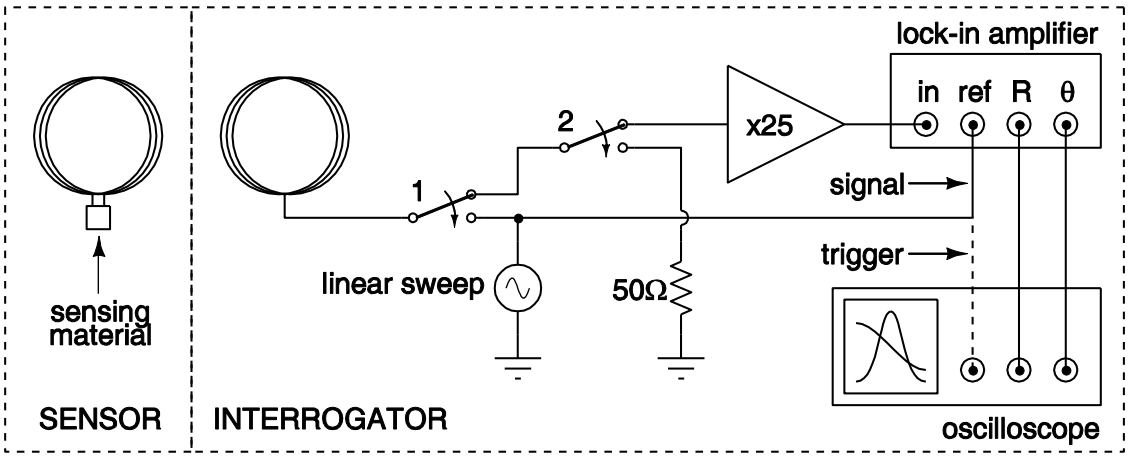

Figure 1. Block diagram of the sensing system.

A block diagram of the sensing system is shown in Figure 1 (with the switches in the receive position). The sensor is a RLC resonant circuit magnetically coupled to an interrogation unit. The interrogation system first energizes the sensor coil through the inductive coupling of the interrogator coil with the sensor coil. After enough time has elapsed to allow the induced energy in the coil to reach equilibrium, the system switches to a receiving mode where energy is coupled back into the interrogator system. The returned signal is an exponentially decaying signal that depends on the Q factor of the sensor. For the system we have constructed, equilibrium will occur in approximately 16 μs. The signal is amplified and the peak value determined by a lock-in amplifier. The second switch is used as a time-domain gate to eliminate the effects of unwanted reflections from objects in the environment and to dampen the transient response of the interrogator coil. A delay of approximately 1 μs is used. By sweeping frequency, the resonant frequency of the sensor coil can be determined.

2.2 Coupled coil circuits

Due to the mode of coupling, the sensors discussed in this paper are series RLC circuits whose capacitance is designed to vary with a particular parameter. For example the capacitance may vary with %RH. For $R \ll \sqrt{L/C}$, the location of the resonant peak in a circuit's frequency response is given by

$$\omega_0 = 2\pi f_0 = \frac{1}{\sqrt{LC}}, \tag{1}$$

and the quality factor of the circuit is given by

$$Q = \frac{\omega_0}{\Delta\omega} = \frac{1}{R}\sqrt{\frac{L}{C}}. \tag{2}$$

Combining (1) and (2), the width of the resonant peak is given by

$$\Delta\omega = \frac{\omega_0}{Q} = \frac{R}{L}. \tag{3}$$

After removing the excitation, the response of the circuit will decay with time constant

