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Readout methods for an inductively coupled resonance sensor used in pressure garment application☆

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ABSTRACT

The methods needed to inductively read a passive resonance sensor in pressure measurement are studied. A simple dual-layer pressure sensor, a small portable phase response measurement unit and the methods to extract a coupling coefficient compensated resonance frequency are presented. The functionality and accuracy of the measurement are tested in a test rig and demonstrated in a realistic measurement environment. According to the test measurements, the overall performance of this wireless system is promising and the accuracy is within the typical range of the measurements made in the field of pressure garments.

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 coil. Depending on the sensor, the measurand affects the capacitance, inductance or resistance of the sensor circuit. Despite the obvious advantages, like simplicity, small physical size of the sensors and the ability to read the sensors wirelessly through non-conductive barriers, these sensors have not had a major breakthrough. This is partly due to two major constraints: the difficulty and ambiguity in the interpretation of the reflected impedance and impracticality of the instrumentation (size and price especially) required for the data acquisition.

Network or impedance analyzers are commonly used in the recent studies as readout devices for the 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 (PLL) [3] and devices that sweep over the frequency range, measuring impedance [4,5]. Coosemans et al. have proposed a voltage controlled oscillator (VCO) based readout circuit [6]. Pichorim and Abatti presented a readout system which is based on the simultaneous use of three excitation signals in order to get the sensor resonance frequency and the quality factor [7]. Marioli et al. have demonstrated a measurement distance compensation for determining the capacitance in the inductively coupled resonance sensor in a humidity measurement application [8]. The most common application for inductively coupled sensors is pressure sensing [1,4,6,9,10], especially intra-ocular pressure sensing [1,4,6]. Electrocardiogram has also been measured with this method [3].

A new application for the inductively coupled sensors is to measure the pressure under the pressure garments. The pressure garment treatment has potential to improve the healing process of burns and reduce swelling in legs. The effect of the treatment is depending on the suitable pressure. Too low pressure does not cause the desired effect and too high pressure starts to prevent circulation and cause tissue damage. Thus, there is a need to ensure that the garments create the desired pressure. This pressure can be measured with a sensor which utilizes an air filled pouch and a tube to transfer the pressure under the garment to a pressure sensor [11]. Capacitive [12] and piezoresistive [13] pressure sensors have been tested in the pressure garment application. McLaren et al. tested a system based on multiple piezoresistive sensors to measure dynamic pressures [14]. Giele et al. measured the pressure directly from tissue using needles [15].

We present an alternative method for the measurement of pressure produced by the pressure garments. In this method, neither tubing nor electrical wiring is required because of the inductive link. This is an advantage since wiring makes measurement unpleasant, because pressure garments are usually worn over scarred skin. In this paper, we present a wireless pressure sensor, a hand-held phase response measurement device, a method for extracting the resonance frequency of the sensor from the measured data, and a

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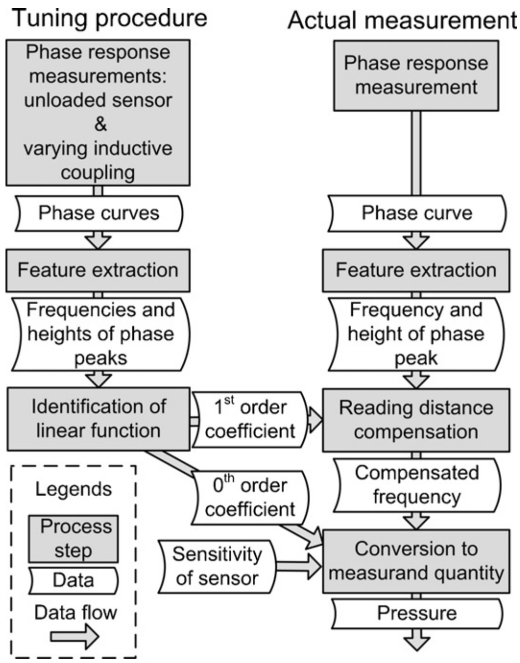

Fig. 1. The flow chart of the measurement process.

method for compensating the errors in the measured values related to the changes in the inductive coupling coefficient.

2. Methods

In order to make a robust and easy-to-use instrument capable of reading sensors in a wide frequency range, an impedance analyzer-like approach combined with PC post processing was adopted. In this approach, the small portable measurement instrument sweeps over the specific frequency range and measures the phase response of the resonance sensor, which is an LC-resonance circuit with a pressure sensitive capacitor. The PC post-processing software calculates an estimate for the resonance frequency and compensates the error caused by the varying reading distance. The flow chart of the developed measurement process is illustrated in Fig. 1.

