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Challenging task of identification of cardiac cycle tones: refined development of a PCG signal processing system

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Abstract

This article presents some results of processing of phonocardiography signals (PCG signals) for cardiac cycle tone identification under ambient noise of varying intensity. For PCG signal processing, proposed is a refined approach based on active band pass filter bank, which allows improving an accuracy of cardiac cycle tone identification under ambient noise. The efficiency of the application of the proposed approach has been demonstrated by the respective qualitative, quantitative results and experimental data obtained upon processing of PCG signals according to the offered technique. A 3D model of the cardiac cycle tone identification system has been developed based on this conceptual idea.

Keywords

Processing, Phonocardiogram, Filter bank, Identification, Cardiac cycle tones, Electronic stethoscope, Visualization, Heart biomechanics

Imprint

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Introduction

According to statistics from the World Health Organization (WHO), cardiovascular diseases are the primary cause of death worldwide [1,2]. To diagnose diseases of the cardiovascular system, phonocardiography, electrocardiography, electronic auscultation, and many other methods are currently used in medicine [2–4]. Phonocardiography is a method for studying the biomechanical heart activity, based on recording sound vibrations of the heart muscle and valve apparatus [2]. In the scientific literature, the identified phonocardiography signals (PCG signal) are usually called cardiac cycle tones, and their activity is conventionally referred to as biomechanics [2,3]. In practice, the cardiac cycle tones are identified by phonocardiographs or electronic stethoscopes. To simplify the recording procedure for cardiac cycle tones, on a person's torso, a stethoscope with an electronic microphone embedded into the head is utilized [4-8]. A stethoscope is an acoustic device for listening to sound phenomena (auscultation) of internal organs (part of body). The use of electronic microphones in heads of a stethoscope for phonocardiography studies today is quite justified [4–9].

The process of identifying cardiac cycle tones consists of the following stages: recording a PCG signal at the auscultation points of the heart, an amplification of the PCG signal and its subsequent processing (filtering) with further visualization with a specialized device [3,9]. However, in practice, the identification of cardiac cycle tones is greatly complicated by the influence of ambient noise of varying intensity [3,4,9]. Under the influence of such noise, the accuracy of identification of cardiac cycle tones is significantly reduced that may lead to inaccurate visualization of phonocardiography information [9]. Thus, the development and study of filtering approaches to improve the accuracy in identifying cardiac cycle tones against the background of noises are actually a very challenging task.

At present, to solve this problem, known are some approaches [5–8], which are based on active, passive (low-frequency and high-frequency) PCG signal filtering. An analysis of the well-known works has revealed the following features of these conventional approaches: during the passage through the filtering blocks, the identified cardiac cycle tones are smoothed and clipped that results in a crackling of the identified tones of the cardiovascular system performance and noise distortion and that demonstrates the narrowness of the transmission bandwidth low-frequency and high-frequency components of the filters. Considering the revealed drawbacks and disadvantages of the known approaches, a pioneering approach, based on active cascade band pass filtering, has been proposed in [9] to improve the accuracy of identifying tones. This fresh approach makes for extended frequency bands, namely in the mid-frequency range of cardiac cycle tones from 40 to 120 Hz, possible to reduce ambient noise. To justify the practical significance of the proposed fresh approach, experimental studies have been conducted. As a result of the study, the effectiveness has been confirmed by visualization of the PCG signal processing data on the recorded phonocardiograms with the use of Software Proteus.

As an extension of the approach presented in [9] in this work it is proposed to use a filter bank consisting of active band pass filters on operational amplifiers, where their frequency range overlaps. Our refined approach allows eliminating noise on extended frequency bands and identifying low-frequency, mid-frequency and high-frequency tones in a cardiac cycle. A similar conceptual idea is used in the processing of respiratory signals of the lungs and demonstrates the results of high accuracy [10].

This article discusses our refined approach for identifying cardiac cycle tones using the filter bank, which allows us reducing noises of varying intensity at extended frequency bands, thereby increasing accuracy in the PCG signal identification.

