Passive Telemetric Readout System

Sajeeda and Todd J. Kaiser, *Member, IEEE*

***Abstract*—A technique for remote query monitoring of environmental parameters such as pressure, humidity, complex permittivity, temperature, strain, and gases such as carbon dioxide, oxygen, and ammonia is presented. Resonant peak passive telemetry is used for wireless remote monitoring. The resonance frequency of an inductor–capacitor sensor circuit changes with the surrounding environmental parameter, and a detector circuitry, which employs a loop antenna, is used to remotely identify the resonance frequency. Mutual coupling between the antenna and the sensor inductor enables wireless monitoring. Various detection techniques available for monitoring the sensor resonance frequency are examined, and a new method is presented for automated and continuous wireless detection of sensor resonance frequency. Results are presented for different sensor resonance frequencies using various sensor capacitance values. The designed system can effectively detect sensor resonance frequency variation in the range of 20 kHz–10 MHz with the highest achievable resolution of 0.01 MHz. Sensor resonance frequency changes that occur faster than 1 s cannot be detected. The automated continuous wireless remote sensor platform design provides significant advantage over past systems, and the entire design is simple, easy to use, and widely applicable for *in vivo*, *in vitro*, and *in situ* monitoring.**

***Index Terms*—Automated frequency generation, loop antenna, personal computer (PC) data acquisition, resonance frequency, sensor inductor–capacitor (LC) circuit.**

I. Introduction

MANY industrial, medical, and commercial applications require wireless monitoring of environmental conditions inside sealed environments such as food containers, packages of medicine, fermentation chambers, plastic water pipes, and the human person. Several telemetry systems with reduced cost, power consumption, size, and weight, which are the main design criteria in a telemetry system [1], appear in the literature [2]–[13]. Passive telemetry, which uses a transformer with loose coupling between an external loop antenna and an inductor in a remote sensor that receives power through this inductive coupling, is used [14], [15]. The sensor consists of an inductor–capacitor (LC) circuit and is embedded or implanted in the system where the parameter is to be monitored. The resonance frequency of the embedded sensor changes when either its capacitance or inductance changes. An inductance [8] or capacitance [3]–[5], [7], [9], [10], [14], [16]–[18] change in the sensor is caused by the parameter of interest, and the consequent change in the resonance frequency is wirelessly and remotely detected by the antenna through mutual inductive coupling. Resonant peak passive telemetry detects the change in sensor resonance frequency by monitoring the impedance magnitude and phase spectrum of the antenna.

The LC sensor design depends on the environmental parameter to be measured, the value of the parameter to be measured (absolute or relative), the range of values to be measured, and sensitivity. Depending on whether the LC tank circuit is used to monitor pressure [2]–[5], [7], [10], [12], [14], [16], strain [8], environmental gases [9], humidity [13], or food quality [6], [18], the sensor design is chosen. The main advantage of these sensors is that they do not require a power source for their operation or wired connection between the sensor and data processing electronics. In addition, the size of the sensors is very small, and they can be inexpensively fabricated using printed circuit technology [2], [3]. Their remote wireless monitoring capability makes them highly useful in applications that require the sensor to be powered remotely and to occupy a small volume, such as harsh and sealed environments where physical access to the sensor is difficult, e.g., the human body [11]. Passive telemetry is also used with radio frequency identification (RFID) devices for reading tags in tracking and security applications [19], [20].

A. Wireless Remote Query Operation

The LC sensor is monitored using a loop antenna that is mutually coupled to the sensor. Electromagnetic waves are transmitted to the sensor through the loop antenna, and sensor resonance frequency is detected by monitoring the impedance and phase of the antenna as a function of frequency. The mutual inductive coupling link between the loop antenna and the sensor causes the real portion of the antenna impedance to go to the maximum amplitude and the imaginary portion of the antenna impedance to go to zero at sensor resonance [2], [3], [6], [18]. The phase of the antenna impedance dips to a minimum at sensor resonance [5], [12]–[14], [17]. The phase dip amplitude depends on the mutual inductive coupling between the antenna coil and the sensor inductor, but the position of the phase dip does not [10].

