Non-contacting Monitoring of Respiration and Pulse Based on Capacitive Coupling with Thoracic Tissue

Daniel Teichmann, Jérôme Foussier, Jing Jia and Steffen Leonhardt

***Abstract*—In this paper a system using mutual capacitive sensing for non-contacting monitoring of respiration and pulse is described. The principle is based on two metal electrode plates changing their capacitance due to variations of the dielectric properties of biological tissue. The system's sensitivity to the dielectric properties of an object is verified by laboratory tests.**

By oppressing precordial motion towards the sensor surface, the potential of this sensor principle for monitoring inner thoracic activity, i.e. inner organ boundary displacements due to respiratory and cardiac activity, can be proved.

***Index Terms*—non-contacting, tissue properties, capacitive sensing, respiration, pulse.**

I. INTRODUCTION

PHYSIOLOGICAL activity can be measured without contact by electromagnetic coupling. A commonly used technique is magnetic induction monitoring. Here an alternating magnetic field induces eddy currents into the body. These eddy currents generate a secondary magnetic field correlating with respiratory and cardiac activity [1],[2]. The main source for measurement errors is parasitic capacitive coupling, mainly by the stray capacitances between the surfaces of the sensor and the thorax [3].

Another method for non-contacting monitoring physiological activity is to measure the electromagnetic coupling between the thorax and the sensor capacitively instead of inductively. Generally, self (or surface) as well as mutual capacitance type sensors can be used for this purpose.

Using the self capacitance type [4], the capacitance between an electrode surface, i.e. a metal plate, and the thoracic wall is measured. This means that the effect, identified as the main source of errors when monitoring by inductive coupling, is used now as the recorded signal. Since this measurement is completely caused by motion of the precordium, it is not directly sensitive to motion of the inner thoracic organs. Therefore, it is not possible to distinguish between motion due to lung or heart and other motion performed by the subject. Furthermore, if deriving a cardiac related signal content is desired, only measurement positions in front of the heart seem to be feasable, because otherwise the change in the air gap distance between thorax and sensor electrode due to heart motion would be too low.

The mentioned disadvantages of the self capacitance type sensor could be reduced by using a sensor based on mutual capacitance. Here the mutual capacitance between two planar electrode plates is measured and varies when placing a body in front of the electrodes depending on the electric properties of the body.

Although the use of mutual capacitance sensors for non-contacting monitoring by electromagnetic coupling has come up during the last decade, its origin lies in 1932 when Atzler et al. [5] used this measurement principle for the first time.

Korjenevsky et al. [6] applied this technique in a relatively complex scenario by using several measurement channels in order to obtain tomographic images. To our knowledge this group has not conducted in vivo measurements, so far.

Oum et al. [7] integrated the capacitive sensor into a LC oscillator based measurement circuitry as it is known from several magnetic induction monitoring systems [1], [8], [2]. They attached the sensor electrodes onto the chest and showed good correlation between the derived signal and respiration as well as pulse. They made no attempts to distinguish between signal contents due to precordial and inner organ motion. They stated in [9] that precordial motion was measured but did not further substantiate it.

In this paper we present measurements of dielectric samples as well as of a healthy volunteer, to prove the method's sensitivity to dielectric object properties and inner thoracic activity. Furthermore, we show for the first time that using this method it is possible to obtain cardiac activity even when measuring form the rear side of the subject.

II. MATERIALS & METHODS

In II-A the physical principle of the measurement method is briefly described and an overview of the developed system is presented. The setups of the measurements carried out in this work are described in II-B.

A. Monitoring System

If an alternating voltage is applied onto two metal electrode plates, they excite an alternating electric field. Placing a dielectric object in the vicinity of the electrodes changes the electric field due to the displacement currents induced into the object. This principle can be seen in Fig. 1.

In other words, the two electrode plates form a capacitance C_{sensor}. Next to the size and the distance of the electrodes, their capacitance depends on the dielectric material between them.