Aim

The aim of our research is to confirm the possibility of using an active band pass filter bank to improve the accuracy of identifying cardiac cycle tones when visualizing biomechanical activity of the cardiovascular system.

Materials and methods

To obtain quantitative and qualitative results, test patterns of a PCG signal and noise at different intensities have been employed. The PCG-signal model with the present noise is taken additively, in the form of

$$x(t)=S(t) + n(t), \quad (1)$$

representing PCG signal S(t) and ambient noise n(t). When using model distorting effects, a priori information about the nature of noise is mainly applied. Models of ambient noise are based on normally distributed white noise, which is limited throughout the signal frequency band [11]. White noise models at various power values have been obtained utilizing Adobe Audition 1.5 software (developed by Adobe System) [12]. The test model of the PCG signal has been obtained from the certified International Database of the Massachusetts Institute of Technology (MIT) [13].

The phonocardiographic signals are filtered by a bank of active band pass filters on operational amplifiers, whose frequency range is overlapped. Such a PCG signal filtering scheme has been chosen on the basis of the expediency to increase the accuracy characteristics of the consequentially identified cardiac cycle tones, namely, components S1 and S2 against the background noise. The frequency range of these filters is designed for an extended frequency band filter bank with the series connection of active band pass filters. For filter synthesis, a frequency analysis of components S1 and S2 is performed using the Fourier transform on the amplitude spectrum [2, 3].

A filter characteristics analysis is performed on the basis of calculation of the transfer function of the active band pass filter [14]. The frequency and phase characteristics of the analyzed filter are investigated on the basis of the Bode diagram in software MATLAB.

The effectiveness of PCG signal filtering is estimated by the respective qualitative and quantitative results. An analysis of the processing quality is performed by visual imaging [15]. An analysis of the quantitative processing results is evaluated by several criteria. These criteria are the following indicators: the signal-to-noise ratio (SNR) before and after filtering the signal (2), (3) [15], the root mean square error of signal filtering (RMSE) (4) [3] and the correlation coefficient between the filtered and the test PCG signal (r) (5) [3].

$$SNR_{\substack{before\\filtering}} = 10\log_{10}\left[\frac{\sum_{n=1}^{N} x(n)^2}{\sum_{n=1}^{N}(s(n)-x(n))^2}\right], \quad (2)$$

$$SNR_{\substack{after\\filtering}} = 10\log_{10}\left[\frac{\sum_{n=1}^{N} x(n)^2}{\sum_{n=1}^{N}(x'(n)-x(n))^2}\right], \quad (3)$$

$$RMSE = \sqrt{\frac{\sum_{n=1}^{N}(x(n)-x'(n))^2}{N}}, \quad (4)$$

$$r = \frac{\sum_{n=1}^{N}(x_i-\bar{x})\cdot(y_i-\bar{y})}{\sqrt{\sum_{n=1}^{N}(x_i-\bar{x})^2\cdot\sum_{n=1}^{N}(y_i-\bar{y})^2}}, \quad (5)$$

where x(n) – test PCG signal, s(n) – noised signal, x' – de-noised signal, x_i – current value length of the filtered PCG signal, $\bar{x}$ – mean value length of the filtered PCG signal, y_i – current value length of the test PCG signal, $\bar{y}$ – mean value length of the test PCG signal.

To study the correlation strength of the signal values between the filtered signal and the test one, it is estimated employing a scatterplot with the use of the STATISTICA 10.0 application software (developed by Stat Soft) [16].

Our experimental studies have been performed using an electronic stethoscope with an embedded electronic microphone [9]. Recording and processing of cardiac cycle tones have been conducted in a human individual, aged twenty-seven, in the absence of any physical activity, in his upright position. Visualization of the identified tones cardiac cycle has been carried out using software product Proteus 7.10 (developed by Labcenter Electronics) [17]. 3D-modelling of the developed system has been realized also with the above mentioned software product.

