Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

Analysis of Simulated Heart Sounds by Intrinsic Mode Functions

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Abstract: The mechanisms involved in the generation of heart sounds have always been of interest, mainly for diagnosis purposes. As a result, mathematical models have been proposed for first (S1) and second (S2) heart sounds and different efforts have been made to select the best signal processing tool to analyze them. Different frequency analysis techniques have been used to relate cardiac structure to the vibration they emit. In this work, we applied the empirical mode decomposition (EMD), a recently developed technique, for time-frequency (TF) analysis of heart sounds. EMD has shown interesting properties for biomedical signals related to nonlinear and non-stationary analysis. EMD is an adaptive decomposition since the extracted information is obtained directly from the signal without the use of kernels or mother waveforms. In this paper, EMD is first investigated in simulated scenarios through mathematical models for S1 and S2 to validate its performance. Later, a real heart sound acquired over the thoracic surface of a healthy subject is analyzed. The work points out the advantage of EMD for this task.

I. INTRODUCTION

Heart sounds have received a lot of attention for several decades since an understanding of the mechanisms involved in their genesis, and their changes by different valvular and myocardial pathologies are required [1]. Other reason to understand their structure has to do with heart sounds as interference signal; for example, the analysis of breathing sounds. In this case, heart and breathing sounds show non-stationary behavior and overlapping of frequency contents. Multichannel acquisition systems have been proposed recently for lung sounds analysis and consequently, an understanding of the structure of heart sounds over the thoracic surface is relevant for interference cancellation purposes [2, 3].

Traditionally, S1 and S2 heart sounds have been considered as generated mainly by valve impact, where it is recognized that both sounds consist of several components with short transients and nonstationary behavior [1]. The classical frequency analysis techniques as Fourier transform and autoregressive spectral estimation are not appropriate since they assume a stationary behavior for the time interval under analysis. So, time-frequency (TF) transform have been analyzed for studying S1 and S2 sounds, from short time Fourier transform (STFT) to Wigner-Ville (WV) TF representations in an attempt to separate their different components; however, these techniques possess different limitations. This work explores empirical mode decomposition (EMD), an adaptive TF decomposition recently developed, for analyzing heart sounds using simulated scenarios through mathematical models for S1 and S2 heart sounds to validate EMD performance. Afterward, a real heart sound acquired over the thoracic surface of healthy subjects is analyzed.

II. PROBLEM STATEMENT

For STFT, shorter analysis windows produce good time resolution but result in spectral resolution degradation. The WV provides an improved TF resolution although with multicomponent signals, such as S1 and S2, cross-term artifacts complicate the interpretation of the signals' frequency dynamics [4]. Others TF transforms, such as binomial transform, deal with cross-terms to reduce them but there is resolution degradation since this effect depends on the convolving kernel [4].

Alternatively, EMD allows dealing with nonstationary and nonlinear signals and it can be seen as an adaptive time-varying filtering [5, 6]. EMD has been applied to biomedical signals mainly for the analysis of gastroesophageal information [7], interference reduction in electrogastograms [8], and for dynamics of cerebral autoregulation in stroke and hypertension [9] but, up to the knowledge of the authors, EMD has not been applied to heart sounds.

II. BACKGROUND

A. Empirical mode decomposition (EMD)

The central idea of EMD is to identify the intrinsic oscillatory modes of a signal, the so-called intrinsic mode functions (IMF), using its characteristic time scales extracted from signal's extrema [5]. The IMFs are obtained directly from the signal without the use of kernels or mother waveforms; in this sense, EMD is an adaptive decomposition. The signal s(t) to be analyzed is represented by:

$$s(t) = \sum_{k=1}^{N} IMF_k(t) + r_N(t) \qquad (1)$$

where N is the number of IMFs, and $r_N(t)$ represents a residual signal. There are two conditions that IMFs must satisfy: (a) the number of extrema and the number of zero crossings must be equal or differ at most by one, in the whole data set and; (b) have symmetry with respect to local zero mean.

