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Eliminating the Trade-off Between Resolution and Sampling Rate in Magnetic Induction Based Cardiorespiratory Sensors

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***Abstract*— This paper proposes a novel algorithm that allows a significant improvement of the resolution of frequency modulated magnetic induction sensors while providing high sampling rates. We have implemented this approach in a frequency modulated magnetic induction sensor and our first measurements demonstrate the improvement of the sensor's signal quality.**

I. INTRODUCTION

Home monitoring setups need a non-contact and reliable respiration rate monitoring method for broad adoption [1]. This paper describes a high-resolution frequency-modulated magnetic induction sensor for non-contact monitoring of respiration and heart rate. The measurements are not affected by the subject's clothing. The system promises real-life applications in multiple settings as it can operate without any transducers and cables attached to the body.

Compared to similar devices [2][3][4], the system we present in this paper provides a significant improvement of, both, measurement resolution and sampling rate. This is achieved through a novel frequency measurement algorithm that is discussed in the Methods section.

II. METHODS

A. Measurement Principle

Cardiorespiratory magnetic induction sensing is based on the interaction between a sensing coil and the thorax. The current that flows through the coil excites a magnetic field that interacts with the body. This interaction causes changes in the reflecting impedance of the coil.

The most common setup for single coil induction sensor measurements is to use the coil as the frequency determining part of an oscillator. The frequency of the current changes with the impedance of the coil, and hence with respiration and heart rate. This results in a frequency-modulated cardiorespiratory sensor.

B. Algorithm

The output from the oscillator is a signal of a high frequency f (usually 5 - 20 MHz). We can divide this signal into two parts. A base frequency f_0 that is constant and does not contain any new information about the respiration or heart rate, and the deviation Δf that changes with the variation of the impedance distribution within the investigated body.

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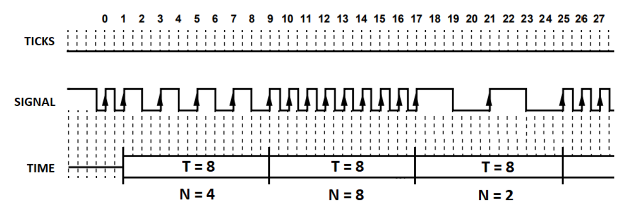
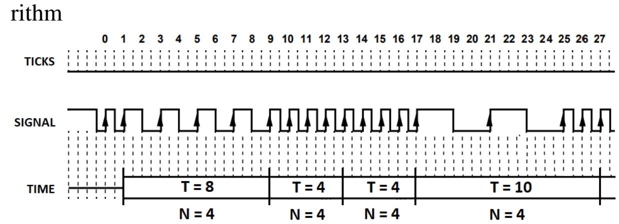
$$f = f_0 + \Delta f$$

Since $f_0 \gg \Delta f$, the frequency deviation Δf is only a small part of the signal. For this reason, we need a frequency monitoring unit that is capable of high-resolution measurements.

1) Traditional Approach: The traditional frequency monitoring approach feeds the oscillatory signal output to a microcontroller and counts the number of periods N within a given time slot, the gate time T_{Gate}. The illustration of this approach is displayed in Fig. 1a.



(a) Illustration of Traditional Frequency Measurement Algorithm



(b) Illustration of Proposed Frequency Measurement Algorithm

Fig. 1: Frequency Algorithms - Comparison

In this approach, T_{Gate} is constant, and N is proportional to f. The sampling rate f_{Smpl} is:

$$f_{Smpl} = \frac{1}{T_{Gate}}$$

The resolution Δ of the measurement is:

$$\Delta = \frac{1}{T_{Gate}}$$

The drawback of this approach is the trade-off between resolution and sampling rate. A higher resolution can only be achieved by a longer time of measurement, that in turn results in a lower sampling rate. This is problematic if both high sampling rate and high resolution are needed.

It has been proposed in the literature, to bypass this trade-off by applying overlapping gate times at the cost of deforming the signal [5]. While this can work well for

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respiration rate measurement, it can pose difficulties for detection of the smaller and faster heart rate and makes the extraction of any diagnostic information based on the morphology of the respiration and cardiac signal impossible.

2) Proposed Algorithm: The proposed algorithm aims at escaping the trade-off discussed in the previous passage. This allows us to realize a system with both high sampling rate and high resolution. Instead of counting the number of periods within a constant gate time, it measures the time between a given number of periods N. This time is inversely proportional to f of the signal. This approach is illustrated in Fig. 1b.