2.1. Instrumentation

The measurement instrumentation (Fig. 2) used in this work includes the measurement unit, the measurement cable (regular 50 Ω coaxial), the reader coil (average diameter 4.8 cm) and the wireless pressure sensor. The radio frequency section of the designed measurement unit is shown in Fig. 3. The excitation signal is generated with a direct digital synthesizer (DDS). This type of oscillator has a wide output frequency range (unlike VCOs), very fine frequency resolution (unlike fast PLLs) and the output frequency changes almost instantly (unlike PLL's output). These features enable fast frequency sweeps over wide frequency ranges with adjustable step size. After filtering and amplification, the signal is fed to a low pass – high pass type phase shifter. Such a phase shifter produces two outputs, which have relatively frequency-independent phase difference between them. One of the generated phase-shifted signals is then fed to the reader 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 input signal of the phase detector (Analog Devices' AD8302) to mid-scale, so that it can measure both leading and lagging phase differences (±90° maximum) unambiguously. The phase detector then measures

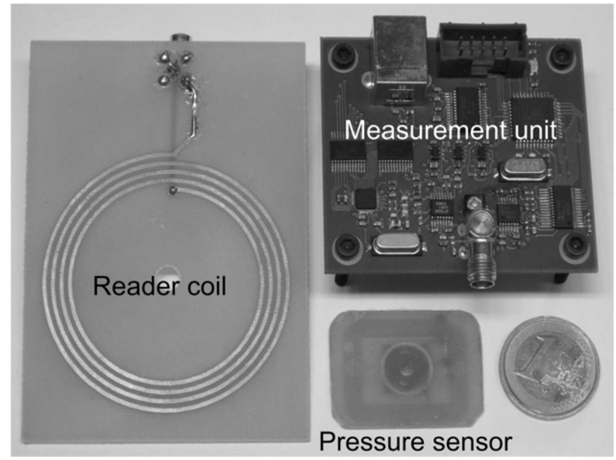

Fig. 2. The instrumentation used in this work.

the phase difference between the reference and the reader coil signals.

The measurement unit also contains a microcontroller unit (MCU) for controlling the DDS and communicating with the PC via a USB port. A fast 12-bit ADC is used to convert the output of the phase detector to numerical form. The MCU communicates with the PC and performs the requested frequency sweeps at the specified speed and with the specified starting and ending frequencies. The measurement unit is able to measure frequencies between 8 MHz and 80 MHz. The device is also able to measure the magnitude simultaneously with the phase but this option is not used in this study. The methods used to extract the measurand are based on the changes in the shape of the measured phase response curve, especially the shift of the resonance peak along the frequency axis. The main design objectives of the instrumentation are speed and the repeatability of the shape of the phase curve. Thus, the accurate measurements of the true impedance phase values are not required and the measured phase curves may differ from the values measured with an impedance analyzer [16].

2.2. Characteristics of the measured data

The measurement instrument sweeps over the specified frequency range at regular time intervals. Thus, the measured data consist of the series of phase response curves. Each curve contains phase values at discrete frequencies. If there is a resonance sensor present in the vicinity of the reader coil, it will alter the phase curve by forming a peak. The measured curve also has other features, like the gradual phase change and noise caused by the instrumentation. These other features can be more pronounced than the peak caused by the resonance sensor itself. An example of raw data is shown in Fig. 4a. The measured phase values are the combination of phase shifts caused by the circuit elements in the measurement unit, the measurement cable, the reader coil and the reflected impedance of the sensor circuit. The reflected impedance is based on the impedance of the sensor circuit, but it is modified by the inductive coupling. The inductive coupling between the coils depends on the coil geometry, the distance between the coils and their orientation. In Fig. 4a, the phase peaks are measured at two distances, 15 mm and 20 mm, between the reader coil and the sensor coil with no extra load on the sensor. Each data point is the mean of 220 individual observations. Note that, the measured resonance peaks appear at different frequencies, because of the different inductive coupling. In most real applications, the distance and orientation are unknown. This makes the frequency of the phase peak ambiguous to explain the measurand. The severity of the error caused by this

