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Recognition of heart sound based on distribution of Choi-Williams

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Abstract **Introduction**: To realize noninvasive diagnosis and early diagnosis of coronary heart disease, the study proposes a new time-frequency method for analyzing heart sound signals. This method is based on Choi-Williams Distribution (CWD). **Methods**: CWD distribution is developed and modified from Wigner Ville distribution (WVD). To solve the problem of cross-term interference existing in WVD there is an improved version of WVD, called Choi-Williams Distribution (CWD), which introduces the smoothing window as the kernel function and deals with the time-frequency analysis of heart sound signal. **Results**: The improved method has good performance and can be implemented simply without much increase of operation complexity. **Conclusion**: In this paper, 21 cases of heart sound signals are acquired from the outpatients and hospitalized patients with coronary heart diseases. The research results of 21 cases show that the CWD method can be used to analyze heart sounds. It accurately identifies the 9 cases of heart sounds of health people and 12 cases of heart sounds of patients with coronary heart disease. Besides, the CWD displays obvious differences between heart sounds of healthy people and abnormal heart sounds. The contour line of heart sounds from healthy people shows the following characteristics: concise, columnar and non-divergence; while the contour line of abnormal heart sounds is divergent and has many columnar links. These research shows that CWD method can effectively distinguish heart sounds between healthy people and patients with coronary heart disease.

Keywords: Heart sound signals, Choi-Williams distribution, Biomedical signal processing, Non-invasive diagnosis, Time-frequency analysis.

Introduction

Owing to the continuous improvement of living standard and increasing life rhythm, the incidence of cardiovascular diseases is higher in recent years. Modern medical research shows that heart sound reflects the movement status of heart and cardiovascular system, and contains a lot of information obtained from clinical diagnosis of cardiovascular disease (Zhao et al., 2005). Heart sounds diagnosis reveals the relationship between heart sounds and heart disease by using modern digital signal processing technology and biomedical engineering technology. Before the occurrence of ECG abnormalities, which are caused by diseases associated with heart, pain and other symptoms, as well as the noise and distortion of heart sounds are mainly adopted to diagnose cardiac disease in early-stage (Chen et al., 2010). Therefore, the diagnosis and treatment of cardiovascular diseases are of great significance, especially the noninvasive diagnosis technology based on modern information technology.

Heart sounds and their composition

In the cardiac cycle, heart sounds are caused by mechanical vibration of myocardial contraction and relaxation, and the opening and closing of valves. Blood flow impacts ventricle, the aorta, etc., through the surrounding tissue to the chest wall and generates weak vibration signal. When you put the ear or a sensor, such as, a stethoscope close to chest wall or related parts of chest hall, we can listen or detect heart sound signals. The first and second heart sounds can be easily detected form the normal heart sounds, while the third or the forth heart sounds can only be detected in some cases. Each component and duration of heart sounds as shown in Figure 1 (Chen et al., 2010).

S1 starts 0.02~0.04 seconds lagging behind the beginning of QRS wave in the electrocardiogram, lasting for about 0.08-0.15 seconds. It is caused by the flowing of blood into aorta, when both the mitral valve and the tricuspid valves close, and ventricular systole occurs. S2 starts from the tail of T wave in the electrocardiogram, caused by 1) the vibration of ventricular wall when ventricular diastole happenes and 2) the flowing of blood from atrium into ventricle, when both aortic valve and pulmonary valve close and atrio-ventricular valves open. S2 happens at the beginning of diastole. Its frequency is comparatively high and its duration (about 0.07~0.12 seconds) is shorter than S1.

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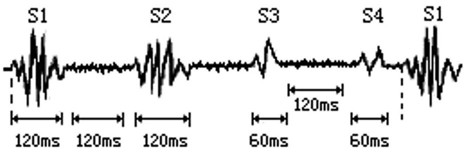

Figure 1. Heart sound signal and its components.

S3 shows low-frenquency and small- amplitude. It is 0.12~0.20 seconds away from S2 behind the T wave in the electrocardiogram and lasts for 0.05~0.06 seconds. S3 is caused by the vibration of the ventricular wall. S4 lags behind P wave for 0.15~0.18 seconds, and S4 generally has small- amplitude and is caused by the case that blood stream flows rapidly into the ventricle and vibrates the ventricular wall.