The sampling rate and resolution depend on the frequency of the measured signal. The sampling rate is defined as:

$$f_{Smpl} = \frac{f}{N}$$

For correct operation, this algorithm needs high real time clock frequency f_{RTC}. This is because of the fact that the time is measured by counting the ticks of the real time clock N_{time}. The accuracy of the time measurement is directly proportional to f_{RTC}. The algorithm calculates the frequency of the investigated signal as:

$$f = \frac{N}{N_{time}} f_{RTC} \tag{1}$$

The frequency measurement resolution is defined as the difference between two measurements when N_{time} changes by one tick:

$$\Delta = f(N_{time}) - f(N_{time}+1) \tag{2}$$

Ultimately, combining 1 and 2, we get the following dependency for resolution Δ:

$$\Delta = N f_{RTC}\left(\frac{1}{N\frac{f_{RTC}}{f}} - \frac{1}{N\frac{f_{RTC}}{f}+1}\right)$$

By increasing N we can improve the resolution of the measurement. This comes at a cost of decreasing the sampling rate, but in this case we have lots of room for action. As we discussed before, f is high, and it is much higher than the sampling rate that we are aiming for. Thanks to this adjustment we can achieve higher resolutions at a given sampling rate.

C. Implementation

We will compare the operation of two frequency measurement algorithms using a magnetic induction sensor. This device is implemented as a CMOS Colpitts oscillator and consists of a planar coil, two 10 pF capacitances and a CMOS inverter. Electrical circuit is displayed in Fig. 2.

CMOS Colpitts oscillator generates an AC current. The frequency of this current depends on the reflected impedance of the coil. As the reflected impedance of the coil is proportional to the changes in breathing rate and heart rate, the system can be interpreted as a frequency-modulated cardiopulmonary sensor.

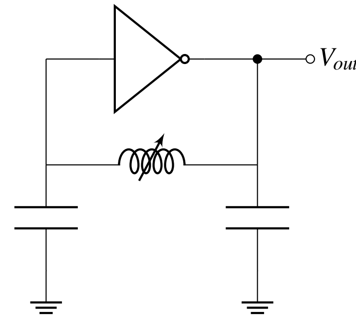


Fig. 2: Colpitts CMOS Oscillator

The output signal V_{out} is measured by two STM32F429 microcontrollers. One of them uses a traditional algorithm, and another one uses a novel algorithm for frequency estimation. f_{RTC} is 45 MHz.

We built two versions of the sensor. The first version uses a small planar coil and the second version uses a big one. They are illustrated in Fig. 3. The small planar coil has 5 windings. Each winding is 1 mm wide and 1 mm away from one another. The inner radius is 25 mm and the outer radius is 35 mm. The inductance of the coil is $L \approx 2.67\,\mu$H. The big coil has 45 windings that are 1 mm wide and 1 mm away from one another. It is an 200 mm wide and 300 mm long elipse of much higher surface and inductance than the small planar coil discussed before. Both coils are made out of copper.

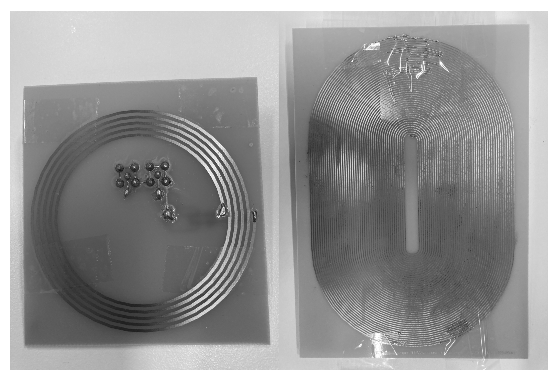
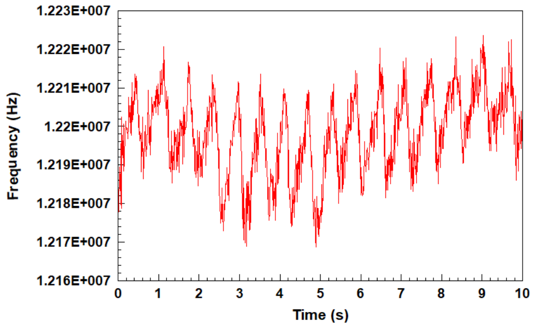


Fig. 3: Coils Used In Experiments

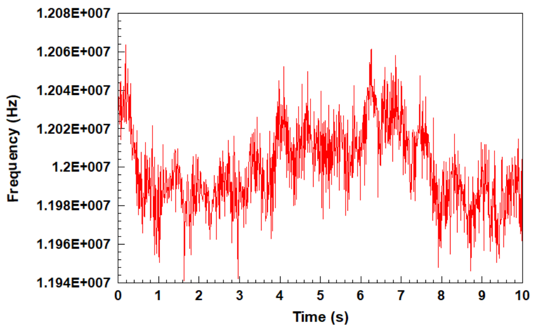
III. Results

We used the two planar coils, which we presented in the previous passage, to conduct several experiments. The aim of these experiments was to demonstrate the accuracy of the sensors in various conditions and to compare the frequency measurement algorithms. We conducted experiments for three different setups. First setup is the small coil located at the chest. Second setup is the small coil mounted at the backrest of a chair. Third setup is the big coil mounted at the backrest of a chair.

