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Respiratory Signal Estimation Using Non-invasive Measurements

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Introduction

Human physiological parameters monitoring system embedded into wearable garment is one of great promise approaches to workers safety secure at workplaces. The system automatically collects and analyses primary physiological data during the worker's daily activity and immediately sends results to remote control center. That ensures the ability to provide an urgent help in the case of any accident or man's health state impairment. Meanwhile most of prototypes of such systems are still under investigation stage. There are many of unsolved problems related to the practical implementation and functionality of the mobile system parts [1,2]. The overall wearable monitoring system first of all must be lightweight, flexible, comfortable, easy-to-use, washable, and, most important, non-invasive, if every worker is going to adopt it. That requires some special measurement methods and algorithms to work out.

In this work we analyze ability to use non-invasive methods and means to monitor respiratory function, which is one of the primary human health state parameters. The main heed is given to parameters and effectiveness of respiratory sensors that highly effect reliability of the acquired data.

Method for respiratory function investigation

Respiratory function parameters are the primary physiological parameters that advisably should be always controlled by wearable monitoring systems. They can be divided into three main groups:

- volume parameters (total lungs capacity, tidal breath, functional remaining capacity and others);
- respiratory system physical parameters (respiratory rate and other mechanical parameters);
- parameters of gas metathesis within the lungs.

All those parameters are interdependent and measurement of some of those parameters gives us possibility to calculate the rest of them. After considering diagnostic importance of various respiratory function parameters as well as accessability of their evaluation, we have selected respiratory rate for our further investigations.

One of the most promising non-invasive methods for respiratory rate and other respiratory function parameters measurement is inductive plethysmography. This is an indirect measurement method. It bases on the principle that self-inductance of inductive coil made of insulated wires fixed on expandable belts and placed around rib cage and abdomen is proportional to its length changes during one's breathing. The inductive coil is made in a wavy formation to allow expansion of the belt (Fig. 1). Signal processing circuitry transforms changes of self-inductance of inductive sensor into the output voltage or frequency variation which could be easily measured. Finally, various digital microprocessor systems are used to calculate values of respiratory function parameters [3].

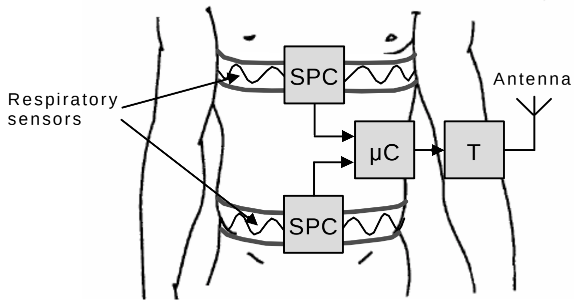

Fig. 1. Respiratory sensors connected to signal processing circuitry (SPC), microcontroller (μC) and signal transmitter (T)

The self-inductance of sensor is proportional to its length and consequently the surrounded area. This area changes along with chest wall movements during breathing. To find out the exact relationship between self-inductance of coils and areas included inside we did computations and practical experiments.

Computation of self-inductance of plane coil

Human cross section shape is something between ellipse and rectangle and it differs at person to person. That was stated after analyzing computerized tomography pictures of human body cross sections of rib cage and abdomen areas. With inspiration the shape approximates to circular, and this is particularly distinct in abdomen area.

In the first approach the simpler case was taken under consideration with two limitary shapes – circular and rectangular. Inductance of one flat coil surrounding the experimental body was calculated. That may correspond the case when sensor is outstretched till the end and no undulation is left.

In the case of circular loop with known wire's radius, self-inductance depends only on loop's radius r. Self-inductance L then could be expressed by the formula [4]:

$$L = \mu_0 r[\ln\left(\frac{8r}{\rho}\right) - \frac{7}{4}], \quad (1)$$

here μ_0 – magnetic constant, ρ – radius of the wire used.

The self-inductance of the loop with 80 cm perimeter length and 0.6 mm diameter wire was calculated is equal to 1.1μH. The perimeter of the human's body changes meanly 1.5% during respiratory cycle. That causes self-inductance to change 0.01μH.

In the case of rectangular loop, the self-inductance will depend not only on loop radius but also on rectangle's sides lengths a and b, or their ratio $k_f = \frac{a}{b}$. Self-inductance then is calculated in this way [4]:

$$L = \frac{\mu_0}{\pi}[a\ln\left(\frac{2ab}{\rho(a+c)}\right) + b\ln\left(\frac{2ab}{\rho(b+c)}\right) + 2c - \frac{7}{4}(a+b)] . (2)$$

Here c is diagonal of rectangular loop.