Results and discussion

For the synthesis of the parameters of the filter bank, the respective quantitative results of the analysis of frequency components of the S1 and S2 tones, based on the Fourier transform, have been obtained. As a result, component S1 has been identified to be in the range from 30 to 120Hz, and S2 from 40 to 200Hz, respectively, as shown in Figure 1 herein. Based on the identified frequency values, a filter bank has been synthesized, the results of which are presented in Figure 2 given herein.

The results of the analysis of the amplitude and phase characteristics depending on the identified frequencies have shown the following: a) the filter bank has the most flat (uniform) frequency response; b) it has moderate phase nonlinearity; c) it has rather a steep fall-off outside the signal bandwidth that is indicated by the proximity to the ideal form of band pass filters (see Figure 2 herein).

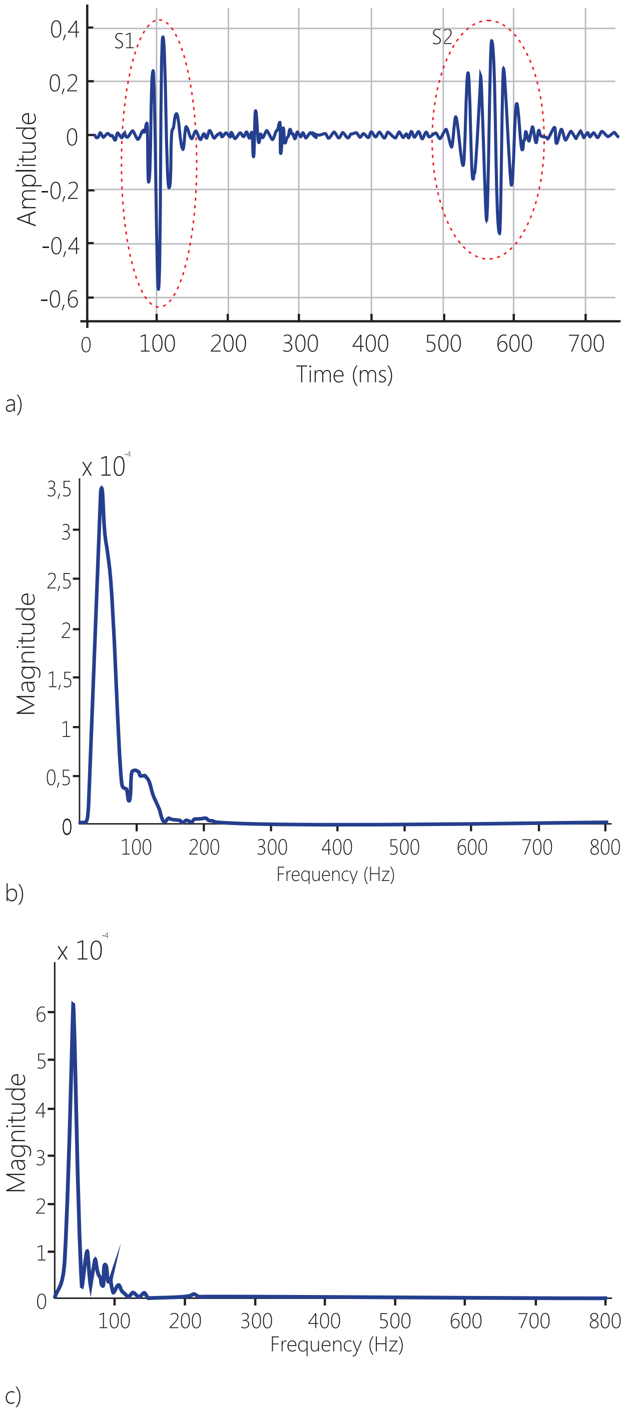

Figure 1. Amplitude-time and frequency-related characteristics of cardiac cycle tones: a) a test signal from the MIT database; b) frequency spectrum of component S1; c) frequency spectrum of component S2