The equivalent circuit model of the antenna and the sensor, using transformer theory [21], is shown in Fig. 1. When an ac signal is transmitted into the loop antenna, it inductively couples power to the sensor [2]–[7], [9], [10], [13], [14], [16], [18]. Because of the magnetic coupling between the sensor inductor and the loop antenna, a magnetic field is created around the loop antenna and sensor. The sensor, if located within the interrogation zone of the antenna, cuts the magnetic flux lines of the antenna coil, and an electromotive force (emf) is induced across the sensor inductor, causing a current flow

Manuscript received August 19, 2005; revised November 1, 2005. This work was supported by the NSF EPSCoR, the VP for Research, and the Department of Electrical and Computer Engineering. The associate editor coordinating the review of this paper and approving it for publication was Prof. Eugenii Katz.

Sajeeda was with the Montana State University, Bozeman, MT 59717 USA (e-mail: sajeedahh@yahoo.com).

T. J. Kaiser is with the Department of Electrical and Computer Engineering, Montana State University, Bozeman, MT 59717 USA (e-mail: tjkaiser@ece.montana.edu).

Digital Object Identifier 10.1109/JSEN.2006.881395

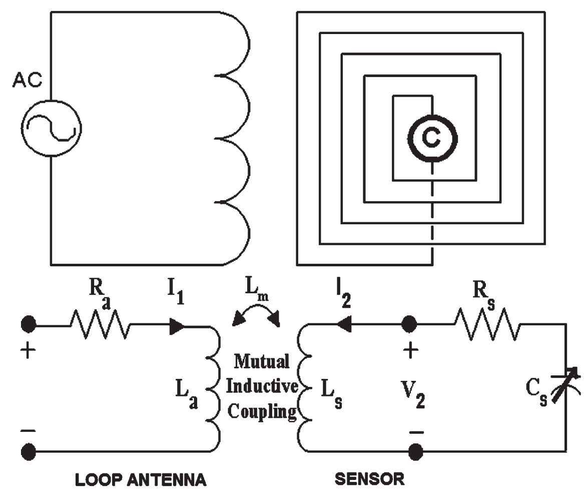

Fig. 1. Equivalent circuit model of loop antenna and sensor.

in the sensor circuit. The antenna coil, in turn, interrupts the magnetic field generated by the sensor inductor, inducing a back emf on the antenna coil. Being a series resonant circuit, the emf on the sensor is maximum at its resonance; thus, the back emf on the antenna coil is maximum at the sensor resonance. Thus, the sensor resonance frequency can be detected by monitoring the impedance or voltage of the remotely located loop antenna as a function of the transmitted frequency.

As shown in Fig. 1, L_a and L_s are the antenna inductor and the sensor inductor, respectively. R_a and R_s are the parasitic resistances of the antenna inductor and the sensor inductor, respectively. C_s is the parallel combination of the sensor inductor parasitic capacitance and the capacitance of the sensor. The resonance frequency of the sensor LC circuit is [22]

$$f_o = \frac{1}{2\pi}\frac{1}{\sqrt{L_s C_s}}. \tag{1}$$

Once detected, the variation in sensor resonance frequency can be used to detect the corresponding change in the parameter, which caused the capacitance of the LC circuit to change.

The sensor resonance detection will be largely affected by the relative position of the coils if the quality factor (Q) of the sensor coil is low [5]. High Q sensors are desired because the dip in the impedance phase and the maximum in the impedance amplitude are sharper [13]. Higher monitoring range can be achieved by increasing the size of the sensor, antenna, or the antenna power level [2], [3].

Various techniques for monitoring sensor resonance frequency exist, depending on the environmental parameter to be monitored. These techniques use either the grid dip or reflected impedance principle [2], [3], [5]–[7], [10], [13], [16], [18] and are based on the detection of the antenna coil impedance and the phase change with respect to transmitted frequency. The antenna impedance spectrum is recorded using an impedance analyzer that is controlled using a computer [6], [18] and the sensor frequency spectrum obtained by subtracting the intrinsic impedance of the antenna from the measured impedance using a background subtraction routine [2], [3], [9]. The impedance of the loop antenna is obtained by measuring the antenna impedance without the sensor. In certain applications, the sensor is monitored by measuring the phase shift of the antenna coil using an impedance analyzer [5], [10], [13], [14], [17] or network analyzer [11].