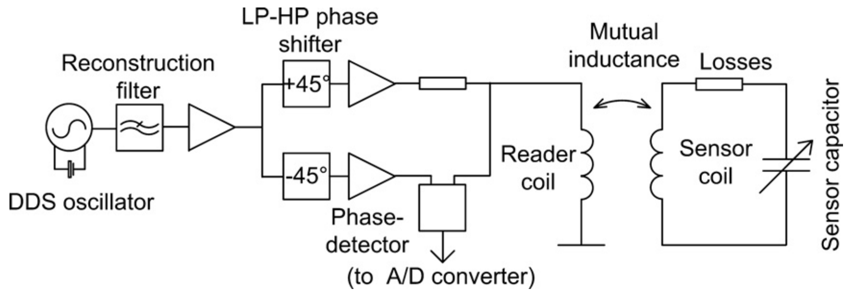

Fig. 3. The radio frequency section of the measurement unit.

phenomenon depends on the instrumentation, the application, and the sensitivity of the resonance sensor.

2.3. PC post processing

A laptop PC is used for post processing the data to take advantage of the versatility and computational power at this stage of the sensor development. The aim of this post processing is to extract a frequency value that can be linked to the measurand unambiguously. The used post processing has two steps: the feature extraction and the reading distance compensation. The feature extraction algorithm is used to describe the measured phase curves in the phase data with two features (the frequency of the maximum value of the phase peak and the height of the phase peak). The second post processing step removes the reading distance related ambiguity by using the extracted features. Finally the compensated frequency reading is converted to a measurand quantity by using the measured sensitivity of the sensor.

2.3.1. Feature extraction

The measurand affects the shape of the phase curve. In this application it is sufficient to characterize the shape with two features, the relative frequency and relative height of the phase peak in the phase response. These features are relative to the baseline of the phase curve, which is typically a descending slope. As the measurement method is based on how the measurand alters these features, their relation to true phase or frequency values are of no interest.

The feature extraction algorithm consists of the following steps:

(1) Remove the baseline
 - Fit and remove the linear trend
(2) Detection of the peak frequency
 - Select data points around the phase maximum
 - Fit a 3rd order polynomial
 - Evaluate the frequency and the phase values of the maximum
(3) Detection of the peak height
 - Limit data between the first measured value and the detected peak
 - Remove linear trend
 - Select data around the minimum
 - Fit a 3rd order polynomial
 - Evaluate the phase value of the minimum
 - Subtract the minimum from the maximum detected in step 2

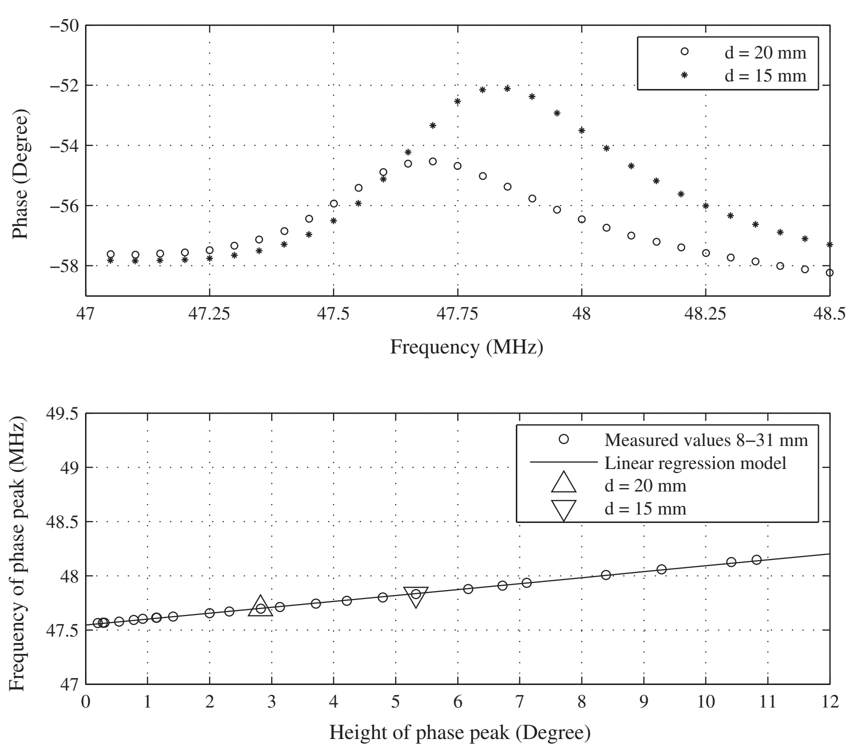

Fig. 4. (a: upper) The phase data measured at the distances of 15 mm and 20 mm with no extra load on the sensor; (b: lower) The frequency of the detected phase peaks and the corresponding heights of the phase peaks.