The analysis of the obtained filter bank characteristic shows that the filter bandwidths for identifying the components S1 (dashed line) and S2 (solid line) are overlapped and suppress ambient noise outside the signal bandwidth. Following the results of the analysis, we will process the PCG signal to identify cardiac cycle tones. To assess the efficiency of our proposed approach

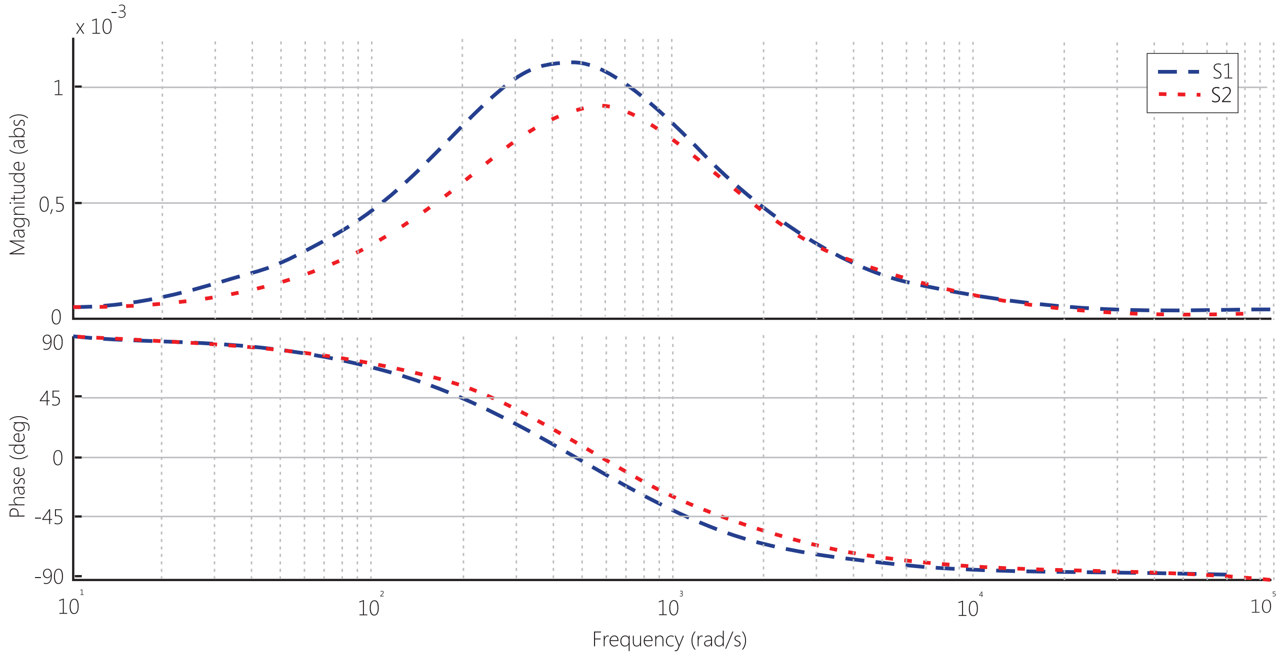

Figure 2. Frequency and phase characteristics of the filter bank

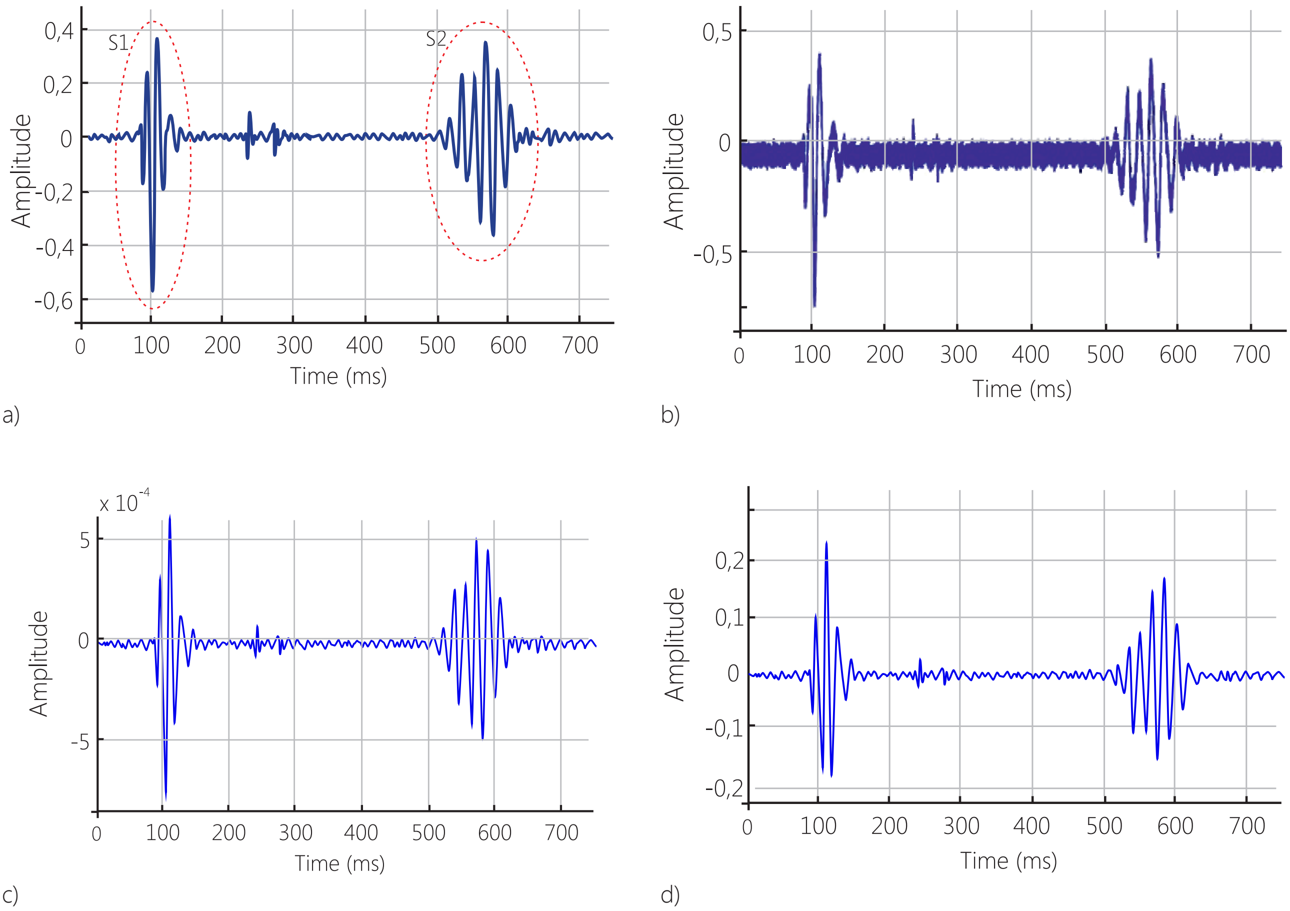

Figure 3. PCG signal processing results; a) the test PCG signal from the MIT database; b) the noisy PCG signal; c) the de-noised PCG signal by the proposed approach; d) the filtered signal according to approach [9]

based on the computer modeling method, the required qualitative and quantitative results of processing are obtained, which are presented in Figure 3 herein.

Based on the obtained qualitative and quantitative results, we note that the developed filter bank allows us to identify the morphology of the S1 and S2 components of the cardiac cycle tones against the background noise. A histogram of the quantitative results for signs of noise stability (noise resistance) and accuracy is presented in Figure 4 given herein.

