Performance of a Near-Field Radio-Frequency Pressure Sensing Method in Compression Garment Application

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Abstract. Information on the applied pressure is critical to the pressure garment treatment. The performance of a close-range radio-frequency pressure measurement method is evaluated. The aim of the measurement is to sense the pressure under pressure garments. The hand-held measurement unit is used to inductively read a passive resonance sensor. The response and the repeatability of a new pressure sensor structure are tested. The performance of the telemetry is tested by altering the distance, angle and alignment between the measurement unit and the sensor. The functioning of the read-out method is tested within the useful frequency range of the sensor. The effects of the measurement environment are studied. According to the results, the tested measurement method is acceptable in this application.

Keywords: RF telemetry, passive resonance sensor, pressure measurement.

1 Introduction

The pressure garment treatment has potential to improve the healing process of burns and to reduce the swelling. The use of suitable pressure is critical to the treatment and thus, in order to ensure the proper functioning of the pressure garment, this pressure has to be measured periodically. Close-range wireless sensors have an obvious niche in this application since tubing and electrical wiring used in conventional sensors make the measurement of pressure inconvenient and unreliable. Tubing and electrical wiring are a significant hindrance, especially when tight pressure garments are put on. An alternative wireless method for obtaining the measurements is to use passive resonance sensors. The advantage of this method, when compared to the more common wireless techniques, is the simplicity of the sensor, which promotes the idea of disposable sensors. In our earlier work, we have presented the methods needed for this measurement [1]. The other applications for this type of wireless telemetry in medical settings include intra-ocular pressure sensing [2,3] and ECG-measurements [4,5].

In this paper, we present the performance of the new hand-held measurement device and the new pressure sensors. The sensor and the read-out methods are

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K.S. Nikita et al. (Eds.): MobiHealth 2011, LNICST 83, pp. 322–328, 2012.

introduced in section 2. The pressure response of the sensor is measured in section 3.1. The effects of the positioning between the reader and the sensor are tested in section 3.2. The functioning of the read-out method is tested within the useful frequency range of the sensor in section 3.3. The effects of the environment on measurement are studied section 3.4.

2 Pressure Sensor and Read-Out Methods

The instrumentation in this work (Fig. 1) consists of a hand-held measurement unit (13 cm by 7 cm by 1.5 cm) and the passive resonance sensors (17 mm by 17 mm by 3mm). The measurement unit uses a radio-frequency inductive link to wirelessly read the sensors through non-conductive materials like clothing. The measurement unit sweeps over the specified frequency range, measuring the phase response (phase dip) of the sensor. The sensor consists of a pressure dependent capacitor and a resonance coil, which also doubles as a link coil. Thus, the pressure on the sensor alters the capacitance, which in turn alters the phase response. The power consumption of the used short-range inductive link is relatively small: the excitation power used by the measurement unit is 600μW or less.

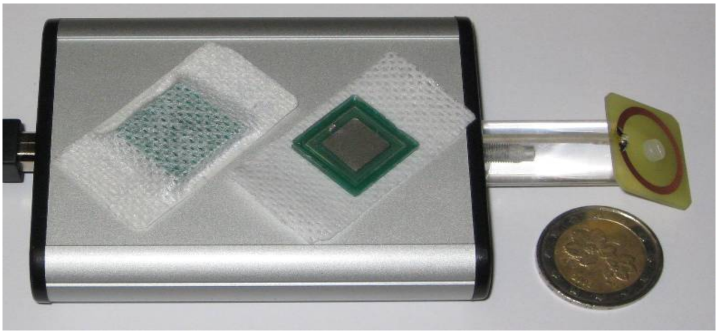

Fig. 1. The hand-held measurement unit and passive resonance sensors (on top of device). The sensors are attached to the measurement target with an adhesive bandage.

The measurement unit transmits the measured data to a PC via a USB port for post processing. First, the phase dip features (uncompensated frequency and the height of the phase dip) are extracted. The value of the height of the phase dip is used to select valid data points (dip height from 3 to 25 degrees). Next the PC post-processing software calculates an estimate of the compensated resonance frequency. The compensated frequency is then compared to the reference value and converted to pressure. The reference value is acquired by the tuning procedure [5]. The preselection of the data points is required, because the data points with a small phase dip are noisy and the data points with a large phase dip do not fit the regression model which is used in the compensation.The more exhaustive description of the used methods can be found in [1,5].