The first step removes the linear trend from the phase curve. This is necessary to facilitate the detection of the resonance peak, which in some cases can be a negligible elevation of the base slope and hard to detect. In this step a straight line is fitted to the phase curve by minimum least squares and the fitted line is subtracted from the phase curve.

The second step finds a value for the frequency (f_m) of the resonance peak. After the trend removal even a small bend in the original phase curve will show up as a distinct maximum. Next, the measurements around the maximum are selected by discarding the values below a certain percentage of the maximum. In this paper 10% was used. The actual measurements are performed at discrete frequency values. A 3rd order polynomial is fitted to the data around the maximum to interpolate the frequency of the maximum. A 3rd order polynomial estimates the frequency of the maximum well also when the peak is not symmetrical. The phase value is also evaluated at the frequency given by the polynomial. Note that the trend removal rotates the resonance peak and the frequency value is not the same as the true peak frequency. However this method is more robust in detecting less distinct resonance peaks and the relative transition of the peak along the frequency axis is the key event in the method.

Finally, the third step calculates the height (θ_m) of the resonance peak. In addition to the maximum phase value detected in step 2 a minimum value is required. A turning point just before the maximum was chosen as the minimum value. This has proven to work well in this application and is detected as follows. The phase curve is limited to frequencies lower than the frequency of the maximum that was detected in step 2. A linear trend is removed from this part of the phase curve (as in step 1). Now the turning point shows up as a minimum. The data around the minimum is selected and a 3rd order polynomial fitted as in step 2. The phase value of the minimum of the fitted polynomial is evaluated. The height of the resonance peak is calculated by subtracting the minimum value from the maximum value detected in step2.

2.3.2. Reading distance compensation

Interpretation of the measured phase peak frequency is ambiguous because of the inductive coupling. In the tested application this means that the reading distance will affect the frequency of the found phase peak maximum. This will cause an error when the measurand is calculated from the change of the resonance peak maximum. In our post processing method, this error is compensated within a certain range of reading distances. The compensation is based on a tuning procedure which gives us information about the relation between the extracted phase peak features when inductive coupling is varied. This information is used to compensate the reading distance related error in the actual measurement.

The reading distance compensation consists of the following steps:

(1) Tuning procedure
  - Measure the phase responses while the measurand is kept constant and inductive coupling is varied
  - Extract the features (f_m and θ_m) for each phase response measured during tuning procedure
  - Indentify a function between extracted features: $f_m = g(\theta_m)$. In this paper the function was assumed to be linear: $g(\theta_m) = p_1\theta_m + p_2$
(2) Compensation of the extracted phase peak frequency value
  - Extract the features of a phase peak (f_m and θ_m) from the measurement data
  - Calculate a compensated frequency value: $f_c = f_m - p_1\theta_m$

The tuning procedure is usually performed before the actual measurement. The idea of the tuning procedure is to identify a function between the features of the phase peak ((f_m and θ_m)) while inductive coupling is varied and the measurand is kept constant. In the case of the tested pressure sensor, several phase responses are measured while there is no pressure on the sensor and the measurement distance is varied. Next the features of the phase peak are extracted and a function is indentified between extracted features.

In order to illustrate this procedure, in Fig. 4b, the frequencies of the phase peaks are plotted against the heights of the phase peaks. The data are measured at the distances ranging from 8 mm to 31 mm with 1 mm intervals. The actual distance values, however, are not needed for compensation. According to this data, we can identify a linear function between the extracted frequency (f_m) of the phase peak and the extracted height (θ_m) of the phase peak: $f_m = p_1\theta_m + p_2$. The coefficients p_1 and p_2 are identified by least mean square (LMS) regression. The coefficients in this example data are: $p_1 = 0.0546$ MHz/° and $p_2 = 47.545$ MHz. The coefficient p_1 describes dependency between the frequency and the height of the phase peak. The coefficient p_2 is an estimate for the frequency of the phase peak in a situation where coupling between coils is weak or insignificant.

In order to get a reading distance compensated frequency reading, a phase curve is measured and the features of the phase peak are extracted as described in the Section 2.3.1. The compensated frequency value f_c is calculated by subtracting the product of the corresponding phase peak height and the coefficient p_1 from the extracted frequency of the phase peak ($f_c = f_m - p_1\theta_m$). In other words, we solve f_c from equation $f_m = p_1\theta_m + f_c$. The coefficient p_1 is acquired from the tuning procedure and it is assumed to be constant within the measurement period.