The first experiment was to measure heart activity. We asked the subject to take a deep breath and stop breathing for a dozen of seconds to isolate the heart signal. The results for small coil are displayed in Fig. 4. The measurement was conducted using our novel frequency measurement approach. N was set to 20000.

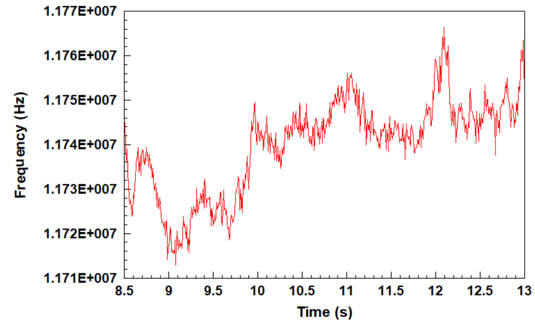


(a) Small coil is located at the chest

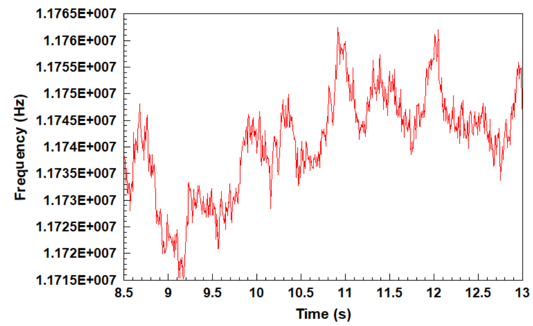


(b) Small coil is located at the backrest of a chair

Fig. 4: First Experiment: Heart Activity



(a) Traditional Algorithm, $\Delta = 140\,\text{Hz}$



(b) Novel Algorithm, $\Delta \approx 36.4\,\text{Hz}$

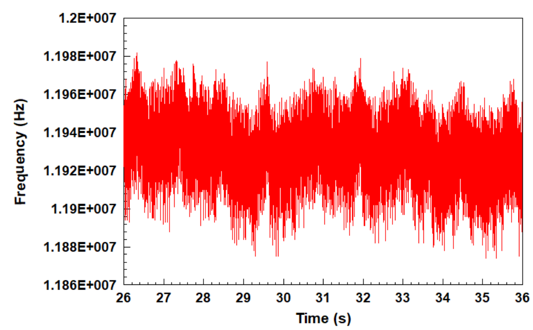
Fig. 5: Second Experiment: Algorithm Comparison $f_{Smpl} = 140\,\text{Hz}$

The second experiment was to compare the algorithms, we measured the signal at $f_{Smpl} = 140\,\text{Hz}$ and at $f_{Smpl} = 1\,\text{kHz}$. For each sampling rate we connected the output of the sensor to two microcontrollers: one of them used the traditional frequency monitoring algorithm, and another one used the novel one. The results are displayed in Fig. 5 and Fig. 6. The novel algorithm improves the signal quality in both cases. For $f_{Smpl} = 140\,\text{Hz}$ the resolution improved from 140 Hz to 36.4 Hz, for $f_{Smpl} = 1\,\text{kHz}$ the resolution improved from 1 kHz to 266.7 Hz. In Fig. 5 the algorithm caught heart beat between 11 s and 12 s that was not captured by traditional algorithm. At Fig. 6 we observed a massive noise reduction.

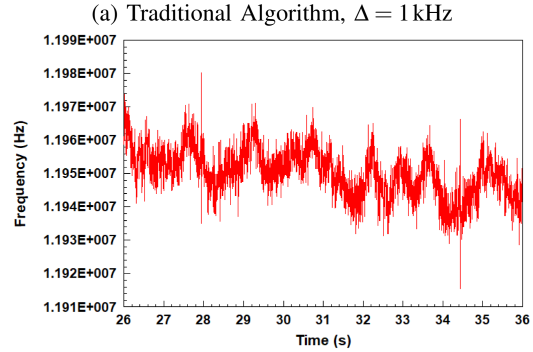
The third experiment was to estimate respiration activity. The results are shown in Fig. 7. We asked the subject to perform four different breathing activities, each 30 s long: deep, normal, quick, and no breathing. The charts plot the changing frequency of the current flowing through the sensors with the elapsing time. Red represents deep breathing, blue represents quick breathing, black represents normal breathing and green represents no breathing. The signals presented here are raw signals and are captured using novel frequency measurement method at N equal to 20000.