3 Performance Tests

In this section, the response of the sensor is measured and the effects of the positioning between the sensor coil and the reader coil are studied. The functioning of the read-out method is tested within the useful frequency range. Finally, the effects of the measurement environment are tested.

3.1 Pressure Response

In order to evaluate the response and repeatability of the new sensor structure, the resonance frequency of the sensor is measured as a function of pressure in a test setup, where the applied pressure can be controlled.

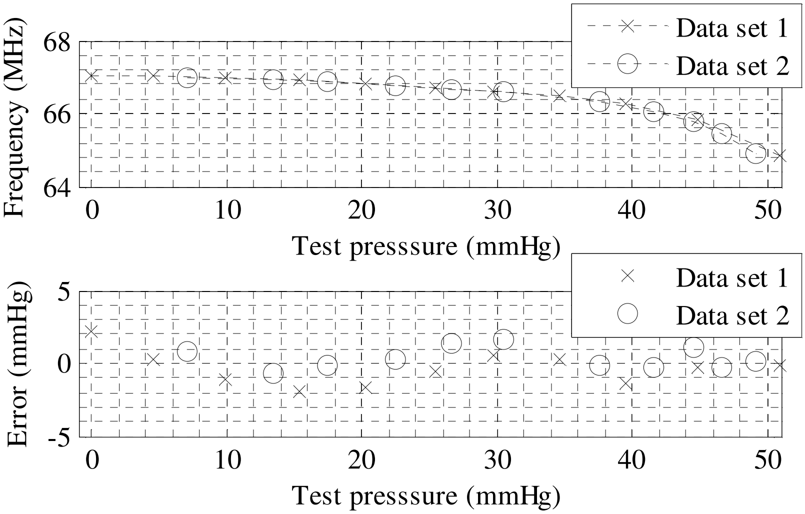

Fig. 2. (a:upper) The response of the sensor was measured with test pressures ranging from 0 to 50 mmHg twice. (b:lower) Identification error.

The resonance frequency of the sensor is measured at each calibration pressure wirelessly with the hand-held reader unit. Each data point is an average of about 100 samples. The pressure response curve measurement is repeated twice. The response curves are shown in Fig. 2a. According to results, the sensor has sufficient repeatability. The maximum measured frequency shift is -2.2 MHz at 50.8 mmHg. The response of the sensor is nonlinear. At around 20 mmHg pressure, 1 mmHg pressure shift equals roughly 80 kHz frequency shift. The model for the response is identified with an ANFIS model [6]. The identification error is calculated (Fig. 2b). These errors are acceptable in this application.

3.2 Effects of Positioning

Since the used coils are smaller than in the previous studies and the reading distance is dependent on the coil dimensions, the maximum reading distance is measured. The effects of positioning (distance, angle and alignment) are also studied because these factors are unknown in real measurement situation and may cause errors to the reading.

