Time-Frequency Signal Processing Approaches with Applications to Heart Sound Analysis

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Abstract

In this paper, it is demonstrated that time-frequency techniques may be used for an enhanced diagnosis of the heart disease. Three time-frequency analysis techniques are compared: spectrogram, Wigner distribution and S-method. The results show that the S-method could be used in the heart sounds analysis, and that is also capable of enhancing the diagnostic techniques available to medical personnel.

1. Introduction

Cardiovascular disease (CVD) remains the leading cause of death worldwide, contributing to more than 17 million deaths or one-third of all deaths each year, according to the World Health Organization [1].

Fortunately, clinical experience has shown that heart sounds can be an effective tool to noninvasively diagnose some of the diseases [2]. Heart sounds are the result of sudden closure of the heart valves during different phases of the cardiac contraction. They are non-stationary, non-deterministic signals that carry information about the anatomical and physiological state of the heart. Each heart beat consists of at least the first heart sound (S1) and second heart sound (S2). The S1 indicates the beginning of ventricular systole and its intensity is closely related to that event. The S2 marks the end of ventricular systole and beginning of ventricular relaxation following the closure of the aortic and pulmonary valves.

A heart problem, known as mitral stenosis, is often manifested through the heart sound known as opening snap (OS), which is a short, sharp sound occurring in early diastole. However, the difficulty lies in the fact that the OS sounds very similar to the third heart sound (S3) and its presence in individuals over the age of 40 usually reflects cardiac disease characterized by ventricular dilatation, decreased systolic function, and elevated ventricular diastolic filling pressure. It is generally difficult to distinguish these two sounds just by listening without going through sufficient training [2].

The time-frequency analysis has already been used for heart sounds analysis, but mainly in analysis of the S1 and the S2 [3] [4]. The time-frequency analysis of the OS and S3 has been performed in [5] [6] by using the linear time-frequency techniques.

In this paper, a quadratic class of the time-frequency transforms is used in the analysis of OS and S3. The objectives of this study are to analyze which of the three quadratic time-frequency techniques: spectrogram [7], Wigner distribution [7] or the S-method [8], produce the best time-frequency description of these sounds. The importance lies in the fact that the OS often sounds similar to the S3 as pointed our earlier. The analysis will be performed on the heart sounds, recorded at St. Joseph's Hospital in Toronto, Canada, during heart auscultations. The recordings contain the S1, the S2 and the OS or the S3.

The main conclusion of the paper is that the S-method consistently provides better time-frequency representation of the heart sounds than the other two methods. Also, it is shown that the S-method can effectively resolve the OS and the S3 in the time-frequency domain, even though their time domain representations are very similar.

This paper is organized as follows: In Section 2, the concept of the time-frequency analysis along with the comparison of the three time-frequency representations is given. The detailed analysis of the heart sounds by using the time-frequency representations is covered in Section 3. Finally, conclusions are drawn in Section 4 followed by a list of references.

2. Methods

The time-frequency analysis provides a two-dimensional domain representation of the one-dimensional time domain signal. In this paper, the short time Fourier Transform (STFT), the Wigner Distribution (WD) and the S-method are investigated. The properties of the STFT and the WD are well known and documented [7]. The S-method combines good properties of both traditional tools, that is, the absence of cross-terms and high resolution [8].

The STFT is obtained by sliding a window function along the signal, and for each portion of the signal multiplied by the window function, a Fourier transform (FT) is found. If a long signal $f(t)$ is consider, spectral components around time t can be obtained using STFT, or in the form of a spectrogram, [7]:

$$SPEC(t,\omega) = |F(t,\omega)|^2 = \left| \int_{-\infty}^{\infty} f(t+\tau)w(\tau)e^{-j\omega\tau}d\tau \right|^2 \quad (1)$$

where $w(\tau)$ is a window, with a width T. The STFT is a time-frequency transformation that is highly dependent on the choice of the window function.

Commonly used methods are based on the Wigner distributions and its variations [7], and the WD is defined by:

$$W(t,\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(t,\omega+\theta)\, F^*(t,\omega-\theta)\, d\theta \quad (2)$$

Unlike the STFT, the WD suffers from cross-terms between signals separated in the time-frequency plane, but the SFTF has a significant leakage due to the window usage, which is less exhibited in the case of the WD. The sampling interval for the WD is two times smaller than the one used for the spectrogram, which results in the increased computational complexity of the WD.