IV. Discussion

The comparison between the algorithms shows that the operation of the sensor improves when we change the frequency measurement method. This is because of the fact

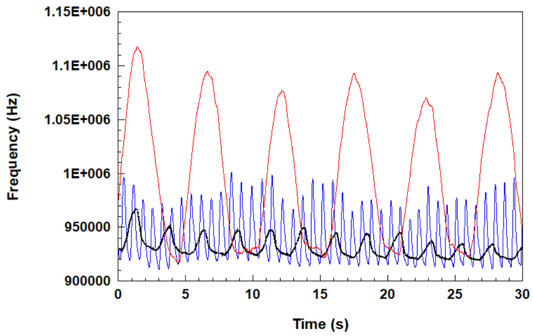


(a) Traditional Algorithm, $\Delta = 1\,\text{kHz}$

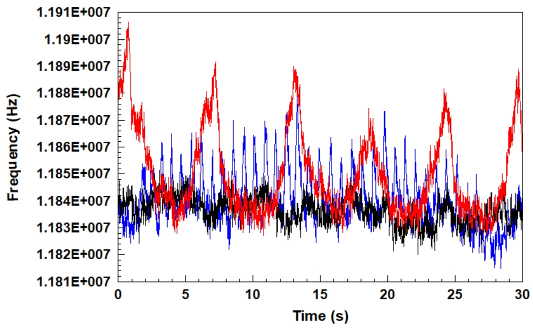


(b) Novel Algorithm, $\Delta \approx 266.7\,\text{Hz}$

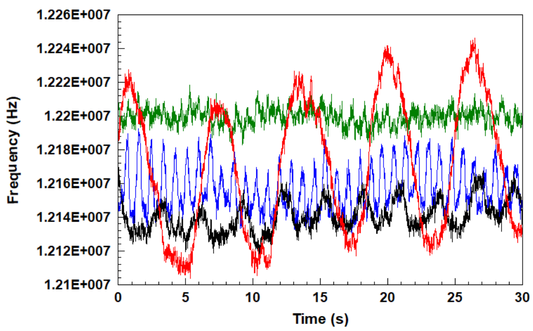
Fig. 6: Second Experiment: Algorithm Comparison $f_{Smpl} = 1\,\text{kHz}$



(a) Big coil is located at the backrest of a chair



(b) Small coil is located at the backrest of a chair



(c) Small coil is located at the chest

Fig. 7: Third Experiment: Respiration Activity

that the novel algorithm allows us to escape the trade-off between the sampling rate and the resolution.

The traditional frequency measurement algorithm has no room to escape the trade-off between f_{Smpl} and Δ:

$$\frac{f_{Smpl}}{\Delta} = 1$$

The novel algorithm gives the designer the tool to change this proportion:

$$\frac{f_{Smpl}}{\Delta} = \frac{f}{N^2 f_{RTC}\left(\frac{1}{N\frac{f_{RTC}}{f}} - \frac{1}{N\frac{f_{RTC}}{f}+1}\right)}$$

This allowed us to achieve higher resolution with acceptable sampling rates. The experiments illustrated in Fig. 5 and 6 prove our point. We reduced the noise (Fig. 6) and detected a heart beat that would otherwise be omitted (Fig. 5).

The change in frequency measurement approach allowed us to integrate the magnetic induction sensor into a backrest of a chair and unobtrusively monitor cardiopulmonary signals as illustrated in Fig. 4b (heart rate) and 7b (breathing rate).

The drawback of the presented algorithm is that it needs hardware with high real time clock frequency. This is necessary for accurate time measurements.

A big challenge for the broad adoption of magnetic induction sensing technology are the low signal strength and motion artifacts. Further work should concentrate on increasing the signal strength of the sensor and mitigating the motion artifacts.

A possible way to achieve that could be changes in the coil topology design. Our experiments show that this change could lead to a higher signal quality as the big coil (Fig. 7a) measured the breathing rate more accurately than the small one (Fig. 7b).

V. CONCLUSIONS

This paper proposed a novel frequency measurement algorithm for magnetic induction sensors that provides high signal resolution and sampling time at the same time. Thanks to this algorithm we were able to increase the quality of the signal. In our setup we were able to improve the resolution by a factor of apprx. 3.8. The improved signal quality of the sensor allowed us to integrate the magnetic induction sensor into a backrest of a chair, and unobtrusively measure cardiopulmonary signals.

The presented sensor is capable of monitoring both heart rate and breathing rate without any conscious cooperation from the patient's side. This makes it well-suited for home monitoring as well as telemonitoring applications. Adoption of this technology would bring great advantages for the society including the automation of breathing rate measurements. However, further work is needed to increase the signal quality of the sensor and mitigate the motion artifacts.

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