When perimeter length is 80 cm and ratio $k_f = 0.6$, self-inductance is equal to 1μH. With the k_f increase by 0.1 the self-inductance increases by 2nH. The change of perimeter length affects here in the same way as for circular loop.

The computation has showed up, that self inductance grows up according to perimeter elongation. Self-inductance also increases when rectangular loop draws to regular shape, i.e. quadrate.

The experimental investigation

The computational results were proved by experiments. A single plane coil was placed around cylindrical models of circular and rectangular shapes. The models were made to allow changing size of their perimeter. Self-inductance of the coil was measured with LCR meter E7-15. Resolution of the LCR meter – 0.1 nH. The accuracy is calculated from the given expression: ±[(0.1+0.1*tg*σ)%+0.2nH], where σ – angle of loss within inductive coil.

The measurements both with circular and rectangular models showed up, that inductance grows up along with perimeter and results are close to those, achieved by computation.

Next, several experiments with inductive sensors made of wavy configured wire were performed. At the beginning, the influence of density of coil waves to the self-induction and sensitiveness of inductive coil was investigated. Rectangular model with four moving compartments that allow perimeter size and sides ratio to be changed easily was used to this end (Fig. 2).

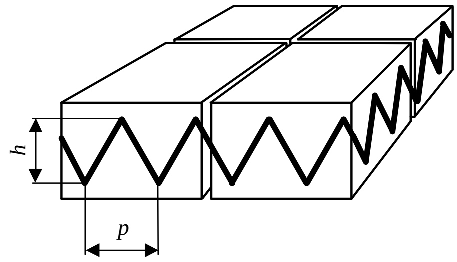

Fig. 2. Experimental model with moving compartments and inductive sensor placed on it

Single coil with triangularly shaped wire and wave's height h = 5 cm was applied. Three different step sizes between waves p were analyzed. Each of the coils was measured several times and results were averaged then. Dependence of the self-induction measured upon the perimeter length is presented in the Fig. 3.

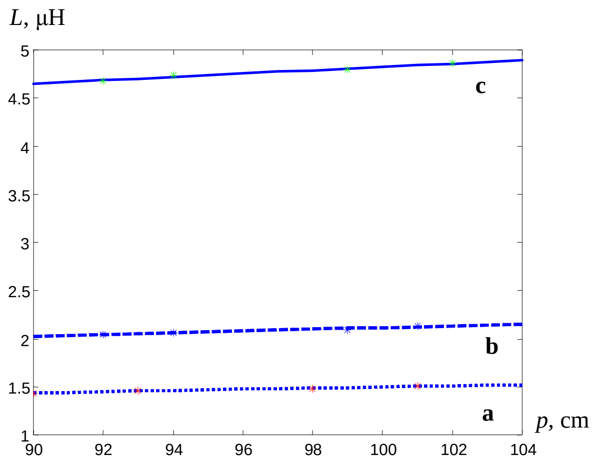

Fig. 3. Measurement of self-inductance against perimeter length of inductive coils with a different step size between the waves: a) 8 cm, b) 5 cm and c) 1 cm

These results could be evaluated best by the sensitiveness η of each sensor. It was calculated that the highest sensitiveness is 17.2 nH/cm and belongs to the densest waved coil. The sensitiveness of another two coils with step size 5cm and 8 cm is 8.9 nH/cm and 6 nH/cm respectively. The highest absolute inductance also belongs to the densest waved coil.

An important thing is that correspondence between self-inductance and small variations of perimeter is almost linear. That improves measurement conditions.

Next the influence of wave height to the self-induction and sensitiveness of inductive coil was investigated. Four coils with height of waves gradually changing from 1.5 cm to 6 cm were produced and analyzed. The step size between waves is 4 cm and it is constant for all coils. Figure 4 illustrates results obtained by measuring self-inductance of the coils.

The sensitiveness varies insignificantly here. It values about 9 nH/cm. Absolute inductance slightly grows up with the height of waves.

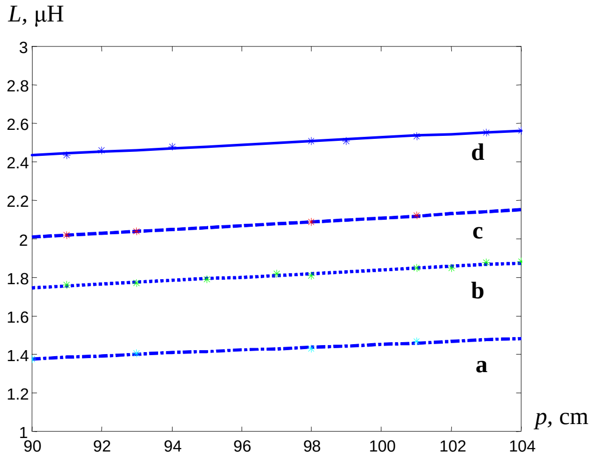

Fig. 4. Measurement of self-inductance against perimeter length of inductive coils with a different height of waves: a) 1.5 cm, b) 3 cm, c) 4.5 cm, and d) 1 cm

Another investigation was performed with imitating real conditions, when a person wears sensors. The same four sensors with a different height of waves were used meanwhile the person was doing some physical exercises. The experiment showed up that during changing of human body posture the belt with the sensor cambers and deforms the waves. That results in changes of self-induction within the sensor. Those changes might be even bigger than those when person is breathing. This is more significant for sensors with higher waves.