$$\tau = \frac{2Q}{\omega_0}. \tag{4}$$

2.3 *Magnetic field coupling*

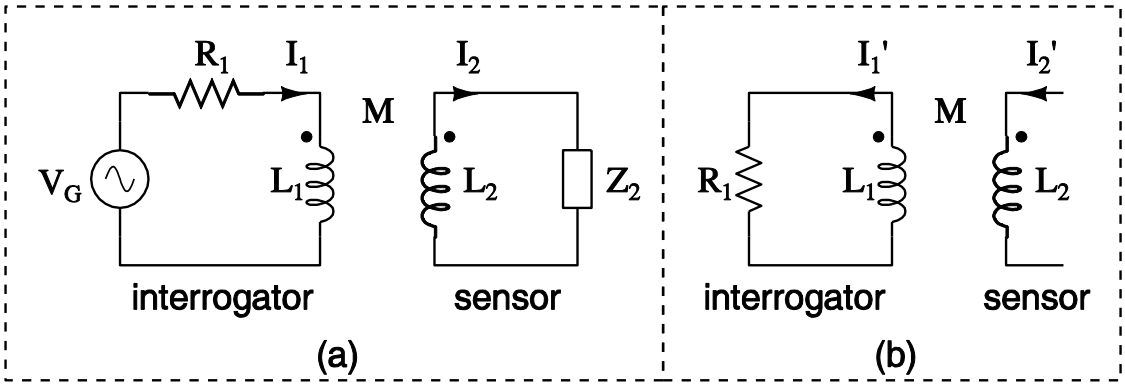

Figure 2. Interrogator/sensor system in (a) transmit mode, (b) receive mode.

Figure 2(a) shows a circuit diagram of the interrogator/sensor system in the transmit mode. The interrogator coil is designed so that the self-resonant frequency is much greater than that of the sensor. The mutual capacitance between the coils is small and neglected. The interrogator source produces a time-varying current I_1 which passes through the interrogator coil (L_1). This current generates a time-varying magnetic flux which links the pickup loop in the sensor coil (L_2). By Lenz's law, a resulting current is induced in the sensor loop given by

$$I_2 = \frac{j\omega M}{Z_2 + j\omega L_2} I_1 = \frac{j\omega M}{Z_S} I_1 \tag{5}$$

where $Z_S = Z_2 + j\omega L_2$. As a result of the coupling between the two coils, the voltage developed on the interrogator coil

$$V_1 = j\omega L_1 I_1 + \frac{\omega^2 M^2}{Z_S} I_1. \tag{6}$$

This gives us the impedance of the coupled coil system. The current through the interrogator coil will then be

$$I_1 = \frac{1}{R_1 + j\omega L_1 + \frac{\omega^2 M^2}{Z_S}} V_G = \frac{Z_S}{Z_S Z_R + \omega^2 M^2} V_G \tag{7}$$

where $Z_R = R_1 + j\omega L_1$.

When the interrogator switches to receive mode (Figure 2(b)), the current induced in the sensor coil begins to decay exponentially with time constant τ. Provided $\Delta\omega \ll \omega_0$ (or equivalently, $1/\tau \ll \omega_0$) for the sensor, phasor analysis can be continued and the current passing through the sensor coil is

$$I_2{}' \approx -I_2. \tag{8}$$

This current induces a corresponding current in the interrogator coil given by

$$I_1{}' = \frac{j\omega M}{R_1 + j\omega L_1} I_2{}' = \frac{j\omega M}{Z_R} I_2{}'. \tag{9}$$

Combining (5), (8) and (9),

$$V_1' = R_1 I_1' = \frac{\omega^2 M^2 R_1}{Z_S Z_R} I_1. \quad (10)$$

Combining (7) and (10),

$$V_1' = \frac{\omega^2 M^2 R_1}{(Z_S Z_R + \omega^2 M^2) Z_R} V_G. \quad (11)$$

For $M^2 \ll L_1 L_2$ (weak coupling), (11) can be simplified to

$$V_1' = \frac{\omega^2 M^2 R_1}{Z_S {Z_R}^2} V_G. \quad (12)$$

At resonance, Z_S reaches its minimum value producing a peak in the plot of V_1' versus frequency. More information regarding magnetic coupling can be found in Tesche et al. (1997). In the ideal case the interference due the presence of the interrogation coil is eliminated and V_1' will be inversely proportional to the impedance of the sensor. Therefore, a plot of V_1' versus frequency in the ideal case will be inversely proportional to the sensor impedance versus frequency, thus yielding a simple means of interpreting measurements.

3 SENSOR MEASUREMENTS

3.1 Apparatus

To test the sensing system outlined in Figure 1 interrogation and sensor coils were constructed of insulated copper wire. The coils are 5 cm in diameter and contain 3-15 turns. A typical set of coils is shown in Figure 3 below.