The procedure to calculate the IMFs is as follows:

1. Determine all local maxima and minima of s(t).
2. By a cubic spline interpolation of local maxima and local minima, generate upper and lower envelopes.
3. Average the two envelopes to get the local mean $m_1(t)$.
4. Calculate $h_1(t) = s(t) - m_1(t)$ and check if $h_1(t)$ accomplishes conditions (a) and (b) to be an IMF.
5. If $h_1(t)$ is an IMF:
   - The residue $r(t) = s(t) - h_1(t)$ is calculated.

   else
   - Replace s(t) with $h_1(t)$ and repeat from step 1.
6. Repeat from step 1 to step 5 by sifting the residual signal r(t). The procedure ends when the residual signal is non-oscillatory [5].

B. The instantaneous frequency

The instantaneous frequency (IF) of an IMF can be defined if an IMF satisfies conditions (a) and (b). As Huang *et al*. point out, the IF is a concept difficult to accept due to the deeply influence of Fourier analysis where one full oscillation of a sine or cosine function is needed to determine the local frequency. This circumstance could not make sense for nonstationary signals. The different ways to define IF was another problem to accept the concept but this has been overcome from the introduction of the Hilbert transform that provides an analytical signal. For a signal x(t) its Hilbert transform is obtained by:

$$y(t) = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{x(t')}{t - t'} dt' \qquad (2)$$

where P indicates the Cauchy principal value. With equation (2), an analytical signal z(t) can be defined as:

$$z(t) = x(t) + jy(t) = a(t)e^{j\theta(t)} \qquad (3)$$

from which the IF can be defined as $\omega(t) = \frac{d\theta(t)}{dt}$.

C. Simulated first and second heart sounds

Mathematical models for S1 and S2 have been proposed for selecting, among other reasons, the best TF representation for their analysis [10, 11]. For S1, it has been hypothesized that a sound acquired over the thorax at the apical area is composed of two types of vibration: (a) vibration related mainly to the atrio-ventricular valves ($s_v(t)$) that is modeled with components of constant frequencies and, (b) vibration related to the myocardium ($s_m(t)$), modeled with components of rising frequency. The model for S1 is given by:

$$S1(t) = s_m(t) + \begin{cases} 0 & 0 \le t \le t_0 \\ s_v(t - t_0) & t \ge t_0 \end{cases} \qquad (4)$$

with t_0 equals to 10 msec and constant frequencies of 50 and 150 Hz for $s_v(t)$ while the frequency modulation for $s_m(t)$ is given by $f_m(t) = -40\cos(34\pi t)$, with an excursion in frequency from 20 to 100 Hz in 60 msec.

In the case of S2, the model considers the aortic (A_2) and the pulmonary (P_2) components, both are modeled by nonlinear chirp signals by:

$$S2(t) = A_A(t)\sin(\varphi_A(t)) + A_P(t - t_0)\sin(\varphi_P(t)) \qquad (5)$$

where $\varphi_A(t)$ and $\varphi_P(t)$ are given by the integral of the IFs:

$$IF_A(t) = 24.3 + 225.7(t+1)^{-0.5} \qquad (6)$$
$$IF_P(t) = 21.83 + 178.17(t+1)^{-0.5}$$

in the time interval $0 \le t \le 60$ msec and t_0 was 30 msec.

IV. METHODOLOGY

In this work equations of section III.C were implemented to simulate S1 and S2, and EMD was applied to them to evaluate its performance to extract their components as well as their IF behavior. Afterward, the EMD was applied to a heart sound acquired from a healthy young subject with no history of cardiac problem. End-expiratory heart sound was recorded at a position close to the heart to prominently pick up the valve sounds. The sounds were acquired at 5 KHz using a subminiature electret microphone with an air plastic coupler. The real S1 signal was processed by EMD for two purposes, first reducing the noise information by removal the IMFs corresponding to it, and later to obtain the IF behavior.