The grid dip principle uses a gate dip meter to detect the sensor resonance frequency changes [8]. An external loop antenna coil is not used here; instead, the inductor on the gate dip meter, which is a small primary coil, is used to mutually couple power to the sensor circuit. The grid dip meter is basically a radio frequency (RF) oscillator that detects the frequency of other oscillators or tuned circuits. The frequency of an oscillator is swept over an RF band, and when the LC sensor is brought close, a portion of the RF power gets absorbed by the sensor. The amount of power absorbed by the sensor is highest at its resonance frequency. Thus, a dip in the antenna coil current is observed on the dip meter at the sensor resonance frequency. The frequency swept versus the dip meter power is displayed on an oscilloscope to determine the change in the sensor resonance frequency.

A function generator [2], [3] is used to generate the frequencies, a voltage-controlled oscillator [7], [16], [17] is used to sweep the frequency range to be transmitted to the sensor, and the voltage across the antenna coil is monitored using an envelope detector to detect sensor resonance. The antenna coil impedance goes to a maximum at sensor resonance frequency, and this impedance variation is used to detect sensor resonance [7].

With the techniques used for detecting the sensor resonance frequency, the recording of the sensor resonance frequency requires manual intervention. Each time the sensor resonates, the sensor resonance frequency displayed on the impedance analyzer or the grid dip meter has to be manually recorded. In addition, with the grid dip meter, the range of resonance frequencies that can be monitored is limited by the frequency range and resolution of the meter. A computer, if used to control the impedance analyzer, can record the sensor resonance frequency automatically, but manual intervention is still needed for continuous recording of sensor resonance frequency. The transmitter frequency has to be manually reset, and the impedance analyzer also needs manual adjustment whenever the monitoring frequency range changes. In addition, with a voltage-controlled oscillator, the control voltage value has to be manually input to the oscillator for the desired output frequency. A microprocessor, if used for reading the antenna coil voltage values, has to be manually reset for recording a different resonance frequency value. Great advantage will be gained if the process of monitoring the sensor is completely automated and continuous so that the sensor resonance frequency can be recorded continuously over a time period without any manual intervention.

This paper describes a method of monitoring the sensor resonance frequency variation automatically and continuously over a period of time. Passive wireless telemetry approach [2]–[7], [9], [10], [14], [16]–[18] is used, and the system detects the sensor resonance frequency variation by transmitting sine wave frequencies to the sensor through a loop antenna that is mutually coupled to the sensor and monitoring the voltage spectrum of the loop antenna. The frequency transmission is