If a narrow window $P(\theta)$ is introduced, it follows that [8]:

$$SM(t,\omega) = \frac{1}{\pi} \int_{-\infty}^{\infty} P(\theta) F(t,\omega+\theta)\, F^*(t,\omega-\theta)\, d\theta \quad (3)$$

which is a definition of the S-method. This formula leads to a computationally very efficient and simple method. If the formula for $SM(t,\omega)$ is considered, some useful effects can be observed with an appropriate choice of window. In particular, two special cases:

- If $P(\theta) = 2\pi\delta(\theta)$, then the spectrogram is obtained, i.e. $SM(t,\omega) = STFT(t,\omega)$.
- If $P(\theta) = 1$, for all θ, then a pseudo Wigner transform is obtained, i.e. $SM(t,\omega) = W(t,\omega)$.

Discrete version of (3) is used in numerical implementation and it is given by:

$$DSM(n,k) = \sum_{i=-L}^{L} P_d(i) F(n,k+i)\, F^*(n,k-i) \quad (4)$$

where $2L+1$ is the width of the discrete window $P_d(i)$.

The two special cases suggest that the S-method is a distribution "between" a spectrogram and the WD and which combines the good properties of both, that is, a high resolution and complete or significant reduction of the cross-terms.

3. Analysis

Phonocardiograph recordings of actual heart sound were obtained from patients at St. Joseph's Hospital in Toronto, Canada, during heart auscultations. The heart sounds are sampled at 4000 Hz and in order to take advantage of the fast algorithms, each recording is 1.024 seconds long. The sampling rate is sufficient since the maximum frequency content of heart sounds is usually below 600 Hz. These recordings have been carefully studied by the chief cardiologist in order to validate the presence of the opening snap or the third heart sound. For the spectrogram calculations, a Gaussian window is used as the analyzing window, defined as $g(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{t^2}{2\sigma^2}}$, where a parameter σ is often associated with the window width. In the computation of the S-method, $L = 4$ is used, where L is defined in [8].

By comparing the three representations for the sample heart sounds, it is rather clear that the WD is unsuitable for the analysis of the heart sounds. The main disadvantage is an appearance of the cross terms, which complicates the task of the analysis of the heart sounds. Another disadvantage is an increased computation requirement as outlined in [8]. By comparing the representations obtained by the spectrogram and the S-method, a clear picture of the sounds can be obtained, since these two transformations provide us with the representations which do not suffer from the cross-terms. However, it is also clear that the S-method provides better time-frequency localization of the heart sounds. Due to this fact, it is easier to diagnose the presence of the certain heart sounds.

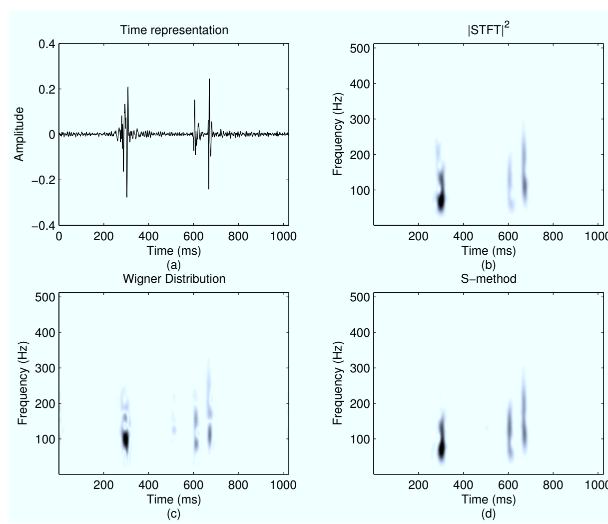

Figure 1. Heart sound with the OS: (a) Time-domain representation; (b) Spectrogram; (c) Wigner distribution; (d) S-method.