V. RESULT

A. Simulated heart sounds

Figs. 1 and 2 show the EMD results for S1 and S2 without noise. Fig. 1(a) shows S1 at the top and their six IMFs while Fig. 1(b) shows the IFs for IMF_1 to IMF_3 since from IMF_4 to IMF_6 seem to be no significant for the information in S1. Also, the IF for IMF_1 is in dash line, for IMF_2 is in continuous line and for IMF_3 is in dot-dash line and all are shown from 0 to 0.08 sec to focus on their details.

Fig. 2(a) shows S2 and its four IMFs while Fig. 2(b) shows the corresponding IFs. Again, instantaneous frequency for IMF_1 is in dash line, for IMF_2 is in continuous line, for IMF_3 is in dot line and for IMF_4 is in dot-dash line. Figs. 3(a) and 4(a) present the EMD results for S1 and S2 with a SNR of 13 dB while Figs. 3(b) and 4(b) show the IFs for IMF_2 (dash line), IMF_3 (continuous line) and IMF_4 (dot-dash line).

B. Real heart sounds

Fig. 5 shows the results for real S1 and the IFs only for IMF_4 and IMF_5.

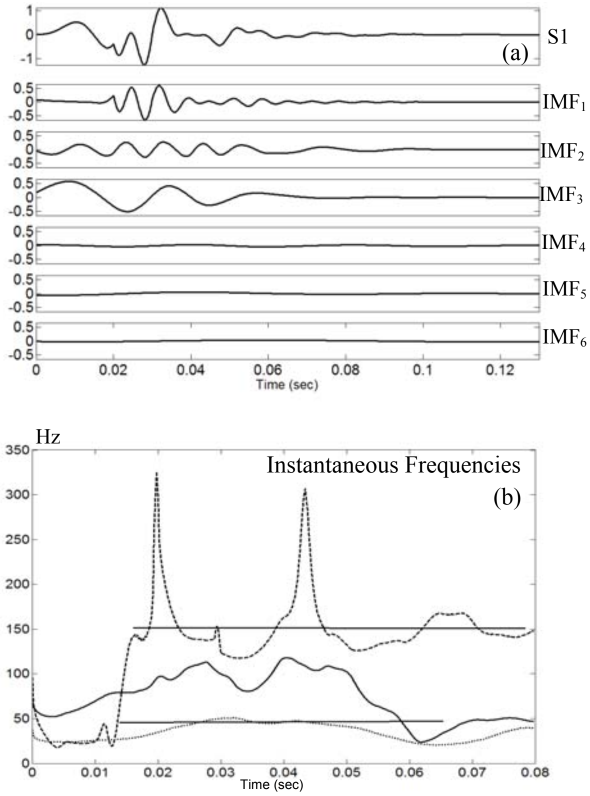

Figure 1. EMD applied to simulated S1.

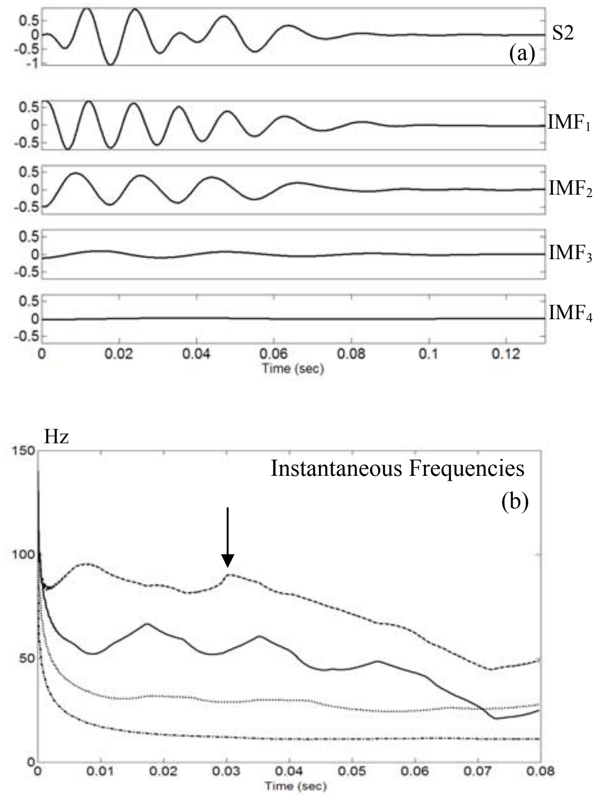

Figure 2. EMD applied to simulated S2.

