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Wireless interrogation techniques for sensors utilizing inductively coupled resonance circuits

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Abstract

The methods needed to interrogate passive resonance sensors are studied. A portable impedance measurement unit and the methods to extract a coupling coefficient compensated resonance frequency are presented. The interrogation methods are demonstrated with ECG and pressure measurements. The results show that the quality of the ECG signal measured with a flexible textile coil is sufficient to extract the heart rate. In the case of a pressure sensor, the errors caused by the changes in the inductive coupling were satisfactorily removed by the introduced method.

Keywords: Inductive coupling; passive resonance sensor; telemetry

1. Introduction

In the passive resonance sensor measurement, the impedance of an LC resonator circuit is detected via inductive coupling between the sensor and the reader coils. Depending on the sensor, the measured quantity affects the capacitance, inductance or resistance of the sensor circuit. Despite the obvious advantages, like simplicity and small physical size of the sensors and the ability to read the sensors wirelessly through non-conductive barriers, these sensors have not really broken through. This is partly due to two major constraints: the difficulty and ambiguity in the interpretation of the reflected impedance and impracticality of the instrumentation required for the measurement.

The network or impedance analyzers are commonly used to read resonance sensors [1,2]. Although these devices are adaptable and accurate, they are bulky and expensive and thus restrict the use of this measurement method outside the laboratory environment. Other options are phase locked loops [3] and devices that sweep over the frequency range, measuring impedance [4,5]. In this paper, we present a hand-held phase-magnitude measurement device, a method to extract the resonance frequency of the sensor from the measured data and a method for compensating the errors in the measured values related to the changes of inductive coupling coefficient.

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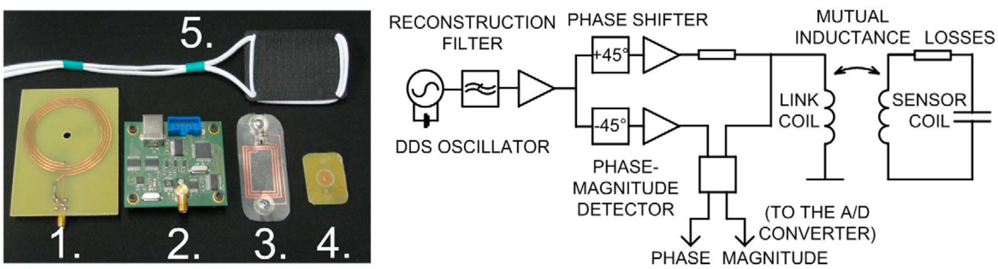
2. Methods

In order to make a robust, easy-to-use instrument capable of measuring sensors with a wide range of operating frequencies, an impedance analyzer-like approach combined to PC post processing was adopted. In this approach, the small portable measurement instrument (Fig. 1a) sweeps over the specified frequency range, measuring the phase and/or magnitude response of the resonant sensor. Then the PC post-processing software calculates the resonance frequency and removes the motion-induced frequency changes.

The radio frequency section of the designed instrumentation is shown in Fig. 1b. The measurement signal is generated with a direct digital synthesizer (Analog Devices' AD9913). After filtering and amplification, the signal is fed to a low pass - high pass type phase shifter. One of the generated phase-shifted signals is then fed to the link coil through a resistor, while the other signal is fed directly to a phase detector. The purpose of the phase shifter is to bias the phase detector (Analog Devices' AD8302) to mid-scale, so that it can measure both leading and lagging phase differences (±90º maximum) unambiguously. The phase detector then measures the phase difference between the reference and the link coil voltage. The instrument also has an MCU for controlling the DDS and communicating with the PC via a USB port. There's also a fast 12-bit ADC to convert the phase detector's output to numerical form. The MCU communicates with the PC and does the requested frequency sweeps at the specified speed and with the specified starting and ending frequencies.