Note that, in this method we need only a simple tuning procedure before the actual measurement which can be done by moving the sensor back and forth in the vicinity of the reader coil. We do not need to know the value of the inductive coupling coefficient or the actual reading distance. Also, there is no need to measure the values of the components of the readout or sensor circuitry. This is an advantage, if for example, sensors are mass-produced and component values vary or the inductive coupling or range cannot be measured in the application.

2.3.3. Conversion to measurand quantity

The last post processing step is to convert the compensated frequency value to the measurand value. The measurand in this application is the change in pressure compared to the situation where there is no stimulus pressure on the sensor. First, the change is determined as a frequency value. The initial value for frequency is acquired from the tuning procedure (coefficient p_2). The change in frequency is calculated by subtracting the coefficient p_2 from the compensated frequency value. The difference is converted to a pressure value by using the measured sensitivity of the sensor. The relation between the change of frequency and the change of the pressure is not linear by nature. However, in this case assumption of nearly linear behavior is made within the dynamic range of the sensor.

2.4. Pressure sensor

The sensor developed in this study is an LC-resonance circuit with a pressure sensitive capacitor. The sensor has a dual-layer structure (Fig. 5) consisting of a planar coil on a PCB (printed circuit board) and a pressure sensitive capacitor made of partly metal coated PDMS silicone (polydimethylsiloxane). The PDMS component of the sensor is fabricated by molding. The mould was created with a milling machine. There is a circular cavity in the PCB that allows PDMS to deform. The physical dimensions of the sensor are: height 2.2 mm, width 16 mm and length 34 mm. The planar coil has rectangular shape with four turns with the average dimensions of

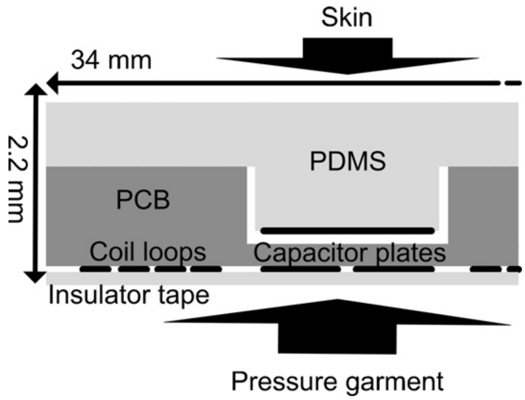

Fig. 5. The cross-sectional view of the pressure sensor.

19 mm by 24 mm. If the pressure is applied to PDMS membrane, it deforms and the metal plate on it moves closer to the two electrode surfaces on the PCB. This alters the two variable capacitances in the sensor circuit (Fig. 6). A fixed capacitor in the circuit moves the resonance frequency of the sensor to the range of the measurement unit. Electrically floating metal plate on PDMS silicone membrane eases the manufacturing of the sensor since there is no need to make a deforming electrical connection to that plate. The backside of the sensor is covered with insulating tape. There is also a hole in the PCB in order to allow air to escape from the cavity when the membrane is deformed. The leading design principles of the sensor were to keep it simple and to avoid microfabricated structures. This will enable affordable mass production and disposability. Another reason for not using somewhat fragile microfabricated structures is the need to withstand significant overloading and rough handling.

3. Pressure garment application

The developed methods were used to measure pressure in pressure garment application. This measurement requires good DC-signal accuracy since we want to monitor the pressures ranging from near zero to 50 mmHg. This measurement is important for pressure garment treatment in order to ensure the proper functioning of the used garment. The principle of the measurement in a pressure garment application is illustrated in Fig. 7. In this application, the reading distance and angle between the coils are unknown and cannot be accurately controlled.

In a pressure garment measurement, the sensor is attached to the skin with an adhesive bandage. PDMS-side of the sensor is facing the skin and adhesive bandage gives support to PCB-side. The tuning procedure is performed by moving the reader coil back and forth in the vicinity of the sensor. The tuning procedure enables reading distance compensation and gives a compensated frequency reading of the sensor without the pressure garment. Then the pressure garment is worn and the new compensated frequency is acquired. The pressure reading is obtained by subtracting unloaded frequency value from the loaded one and converting the frequency to pressure by using the sensitivity of the sensor.