Detection and significance of heart sounds

Heart sounds are a kind of important physiological signals of human body. The signals contain a lot of information about the situation of heart pathology and reflect the structure of heart and cardiovascular and its physiological and pathological information (Zang et al., 2014). Heart sounds are a kind of weak biological signals of the human body under strong noise background, and are easily affected by human factors. The change of heart sounds (including strength and property) and the presence of noise are often early symptoms of heart disease. Therefore, the analysis of heart sounds is of great significance to the diagnosis of diseases of the cardiovascular system.

The generation of coronary heart disease

Cardiovascular disease, as an important factor endangers human health, has become the major disease and important cause of death due to illness. According to the statistics from world health organization, heart disease, cerebrovascular disease, acute lung infection, copd, and AIDS associated heart diseases are top causes of death in the world (Ye et al., 2003). Since 1985, in China, the death toll caused by heart disease has stayed firmly top three. The mortality of coronary heart disease in cities is 36.9/10 and that in countryside is 15.6/10. And the deaths caused by Coronary heart disease account for 4.47% of the total death (male) and 3.72% (female). More than a decade of research and statistical monitoring data from the navy general hospital in Beijing also show that the incidence of cardiovascular disease in Beijing area grows continuously, with an average annual growth rate of 2.3%. The coronary heart disease (CHD) in male rises more significantly than female.

Coronary heart disease is a clinical syndrome caused by the absolute or relative reduce of myocardial blood supply. This disease is caused by the coronary circulation change, coronary artery blood flow, and imbalance between myocardial demands, and leads to myocardial ischemia and hypoxia of coronary artery lesions. Coronary heart disease is mainly caused by the organic artery stenosis or occlusion, while coronary artery stenosis or occlusion can lead to the changes of heart sound signals (Guo and Yuan, 2012).

The diagnosis value of heart sounds

Diagnosis methods of Coronary heart disease can be divided into two kinds, namely, invasive diagnosis and noninvasive diagnosis (Guo and Yuan, 2012; Pang et al., 2014; Saracoglu, 2012). Noninvasive diagnosis is often based on the electrical activity and pump activities of the heart, including the electrocardiogram, dynamic electrocardiogram and phonocardiogram, radioisotope, echocardiography and modern medical imaging technology (such as NMR, CT, PET, etc.). Invasive diagnosis of coronary heart disease mainly refers to the coronary artery imaging technology, which is the most reliable method to diagnosis coronary artery disease. But imaging belongs to traumatic examination, with certain risk. It is complex, more expensive and brings with serious complications and even death in some cases. Therefore, it is not suitable for a wide range of census (Guo et al., 2013; Pang et al., 2014).

It needs to be paid attention to that the existence of the lagging problem in clinical diagnosis of heart disease using ECG. But the heart sound signals can reflect the early pathology information of heart disease, and the inside physical state of the heart will directly affect and change heart sound signals. Similar to the diagnosis of coronary artery disease, only when coronary occlusion rates more than 70 to 75 percent at the time can cause the changes of ECG, however, When the Coronary model next reaches 25%, it can cause heart sounds change (Chen et al, 2010; Guo and Yuan, 2012). This suggests that the analysis of heart sound has the practical significance, which is the realized foundation of early detection, diagnosis, treatment and noninvasive diagnosis of Coronary heart disease.

Methods

Time-frequency analysis of heart sounds refers to represent the non-stationary of heart sound signals using joint distribution function of the time and frequency. It analyzes and processes the signals. This method overcomes the limitations of Fourier transform type. Time-frequency analysis can be divided into linear time-frequency and bilinear time-frequency analysis.

Linear time-frequency analysis is evolved by FFT, mainly includes short time Fourier transforms (STFT), Gabor spread and wavelet transform, etc., and satisfies superposition principle. The main advantage is the simple theory and application, but it is hard to describe the instantaneous power spectrum of signals. Bilinear time-frequency method is also known as quadratic time-frequency analysis, which can reflect the time-frequency distribution of signal energy, but do not satisfy the superposition principle. Quadratic time-frequency analysis mainly includes Cohen class time-frequency distribution, Wigner Ville distribution and Affine class bilinear time-frequency distribution, among which Wigner Ville distribution and its various deformation are most commonly used.