A laptop PC is used for post processing the data, which can contain both magnitude and phase values at discrete frequencies. The measured signals are formed as a combination of circuit elements in the instrumentation unit, the measurement cable, the reader coil and the reflected impedance of the sensor circuit. The reflected impedance is a combination of the coupling coefficient and the sensor circuit. If there is a resonance sensor present in the vicinity of the reader coil, it will alter the monotonicity (a descending slope in this configuration) of the phase behavior. The typical magnitude and phase curves of a pressure sensor at varying inductive coupling are shown at Fig. 2a. The same signals were measured with an impedance analyzer as a reference. In this application, we are not interested in the exact magnitude or phase values. Instead we try to detect how the measurand dependent component alters the measured reflected resonance curve as a function of frequency. At the moment, only phase data is used. Our post processing algorithm finds the frequency of the phase peak and the height of the phase peak. At first, the baseline is removed. Then the data points under 10 % of the maximum phase value are removed. Finally, a 3rd order polynomial is fitted to data and the maximum of the polynomial is evaluated. The same method is used to find the local minimum between the first measured value and the detected peak. The height of the phase peak defined as the difference of the minimum and maximum phase shifts inside the resonance transition.

The inductive coupling between the reader coil and the sensor coil will affect the frequency at which the resonance curve of the sensor circuit will be detected in the measured magnitude and phase data. The inductive coupling between the coils depends on the coil geometry and the distance and orientation between the coils. In most applications distance and orientation are unknown and thus make the detection of the resonance frequency ambiguous. The severity of the error caused by this phenomenon depends on the instrumentation, the application and the sensitivity and Q value of the resonance sensor.



(a) (b)

Fig. 1. (a) The equipment used in this work: reader coil (1), phase-magnitude measurement unit (2), ECG sensor (3), Pressure sensor (4) and flexible textile reader coil (5).The dimensions of the measurement unit are 55 mm x 60 mm x 11 mm. (b) Block diagram of the phase-magnitude measurement unit.

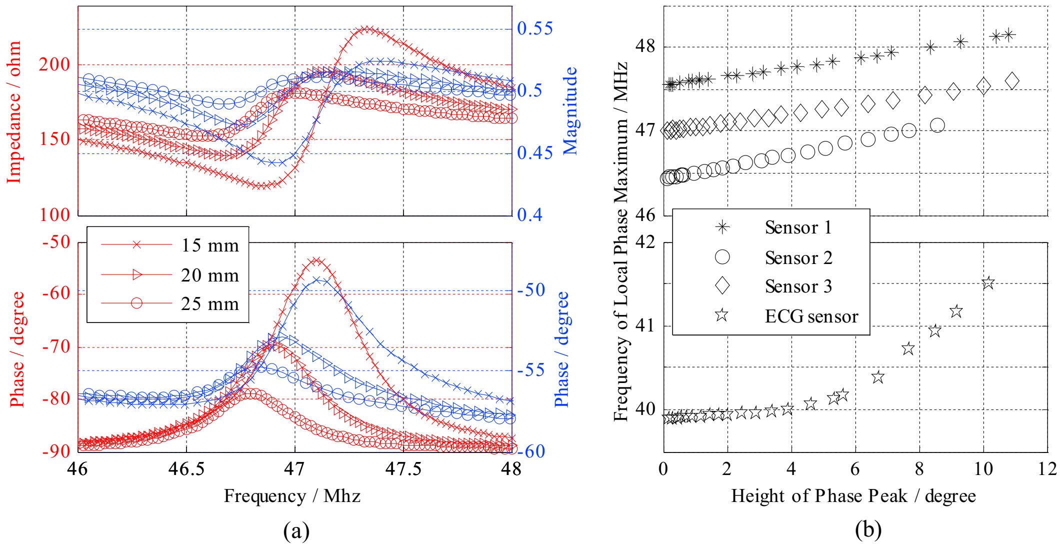


Fig. 2. (a) The impedance magnitude and phase curves of a pressure sensor were measured at three different distances with the hand-held device (blue curves). As a reference, an Agilent 4396B with impedance test adapter was used to measure impedance and phase (red curves). The measurement cable is dominating factor in the phase curve (b) The relation between the frequency of the maximum of the phase peak and the height of phase peak with increasing inductive coupling. The sensors 1-3 are pressure sensors similar to Fig. 1a. The curve of an ECG sensor is not linear near the reader coil (phase peak height higher than six degrees) because the used varactor starts to conduct.

Our motion compensation is based on the idea to explain the frequency of the maximum value of the resonance peak in the phase curve with the height of the phase peak. As in Fig. 2b, we can find a linear dependency between the frequency of the phase peak and the measured height of the phase peak. This sensor specific dependency can be found by measuring data with no stimulus on the sensor at varying inductive couplings. The unloaded sensor is moved back and forth in the vicinity of the reader coil and a 1st order polynomial is fitted to the phase peak frequency - peak height data. The found phase peak frequency is compensated by subtracting the product of the corresponding phase peak height and the 1st order coefficient of the polynomial fitting.