Let's examine how the distance between the S2 and the

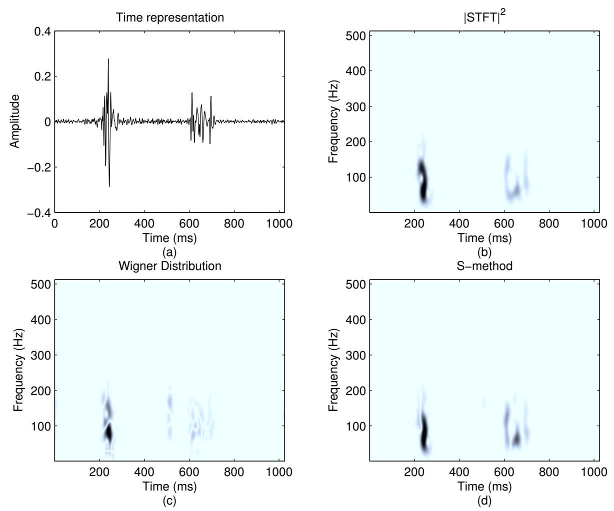

Figure 2. Heart sound with the OS: (a) Time-domain representation; (b) Spectrogram; (c) Wigner distribution; (d) S-method.

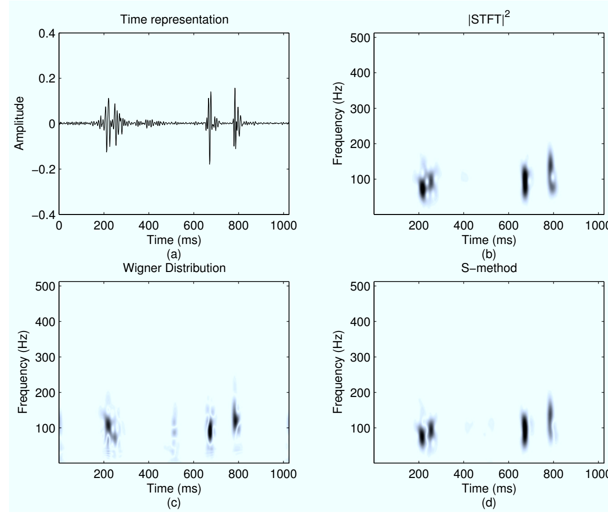

Figure 3. Heart sound with the OS: (a) Time-domain representation; (b) Spectrogram; (c) Wigner distribution; (d) S-method.

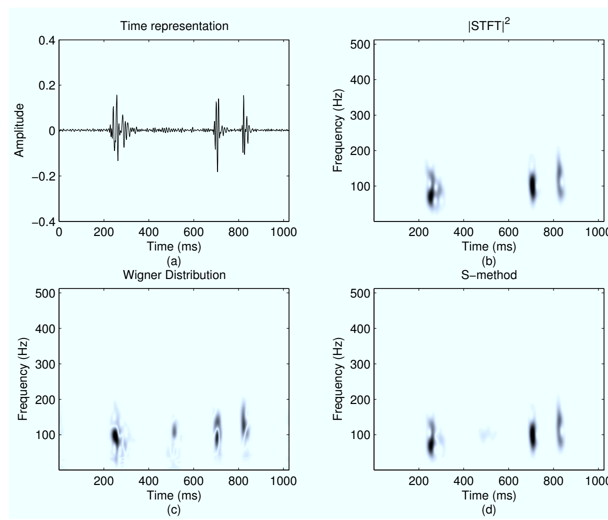

Figure 4. Heart sound with the OS: (a) Time-domain representation; (b) Spectrogram; (c) Wigner distribution; (d) S-method.

OS is affected by the time-frequency analysis. Figures 1 and 2 provides us with two scenarios. In the first one, the S2 and the OS are separated, and both the spectrogram and the SM provide us with the legitimate representations, with the SM providing slightly higher resolution. In second scenario as depicted in Figure 2, the OS is very close to the S2. In Figure 2(d) the aortic and pulmonary components of the second heart sound are separated also, and one may unambiguously state that the component after that is the OS. However, by observing the time-frequency representation given by spectrogram in Figure 2(b), one might not be sure whether the OS is present, or the patient has a condition called split S2, where the aortic and pulmonary components of the second heart sound are more apart than usual.