Choi-Williams distribution

Wigner distribution was mainly used for quantum mechanics research in theoretical physics when it was early produced; later Ville introduced this distribution to signal analyzing field. In the 1980 s, Claasen and Mecklenbraker published their research papers, which concretely discuss the concept, nature, purpose and numerical calculation method of Wigner Ville distribution. Wigner Ville distribution is the distribution of signal energy in time domain and frequency domain, which has a clear physical meaning. In the processing of nonstationary signals, this distribution is one of the most basic and commonly used transform methods. This distribution is the important approach for the analysis of non-stationary random signal and the solution of problems existing in the application of short time Fourier transform (STFT) to certain extent.

As Wigner Ville distribution has been widely used in the field of non-stationary random signal processing, the distribution has attracted the attention of many scholars. When Cohen had an in-depth study on Wigner Ville distribution, he found that the introduction of kernel function in Wigner Ville distribution can exporte to other forms of time-frequency distribution, so Wigner Ville distribution can use the following unified form:

$$p(t,f)=\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} s(u+\frac{\tau}{2})s^*(u-\frac{\tau}{2})\varphi(\tau,v)e^{-j(tv+\tau f-uv)}dudvd\tau \quad (1)$$

Where $\varphi(\tau,v)$ is the kernel function of time-frequency distribution of Cohen class.

According to unified definition of Cohen class time-frequency distribution, Wigner Ville distribution of S (t) signal can be easily obtained. In the definition, set $\varphi(\tau,v)=1$, Wigner Ville distribution can be concluded as follows:

$$W(t,f)=\int_{-\infty}^{+\infty} s(u+\frac{\tau}{2})s^*(u-\frac{\tau}{2})e^{-j2\pi f\tau}d\tau \quad (2)$$

Wigner Ville distribution has high time-frequency resolution, and symmetry, time shift characteristics, frequency shift characteristics, expansionary in time domain and frequency domain, modularity, reversibility, normalization, complex conjugate, etc.

The fuzzy function

In the definition of time-frequency distribution of Cohen class, we can assume:

$$A(\tau,v)=\int_{-\infty}^{+\infty} s(t+\frac{\tau}{2})s^*(t-\frac{\tau}{2})e^{-j2\pi tv}dt \quad (3)$$

$A(\tau,v)$ is the fuzzy function in Cohen class time-frequency distribution and the instantaneous correlation function is defined by

$$k(t,\tau)=s(t+\frac{\tau}{2})s^*(t-\frac{\tau}{2}) \quad (4)$$

Therefore, the fuzzy function can be regarded as the Fourier inverse transformation from instantaneous correlation function about the independent variable t, namely:

$$A(\tau,v)=F^{-1}[k(t,\tau)] \quad (5)$$

Time-frequency analysis can facilitate to descript the law that the signal energy of heart sound change with time and frequency, Wigner Ville distribution (WVD) is a typical kind of Cohen class time-frequency distribution. It has high time-frequency resolution and time-frequency characteristic, but its disadvantage is difficult to eliminate cross interference item. Aiming at this defect, an improved Wigner Ville distribution, namely, Choi-Williams distribution (CWD) is put forward to analyze the heart sounds.

In order to reduce or eliminate the influence of cross interference terms, and introduce a smooth window function (kernel functions), for time-frequency distribution of Cohen class, when the kernel function is $\varphi(\theta,\tau)=e^{-\tau^2v^2/\sigma}$, and satisfy the $\sigma>0$, Cohen class time-frequency distribution becomes Choi-Williams distribution (CWD) distribution. From level of signal processing, kernel function is one low pass filter in fuzzy domain, and controls the smooth strength of kernel function. For some of multi-component signals, their cross terms can be obviously suppressed. The greater the parameters, the more obvious inhibitory effect of cross terms.

As CWD exhibits excellent properties, such as invariant feature of time and frequency shift, time and frequency edges, supported time and frequency characteristics ($\sigma>1$), etc., CWD basicaly reflects the energy distribution of heart sound signals in time-frequency plane. When $0.1\leq\sigma\leq 10$, Choi-Williams distribution obtains high time-frequency resolution, and suppresses more cross items. Based on a large number of normal and abnormal heart sounds signal testing, the results show that, when σ=3, the time-frequency diagram of heart sound signals can freshly show the time zone, frequency range and the size of intensity of first and second heart sounds signals.

