CONTACTLESS MEASUREMENT OF THE RESPIRATION FREQUENCY BY VIBROMETRY

Kristian Kroschel [1]*, Jürgen Metzler* [2]
[1] *Karlsruher Institut für Technologie (KIT)*
[2] *Fraunhofer Institut für Optronik, Systemtechnik und Bildauswertung (IOSB)*
e-mail: kristian.kroschel@kit.edu

Abstract: The respiration frequency is currently measured by devices which need the contact with the body of the client. For burnt clients, premature infants and people with a contagious desease techniques with remote sensing are required. A very promising approach is based on vibrometry with infrared lasers.
The respiration frequency of adults ranges from 8/min up to 35/min including physical stress. The raw vibrometry signal includes besides respiration also cardiac activity and the influence of the movement of the client. Therefore a low-pass filter separates the respiration component from the others.
Since the calculation of the respiration frequency requires processing time and there is the demand of continuous monitoring of the frequency the filtered data are cut into blocks, each 20 ms long. These data blocks are overlapping by 19 ms so that every second a new value of the respiration frequency is displayed. For the calculation of the respiration frequency three methods are discussed. The first one is based on the fast Fourier transform (FFT), the second one exploits the properties of the auto-correlation function and the third one is based on the zero-crossings of the respiration signal.
Generally the vibrometer signal can be picked up on the thorax, the neck or the forehead. The quality of the signal depends on the measuring point. Therefore the vibrometer is directed by a pan-tilt unit to the optimal measuring point. The criterion of optimalty depends on parameters of the correlation function calculated from the data block and is used to control the pan-tilt unit.
Currently the new method is planned for application and test in a hospital.

1 Introduction

Respiration is not only the basis for speech production but can also tell about the health state of a client such as hyperventilation, gasping, Chayne-Stokes respiration and others [1]. Furthermore, respiration has to be observed in cases of apnoea or the sudden infant death syndrome.

Currently respiraton is measured by mechanical and optical methods. The expansion of the chest is measured machanically, the change of the mean arterial pressure is also a measure of the respiration, the movment of the auditorial channel is exploited and the amplitude modulation of the R-peak of the electrocardiogram (ECG) is proportional to the respiration frequency. All these methods require the contact with the client. An alternative is the exploitation of the vibrometry signal [2] which is picked up either on the chest, the neck or the forehead. The eye-friendly infrared laser vibrometry signal has a wavelength of $\lambda = 1550$ nm.

The received vibrometry signal is not only influenced by the respiration but also by the heart beat and the muscle tension and relaxation evoked by the movements of the client. The range of the respiration frequency extends from 14/min up to 20/min [3] for an adult without physical stress. Frequencies below 8/min are identified as bradypnoea and above 35/min as tachypnoea. For children up to 4 years a frequency from 16/min up to 45/min is regular. Since the heart beat is around 60/min it can be easily separated by filtering. The influence of the movement of the

client might also attenuated by the low-pass filter adapted to the respiration and by averaging. Furthermore, the optimization of the measuring point will contribute to the improvement of the quality of the measured respiration signal.

2 Setup of the Measuring System

The vibrometer is the heart of the measuring system and will be directed to the measuring point by a pan-tilt unit. The raw vibrometer output signal is pre-processed, filtered and displayed. Furthermore, the respiration frequency is extracted and recorded over the time on a monitor. Finally, there is a component to control the pan-tilt unit as shown in Figure 1.

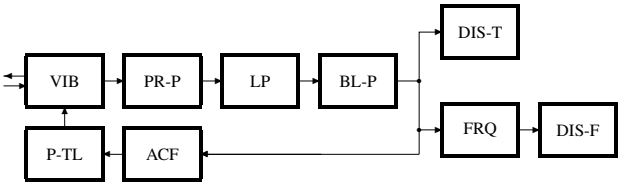

Figure 1 - Components of the measuring system for the respiration function and the extracted frequency.