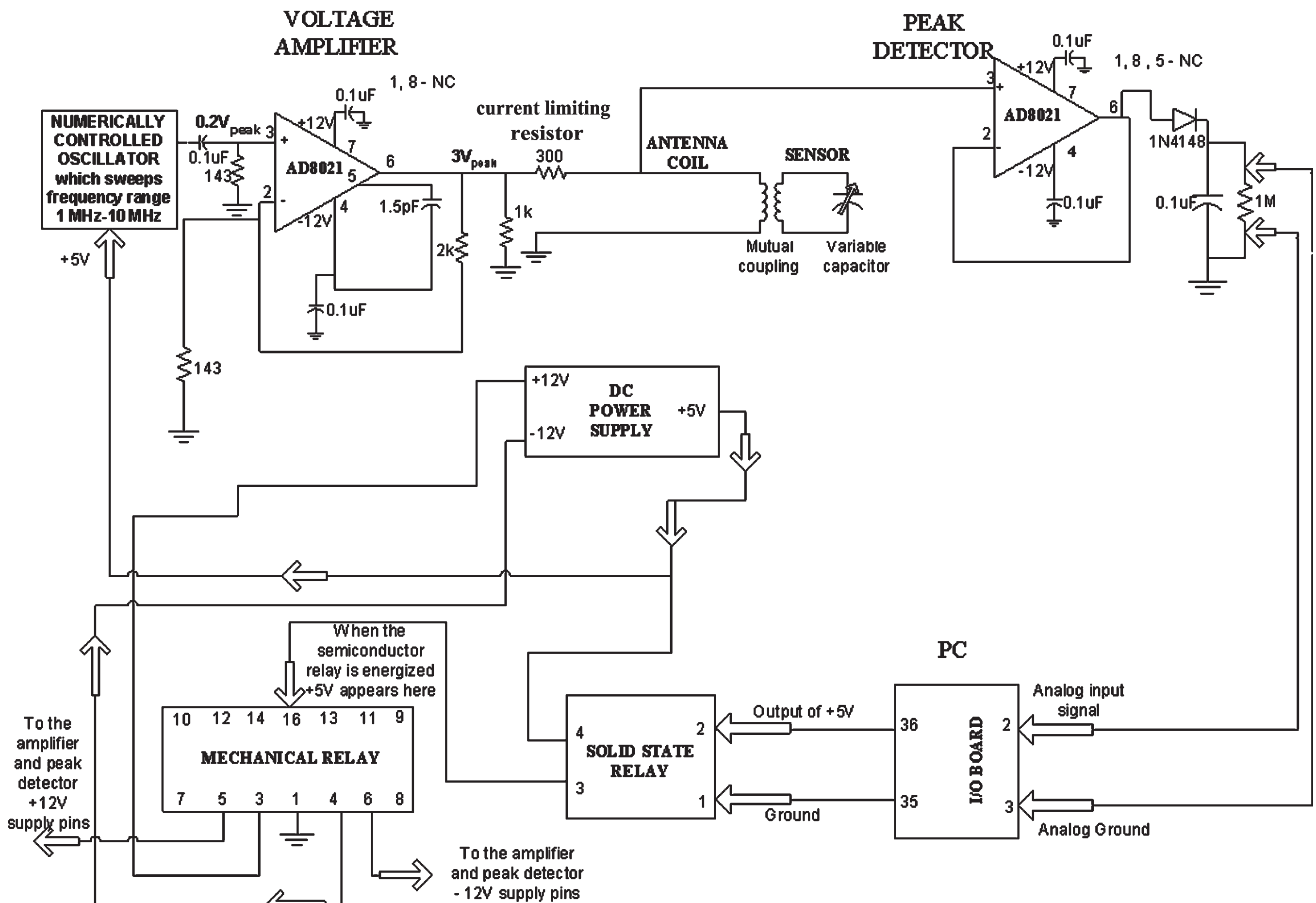

Fig. 2. Experimental setup for automated and continuous monitoring of the LC sensor resonance frequency.

done using a numerically controlled oscillator (NCO), and the automatic monitoring of loop antenna voltage spectrum is achieved using personal computer (PC) data acquisition. Section II presents the measured data, and though only resonance frequency measurements of a sensor circuit designed with an air core solenoid and ceramic capacitor are presented, the system can still be effectively used for detecting the resonance frequency variation of a sensor designed for environmental parameter monitoring.

II. Experiment and Results

For test purposes, air core solenoids are designed for the loop antenna coil and for the sensor inductor using a 27 American Wire Gauge wire. Both the solenoids have 15 turns, and the inductance values of each turned out to be 2 μH when measured using an LCR meter. The parasitic resistance and parasitic capacitance of each of the solenoids is 0.15 Ω and 2.53 pF, respectively. The solenoids are coupled to each other with a coupling ratio of 0.3.

A NCO with a programmable evaluation board that is manufactured by Analog Devices Inc. generates the electromagnetic waves to be transmitted into the loop antenna. Using the software provided with the board, the frequency could be swept over a range of values from 1 Hz to 25 MHz automatically without any tuning. Entering the start value, the end value, the frequency step, and the number of loops desired and clicking the start button generates the frequency sweep. A delay exists between each frequency step, which can be set to a value between the limits 1–10 000 ms. However, the NCO output amplitude is of the order of a volt, thus requiring amplification of the output frequencies before transmitting them using the loop antenna. In addition, the output has a dc component with a value of 0.5 V, which has to be eliminated. The NCO software source code is modified to stop and restart automatically without using the buttons and also to display the frequency and the number of sweeps done as sweeping progresses.

For automated sensor resonance frequency recording using PC data acquisition with reduced cost, an input–output (I/O) board with a sampling rate of 330 kHz and 12-bit analog-to-digital converter (ADC) manufactured by Measurement Computing Corporation is chosen. A peak detector circuit feeds the peak values of the antenna voltage to the I/O board, and Matlab acquires and processes the peak detector output data.