During breathing as well as heart beating, the boundaries of the inner organs will displace. Hence, there will be a variation of the conductivity as well as permittivity distribution within the thorax that changes the capacitance of

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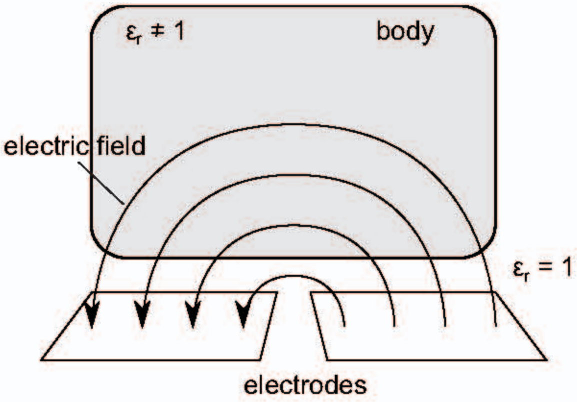


Fig. 1. Physical principle

the electrodes. Measuring this change in capacitance yields information about respiration and pulse.

An overview of the developed system is presented in Fig. 2(a). The capacitive sensor head formed by the two electrode plates is a frequency-determining part of a Colpitts oscillator. This means that the sending frequency of the electric field is equal to the oscillatory frequency. If the capacitance of the sensor head changes due to variations of the dielectric properties within the object, the working frequency of the oscillator changes as well. This change in frequency can be measured and is the derived signal. Thus, the system is based on frequency modulation while changes within the object cause this modulation.

The actual system can be seen in Fig. 2(b). The electrode plates are realized by etched copper squares on a printed circuit board. These squares have a diameter of 3 cm and their centers are placed in a distance of 5 cm. In order to reduce parasitic capacitive coupling the oscillatory circuit is shielded by a grounded aluminium housing and is placed near to the electrode plates without the use of cables. The alternating signal of the oscillator is transmitted to a frequency counter by a coaxial cable.

The frequency counter is realized by using the counter input of a microcontroller (MSP430F5435). Therefore, the oscillator output is rectified and passed to the counter. The value of the counter C during a constant gate time $T = 130\ ms$ is read out and the oscillatory frequency is derived by

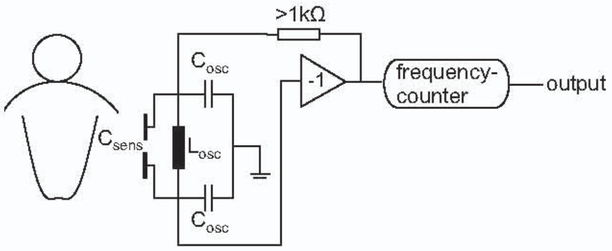
$$f_{meas} = \frac{C}{T} \qquad \Rightarrow f_{meas,min} = 7.7\ Hz \tag{1}$$

Choosing the gate time is a trade off, since a longer gate time enhances the frequency resolution but unfortunateley also increases the probability of smearing the monitored signal information. The read-out of the counter is performed with a sampling rate f_{sample} of 30 Hz, i.e. the gate intervals are interlaced.

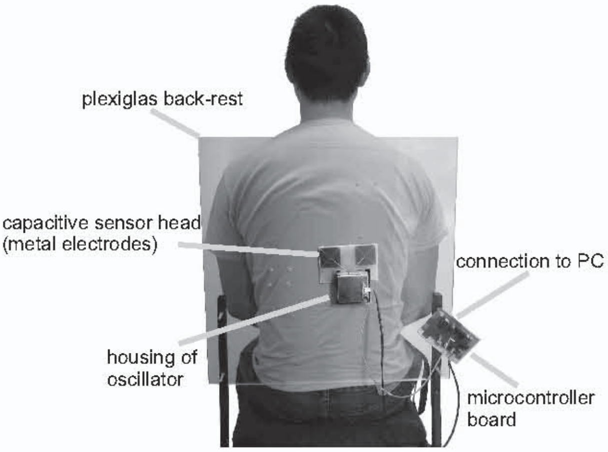
Additionaly, the simultaneous measurement of two reference sensors is possible. The data is transmitted via USB to a PC where the signal is displayed and recorded by a Graphical User Interface programmed in MATLAB.