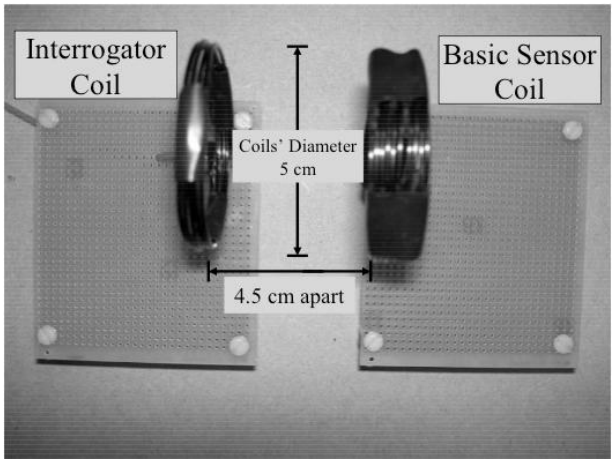

Figure 3. Typical set of interrogation and sensor coils used in this work.

A programmable signal generator (Stanford Instruments SR345) is used to provide a tunable frequency source. A custom designed clock generator provides the required signals to switch between the send and receive modes. An RF lock-in amplifier (SR844) is used as the synchronous signal detector. By sweeping frequency and measuring the response with the lock-in amplifier, the resonant peak of the sensor coil can be easily observed. In Figure 4 the response of a typical sensor coil sensing a fixed reference capacitance is shown. A simple peak-fitting algorithm is used to find the peak of the curves. A parabola is fit to points above a threshold of ½ the maximum. The location of the peak is taken to be the location of the maximum of the fitted parabola (Hliadio et al. (2006)). Using this method, the peak positions in the spectra below can be measured with a resolution of ~0.003 MHz or about 400 parts per million.

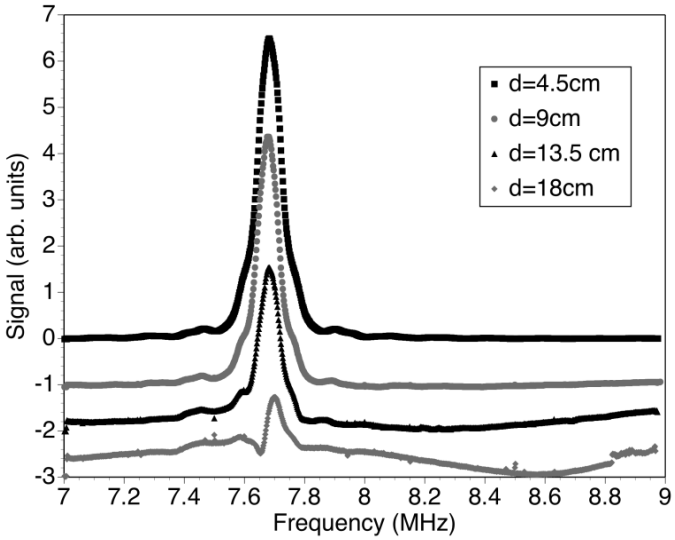

Figure 4. Typical response of a sensor coil coupled to a fixed reference capacitance (33 pF) for various interrogation distances. The spectra have been scaled and offset vertically for illustrative purposes.

One major advantage of the technique presented in this work can be observed in Figure 4. The background inference is small and the sensor dominates the response. This is an advance over previous work using coupled coils, where the interrogator coil dominates the response, limiting the signal-to-noise ratio and hence the distance at which the sensor can be interrogated (Andringa et al. (2005)). For example, the sensor presented above can be interrogated up to distances of ~15 cm without significant loss in signal-to-noise ratio. This is to be compared to previous work where distances of no more than a few cm have been achieved (Andringa et al. (2005)). This increase in interrogation distance is of significant advantage for civil structural health monitoring, where it is expected that sensors will be more than a few cm below the surface.

3.2 Corrosion sensor

A simple embeddable LC corrosion sensor was constructed similar to that reported in (Andringa et al. (2005)). When intact, a thin iron wire connects two capacitors $C_1 = 33$ pF and $C_2 = 5.6$ pF in parallel for total capacitance of $C = C_1 + C_2 = 38.6$ pF. Once the iron wire corrodes, the connection is severed to capacitor C_2, reducing the total capacitance to $C = C_1 = 33$ pF and increasing the resonant frequency. This sensor could be made to operate reliably up to interrogation distances of 9 cm.

