3rd URSI AT-AP-RASC, Gran Canaria, 29 May – 3 June 2022

Wearable Chipless Sensor for Breath Rate monitoring

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Abstract

Respiratory rate is one of the most important vital signs for complete monitoring of the health condition of individuals and early detection and diagnosis of illnesses related to the respiratory system. In this work, a novel sensor for breath rate monitoring is presented. The proposed sensor relies on the movement of the body during respiration for the estimation of the respiratory rate. The sensor is composed of two main components; spiral resonator (SR) tag that is realized on by means of ink-jet printing of conductive ink on a flexible substrate, and a microstrip probing loop. The tag is integrated in the innermost garment worn by the individual and located on the abdomen at the level of the umbilicus. The sensing principle is based on the variation of the measured input impedance with the distance between the interrogating probing loop, that acts as the antenna of the reader, and the SR tag. The design of the proposed sensor presented and verified using experimental measurements. The proposed sensor is characterized by its simple design, single-operating frequency, and high accuracy.

1 Introduction

The monitoring of the respiratory rate is important in complete vital sign monitoring in healthcare. Tachypnea is defined as an increase in the rate of breathing and is classified as an indicator of the infection with respiratory system illnesses. Therefore it is of great importance to track the number of breaths taken per minute (bpm) of the individual for early diagnosis of these respiratory system diseases [1]. Moreover, Reports from clinical data have demonstrated that monitoring of the breath rate is useful in the prediction of cardiac arrests [2]. It has also been reported that the respiratory rate is one of the first indicators of patients' health deterioration and setbacks after being discharged from the Emergency Department [3]. Even though the respiratory rate is a critical vital sign to monitor, it is almost always measured using manual and rudimentary methods for example by visually observing the patient and counting the number of breaths they take. The intermittent nature of this basic and manual monitoring techniques can lead to inaccurate conclusions about the patient's health condition [4].

The breath rate measurement techniques can be classified into two main categories; contact and contact-less measurements. In contact-based respiratory sensors, the sensing element is attached to the body. Whereas in contact-less sensors, the measurement is taken wirelessly and the body is not in contact with the sensing element. Spirometer masks are very accurate in the measurement of the respiratory rate, however, they are not suitable for long-term or continuous monitoring as the subject has to keep the sensor mask on during the whole measurement period, which might be unsuitable in many cases [5, 6]. For contact-less sensors on the other hand, several examples were found in the literature for sensors relying on the movement of the abdomen or the thoracic cage during breathing for the estimation of the respiratory rate [7–9]. Respiratory rate measurement technologies employing radio waves in mm-wave range have also been developed due to their accuracy in the detection of very small variation of body movements during breathing [10, 11], however, such systems are often associated with high complexity and cost.

In this paper, A contact-less wearable sensor for continuous respiration monitoring is presented. The proposed sensor is based on a Spiral Resonator (SR) tag, operating in the sub-GHz range, realized on a thin flexible nylon textile substrate integrated in clothing. The tag is located at the abdomen level and is interrogated by a microstrip probing loop integrated in an external layer of (a loose) garment, such as a coat. The sensing principle of the presented device is based on the expansion and contraction of the abdomen during respiration. This movement changes the distance between the tag and the probe which is inversely proportional to the real part of the measured input impedance of the probing loop. The proposed sensor features a non-invasive design compared to other respiratory rate sensors based on chest wall and abdomen movement found in the literature. This wireless respiratory rate sensor can provide continuous monitoring without uncomfortable or invasive equipment. The real input impedance is measured at a single-operating frequency thanks to the design of the tag, and this is considerable advantage over other sensors in the literature relying on the same working principle.

The design of the sensor and its working principle are presented in section 2. Section 3 is focused on the experimental measurements. Finally, the concluding remarks are discussed in section 4.

2 Working Principle and Sensor Design

The breath rate sensor proposed here is based on extracting a respiratory signal from the movements of the body during respiration. This signal is due to the expansion and contraction movement of the respiratory system muscles, particularly the diaphragm which accounts for 75% of the chest cavity expansion. During inhalation, air is allowed into the lungs due to the downward movement of the diaphragm allowing the exchange of gases with the atmosphere as shown in Fig. 1. On the other hand during exhalation, the diaphragm relaxes and air is expelled from the body.