B. Measurement Setup

The setups of the measurements carried out in this work are presented in the following.



(a) System overview.



(b) Actual system attached to a chair.

Fig. 2. Design of the developed system for non-contacting monitoring respiration and pulse by capacitive coupling.

1) Measurement of Different Dielectric Samples: In order to access the system's sensitivity to dielectric changes, samples of different permittivity but equal volume have been placed in front of the capacitve sensor head in a defined distance of 7 mm. The inductive value of the oscillatory tank was $L = 1.5\ \mu H$, the damping resistance $R_L = 0\ \Omega$ and the oscillatory capacitance $C_{osc} = 500\ pF$. The working frequency was $f = 13\ MHz$.

The different sample materials and their permittivity can be found in table I.

TABLE I
DIELECTRIC SAMPLES FOR PERMITTIVITY MEASUREMENTS [10][11].

dielectric material	relative permittivity ϵ_r
paper	1,5
oil	3
salt	5
ethanol	25
deionized water	80

Additionally, the value of the oscillatory tank capacitance C_{osc} has been decreased successively while measuring the frequency response to a fix relative permittivity of $\epsilon_r = 80$, in order to investigate the effect of C_{osc} on the sensitivity of the sensor.

2) Measurement of thoracic activity: Although by measuring the mutual capacitance information about the tissue properties is obtained, the signal is still sensitive to thoracic wall motion due to the coupling capacitance between the sensor surface and the thoracic wall. In order to obtain signal changes that are completely caused by the changes of electric tissue properties, the distance between sensor and subject had

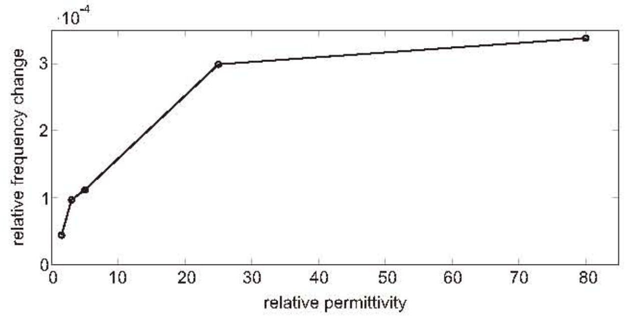


Fig. 3. Frequency response in dependancy on permittivity

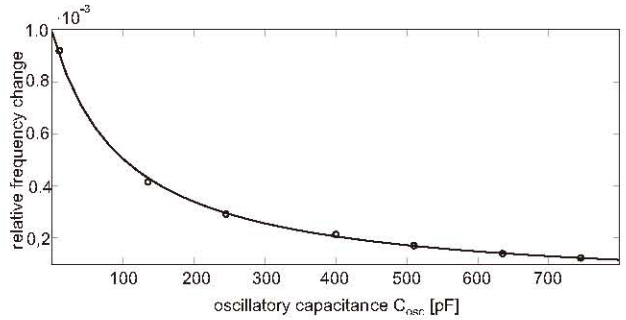


Fig. 4. Frequency response in dependancy on oscillatory capacitance C_{osc}

to be kept constant. This was achieved by attaching the sensor to the rigid back-rest of a chair (see Fig. 2(b)) instead of placing it in front of the chest. The 1 cm thick back-rest was build out of transparent plexiglas facilitating the positioning of the sensor in respect to the subject's back.

The subject was asked to perform 60 sec of normal breathing. The recorded signal was digitally bandpass-filtered (f_{low} = 0.08 Hz and f$_{high}$ = 10 Hz) by the sequential application of a low and a high pass FIR-filter.

A flow meter and a finger pulse plethysmographic sensor (PPG) were measured simultaneously as reference signals for respiration and pulse, respectively. The working frequency of the sensor was $f = 13\ MHz$.

III. RESULTS

The results presented in this section correspond to the measurement setups described above.