This automated sensor resonance frequency monitoring has to be continuous. An interface is setup between NCO and Matlab so that Matlab data acquisition starts and stops with the NCO frequency sweep start and stop. Microsoft Excel is

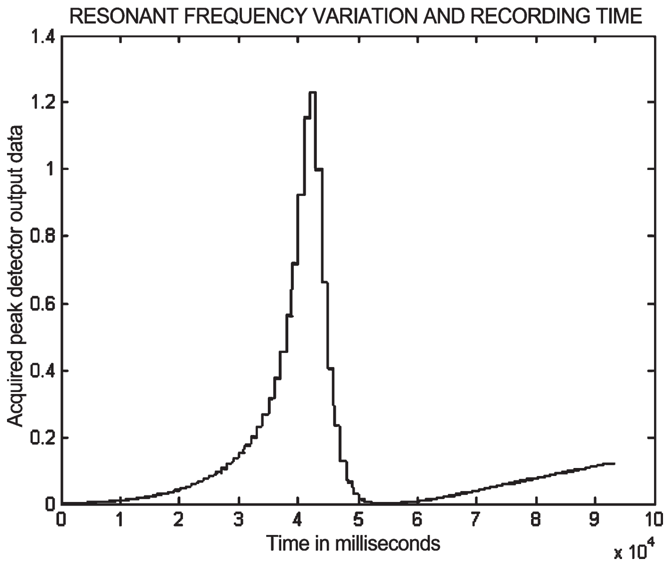

Fig. 3. Matlab output plot with a 2 μH sensor inductor, a 0.49 nF sensor capacitor, and a 0.1 MHz NCO frequency step.

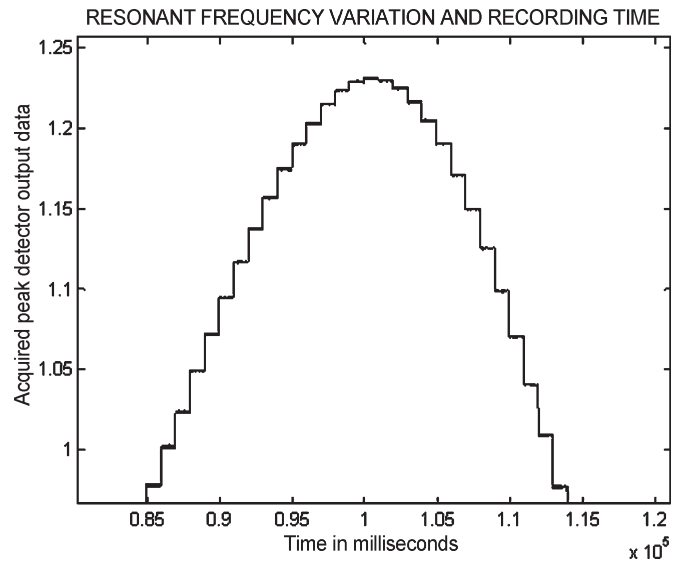

Fig. 4. Matlab output plot with a 2 μH sensor inductor, a 0.49 nF sensor capacitor, and a 0.01 MHz NCO frequency step.

used as the interface. The Matlab data acquisition program continuously samples the antenna coil voltage 1000 times every second and outputs a plot of the acquired data versus time in milliseconds. Since Matlab data acquisition and NCO frequency sweep are synchronized, the time instant at which the maximum antenna voltage value appears in Matlab corresponds to a particular NCO frequency, which will be the sensor resonance frequency. Matlab also outputs the sweep beginning time in the command window in the following format: year month day hour minutes seconds. Thus, Matlab outputs a plot of the acquired data and the sweep start time, and this automatically repeats for each sweep run by the NCO.

A mechanical relay is set up in the system to disconnect the supplies to the amplifier and peak detector circuits, once Matlab program finishes data acquisition. Matlab controls the mechanical relay through a semiconductor relay.

Using the solenoids built for the sensor inductor and the antenna inductance, each having a value of 2 μH, the system built, as shown in Fig. 2, is tested for automated and continuous recording of the resonance frequency of the sensor circuit. In the NCO software, the start and end values of the frequency sweep are entered as 1 and 10 MHz, respectively, and the number of times the sweep needs to be run is entered as 1. In addition, the delay between the frequency steps is set to 1 s because of the minimum sampling rate of 1 Hz in Matlab.

Matlab data acquisition starts with the NCO frequency sweep and acquires 1000 samples of data every second. It stops with the NCO frequency sweep and generates a plot of the data acquired. The Matlab program output plot of the acquired peak detector output versus time in milliseconds for one NCO frequency sweep from 1 to 10 MHz in steps of 0.1 MHz, with a 2 μH sensor inductor and a 0.49 nF sensor capacitor, is shown in Fig. 3. The sensor resonance frequency recording time is the time at the beginning of the sweep, which is output by Matlab, added to the time at which the maximum antenna voltage value appears in the peak detector output plot.