To obtain the ideal effect in using Choi-Williams distribution for heart sound signals, the confired parameters of this distribution include σ, window type, width of time window, window type, and width of frequency window. If the types of time and frequency window have been identified, only three parameters that are frequency parameter, and the width of time window and frequency window should be determined depending on the situation.

Results

Heart sound analysis experiments

The analysis and processing of the heart sound signals are very important for diagnosing cardiovascular diseases. To acquire accurate and reliable heart signals, the project team has specially developed a heart sound acquisition system in this research. And the structure of the system is showed in Figure 2.

Heart sound sensor is also known as the transducer, which is a widely used medical sensor. It can convert the mechanical vibration sound signals formed in the impact of the blood stream on the heart wall and the aorta to electrical signals. Amplifiers zoom in the slight heart sound signal. Analog signals are transformed to digital signals using 12 bit A/D converter, then sent to the computer via serial communication port, and processed by computer using digital methods according to requirements. The digital methods include the digital filtering and other analysis and processing methods. Then, pre-processing circuit amplifies and filters the heart sound signals, and transforms analog signals to digital signals utilizing the 12 bit A/D converter. Finally, the digital signals are transmitted to the DSP, where heart sound signals are filtered and then sent to computer via serial communication port, and processed by the computer.

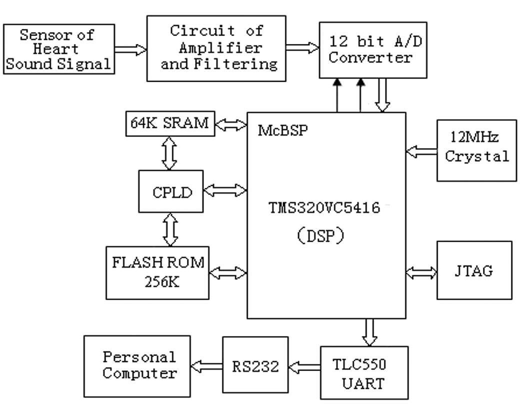

Figure 2. Heart sound detection system - structure diagram.

Heart sound signals of 21 cases of were acquired in the First Affiliated Hospital of Hunan University of Traditional Chinese Medicine, the Affiliated Hospital of Shandong Medical University and the Air Force General Hospital by using this acquisition system, and obtained the permission of the patient. In Chinese government, there are no corresponding organizations taking charge of approving the ethics commission.

In this paper, some commonly used orthogonal wavelets in heart sound processing such as Haar, db6, sym8, coif5, etc. are acquired and compared experimentally. As a result, db6 wavelet's de-noising effects are comparatively better. At the same time, the same wavelets with different decomposition levels are compared as well. Experiments show that when decomposition level is less than 5 layers, the effect is far from ideal; when the decomposition level equals to 5, the denoising effect is ideal; when the decomposition level is greater than 5, though the noise cancellation works well, it filters a considerable part of heart sound signals at the same time. Therefore, optimal de-noising effect is obtained by using the 5-layer db6 wavelet decomposition.

Heart sound signal belongs to one time-varying and non-stationary biomedical signal. The traditional analysis method of steady-state signal can only reflect the characteristics of the static frequency spectrum of signals. But the beating of the heart is a continuous dynamic process, if we want to obtain continuous dynamic change characteristics of the heart, we need to analyze and study the changed over- time characteristics of frequency components of heart sound. Therefore, using time-frequency analysis to study heart sound signals is an effective analysis method. Due to the good performance in analysis and processing of non-stationary signal, time-frequency analysis has been widely used in the field of analysis and processing of signal in recent years, which has developed into an important branch of the signal processing disciplines.

Choi–Williams distribution is utilized to analysis heart sound signals, the values of parameter for $\sigma = 3$. Kaiser window is adopted in time domain and frequency domain. The length of time window is $g = 9$ and the length of frequency window is $h = 27$. In this research we have studied 21 cases of clinically diagnosed heart sound signals, including 12 cases of heart signals of patients with Coronary Heart Disease (CHD) and 9 cases of heart signals of normal people. By using

CWD we can correctly distinguish the coronary heart sounds and healthy heart sounds. The analysis results of 5 cases of 21 cases heart sounds, including 2 cases of normal heart sounds and 3 cases of abnormal heartsounds, as it is exemplified in Figures 3-7.