The laser signal is emitted by the vibrometer (VIB) and reflected at the measuring point. The received raw signal with a sampling frequency of $f_s = 480$ Hz is first pre-processed (PR-P) by decimation with the factor $m = 4$ so that the resulting sampling frequency is $f_s = 120$ Hz. Furthermore the frequency component at $f = 0$ Hz is suppressed. In the next step the signal is filtered by a low-pass (LP) [4] of order $n = 6$ with a Chebychev characteristic of type 2, i.e. a constant attenuation in the pass-band. The cut-off frequency is $f_c = 0.75$ Hz which is equivalent to the maximum value of the respiration frequency with 45/min and the attenuation in the stop-band is $a = 60$ dB. The amplitude response, phase and impulse response are shown in Figure 2.

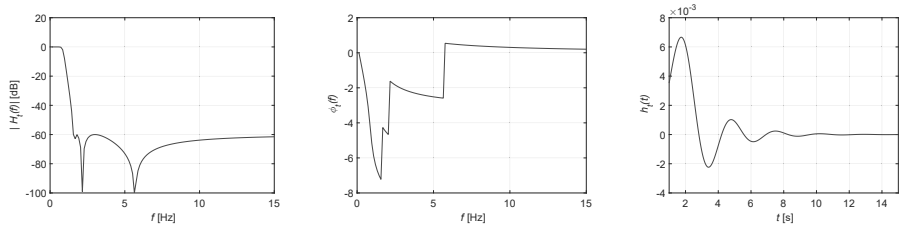

Figure 2 - Low-pass. Amplitude response (left), phase (center), impulse response (right).

Due to the phase characteristic there are phase distortions so that time-related properties are changed by the filter. Since the frequency will be extracted by averaging methods this does not matter.

For the display of the respiration signal the filtered data are cut into blocks (BL-P) of length $t_b = 20$ s which is equivalent to $N_b = 2400$ samples. The next block follows after $t_d = 1$ s so that there is an overlap of $t_o = 19$ s. The data blocks are visualized in the display (DIS-T). From the same data block the auto-correlation function $c_{BB}(\kappa)$ (ACF) is calculated and a signal extracted from $c_{BB}(\kappa)$ is used to control the pan-tilt unit (P-TL) so that the optimal measuring point is found. The data blocks are further fed into the unit (FRQ) where the respiration frequency $f_b(t)$ is calculated and finally displayed (DIS-F).

3 Methods to Calculate the Respiration Frequency

From the three possible measuring regions mentioned above two have been selected due to the signal strength which is the weakest at the forehead. Samples of the raw signal at the output of the

vibrometer are shown in Figure 3.

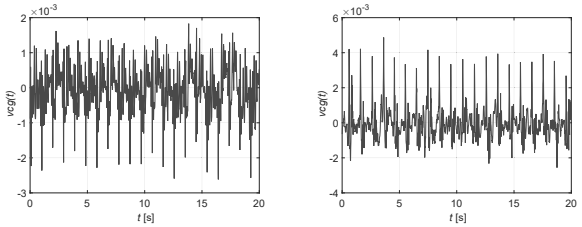

Figure 3 - Vibrograms. Chest region (left), neck region (right).

Both vibrograms show clearly the periodicity of the heart beat which is dominating the raw signal. The signals have been picked up from two individuals and show data blocks of length $t_b = 20$ s. Applying the low-pass filter with the characteristics shown in Figure 2 to the raw data renders the respiration signals represented in Figure 4.

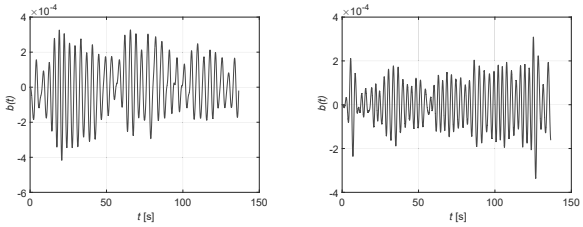

Figure 4 - Respiration signals. Chest (left), neck (right).