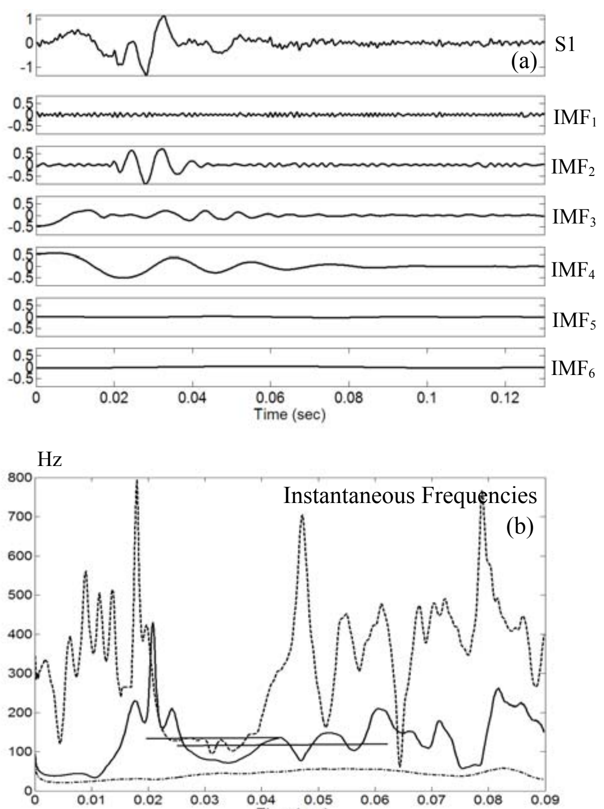

Figure 3. EMD applied to simulated noisy S1.

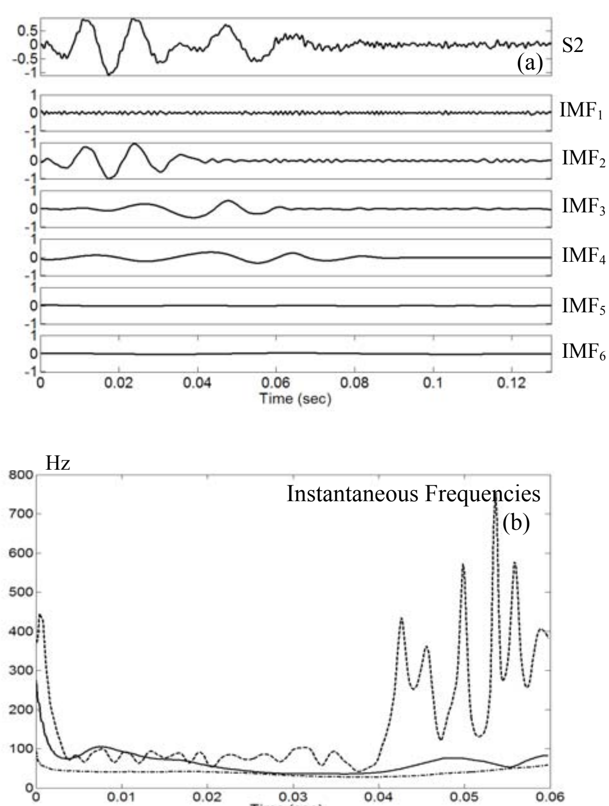

Figure 4. EMD applied to simulated noisy S2.