In Fig. 3, the maximum value in the peak detector output appears in the range of $4.2 \times 10^4 - 4.3 \times 10^4$ ms. Thus, in correlating the Matlab output data plot to the NCO frequency sweep from 1 to 10 MHz, with a 0.1 MHz NCO frequency step size, the corresponding frequency is in the range of 5.2–5.3 MHz. The offset of 0.2 MHz is because of the 1 s delay in the NCO before starting the sweep and because the actual output frequency value is one frequency step behind the displayed frequency value in the NCO software. Thus, the sensor resonance frequency value lies in the range of 5–5.1 MHz. In addition, the time at which this resonance frequency value is recorded is 42 s from the time at the beginning of the sweep.

To increase the resolution further, the NCO frequency step size is decreased to 0.01 MHz. The Matlab output plot with this frequency step in Fig. 4 shows the maximum value in the peak detector output appearing in the range of $1 \times 10^5 - 1.01 \times 10^5$ ms. In correlating this peak detector output to the NCO frequency sweep from 4 to 6 MHz, the sensor resonance frequency value lies in the range of 4.98–4.99 MHz.

The NCO frequency step is now decreased to 0.001 MHz. However, the sensor resonance frequency cannot be derived from the output plot of Matlab since the peak detector output amplitude variation cannot be detected from the plot, as shown in Fig. 5. Thus, the resolution for detecting the sensor resonance frequency variation is limited to 0.01 MHz.

The ability of the system to record sensor capacitance change during an NCO frequency sweep is shown in Fig. 6. The NCO frequency sweep is run from 1 to 10 MHz, with a 0.01 MHz frequency step, and the sensor capacitance is selected to be 2.318 and 1.02 nF at different time instants during the sweep. As shown in Fig. 6, the two peak values in the peak detector output appear in the ranges of $1.355 \times 10^5 - 1.365 \times 10^5$ and $2.545 \times 10^5 - 2.555 \times 10^5$ ms. Thus, in correlating the peak detector output to the NCO frequency sweep, the two sensor resonance frequency values lie in the ranges of 2.33–2.34 and 3.52–3.53 MHz.

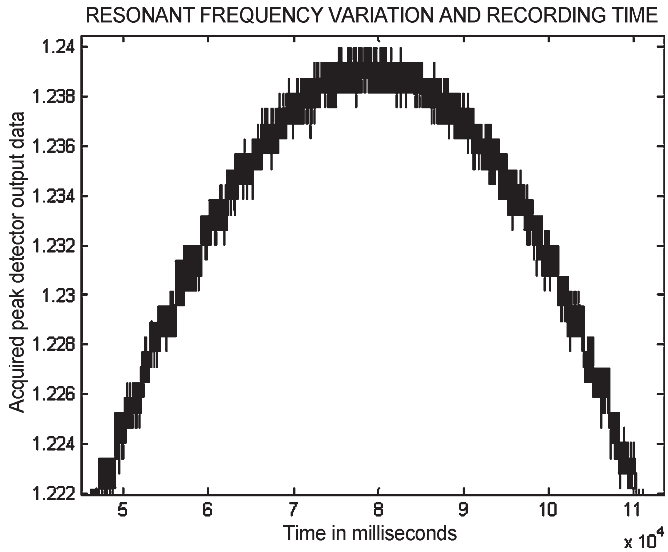

Fig. 5. Matlab output plot with a 2 μH sensor inductor, a 0.49 nF sensor capacitor, and a 0.001 MHz NCO frequency step.

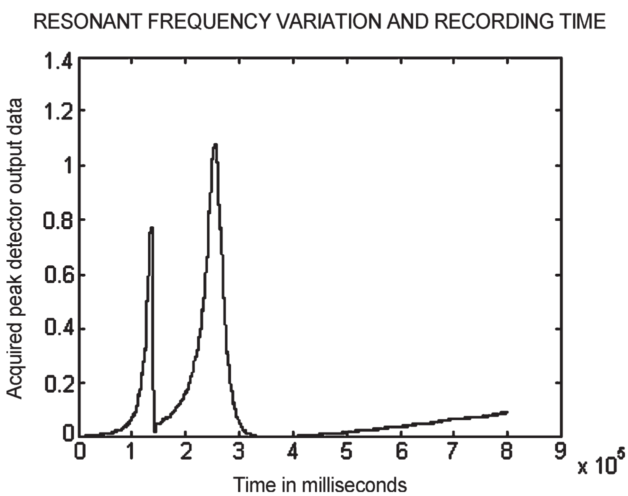

Fig. 6. Matlab output plot with a 2-μH sensor inductor, sensor capacitors with values of 2.318 and 1.02 nF, and a 0.01 MHz NCO frequency step.