3.3 Humidity sensor

A wireless humidity sensor was fabricated by using a polyimide-based capacitor designed to change capacitance in response to changes in relative humidity. The Honeywell HCH-1000 is a parallel-plate capacitor with a polyimide dielectric film. As relative humidity increases, the polyimide film absorbs moisture, increasing the dielectric constant of the material. In addition, polyimide is advantageous as it is minimally affected by prolonged exposure to saturated conditions or atmospheric contaminants. Typically, the response time of this polyimide sensor is 15 seconds and is thus suitable for civil monitoring applications. In the wireless sensor, the HCH-1000 replaces the fixed capacitor. Thus, changes in relative humidity will affect changes in the resonant frequency of the sensor. As the relative humidity changes, the capacitance will also change. By measuring changes in resonant frequency, the relative humidity in the vicinity of the sensor can be measured.

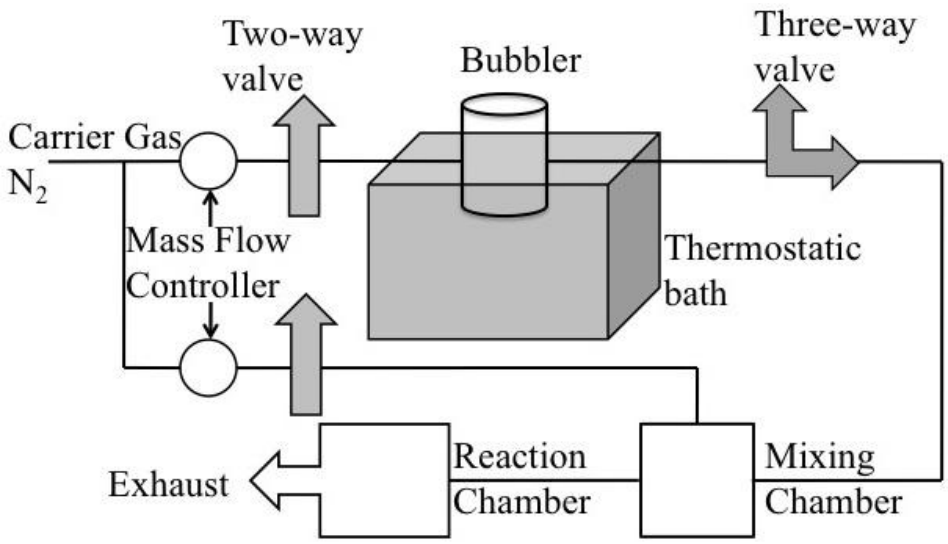

Figure 5. Block diagram of the olfactometer used for humidity sensor testing.

The sensor was constructed as in Figure 3 with the coil wound from insulated copper wire. The HCH-1000 is connected in parallel with the coil to form a resonant circuit. To test the sensor, an olfactometer (Plasmonique) was used. In the olfactometer (Figure 5), a water-saturated air flow and dry air flow are mixed at various ratio to yield a combined flow with a known percent relative humidity (%RH). The humidity sensor was placed in the exhaust. In Figure 6, the response versus frequency taken at 0 and 80%RH show the shift in resonance due to the increase in capacitance with relative humidity. The signal also decreases in magnitude as the relative humidity increases, which is caused by increased electrical loss due to the water absorbed within the polyimide.

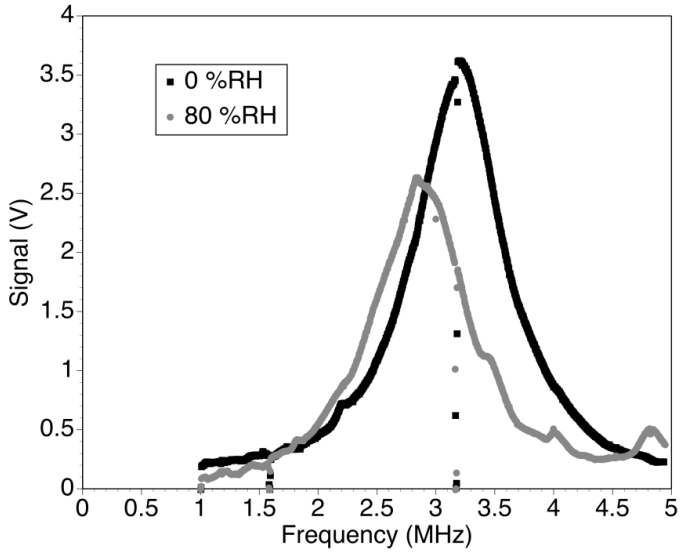

Figure 6. Comparison of the measured response versus frequency for coupled coil humidity sensor for 0 and 80%RH. One data point was lost at approximately 3.2 MHz due to fault with the lock-in amplifier not synchronizing with the source.