Finally, the investigation with several parallel coils connected in series was performed while expecting to get a higher sensitiveness in this way [5]. Up to five parallel coils were employed. The height of each was 1.5 cm and step size between the waves – 2cm. Results obtained by measurements are presented in the Fig. 5.

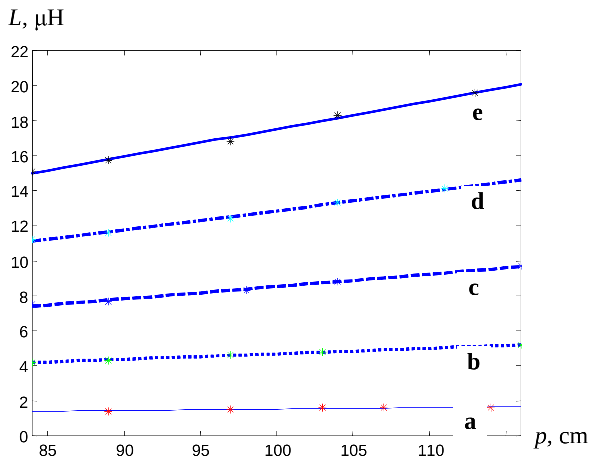

Fig. 5. Measurement of self-inductance against perimeter length of inductive sensors with a different number of parallel coils connected in series: a) 1 , b) 2, c) 3, d) 4 and e) 5 coils

As we can see from a graphs presented in Fig. 5, both the sensitiveness and absolute inductance of sensors increase significantly with the number of coils connected in series. Sensitiveness grows up from 6.5 nH/cm when one coil is used to 154.8 nH/cm when five coils are connected. It should be noticed that a higher number of parallel coils begins to affect the elasticity of the sensor and makes it uncomfortable to use.

Signal processing circuitry

All modern physiological data monitoring systems contain digital microprocessor unit, which controls the overall data collection process, calculates physiological parameters and performs other functions. Respiratory rate can be evaluated from a variable signal from inductive sensor. However, respiratory signal first must be filtered and amplified before it gets ready for further analysis, and this should be done with minimal energy consumption since energy saving is a very important feature in mobile systems [3]. The main problem here is a relatively small variation of inductance caused by breathing.

The signal conditioning circuit proposed in this work contains a variable frequency oscillator (Fig.6 (a)) with an inductive sensor in the oscillatory circuit, respiratory signal demodulator (b), band-pass filter (c) and amplifier (d).

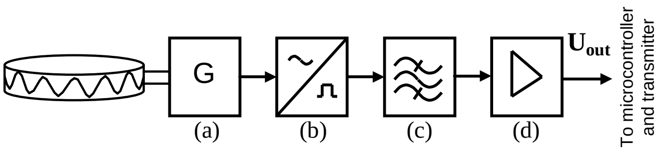

Fig. 6. Structural view of respiratory signal processing circuitry

Frequency of the signal generated by the oscillator varies according to inductance changes produced by inductive sensor. The nominal frequency is set to 300 kHz, which is typical within inductive plethysmography applications.

Demodulator and filter together presents frequency to voltage converter. Demodulator transforms the oscillator signal into a pulse signal with a constant pulse width. Frequency of the pulse signal is the same as generated by oscillator. Band-pass filter cutoffs high and low frequencies and passes respiratory signal, within frequencies from 0,02 Hz to 180 Hz. The filter is followed by signal amplifier. The output signal of required magnitude gets into microcontroller for further processing.

Fig. 7 and 8 present the output respiratory signals, which were measured under different breathing conditions.