III. Discussion and Conclusion

This automated and continuous sensor resonance frequency monitoring system provides significant improvements over past systems [2], [3], [5]–[7], [9], [10], [13], [14], [16]–[18] such as simple system design, simple sensor data processing, absence of bulky devices, low-power consumption, and low cost. Sensor resonance frequency monitoring is completely automated and continuous without any tuning or adjustments. The system automatically records not only the resonance frequency variation but also the recording time. Thus, the rate of change of sensor resonance frequency can be derived over a period of time.

The system is highly sensitive, reliable, and stable. It can effectively detect sensor resonance frequency variation in the range of 20 kHz–10 MHz, with the highest resolution of 0.01 MHz, in the output sensor resonance frequency. The lower frequency limit is due to the resistor–capacitor (RC) high-pass filter at the amplifier input. In addition, the sensor resonance frequency monitoring range is limited up to 10 MHz because the NCO output is distorted above 10 MHz. With a sensor inductor with a value of 2 μH, this system can detect sensor capacitance values in the range of 0.01265–0.0001265 μF.

Care should be taken to make sure that the parasitic interwinding capacitance of the antenna coil does not cause the coil to self-resonate near that of the sensor. The system cannot detect sensor capacitance changes that occur at a rate less than a second. In addition, if the sensor capacitance change produces resonance frequency change with a value that is higher than 0.01 MHz, the change cannot be detected. In addition, sensor capacitance change that produces a resonance frequency value that is less than the frequency value that the NCO frequency sweep has already crossed cannot be detected. It can be detected in the next frequency sweep if the sensor capacitance value does not change until that time.

As the sensor resonance frequency value increases, error occurs in the sensor resonance frequency detection due to the parasitic capacitance on the circuit board and the sensor solenoid interwinding capacitance. However, this total parasitic capacitance value is stable at 0.0113 nF for all the frequencies from 1 to 10 MHz; hence, the system can be accordingly calibrated. In addition, the peak detector output has an offset voltage of 0.2 V due to the AD8021 operational amplifier external RF pickup.

Future work should involve an oscillator with higher output amplitude and bandwidth for a higher monitoring frequency range and elimination of the amplifier in the system. The peak detector output offset voltage can be eliminated using an RC low-pass filter with a cutoff frequency of 10 MHz.

References

[1] R. Puers, "Linking sensors with telemetry: Impact on the system design," *Sens. Actuators A, Chem.*, vol. 52, no. 1–3, pp. 169–174, Mar./Apr. 1996.

[2] K. G. Ong and C. A. Grimes, "A resonant printed-circuit sensor for remote query monitoring of environmental parameters," *Smart Mater. Struc.*, vol. 9, no. 4, pp. 421–428, Aug. 2000.

[3] K. G. Ong, C. A. Grimes, C. L. Robbins, and R. S Singh, "Design and application of a wireless, passive, resonant-circuit environmental monitoring sensor," *Sens. Actuators A, Phys.*, vol. 93, no. 1, pp. 33–43, Aug. 2001.

[4] M. Husak, "One-chip integrated resonance circuit with a capacitive pressure sensor," *J. Micromech. Microeng.*, vol. 7, no. 3, pp. 173–178, Sep. 1997.

[5] O. Akar, T. Akin, and K. Najafi, "A wireless batch sealed absolute capacitive pressure sensor," *Sens. Actuators A, Phys.*, vol. 95, no. 1, pp. 29–38, Dec. 2001.

[6] K. G. Ong, J. Wang, R. S Singh, L. G Bachas, and C. A. Grimes, "Monitoring of bacteria growth using a wireless, remote query resonant-circuit sensor: Application to environment sensing," *Biosens. Bioelectron.*, vol. 16, no. 4/5, pp. 305–312, Jun. 2001.

[7] J. Coosemans, M. Catrysse, and R. Puers, "A readout circuit for an intraocular pressure sensor," *Sens. Actuators A, Phys.*, vol. 110, no. 1–3, pp. 432–438, Feb. 1, 2004.