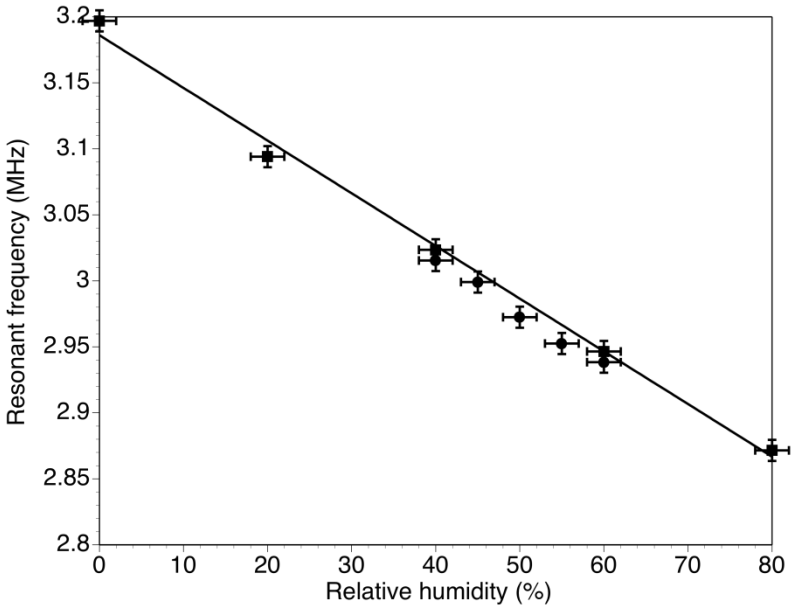

Figure 7. Measured resonant frequency versus relative humidity. The solid line is a fit to the data collected from 0 to 80%RH in 20%RH steps. The points between 40 and 60%RH were taken to determine the repeatability and to estimate the detectable change in relative humidity.

Figure 7 is a plot of the estimated location of the resonant peak for relative humidity ranging from 0 to 80%RH in 20%RH steps with a line fitted to these points. The slope of the line is 4.06 kHz/%RH. The fitted line is an excellent predictor of resonant frequency versus %RH and only deviations slightly larger than the measurement uncertainty were observed. As a test of resolution and repeatability, measurements between 40 and 60%RH in 5%RH steps were taken and are shown on the same figure. From (1), the slope is expected to be 2.75 kHz/%RH given the specified change in capacitance with %RH (0.6 pF/%RH, HCH-1000 data sheet). The larger measured slope may be the result of increases in the loss factor at higher humidity levels. These effects will be more fully investigated in future work.

This sensing system may used for sensing relative humidity in heritage structures where the elimination of wiring may be important. The ability to embed sensors without the need to periodically replace batteries may also be advantageous for monitoring moisture inside masonry walls or structures.

4 CONCLUSIONS

A new method has been demonstrated for the interrogation of coupled coil passive wireless sensors. This method offers increased accuracy (less than 1 part per thousand) and increased range (up to 15 cm). In the present work, a basic theory has been presented that predicts that time domain gating will result in signals directly related to the sensor impedance with low levels of interference. This method has been applied to the passive wireless measurement of relative humidity. Resolution of ~2%RH has been demonstrated.

5 FUTURE WORK

In this work we have demonstrated basic functionality, but we have not optimized the sensor or the interrogator. In the future, further analysis of the magnetic coupling problem will be carried out in order to maximize power transferred to the receiver.

In the present work, a lock-in amplifier is used as the detector. While a lock-in amplifier is high performance, it is also high cost. In the future, the use of low cost devices such as a simple mixers and switched integrators will be explored to reduce the overall interrogator cost.

Other measurands will also be explored. One possibility is the measurement of pH with a passive sensor.

6 ACKNOWLEDGEMENTS

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