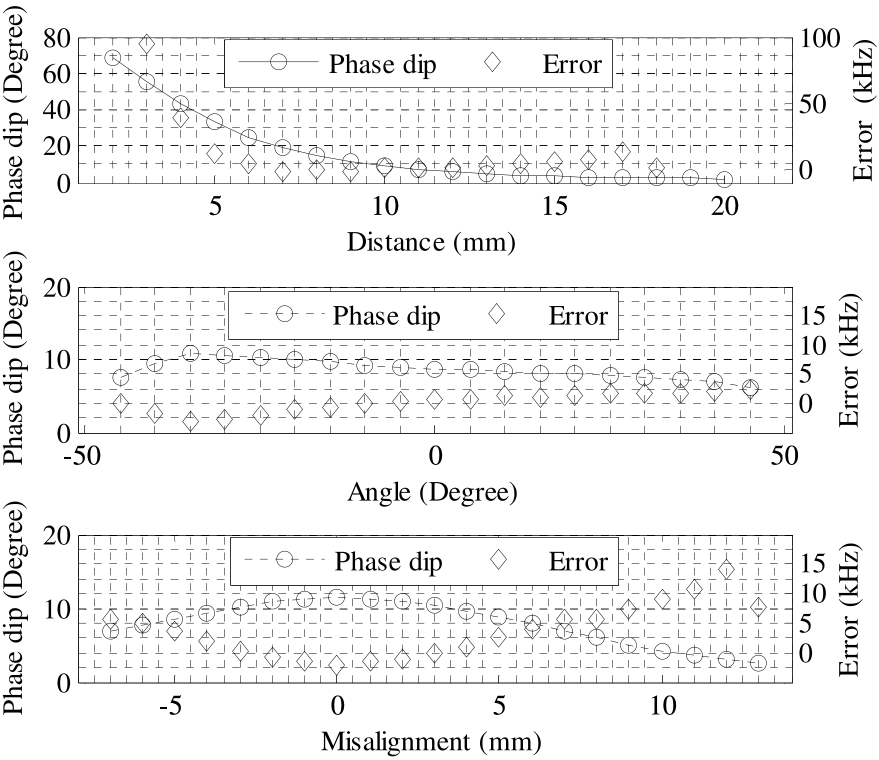

Fig. 3. The performance of the used compensation method is tested by changing the distance (a:upper) and angle (b:middle) between the reader and the sensor coils. The effect of misalignment is also tested (c:lower).

In our measurement method, the sensor causes a dip in the measured phase response curve. The height of the phase dip can be considered as a quantity that indicates the coupling between the coils. The height of the phase dip also shifts the detected resonance frequency but we have a method for compensating this effect. The height of the phase dip and the error in the compensated frequency readings are shown in Fig. 3a as a function of the distance between the coils. These values are an average of about 100 samples. In this measurement, the algorithm is allowed to calculate compensated readings at the extended range (2.02 degrees to 70 degrees). The used read-out method is able to detect the resonance frequency of the sensor between the distances from 2 mm to 20 mm. However, by using regular limits (3 to 25 degrees) the range is limited between 6 mm to 16 mm.

The errors caused by the angle (Fig 3b) and the misalignment (Fig 3c) between the coils are also measured. These measurements are made at the distance of 10 mm. According to these results, neither the angle nor the misalignment cause significant errors compared to the distance.

3.3 Effects of Frequency Range

In this section, the effects of the frequency range of the sensor are studied. Performance of the read-out method is tested when the resonance frequency of the sensor varied within a large frequency range.

First, the uncompensated resonance frequency and the height of the phase dip of a test sensor circuit are measured at the distance varying from 1 mm to 25 mm. This test circuit is similar to used in pressure sensors and it has a 22 pF bulk capacitor. Then 0.5 pF capacitors are added to the circuit to decrease the resonance frequency and the measurement is repeated. The additional capacitors decrease the resonance frequency by 1.75 MHz from 67.64 MHz to 65.89 MHz when all the three 0.5 pF capacitors are added. The frequency decrease is roughly 580 kHz per capacitor. This range of the frequency shifts covers most of the range of the tested resonance sensor. These measured datasets are shown in Fig 4. The corresponding compensated frequencies for each dataset are calculated and drawn at the phase dip value of zero. This drawn value is an average of the valid data points. The standard deviations of the compensated frequencies for the 22 pF and 23.5 pF datasets are 3.4 kHz and 3.7 kHz. In addition, the regression models of each dataset are also shown. These regression models are created according to valid data points which have a phase dip value from 3 degree to 25 degrees.