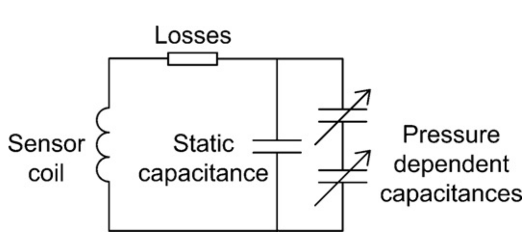

Fig. 6. The electrical equivalent circuit of the pressure sensor.

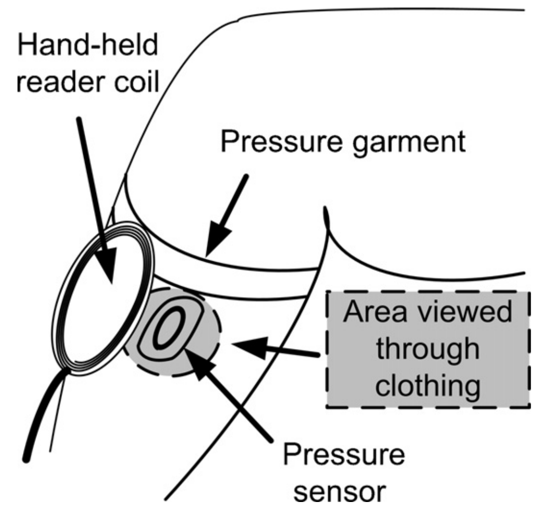

Fig. 7. The principle of measurement in the pressure garment application.

4. Results

The developed measurement system is tested in a test rig, where the pressure can be controlled. The sensor is placed on a rigid plastic plate and the pressure is directed to the PDMS side of the sensor. The pressure is created by using a rubber film which is attached to the opening of a plastic container and the calibration pressure inside the container is modified by using pressurized air. The plastic plate and the sensor on it are firmly attached to the container. The rubber film directs air pressure to the sensor. The air pressure of the container is measured with a pressure calibrator (Beamex PC105). The sensor is read through the plastic plate with the reader coil at varying unknown distances using the sampling rate of 15 Hz. The reader coil is manually held in the vicinity of the sensor (approximately at the distance from 1 cm to 4 cm) and so the distance and the angle between the coils may vary during measurements. This approach was taken, because it simulates the situation of the intended application. The range of the frequency sweep is from 45 MHz to 50 Hz with 0.05 MHz intervals.

4.1. Tuning procedure

First, the pressure is set to zero and the tuning procedure is performed by moving the reader coil back and forth in the vicinity of the sensor and reading the sensor signals through the plastic surface (214 observations). The data of the tuning process are illustrated in Fig. 8. The measured frequencies of the phase peaks are plotted against the corresponding heights of the phase peaks. The actual distance and the angle between the reader coil the sensor coil are unknown. The data points with a limited height (93 points ranging from 0.6 to 6°) of the peak are selected and used in linear regression modeling. The lower limit is set because of the noise and the higher one because of the capacitive coupling between coils at the short distances. The selected points are shown in Fig. 8. The coefficients of linear regression model are: $p_1 = 0.0462\,\mathrm{MHz}/^\circ$ and $p_2 = 47.537\,\mathrm{MHz}$.

4.2. Calibration

In order to measure the sensitivity of the sensor, the calibration pressure is increased to 30 mmHg by 5 mmHg intervals and phase data are recorded (100 observations for each pressure). In Fig. 9, the compensated frequencies are plotted against of the calibration pressure. Even thought the relation of the pressure and the resonance frequency of the sensor is not linear by nature or according

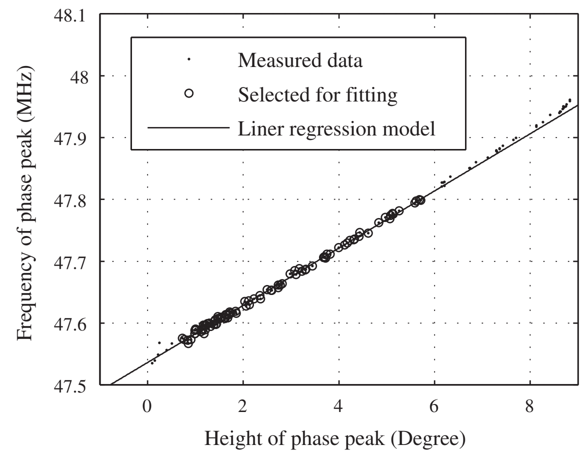

Fig. 8. The parameters required for the measurement distance compensation are acquired from the phase peak frequency-phase peak height data with linear regression modeling. This data is measured by altering the inductive coupling while keeping the measurand constant.

to this data, we decided to estimate sensitivity within this pressure range by using a linear regression model. The sensitivity of the sensor is estimated to be −10.7 kHz/mmHg. While the pressure increases, the capacitance increases and the resonance frequency decreases.