The measuring time has been 2 min from which 100 data blocks can be extracted taking into account that the overlap is 19 s or with other words, after each second a new data block is generated. These data blocks are used to calculate the respiration frequency. There are three methods which will be discussion in the sequel:

- Frequency domain method based on the fast Fourier transform (FFT)
- Time domain method based on the auto-correlation function
- Time domain method based on the zero-crossings within the data block.

3.1 The Frequency Domain Method

The data block of length $t_b = 20$ s and a sampling frequency of $f_s = 120$ Hz contains $N_b = 2400$ samples. Thus the frequency resolution becomes

$$\Delta f = \frac{f_s}{N_b} = \frac{120}{2400}[\text{Hz}] = 0.05[\text{Hz}]. \tag{1}$$

Taking into account that the low boundary of the respiration frequency is at $f_b = 0.13$ Hz and that this frequency should be measured with an accuracy of 10% then the resolution given in Eq. (1) is not sufficient. Of course, the block length might be expanded to meet the resolution of $\Delta f = 0.013$ Hz. Thus $N_b = 9000$ samples or a block length of $t_b = 75$ s are required which renders a very inert measurement. Instead, the resolution could be increased keeping the block length of $N_b = 2400$ samples by applying zero-padding. A factor of four would be appropriate increasing the resolution to

$$\Delta f = \frac{f_s}{4 \cdot N_b} = \frac{120}{9600}[\text{Hz}] = 0.0125[\text{Hz}]. \tag{2}$$

which is equivalent to 3/min. In the final step the spectral peak is searched for in the interval $0.13[\text{Hz}] \leq f_b \leq 0.58[\text{Hz}]$ and the result is taken as the actual respiration frequency. This procedure is repeated after 1 s with the following data block. The result for the input signals with 120 s duration is shown in Figure 5.

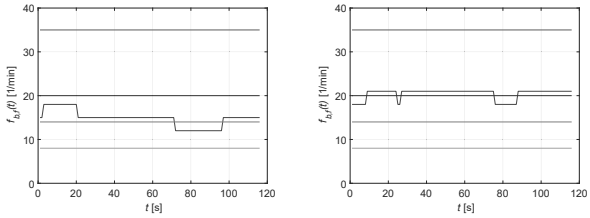

Figure 5 - Respiration frequency $f_b(t)$. Chest region (left), neck region (right). Frequency domain approach.

Clearly, the result is not satisfying due to the coarse resolution.

3.2 The Auto-correlation Method

This method is based on the fact that the correlation function of a periodic signal is also a periodic function with the same frequency. Thus the distance of the peaks is identical with the period of the periodic signal or the inverse of the distance is equal to the frequency. In the first step the auto-correlation function is calculated using the unbiased approach [5]. This is motivated by the fact that the mean value is zero and only the region around the maximum of the auto-correlation function is exploited. To introduce this approach Figure 6 shows a data block of the respiration signal together with the associated auto-correlation function.

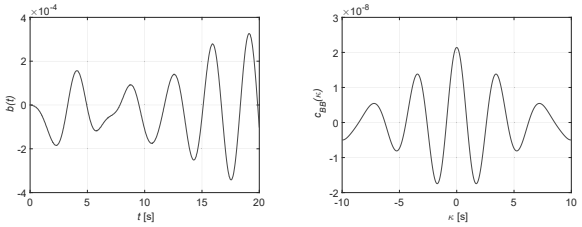

Figure 6 - Data block of the respiration signal (left), correlation function (right).