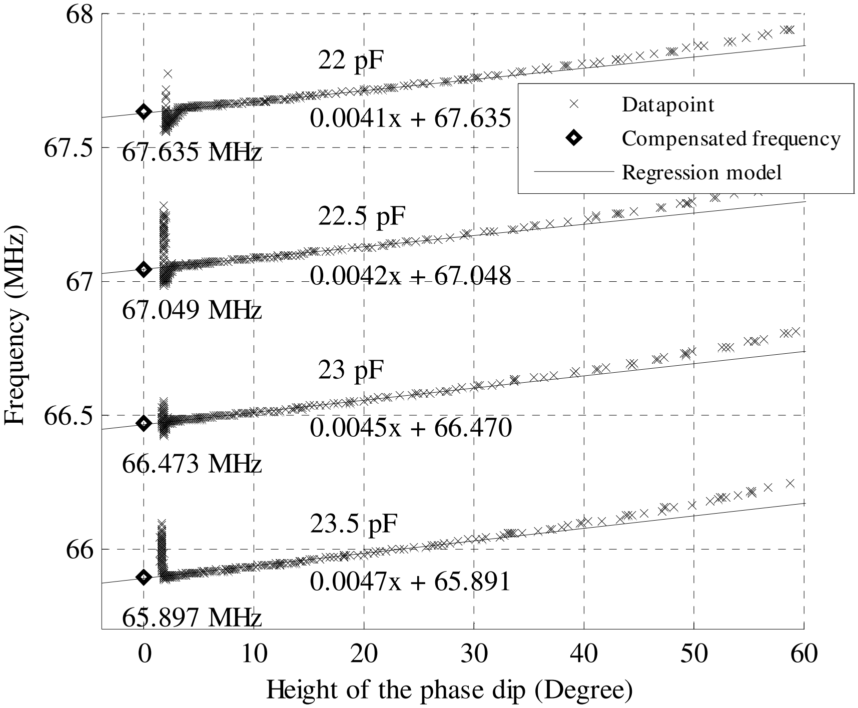

Fig. 4. The resonance frequency is altered by adding 0.5 pF capacitors to a test sensor circuit. The measurements are made from the distance ranging from 1 to 25 mm. The detected uncompensated frequencies are shown with their corresponding heights of phase dips.

The regression model lines almost meet the compensated frequency estimate at the phase dip value of zero. This indicates that the read-out method is valid at tested frequency range. The tuning procedure used for the compensation was done before any 0.5 pF capacitors are added. However, the slope of the regression models seems to increase slightly.

3.4 Effects of Environment

The factors of the environment, for example the changes in the permittivity or permeability, can affect the resonance frequency of an unshielded LC-resonator. Thus, we study the effects of the situations that may occur in the pressure garment application. In this measurement, there is a layer of pressure garment between the sensor and the reader. The garment is prone to absorb sweat and moisture. In addition to that, the effects of the metal objects are tested since a person may carry coins or have snap fasteners in his/her clothing.

The effect of the moisture level in the garment is measured in a test setup in which there is a 10 mm distance between the sensor and the reader. The garment is placed between the sensor and the reader with plastic fasteners. The moisture in the garment is varied by adding salt water. The moisture content in the pressure garment is stated as a percentage of the total mass. The effect of coins and snap fasteners is also tested. The used reading method does not function well if metal objects are placed directly between the sensor and the reader. Instead, we test how the coins or snap fasteners affect the reading if they are placed in the same plane as the sensor. The tests are made by placing the objects right next to and 1 cm away from the sensor.

The errors in the readings are shown in the Table 1. These values are an average of about 100 samples. The errors in pressure are calculated by using the ANFIS-model. There was no external load on the sensor which is the worst case scenario since the sensitivity of the sensor increases with increasing pressure. Results show that, the metallic objects placed in the same plane with the sensor make the measurement underestimate the pressure, while moisture increases the reading. Note that the used ANFIS-model causes a slight error at very small frequency shifts in addition to the environment.

Table 1. The effects of the environmental factors to the reading of a sensor without external load

Disturbance	Error (kHz)	Error (mmHg)
Test setup	-9.7	2.1
Pressure garment (dry)	-20.1	3.0
Pressure garment (10%)	-47.3	5.1
Pressure garment (18%)	-60.2	6.1
Pressure garment (31%)	-121.4	10.8
Pressure garment (47%)	-160.0	13.6
Snap fastener	82.3	-5.1
Snap fastener 1 cm away	-5.3	1.8
Coin	123.9	-8.5
Coin 1 cm away	-5.6	1.9

4 Discussion

The repeatability of the tested sensor is sufficient for this application. The unknown positioning between the reader device and the sensor is not a problem according to the tests. The height of the phase dip indicates when the sensor is within range. This can be indicated to the user. The reading distance that can be achieved is acceptable in this application since the pressure garments are usually made of thin fabric.

The tests made by varying the resonance frequency of the sensor by adding capacitors show that the used compensation method is functioning within the range that is required to measure the resonance frequency of the tested pressure sensor. However, the slight increase in the slopes of the made regression models indicate that the performance of the compensation will decline when the shift in the resonance frequency of sensor increases.

According to the tests made by varying the environment around the sensor, the moisture in the pressure garment has a notable effect on measurement if the garment is soaked. This is a problem especially at the beginning of the pressure range. However, this pressure range is not very important to the application. A dry pressure garment does not seem to disturb the measurement significantly. The metallic objects right next to the sensor affect the measurement, but this effect is insignificant if the objects are moved at least 1 cm away from the sensor.

The overall performance of the used method is good according to the tests. The hand-held measurement device allows much more convenient and unobtrusive measurement of pressures compared to the wired methods. The convenience of the measurement promotes the more regular pressure measurements, which will lead to better pressure garment treatment.

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