4.3. Test rig measurement

The measurement method is evaluated in the test rig by measuring test pressures from 0 mmHg to 35 mmHg by 5 mmHg intervals. The compensated frequency readings are converted to pressure by using the sensitivity value of the sensor. The mean of the 100 observations are shown in the Fig. 10a. The mean of the absolute errors and the two sigma limits of the error are shown in Fig. 10b. As the pressure approaches 35 mmHg, the signal of the sensor starts to saturate. The maximum error (nearly 3 mmHg) occurs at the pressure of 30 mmHg. The absolute error is the smallest in the middle of the pressure range (0–30 mmHg).

4.4. Pressure garment measurement

Finally, we test the developed methods in the pressure garment application. The sensor was attached to a leg with an

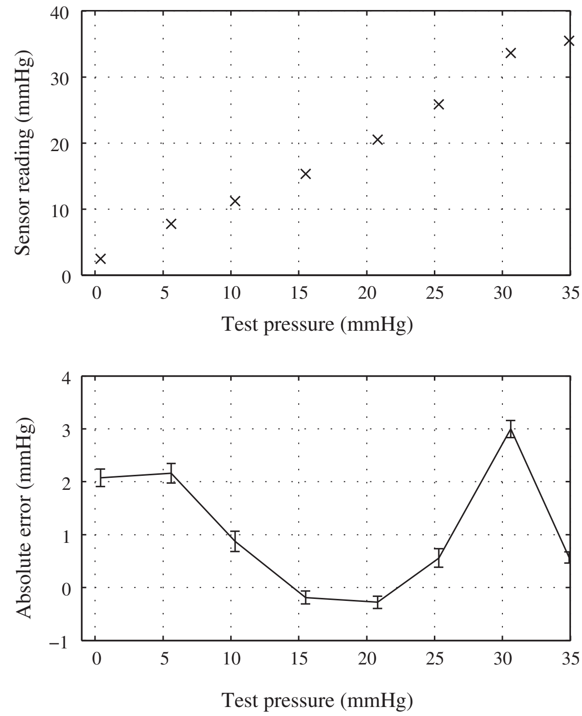

Fig. 10. (a: upper) The response of the sensor was measured with test pressures ranging from 0 mmHg to 35 mmHg; (b: lower) The absolute error of test measurements.

adhesive bandage. The tuning procedure was performed in order to get resonance frequency without the pressure garment. The coefficients of this linear regression model are: $p_1 = 0.0525$ MHz/° and $p_2 = 47.464$ MHz. Next, a custom-made pressure garment was worn. The garment has been designed to form a pressure of over 20 mmHg. Besides the pressure garment, the actual pressure on the sensor is also modulated by the position of the leg for example. The reader coil was moved back and forth in the vicinity (1–4 cm) of the sensor and the reading of the sensor was read at the sampling rate of 20 Hz. The test lasted 10 s. The compensated pressure readings are presented in Fig. 11. The uncompensated reading is also shown in order to demonstrate the need for compensation in this case. The uncompensated reading approaches the compensated reading when the reader coil is far away from the sensor and

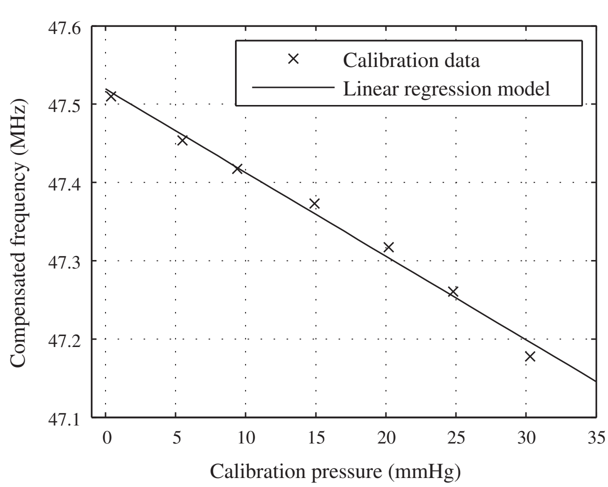

Fig. 9. The sensitivity of the sensor was measured in a test rig by using pressure excitation and linear regression modeling. The sensitivity is −10.7 kHz/mmHg.