The unbiased auto-correlation function is first calculated

$$c_{BB}(\kappa) = \frac{1}{N_b - \kappa} \sum_{k=0}^{N_b-\kappa-1} b(k) \cdot b(k-\kappa) \tag{3}$$

with k and κ being multiples of $1/f_s$. Then the maximum at κ_{max} closest to the main maximum at $\kappa = 0$ is determined and the respiration frequency f_b is calculated :

$$f_b = \frac{1}{\kappa_{max}} \tag{4}$$

with κ_{max} measured in seconds. Due to the sampling frequency $f_s = 120$ Hz the resolution of the auto-correlation function is given by

$$\Delta\kappa = \frac{1}{f_s} = \frac{1}{120\text{Hz}} = 0.0083\text{s}. \tag{5}$$

The spectral resolution Δf is equal to the inverse of the distance of two neighbouring samples of the auto-correlation function:

$$\Delta f = \frac{1}{\kappa_{max}} - \frac{1}{\kappa_{max} + \Delta\kappa} = \frac{\Delta\kappa}{\kappa_{max}(\kappa_{max} + \Delta\kappa)}. \tag{6}$$

For example, if $f_b = 0.33$ Hz the distance between the main maximum and the maximum closest to the main maximum is $\kappa_{max} = \frac{1}{f_b} = 3$ s. Then the frequency resolution is $\Delta f = 0.0009$ Hz $= 0.05$ 1/min. This is a much better resolution than the one given in Equ. 2 for the FFT based method with zero-padding by four!

An example of the respiration frequency for the auto-correlation method is shown in Figure 7.

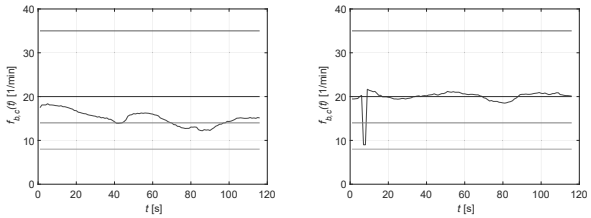

Figure 7 - Respiration frequency $f_b(t)$, auto-correlation method. Chest region (left), neck region (right).

The resolution is much higher as with the FFT-based method. There is an outlier in the measurement in the neck region. This might be identified easily and suppressed by interpolation, e.g. Furthermore, the method might be improved by observing not only the maximum closest to the main maximum but also the second closest maximum etc.

3.3 The Zero-Crossing Method

In the first step the zero-crossings of the respiration signal are detectd and the signal is replaced by the signum-function with the same zero-crossings as the respiration signal. Then the number N_N of zero-crossings in the data-block of $t_b = 20$ s duration are counted. Furthermore the time instant t_{b1} of the first zero-crossing and the time instant t_{bN} of the last zero-crossing in the data-block are determined. Finally, the respiration frequency is calculated by averaging the zero crossings within the intervall of length $t_{bN} - t_{b1}$:

$$f_b = \frac{1}{\frac{t_{bN} - t_{b1}}{(N_N - 1)/2}} = \frac{2(t_{bN} - t_{b1})}{N_N - 1}. \tag{7}$$

For comparison Figure 8 shows the result of the zero-crossing method to determine the respiration frequency $f_b(t)$ with the same data which have been used for the FFT-based method and the auto-correlation method.

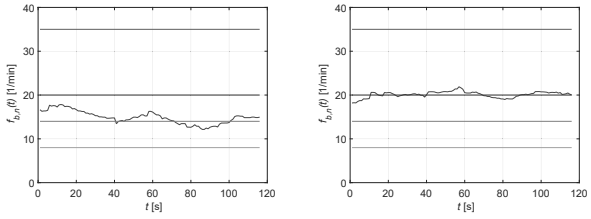

Figure 8 - Respiration frequency $f_b(t)$. Chest region (left), neck region (right). Zero-crossing approach.

The measured respiration frequency is comparable with that obtained from the auto-correlation mathod and outperforms signifantly the FFT-based method. There seems to be a more discontinuous course of $f_b(t)$ compared to Figure 7. Unfortunately no ground truth is available so that an evaluation with respect to the ground truth is not possible. Of course smoothing techniques would remove the discontinuities. The parameters for the smoothing process could be found dy deriving a model of the respiration process with a bandwidth extracted by observing the respiration process.

All the approaches to extract the respiration frequency from the vibrometer signal deliver values which are not far away from each other. The FFT-based method lacks from the low resolution. The other two methods have a resolution which is good enough for practical application. Nevertheless, improvements could be the suppression of outliers and the smoothing of discontinuities.