Discussion

Heart sound signals of human are biologic signals in strong noise background. Heart signals have specific and obvious characteristics, including weak signals, strong noise, narrow frequency, and more randomness, that normal signals do not have. Distribution of Choi-Williams can reflect the time-varying characteristics of the signal and the energy distribution on time- frequency plane, which is very beneficial to recognize the heart sound. According to distribution of Choi-Williams of heart sounds experimental, we can see that the distribution of Choi-Williams from normal mind and abnormal heart sounds has obvious difference. Figures 3 and 4 show that the normal heart sounds of energy distribution are concentrated, and Figures 5-7 show that abnormal heart sound energy distribution is dispersed apparently. These indicate that abnormal heart sounds have more heart murmurs. The results completely accord with doctors' clinical diagnosis.

In this paper, 21 cases of heart sound signals were acquired from the outpatients and hospitalized patients with coronary heart diseases. The research results of 21 cases shown that the CWD method can be used to analyze the heart sounds, and the CWD displays obvious differences between heart sounds of healthy people and those abnormal heart sounds. The contour line of heart sounds from healthy people exhibits the following characteristics: concise, columnar and non-divergence; while the contour line of abnormal heart sounds is divergent and has many columnar links. This research shows that CWD method can effectively distinguish the heart sounds between healthy people and patients with coronary heart disease, and can be used as an auxiliary diagnosis for coronary heart disease.

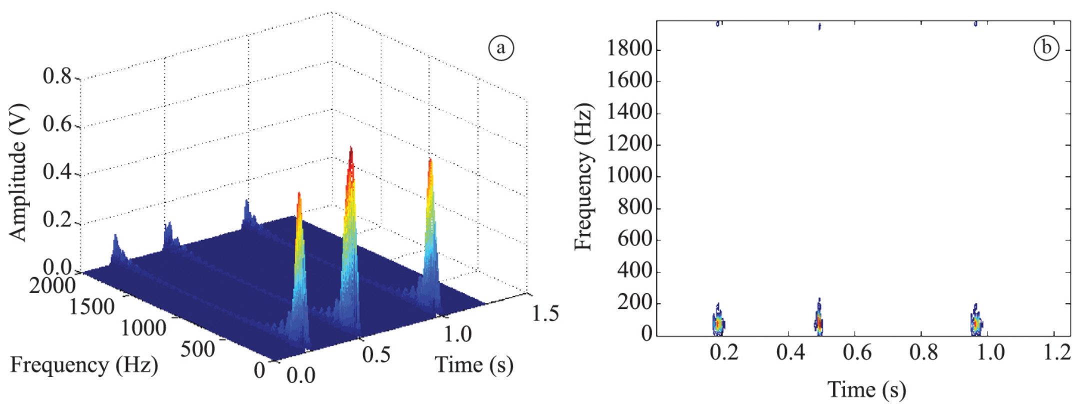

Figure 3. Signals from normal heart sounds 1: (a) Three-dimensional plot and (b) Contour line.

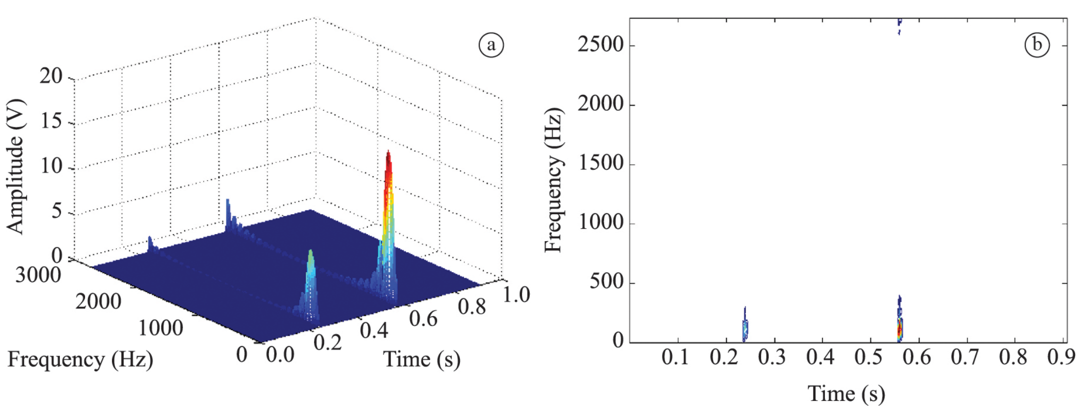

Figure 4. Signals from normal heart sounds 2: (a) Three-dimensional plot and (b) Contour line.