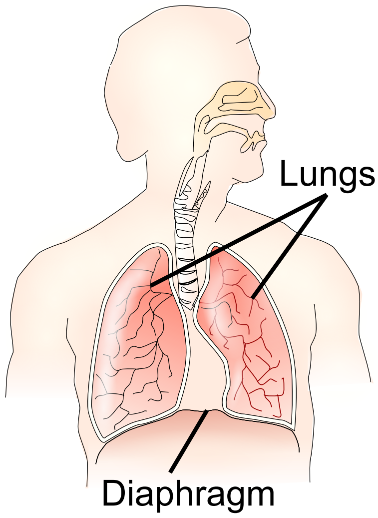

Figure 1. Respiratory system showing the lungs and the diaphragm

The typical respiration frequency for healthy adults at rest is between 12 and 20 bpm [6]. The sensor proposed in this work measures the normal displacement of the abdomen during respiration and uses this information to estimate a number of breaths per minute by counting the peaks or valleys of the measured displacement periodic signal. The respiration rate is measured by monitoring the signal generated due to the body movement during breathing. This can be achieved by placing a displacement sensing tag on the thoracic cage or on the abdomen at the level of the umbilicus [12]. The proposed sensor is based on a Spiral Resonator (SR) tag interrogating by a microstrip probing loop that is the reader's antenna [13]. The displacement of the SR tag modulates the input impedance of the probing loop antenna.

The sensing setup is shown in Fig. 2 where a 2-turn square SR tag is attached on the subject's abdomen at the level of the umbilicus. Whereas the probe antenna is placed in front of the body. The working principle of the sensor is based on the fact that during respiration the distance between the probe and the SR varies periodically due to the expansion and contraction of the body during breathing. The real input impedance depends on the distance between the probing loop and the tag, therefore, the periodic breathing signal can be obtained simply by measuring the impedance at the probe terminals.

Figure 2. Sensor setup showing the wearable SR tag worn by the test subject and located in front of the probing loop

2.1 Sensor model

The sensor can be modelled using the equivalent circuit shown in Fig. 3 where the RLC circuit on the right side of the figure represent the SR, whereas the left part of the figure is the probing loop connected to the alternating voltage source. The two components are inductively coupled via the mutual inductance term, M [13]. The evaluation of the lumped circuit parameters in Fig. 3 can be found in [14–16].

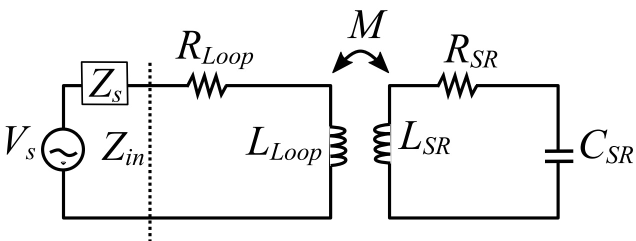

Figure 3. Equivalent circuit model of the proposed SR-based sensor sensor; the SR (right side) is coupled to the probing loop (left side) through the mutual inductance, M

The input impedance, (Z_{in}), shown by the dashed line in Fig. 3, can be expressed in terms of the equivalent lumped circuit parameters:

$$Z_1 = R_{Loop} + j\omega L_{Loop} + \frac{\omega^2 M^2}{j\omega L_{SR} + \frac{1}{j\omega C_{SR}} + R_{SR}}. \quad (1)$$

The expression in (1) means that the value of the input impedance depends on the value of M which is inversely proportional to the distance between the SR and the probe.

The respiration signal is extracted by measuring the real part of the input impedance at a fixed frequency (474 MHz; the resonant frequency of the SR) as the distance between them varies during breathing.

The SR tag shown in Fig. 2 has a side-length equal to 30 mm. The metallic traces are 2 mm wide and are separated by 2 mm. The presented SR tag was fabricated using the Voltera® V-One PCB printer using a conductive ink used composed of 70% silver. The SR is printed on a substrate made of Nylon fabric which is a thin, flexible, strong, and light-weight material.