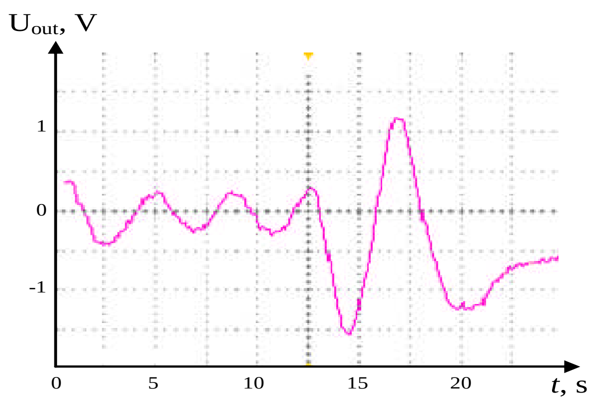

Fig. 7. Respiratory signal measured during quiet breathing (on the left side) and deep breathing (on the right side)

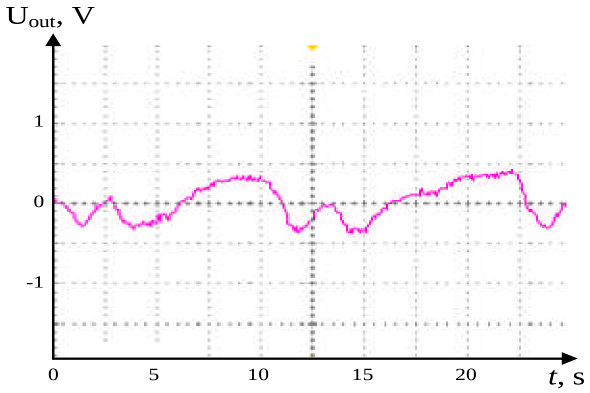

Fig. 8. Respiratory signal measured when the man talks

As we can see there, signal amplitude depends on inspiration deepness. It is also affected by motion and speech. However, those artifacts suppose will be eliminated by programmable means. The negative reciprocity of two separate channels was not observed.

Conclusions

The changes of self-inductance that normally occur during inspiration and expiration cycles when a person breathes are only about 1%. To evaluate one's respiratory rate during his daytime activity, the self-induction of two inductive sensors must be measured with certain accuracy.

Noise and distortion of signals in the measuring circuitry caused by the body motion can be reduced by using sensors with lower waves. The experimental investigation showed up that sensitiveness of the sensor slightly depends on wave's height. Otherwise, the waves are basically required for unhampered stretching of sensor's belts.

The sensitiveness and self-inductance of the sensor could be significantly increased by using several parallel coils connected in series. Another way to improve the sensitiveness is to use sensors with a denser wave's formation.

Frequency modulation principle used in respiratory signal processing circuit ensures both reliable extraction of respiratory signal and required signal amplification. The negative reciprocity of separate channels was not observed.

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Non-invasive human respiratory function monitoring system, based on inductive plethysmography method is analyzed. The system is intended to be used as worker's wearable equipment. It employs inductive sensors made of wavy insulated wire secured on expandable belts that surround human rib cage and abdomen. Various parameters of inductive sensors and their influence on sensitiveness were investigated. Signal demodulation is used to produce respiratory signal from an output signal of oscillator with an inductive sensor in circuit. Both signal processing equipment and signals achieved are discussed. Ill. 8, bibl. 5 (in English; summaries in English, Russian and Lithuanian).

М. Вайткунас, А. Досинас, В. Барткявичюс, И. Даунорас. Оценка сигналов дыхания методом неинвазных измерений // Электроника и электротехника. – Каунас: Технология, 2009. – № 1(89). – С. 35–38.

Рассматривается неинвазная система мониторинга дыхания о человеке, основанная на использовании методов индуктивной плетизмографии. В качестве индуктивных датчиков использованы волновидные обмотки, опоясывающие тело человека в области грудной клетки и живота. Исследована зависимость чувствительности датчиков от различных их параметров. Сигналы, характеризующие дыхание человека, получены в качестве демодулированных сигналов генератора, в колебательный контур которого включен индуктивный датчик. Приведено устройство обработки сигналов дыхания и полученные их образцы. Ил. 8, библ. 5 (на английском языке; рефераты на английском, русском и литовском яз.).

M. Vaitkūnas, A. Dosinas, V. Bartkevičius, J. Daunoras. Kvėpavimo signalo įvertinimas neinvaziniais matavimais // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2009. – Nr. 1(89). – P. 35–38.

Nagrinėjama neinvazinė žmogaus kvėpavimo stebėsenos sistema, pagrįsta induktyvinės pletizmografijos metodų taikymu ir skirta naudoti darbuotojų aprangos technologijose. Kaip induktyvinės pletizmografijos jutikliai naudojamos banguotos formos vijų induktyvinės ritės, juosiančios žmogaus kūną krūtinės ir pilvo srityse. Ištyrinėta šių jutiklių įvairių parametrų įtaka jų jautrumui. Kvėpavimą apibūdinantis signalas gaunamas demoduliuojant generatoriaus, kurio virpamajame kontūre įjungtas induktyvinis jutiklis, signalą. Aptarta jutiklių signalų apdorojimo įranga ir gautieji kvėpavimo signalai. Il. 8, bibl. 5 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).