3. Results

In order to evaluate our method for reading inductively coupled resonance sensors in real applications, we measured ECG and the pressure caused by compression garments. These biomedical measurements have dissimilar requirements for instrumentation. In the ECG measurement, high limiting resolution, sampling rate and low noise are needed. The pressure measurement requires good DC-signal precision.

In the ECG measurement, the sensor is similar to the design used by Riistama et. al. [3]. The core idea of the sensor is to convert the voltage signal to the changes of capacitance with a varactor. The sensor was attached to the chest, below the left pectoral muscle with a pair of Ag/AgCl-electrodes. The sensor signal was recorded with a flexible textile coil trough T-shirt at sampling rate of 100 Hz. The measured signal is presented in Fig.3a.

The pressure between a compression garment and skin was measured with a custom-made resonance sensor. This measurement is important for compression garment treatment in order to ensure the proper functioning of the used garment. The used sensor has a dual-layer structure consisting of a planar coil on a PCB and a pressure sensitive capacitor made of partly metal coated PDMS-silicone. A practical test was carried by simulating a typical operation situation of a compression garment measurement. The results are shown in Fig. 3b. At the beginning, the sensor was attached to a leg with an adhesive bandage. At this stage, the only external pressure is caused by the bandage. Then a compression garment was worn over the sensor to create a pressure stimulus to the sensor. To create more pressure, an extra rubber bandage was applied over the compression garment to increase pressure. Finally, the rubber bandage was tightened even further. The reader coil was brought in the vicinity of the sensor six times during stage 2 and three times during other stages.

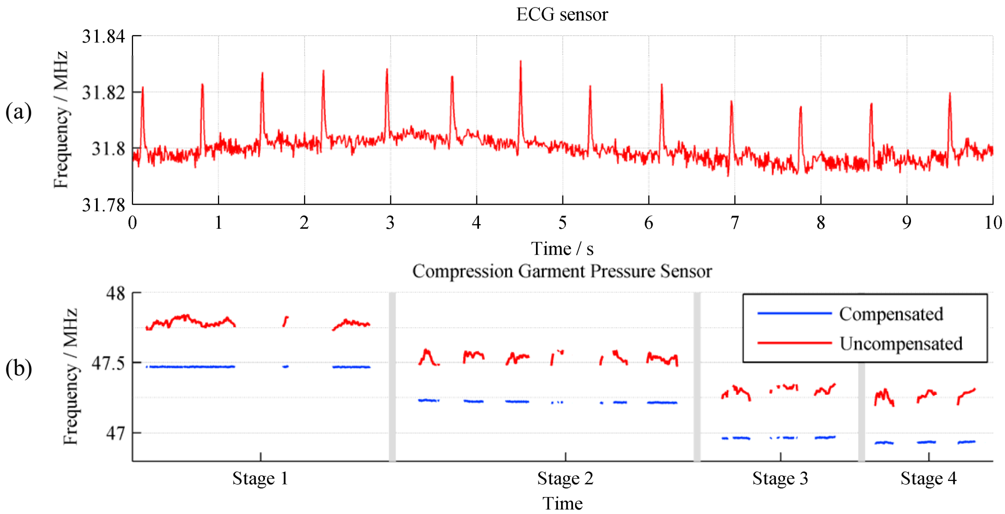


Fig. 3. (a) The uncompensated ECG signal measured from the chest area with regular wet gel electrodes. (b) The signal corresponding to pressure was recorded from a leg in various pressure conditions (1 adhesive bandage, 2 compression garment, 3-4 rubber band and compression garment). The movement between the reader and sensor coils was compensated.

4. Discussion

The overall performance and the versatility of the used interrogation method justify the further studies. The compact hardware of the system supports the use of this method in portable biomedical applications. At the moment, most of the calculations are done with a PC. However, developing the detection algorithms further to lower their processing power and memory requirements is a worthwhile endeavor. This could allow running the analysis algorithms in the reader device itself, leading to a hand-held instrument which can instantly determine the pressure reading. In the case of the ECG measurement, the heart rate can be easily extracted from the signal. However, the sampling rate and the resolution are only barely sufficient for the typical ECG application. In the case of the compression garment measurement, the motion compensation method is mandatory for a satisfactory measurement.

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