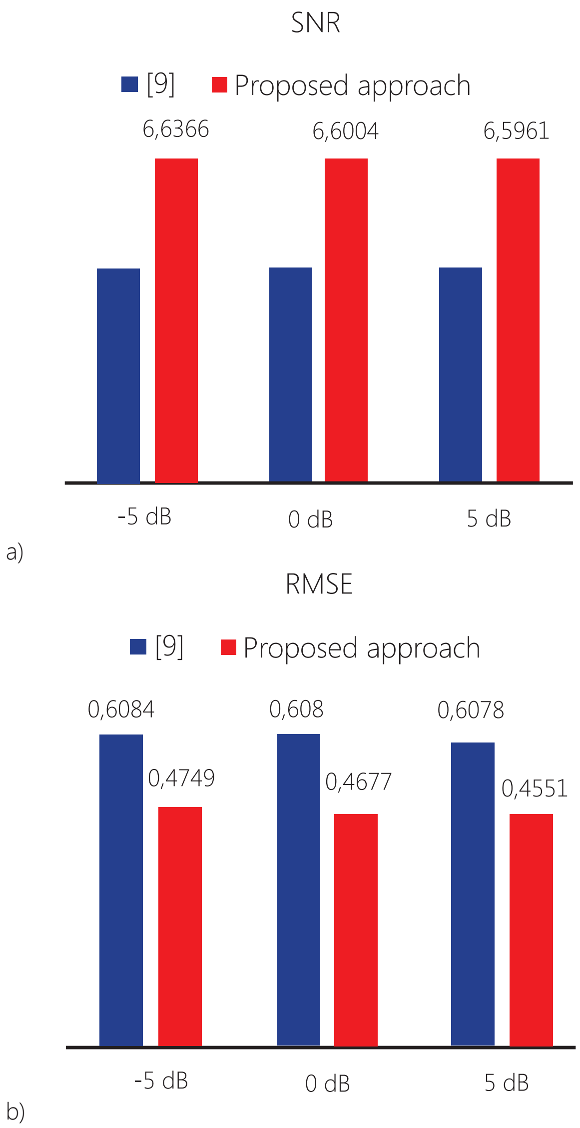

Figure 4. Histogram of quantitative results of PCG signal processing; a) indicator SNR; b) indicator RMSE

The quantitative results and high SNR index values as exhibited by the histogram indicate the noise stability of the PCG signal (noise resistance) to noise at -5dB, 0dB, 5dB compared with the approach in [9]. Low RMSE values show the accuracy of identifying cardiac cycle tones, namely, components S1 and S2. Furthermore, the correlation coefficient between the filtered and test signal is r = 0.968. When using the known approach [9], the value of the correlation coefficient is r = 0.839. Thus, to systematize the quantitative results obtained, Figure 5 herein shows a scatter plot showing the strength of the correlation of values between the filtered and the test PCG signal.

The scatter plot results have demonstrated that the developed approach (Figure 5a) herein) reveals a very high correlation r = 0.96880 with a probability of 0.95, with statistical significance $p < 0.05$. At the same time, the approach [9] shows a high correlation, but with