[8] J. C. Butler, A. J. Vigliotti, F. W. Verdi, and S. M. Walsh, "Wireless passive resonant circuit, inductively coupled, inductive strain sensor," *Sens. Actuators A, Phys.*, vol. 102, no. 1/2, pp. 61–66, Dec. 2002.

[9] K. G. Ong, K. Zeng, and C. A. Grimes, "A wireless passive, carbon nano-tube based gas sensor," *IEEE Sensors J.*, vol. 2, no. 2, pp. 82–88, Apr. 2002.

[10] J. M. English and M. G. Allen, "Wireless micromachined ceramic pressure sensors," in *Proc. 12th IEEE Int. MEMS Conf. Tech. Dig.*, 1999, pp. 511–516.

[11] H. J. Yoon, J. M. Jung, J. S. Jeong, and S. S Yang, "Micro devices for a cerebrospinal fluid (CSF) shunt system," *Sens. Actuators A, Phys.*, vol. 110, no. 1–3, pp. 68–76, Feb. 2004.

[12] M. A. Fonseca, J. M. English, M. von Arx, and M. G. Allen, "High temperature characterization of ceramic pressure sensors," in *Proc. Conf. Solid-State Sens. and Actuators*, Munich, Germany, Jun. 10–14, 2001, pp. 486–489.
[13] T. J. Harpster, B. Stark, and K. Najafi, "A passive wireless integrated humidity sensor," *Sens. Actuators A, Phys.*, vol. 95, no. 2/3, pp. 100–107, Jan. 2002.
[14] A. DeHennis and K. D. Wise, "A double-sided single-chip wireless pressure sensor," in *Proc. IEEE Conf. Micro Electro Mech. Syst. Dig.*, Las Vegas, NV, Jan. 2002, pp. 252–255.
[15] ——, "A pressure sensing system for implantable wireless telemetry," in *Proc. North Amer. Solid-State Sens., Actuators, and Microsyst. Workshop*. Hilton Head, SC, Jun. 2002, pp. 6–9.
[16] E. C. Park, J. B. Yoon, and E. Yoon, "Hermetically sealed inductor–capacitor (LC) resonator for remote pressure monitoring," *Jpn. J. Appl. Phys.*, vol. 37, no. 12B, pp. 7124–7128, Dec. 1998.
[17] S. Y. Kim, H. J. Kim, J. S. Park, and S. S. Yang, "A telemetry silicon pressure sensor of LC resonance type," in *Proc. SPIE—Design, Test, Integration and Packaging of MEMS/MOEMS*, 2001, pp. 452–462.
[18] K. G. Ong, J. S. Bitler, C. A. Grimes, L. G. Puckett, and L. G. Bachas, "Remote query resonant-circuit sensors for monitoring of bacteria growth: Application to food quality control," *Sensors*, vol. 2, no. 6, pp. 219–232, 2002.
[19] K. Finkenzeller, *RFID Handbook*. Chicester, U.K.: Wiley, 1999.
[20] J. Ryan, Jr., "Antishoplifting labels," *Sci. Amer.*, vol. 276, pp. 120–125, May 1997.
[21] K. L. Su, *Fundamentals of Circuits, Electronics and Signal Analysis*. Boston, MA: Houghton Mifflin, 1978, pp. 587–614.
[22] C. R. Paul, *Analysis of Linear Circuit*. New York: McGraw-Hill, 1989.

Sajeeda received the B.S. degree in electronics and communication engineering from Shadan College of Engineering and Technology, Hyderabad, India, in 2001 and the M.S. degree program in electrical engineering from Montana State University, Bozeman, in 2004.

She was a Research Assistant with Montana State University from 2001 to 2004. Her research interests include the development of low-power readout systems for wireless remote query environmental sensor applications.

Todd J. Kaiser (M'00) received the B.S. degree in physics from Montana State University, Bozeman, in 1981, the M.S. degree in physics from Oregon State University, Corvallis, in 1984, and the Ph.D. degree in electrical engineering from the Georgia Institute of Technology, Atlanta, in 2000.

From 1985 to 1994, he was with Draper Laboratory, Cambridge, MA, where he designed optical gyroscopes. From 1994 to 2000, he was a Program Manager with Milli Sensor Systems and Actuators, West Newton, MA, where he worked on the development of micromechanical inertial instruments. He is currently an Assistant Professor with the Department of Electrical and Computer Engineering, Montana State University. His research interests include microelectromechanical systems fabrication, inertial sensors, and micromechanical actuators and sensors.