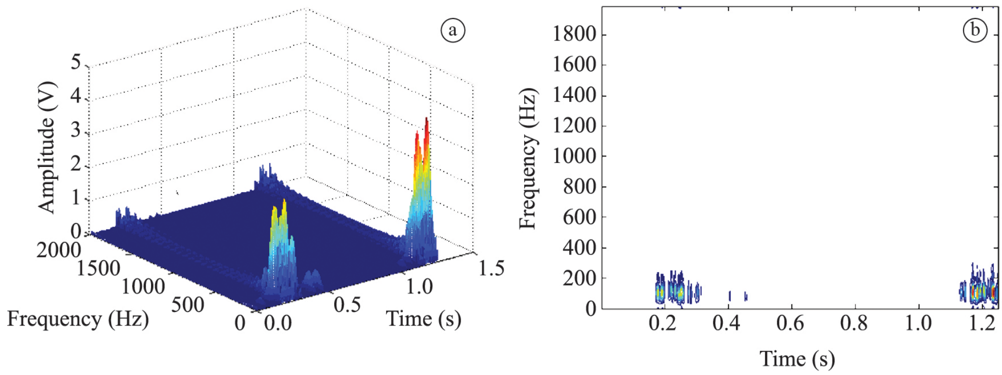

Figure 5. Pulmonary stenosis: (a) Three-dimensional plot and (b) Contour line.

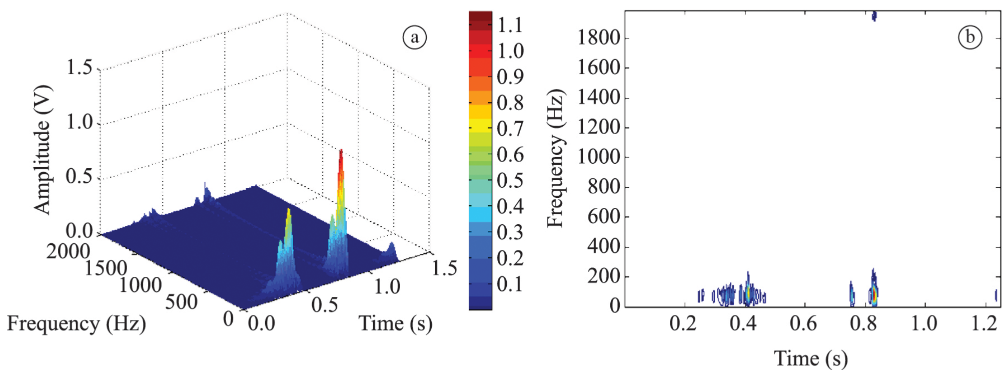

Figure 6. Mitral stenosis: (a) Three-dimensional plot and (b) Contour line.

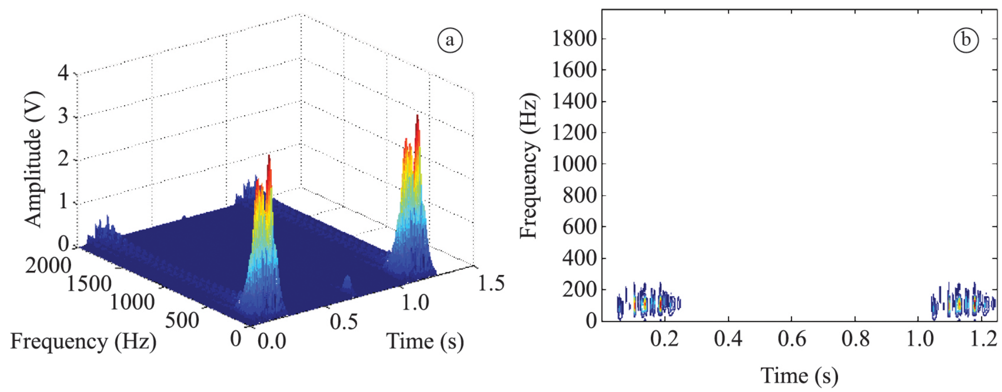

Figure 7. Aortic valve insufficiency: (a) Three-dimensional plot and (b) Contour line.

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