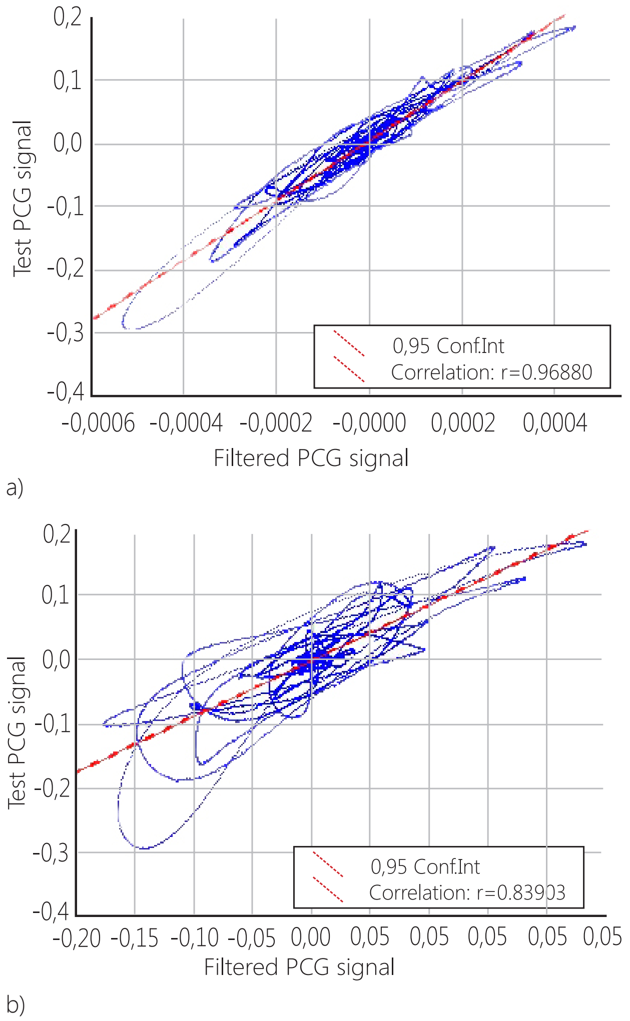

Figure 5. The scatter plot diagram dependence filtered and test PCG signal: a) the proposed approach; b) the known approach [9]

r = 0.83903, with a probability of 0.95, also with statistical significance $p<0.05$. A very high correlation processing result r = 0.96880 is available due to minimal distortions of the PCG signal processing results and accuracy of identification cardiac cycle tones against the background noise.

Thus, our analysis of the obtained qualitative and quantitative results upon processing the PCG signals makes it possible to note that the developed filter bank allows improving the accuracy of identifying cardiac cycle tones in the presence of noises of varying intensity. This refined approach maximally eliminates ambient noise with minimal distortion of low-frequency, mid-frequency and high-frequency cardiac cycle tones that is confirmed by the qualitative, quantitative and statistical results of the analysis of signal processing relative to [9].

To justify the practical significance for the developed filter bank intended for identifying tones, when processing the PCG signals, Figures 6–8 herein pres-

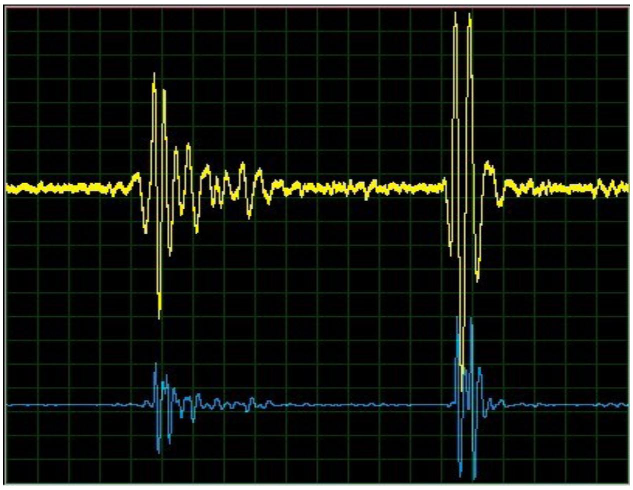

Figure 6. Recorded (yellow) vs. processed (blue) phonocardiogram at mitral point of auscultation. The ordinate is the amplitude, the abscissa is time. In both cases: the amplitude is represented on the ordinate, and the time is laid off as the abscissa.