A. *Measurement of Different Dielectric Samples*

The relative frequency response of the capacitive sensor in dependancy on different dielectric samples is presented in Fig. 3. It shows a clear logarithmic dependancy on the relative permittivity.

Very interesting is how the oscillatory capacitance C_{osc} affects the relative frequency change which can also be interpreted as the sensitivity of the sensor. In Fig. 4 the relative frequency change in dependancy on C_{osc} is plotted. With decreasing C_{osc}, the sensitivity increases significantly. A regression curve has been plotted over the measuring points. Its equation is

$$y = 0.088368 \cdot x^{-0.97252} \qquad (2)$$

and the coefficient of determination is $R^2 = 0.9989$.

B. *Measurement of thoracic activity*

In Fig. 5(a) the recorded signal during the whole measurement period is presented with the signal of the flow meter overlayed as a reference for respiration. The good correlation between the sensor signal derived by capacitive measurement and the flow meter indicates a high sensitivity of the sensor to respiration. Noting the different waveforms of the two signals (and considering flow as the first derivative of volume) attests that the derived sensor signal has to be interpreted as information linked to lung volume. It has to be stated that the breath-related signal content is very dominant and nearly suppresses the cardiac activity.

When examining the signal in a small time interval of a single respiration cycle as it is plotted in fig 5(b) and comparing it to the recorded reference PPG signal a cardiac related signal content is easily noticeable. This is further verified by observing the same interval in the frequency domain. This is illustrated in Fig. 5(c) where the FFT of the signal is presented. The derived capacitive sensor signal and the PPG signal show both a significant peak at 1.25 Hz. Nevertheless, the signal-to-noise ratio is quite high.

The correlation with the PPG signal demonstrates that, when the heart is moving, the displacement of its wall alters the permittivity distribution within the thorax. Hence, this can be monitored in a non-contacting way by the developed capacitive sensor.

IV. DISCUSSION

The results in chapter III attest the system's sensitivity to permittivity changes of an object as expected by the model principle in II-A. Nevertheless, it has to be stated that this model is simplified, because biological tissue is not an ideal dielectric medium but a lossy one.

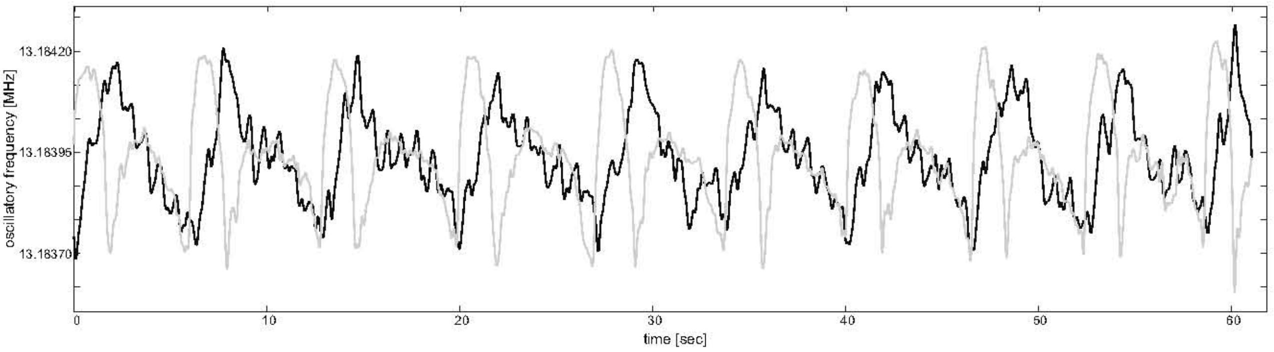
Furthermore, in chapter III it was found out that the sensitivity of the sensor can be enhanced by decreasing the capacitance C_{osc} of the oscillatory tank. This can be qualitatively explained, since decreasing C_{osc} let the sensing capacitance C_{sens} become more dominant. Unfortunately, reducing C_{osc} is limited by the fact that it yields to an increase of the sending frequency ω_s and hence lowers the penetration depth ρ of the electric field [12]:

$$\delta = \sqrt{\frac{2}{\omega_s \mu_0 \mu_r \sigma}} \qquad (3)$$

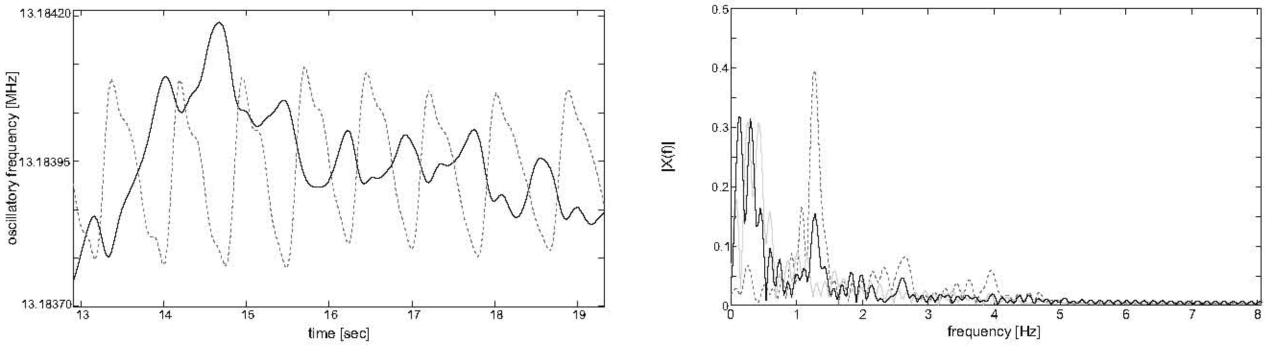
As penetration into the body is necessary, if measuring tissue properties is desired, this can only be tolerated to some extend.

The signal-to-noise ratio appeared to be very low making it difficult to assess cardiac activity. Due to the frequency modulation technique the developed system is based on, frequency noise has to be reduced. This reduction can be achieved by increasing the Q factor of the oscillator. It is possible that the Q factor of the oscillator is lowered by current losses inside the aluminium housing of the oscillatory circuitry that are induced by the electric field of the sensor electrodes. Therefore, choosing a higher distance between sensor head and the housing including the circuitry could decrease frequency noise.

If measuring by mutual capacitive sensing, the coupling path consists of the capacities between the electrode surfaces



(a) Signal of the capacitive sensor in MHz (black) and the absolute value of the flow meter in a.u. (grey) during whole measurement interval



(b) Signals of capacitive sensor in MHz (black) and PPG in a.u. (grey dashed) during a single respiration cycle

(c) FFT of capacitive sensor (black), flow meter (grey solid) and PPG (grey dashed) durig the single respiration in 5(b)

Fig. 5. Measurement of thoracic activity during normal breathing; sensor signal is given in MHz, reference signals in Arbitrary Units (a.u.)

and the thoracic wall and the capacitance formed by the body tissue due to its permittivity. Measurements presented in III-B prove that it is possible to measure respiration as well as pulse by capacitive coupling, even if any motion between the sensor surface and the thoracic wall is inhibited by performing the measurement from the patient's rear side and by using a rigid plate, in our case the chair's back-rest. Using this setup, signal changes due to changes of the body-object distance are reduced. Thus, signal changes have to be caused by the electric properties of the thoracic surface. Respiration and pulse related signal contents were therewith evoked by motion of the inner organs.

V. CONCLUSION

A system for non-contacting monitoring of thoracic activity by mutual capacitive sensing was developed. It consists of two electrode plates and a low energy measurement circuitry. The working frequency of the emitted electric field is 13 MHz. The sensor's sensitivity to the dielectric properties of measured objects was verified by laboratory tests.

A measurement using the sensor on a healthy volunteer during normal breathing was also conducted. While reducing any effect due to precordial motion, it was possible to monitor inner thoracic activity, i.e. inner organ displacements due to respiratory and cardiac activity.

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