The next objective of this paper is to analyze the time-frequency representations of the well separated S2 and the OS, and the time-frequency representations of the heart beat in which the S3 is present. As mentioned previously, it is of paramount importance to differentiate the OS and the S3 properly, since they represent two different diseases, but sound very similar to an inexperienced physician.

Figures 3 and 4 depict the time-frequency analysis of the heart sounds with the OS present, and the S2 and the OS are well separated. Figures 5 and 6 show the time-frequency representations of the heart beats in which the S3 is present. By comparing the time domain representations of these sounds, it is rather clear that the differences among the different diseases are not noticeable. The differences are becoming noticeable in the time-frequency domain. Again, the S-method achieves favorable performance in comparison to the other two transforms. In comparison to the WD, it does not have cross-terms which appear in some of the representations, and in comparison to the spectrogram, it provides higher resolution. Also in some cases, as shown in Figure 5 and 6, it is capable of resolving the S2 lot better than the spectrogram.

Due to the fact that the S-method provides better representation than the other methods, it is natural that the differences between the OS and S3 will be more easily noticed. By comparing the time-frequency representations for these two diseases, it is quite clear that the OS contains slightly higher frequencies than the S3. This was also no-

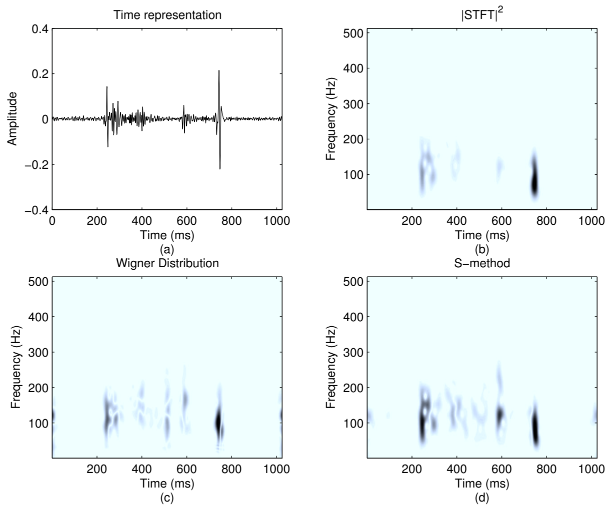

Figure 5. Heart sound with the S3: (a) Time-domain representation; (b) Spectrogram; (c) Wigner distribution; (d) S-method.

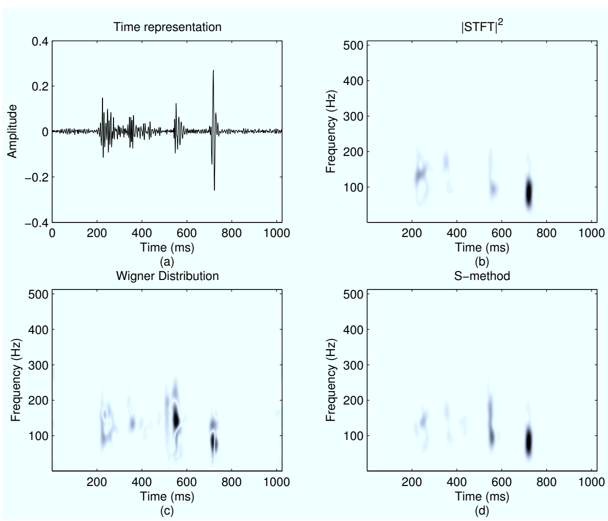

Figure 6. Heart sound with the S3: (a) Time-domain representation; (b) Spectrogram; (c) Wigner distribution; (d) S-method.

ticed in previous works, and is in accordance with medical theory. However, the advantage of the S-method is that it provides higher resolution than the linear time-frequency methods.

4. Conclusions

In this paper, a time-frequency analysis of heart sounds is performed in order to examine the suitability of such analysis for the diagnosis of the heart diseases. The spectrogram, the Wigner distribution and the S-method have been considered, and it has been shown that the S-method provides the best time-frequency localization among the considered transforms. It is also capable of resolving closely spaced S2 and OS, when the other two transforms are incapable of doing so.

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