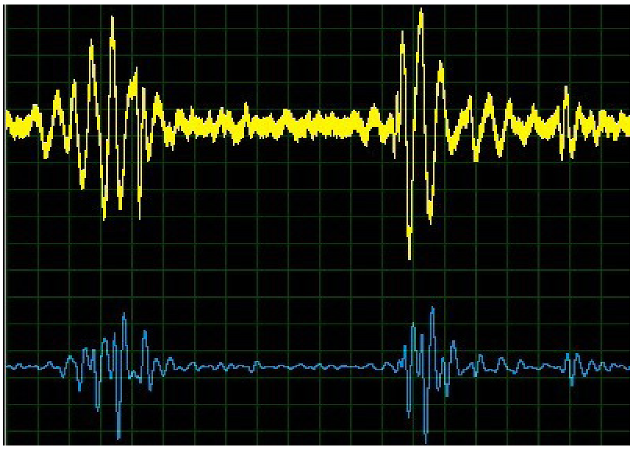

Figure 7. The recorded (yellow) vs. processed (blue) phonocardiogram at tricuspid valve auscultation point. In both cases: the amplitude is represented on the ordinate, and the time is laid off as the abscissa.

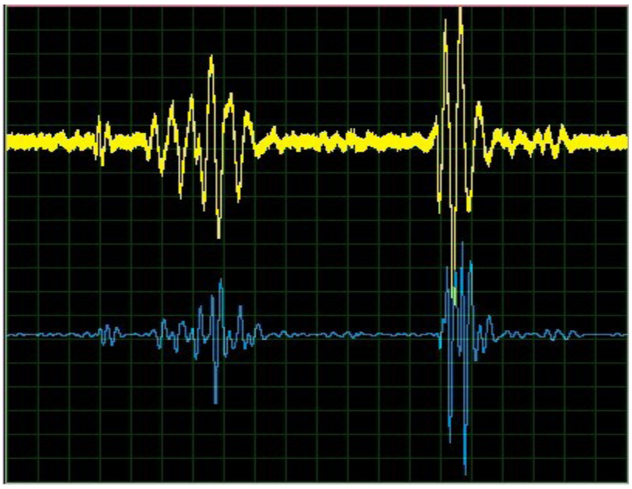

Figure 8. The recorded (yellow) vs. processed (blue) phonocardiogram at the Botkin-Erb point. In both cases: the amplitude is represented on the ordinate, and the time is laid off as the abscissa.

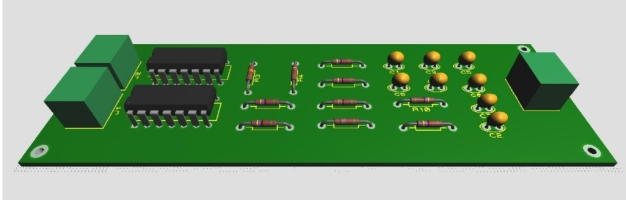

Figure 9. 3D model of the developed PCG signal processing system

ent visualization graphs of our experimental study. During the experiment, the PCG signal has been recorded using an electronic stethoscope and visualized using the Proteus software.

Based on the obtained experimental results (please, refer to Figures 6–8 herein), we can note that our refined approach confirms the identification of the cardiac cycle tones during the biomechanical heart activity in a human individual under study. As it is evidenced by the results of our experimental study, our developed approach allows identifying cardiac tones not only of the test signal in the presence of noise, but also of experimentally generated ambient noise PCG signal. Furthermore, the visualization of the cardiac cycle tones shows that the examined subject has no abnormalities, and the recorded tones completely coincide with the cardiac cycle of the vascular system. Figure 9 herein shows our 3D model of the developed PCG signal processing system.

Conclusion

The paper proposes our refined approach for identifying cardiac cycle tones when processing the PCG signal based on the bank of active band pass filters. This approach allows increasing the accuracy of identification of cardiac cycle tones against the background of noises of varying intensity. The efficiency of this developed approach is supported by the respective qualitative, quantitative and experimental results of the processing. The processing qualitative results reinforce the identity of the filtered waveform with the test PCG signal, and the quantitative results confirm the improved accuracy in the identification of tones when compared with other known solutions. To provide support for the practical significance and the performance of our developed approach, the required experimental studies have been conducted.

Statement on ethical issues

Research involving people and/or animals is in full compliance with current national and international ethical standards.

Conflict of interest

None declared.

Author contributions

All the authors read the ICMJE criteria for authorship and approved the final manuscript.

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