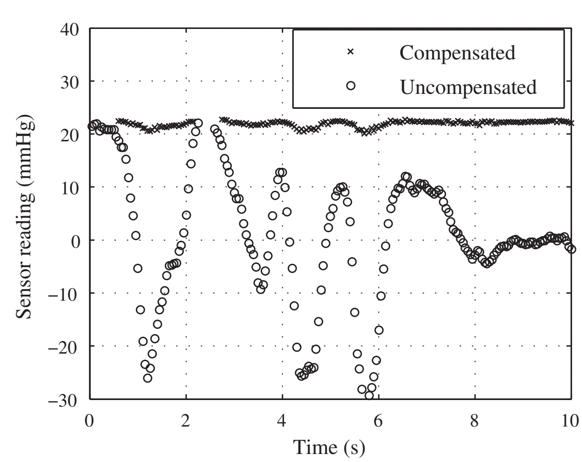

Fig. 11. The pressure between a pressure garment and skin was measured by using a hand-held reader coil. During the measurement, the reader coil was moved back and forth in the vicinity of the sensor. The benefits of the developed compensation method are clear.

vice versa. Even thought the bias of the uncompensated readings could be adjusted, the fluctuations are severe. The average of the valid compensated readings is 22.0 mmHg and the standard deviation is 0.6 mmHg. The maximum difference between the signal and the average (−1.9 mmHg) occurs at the time of 4.6 s when the reader coil is near the sensor. At around three second, the reader coil is too far from the sensor and out of the range. The invalid measurement values are discarded.

5. Discussion

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 are worthwhile endeavors. 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.

At the moment, the pressure range of the sensor does not cover the range needed in pressure garment application (from 0 mmHg to 50 mmHg). The pressure range can be modified by altering the geometry of the sensor. This, however, may lead to problems with the increased nonlinearity of the pressure-frequency dependency of the sensor. This nonlinearity already causes an error according to the data in Fig. 9. One solution for this nonlinearity problem is to use more complicated methods to convert the measured frequency to the pressure reading (lookup tables, linearization methods, calculating the pressure from electrical and mechanical models by using measured constant parameters and the measured resonance frequency). The pros and cons of more complicated systems have to be evaluated against the present system, especially if the number of the used sensors is increased and the component parameters have variation. Having individual lookup tables or measuring multiple component values for each disposable sensor is not a realistic solution. Also, the measurement of the sensitivities of the individual sensors should be avoided if possible.

The measurement distance compensation seems to work well in pressure garment application with the used sensor according to the data in Fig. 11. The limitations of this compensation system should be determined. For example, this method in the presented form will not work if there is significant capacitive coupling between the link coils. This occurs when the coils with similar windings are brought near to each other. This may be the reason for the fluctuation of the compensated reading in Fig. 11 when the coils are near each other. This can be solved by adjusting the limits for the valid phase peak heights. This limits the distance range of the compensation. Another issue is the frequency range of this compensation. The phase response of the device is not totally flat. In the case of designed sensor and reader coil, the phase peak frequency-phase peak height dependency is linear. Whether this applies to other sensor configurations or other measurement environments has to be determined. If the angle between reader coils can be compensated in this way, has to be studied. The presented compensation method and procedures will be further studied in the future.

A tuning process is needed to determine the phase peak frequency-phase peak height dependency. The tuning process includes altering the reading distance. The data processing is automated but the distance is altered manually at the moment. In the pressure garment application, the measurement with alternating reading distance with no stimulus on the sensor can be easily arranged. It is challenging to keep the measurand constant in some applications for example ECG measurement or in the case of implantable measurements. The coefficient p_1 seems to vary according to the performed measurements. This may happen due to the different measurement environments around the sensor configuration or it may just be a result of the difference of the movements of the reader coil during the tuning procedure.

6. Conclusions

An inductively coupled passive pressure sensor and the required readout methods were tested in a pressure garment application. The readout methods also include a method to compensate unknown inductive coupling. The overall performance and the versatility of the used readout methods justify the further studies. In the tested application, the wireless measurement method will give an advantage over the earlier methods, because the wiring or tubing makes the wearing of the pressure garments on damaged skin unpleasant. The compact hardware of the system can also be utilized in other portable applications, since the developed device can be used instead of the network or impedance analyzers as a readout device for inductively coupled resonance sensors. A possibility to take the measurements out of laboratory conditions will endorse the development of passive resonance sensors.

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