4 The Search of the Optimal Measuring Point

The quality of the measured signal depends significantly on the point of measurement. The following investigation has been concentrated on the neck region and on one client only. Of course, the same could have been done in the thorax region but the neck region is preferred since the measurement is not influenced by clothes. If the clothes covering he chest are thin like underwear or a shirt the output of the vibrometer is still useful but the lower accessability in comparison with the neck remains.

To investigate the quality of the measured signal with respect to the measuring point, nine equally spaced locations have been selected in a region around the carotis as shown in Figure 9.

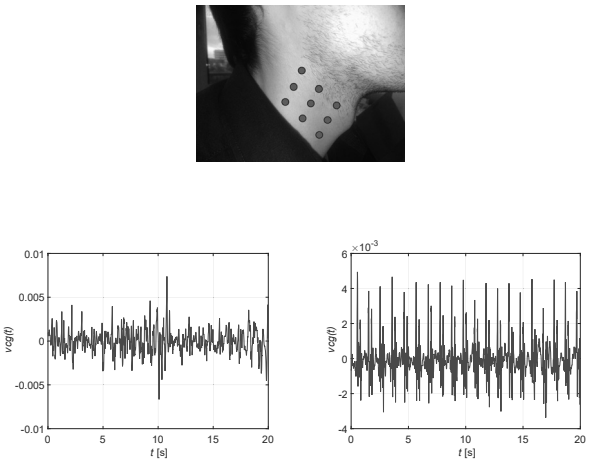

Figure 9 - Measurement locations on the neck (top). Vibrometer signal top left and bottom right (bottom).

The difference of the quality of the two vibrometer signals becomes obvious by visual inspection. It has to be taken into account that the measurements have not beeen executed in parallel but one after another with the same client. The periodicity is clearly visible in the right bottom location which is not true for the measurement at top left. The reason is that the carotis is closer to the bottom right positian than to the top left.

The question is how to find an appropriate measuring point. Since the correlation function has proven to be a good basis for the calculation of the respiration frequency it has also been used to find a good measuring point [6]. As has been said earlier, periodic signals generate periodic auto-correlation functions $c_{BB}(\kappa)$ with maxima of more or less equal hight. Therefore a measure of reliablity $r(t)$ has been investigated which depends on the the amplitude of the main maximum $c_{BB}(0)$ at $\kappa = 0$ and the amplitude $c_{BB}(\kappa_{max})$ of the maximum at κ_{max} closest to the main

maximum:

$$r(t) = \frac{c_{BB}(\kappa_{max})}{c_{BB}(0)}. \tag{8}$$

The dependence on t is caused by the fact that this value is calculated for each data block, i.e. each second. Examples of the figure of reliability are shown in Figure 10 for a measurement in the thorax and neck region, respectively.

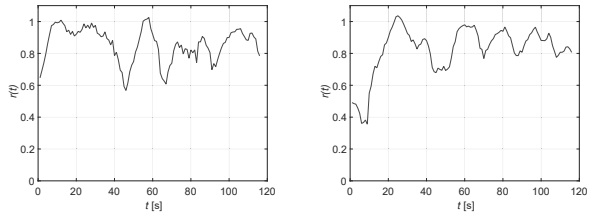

Figure 10 - Figure of reliability $r(t)$. Chest region (left), neck region (right).

The results shown are based on measurements from different clients but look very similar. The average value is around $r = 0.8$ which means that the compared maxima are of similar size, or with other words, the amplidude of the maxima is decaying quite slowly. If there would be no decay, the value would be $r = 1$.

Coming back to the measurements in the neck region the respiration signals extracted from the vibrometer signals at the nine mesuring points are shown in Figure 11.