VI. DISCUSSION

From Fig. 1(a), the number of significant IMFs is three and their IFs (Fig. 1(b)) show that IMF_1 and IMF_3 behave with constant frequencies with mean values of 150 and 50 Hz from 0.01 sec, as shown by lines with zero slope. Conversely, IMF_2 shows a frequency behavior (continuous line) that varies with time from 50 to 100 Hz, starting at 0 sec. Alternatively, although A2 and P2 components of S2 are not well separated, EMD provides an IMF_1 that evidences a change from 0.03 sec (Fig. 2) and the corresponding IF also shows a different frequency behavior from 0.03 sec, where the P2 component starts (an arrow points the event). Also, after 0.03 sec the decay in frequency is more steeped for IMF_1. Each IMFs shows an IF that resembles a nonlinear chirp signal from 100 Hz towards 25 Hz. For this case, IMF_3 and IMF_4 do not seem to contribute significantly to S2.

Overall, EMD provides clear information about the components of S1 and S2, and their IF behavior. However, as noise appears, IF estimation is slightly degraded. The IMF_1 for S1 and S2 (Figures 3(a) and 4(a)) are totally related to noise, and they can be neglected for the analysis of heart sounds. From IMF_2 to IMF_4 the components of S1 are represented while for S2, IMF_2 and IMF_3 contain the relevant information. Also, note that all IMFs contain some oscillatory information belonging to noise. For S1, the IF corresponding to IMF_2 indicates a constant frequency behavior, 150 Hz from 0.02 sec, again a line with zero slope specifies the mean IF (Fig. 3(b)). Outside the interval 0.02 - 0.04 sec, the IF shows many ups and downs due to noise in IMF_2. Also, the IF corresponding to IMF_3 jumps from 50 Hz to 100 Hz from 0.01 to 0.02 sec but also the noise difficult the interpretation. The IF for IMF_4 indicates a constant frequency behavior of 50 Hz. Regarding the EMD for noisy S2, the IFs for IMF2 and IMF3 indicate a nonlinear chirp frequency behavior but there is not a strong indication where the change in frequency appears.

Fig. 5 shows the EMD and IFs for a real S1 where IMF_1 to IMF_3 relate to noise while IMF_4 and IMF_5 resemble two of the theoretical IF. The corresponding IFs certify this observation. The component with constant frequency of 150 Hz did not show up and the reason can be due to the acquisition position of the heart sound.

VII. CONCLUSIONS

The EMD is a promising technique for heart sounds analysis since it provides their components as well as their IF behavior. It is possible that EMD analysis can give different IFs depending on the spatial thoracic location to analyze and depending on the heart disease and the degree of severity.

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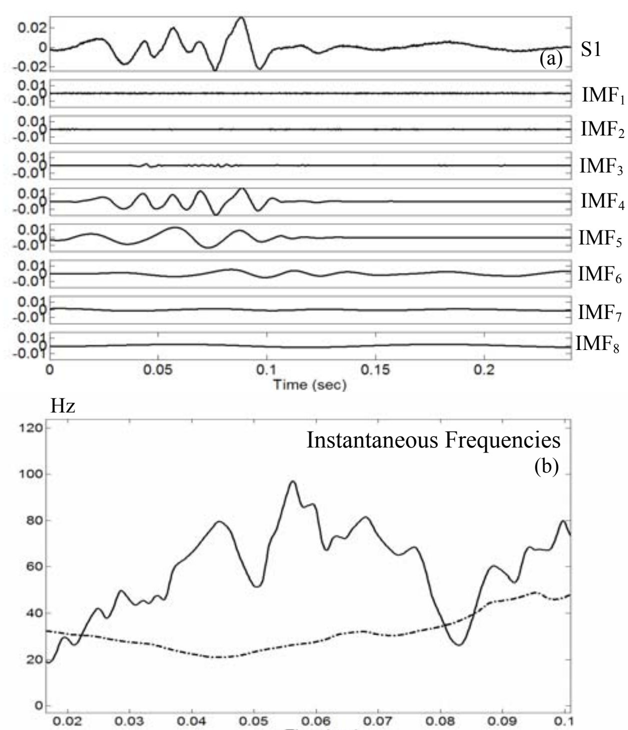

Figure 5. EMD applied to a real S1.