3 Experimental Results

The fabricated prototype presented in section 2 was used to experimentally verify the sensing concept of the proposed breath rate sensor. The experimental setup shown in Fig. 2 showing where the tag is placed on the subject's T-shirt. The tag is interrogated by the probing loop which is connected to an Anritsu® Shockline MS46524B Vector Network Analyzer (VNA). The VNA measures the reflection co-efficient (S_{11}) of the probe. A signal acquisition script was written on Matlab® software for signal acquisition and recording. The measurement system is configured to take the measurement at the operating frequency of the SR (474 MHz). The measured (S_{11}) is then transformed to impedance [Ω] using the following relation from transmission line theory:

$$Z_1 = Z_0 \frac{1+S_{11}}{1-S_{11}}. \tag{2}$$

where Z_0 represents the characteristic impedance of the coaxial cable.

3.1 Results

The results from the proposed sensor are plotted in Fig. 4, where the real input impedance (shown on the y-axis) is plotted against the time. It can be observed from the figure that the measured real input impedance varies in a periodic manner as predicted by the sensing principle. Moreover, the crests and troughs of the measured signal are clearly distinguishable indicating that the proposed device is able to accurately retrieve the respiratory signal. Each peak in the acquired signal represents the time instant when the distance between the SR tag and the probe is minimum, which corresponds to the end-point of the inhalation phase, whereas the valleys represents the exhalation.

Another observation that can be made from Fig. 4 is that the number of breaths per minute can be obtained simply by counting the number of maximum points in the time signal; one can observe that in the acquisition period shown in the figure, about 24 breaths where registered (24 bpm).

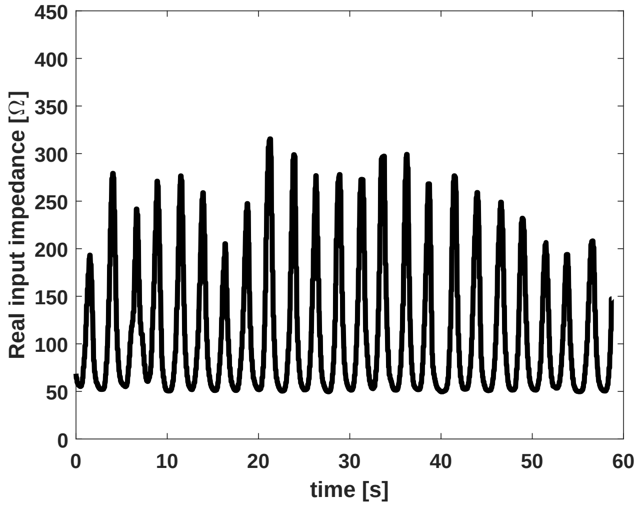

Figure 4. Measured breath rate signal from the SR

It can be expected that in a real practical scenario featuring a dedicated wearable reader board, the acquired signal will be significantly more noisy, however, the respiration frequency can still be extracted as it will be periodic unlike other contributions in the measurement.

4 Conclusion

A novel sensor for monitoring of the respiration rate has been introduced in this work. The proposed device is based on a spiral resonator tag which is realized on a thin wearable substrate. The basis of the sensing principle relies on the movement of the body during inhalation and exhalation. The respiration signal is acquired by means of a microstrip probing loop that acts as the antenna of the reader. The sensor proposed has a simple and non-invasive design compared to other breath rate sensors in the literature. The tag is attached to a clothing item, such as a T-shirt and positioned on the abdomen and is interrogated wirelessly by the reader. Moreover, the design of sensor allows the use of a simple single-frequency reader eliminating the need to for complex circuitry required for carrying out a frequency sweep at the reader side. The sensor was used for experimentally measuring the breath rate of a test subject in quasi-real scenario and the respiration signal was accurately retrieved.

5 Acknowledgements

This Work partially supported by the Italian Ministry of Education and Research (MIUR) in the framework of the CrossLab project (Departments of Excellence) and of the PRIN2017 GREEN TAGS "Chipless radio frequency identification (RFID) for GREEN TAGging and Sensing" (2017NT5W7Z).

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