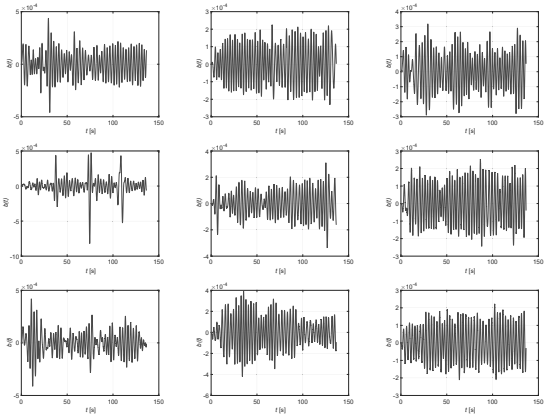

Figure 11 - Respiration signals at the 9 measuring points.

Again, the signals have been picked up for 2 min. The client sat on a chair and was not fixed so that movements influence the measurement result. The measurements were executed serielly and not in parallel. The vibrometer was fixed on a stand in a distancs of about 2 m from the client and moved from measuring point to measuring point which were marked on the neck. The client was not instructed to breathe constantly with respect to the respiration frequency and depth. Thus there are signifcant variations in amplitude. The fluctuations of the amplitudes in the left column are much higher than in the right column. A reason for this result cannot be given.

Finally the respiration frequency has been extracted from all the nine signals using the zero-crossing method because this method is not influenced by the amplitude of the signals. The result is shown in Figure 12.

The respiration frequency is in all cases around $f_b = 20$/min. On the right columns almost no discontinuities are visible. This is in contrast to the results in the left column, especially in the lower figures. Also the result at the bottom in the center column shows discontinuities.

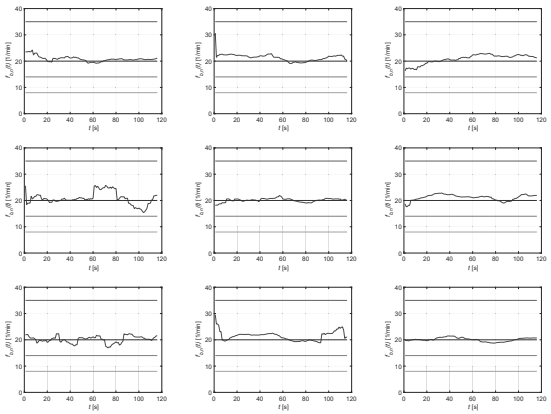

Figure 12 - Respiration frequency at the 9 measuring points calculated with the zero-crossing method.

5 Conclusion

It has been proven that vibrometry can be used to measure the respiration frequency without contact to the body of the client. Based on the eye-friendly infrared laser there is no hazard for the client.

Using a low-pass filter the respiration signal is separated from the rest of the raw vibrometer signal. The time delay is short but there are distortions of the signal. Using overlapping data blocks, the measured respiration frequency is updated every second and its reliability and frequeny resolution is sufficient.

From the three ivestigated methods for frequency measurement, the one based on the zero-crossings was the most attractive one. The optimal measuring point was found by explotation of the correlation function calculated from the data block.

In the future the new method will be tested in a hospital.

References

[1] HICK, C., HICK, A.: *Physiologie*. Elsevier, Urban & Fischer, München, 7. Auflage, 2013

[2] TABATABAI, H., OLIVIER, D.E., ROHRBOUGH, J.W., PAPADOPULOS, C.: *Novel Applications of Laser Doppler Vibration Measurement to Medical Imaging*. Sens. Imagery 14, 2013, pp. 13-28

[3] GANONG, W.F.: *Review of Medical Physiology*. 15th ed. Prentice Hall Int. London, 1995

[4] KAMMEYER, K.-D., KROSCHEL, K.: *Digitale Signalverarbeitung*. Springer-Vieweg, Wiesbaden 2012

[5] KROSCHEL, K., RIGOLL, G., SCHULLER, B.: *Statistische Informationstechnik*. 5. Aufl., Springer, Heidelberg u.a., 2011

[6] KROSCHEL, K., METZLER, J.: *Lokalisation des optimalen Messorts zur berührungslosen Bestimmung von Puls- und Atemfrequenzen*. 28. Konferenz Elektronische Sprachsignalverarbeitung, Saarbrücken 2017, pp. 300-387