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RECONSTRUCTION OF MAXIMUM BLOOD FLOW VELOCITY WAVEFORMS FROM DOPPLER ULTRASOUND MEASUREMENTS

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Abstract -**This paper presents a novel algorithm for the extraction of maximum blood flow velocity waveforms from Doppler measurements. This method is based on the short-term integrated spectrum of the Doppler signal, and does not require a pre-selected threshold level to deal with the background noise. Experimental results indicate that this method is more robust and better suited for the maximum frequency estimation than currently used methods.**
Keywords- **Doppler ultrasound, maximum flow velocity**

I. INTRODUCTION

Doppler ultrasound measurements are commonly used for detecting and evaluating the characteristics of blood flow in arteries and veins. Blood velocity is directly proportional to the Doppler shift. It is estimated using the relationship

$$\nu = \frac{cf}{2f_o \cos\theta}, \quad (1)$$

where c is the velocity of ultrasound in the medium in m/s, f is the frequency of the Doppler signal in Hz, f_o is the frequency of the incident ultrasound beam in Hz, and θ is the angle of incidence in radians [1]. The maximum frequency of the Doppler spectrum, f_{max} is proportional to the maximum blood flow velocity. In current practice, the maximum frequency is extracted by choosing a threshold above the noise level of the Doppler spectrum [2]. The maximum frequency at which the signal power equals the threshold level is chosen as the maximum Doppler frequency. This paper presents a novel algorithm for maximum blood flow velocity waveform reconstruction based on the integrated power spectrum.

II. METHODOLOGY

Let

$$y(t) = x(t) + \eta(t) \quad (2)$$

represents the received signal, where $x(t)$ is the Doppler signal of interest that is band-limited to the frequency f_{max}, and $\eta(t)$ is a zero-mean and white Gaussian noise process. The integrated spectrum of the signal component $x(t)$ is

$$\phi_X(f) = \int_0^f S_X(\lambda)d\lambda, \quad (3)$$

where $S_X(f)$ is the signal spectrum at frequency f. Then, the integrated spectrum of $y(t)$ is given by

$$\phi_Y(f) = \begin{cases} \phi_X(f) + \sigma_\eta^2 f & ;0 \le f \le f_{max}, \\ \phi_X(f_{max}) + \sigma_\eta^2 f & ;f > f_{max}. \end{cases}$$

At f_{max} the gradient of the integrated spectrum falls to the noise density. In order to estimate f_{max}, first we rotate the integrated spectrum such that

$$\phi_{rot}(f) = \phi_Y(f) - f\tan\theta, \quad (4)$$

where $\tan\theta = \frac{S+N}{f_N}$. Here, S and N are the total signal and noise powers, respectively, and f_N is the Nyquist frequency. $\phi_{rot}(f)$ is independent of the noise distribution due to rotation. It is maximum at f_{max} and decreases linearly afterwards. Therefore, we can estimate the maximum Doppler frequency f_{max} as the frequency at which $\phi_{rot}(f)$ is maximum.

III. RESULTS

The algorithm was evaluated both for simulated and real Doppler signals.

A. Simulated Doppler Signals

Simulated Doppler signals were generated using the algorithm described by Sirmans et al [3]. For the experiments, the signal spectrum was

$$S(f) = \begin{cases} \frac{1}{\sqrt{2\pi\sigma_f^2}} e^{-\frac{(f-\bar{f})^2}{2\sigma_f^2}} & ;f_{min} \le f \le f_{max}, \\ 0 & ;\text{otherwise}, \end{cases}$$

where $\bar{f}$ and σ_f were constant parameters of the model. The signal was generated using $\sigma_f = 300$ Hz, $\bar{f} = 1800$ Hz, $f_{min} = 1$ Hz and $f_{max} = 2250$ Hz. The sampling frequency was 12000 Hz. 1000 independent experiments were

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performed at several SNR values from 0 to 30 dB. 512 samples of the data were used for each estimation and the power spectrum was estimated using the periodogram method. A Hann window was employed to reduce the spectral leakage.

The maximum frequency values were estimated using the rotated-integrated spectrum algorithm and the thresholding method described in [2]. Fig. 1 shows a comparison of the normalized root mean square estimation error for the two algorithms.

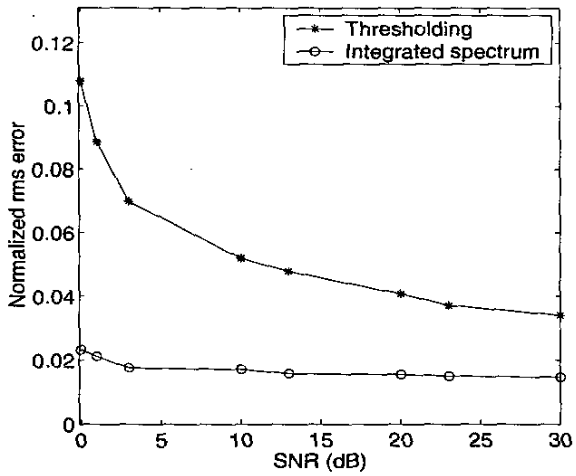

Figure 1: The comparison of rms estimation error versus SNR for the maximum frequency estimation.

The maximum frequency estimator based on the integrated spectrum shows a lower rms error than the maximum frequency estimator based on thresholding.

B. Real Doppler Signals

Ultrasound measurements performed at the Department of Obstetric and Gynecology, Academic Hospital, Erasmus University, Rotterdam, The Netherlands were used for the comparison of reconstruction algorithms for real blood velocity waveforms. Flow velocity waveforms were obtained from the free floating loop of the umbilical artery. The Doppler signals were digitized at 12 kHz. To perform the reconstruction, the Doppler signals were first segmented into smaller blocks of 512 samples with 75% overlapping. Then, the maximum frequency value was estimated for each block and blood velocity value was computed using (1). We used $c = 1540$ m/s, $f_o = 3.5$ MHz and $\theta \approx 0$. Finally, a 3-point moving average filter was employed for smoothing. Fig. 2 depicts the maximum umbilical arterial blood flow waveform reconstructed using the two algorithms.

In the maximum frequency estimation algorithm based on thresholding, when the signal power drops below the adopted threshold, output of the frequency estimator goes to zero. However, the rotated integrated spectrum method is less sensitive

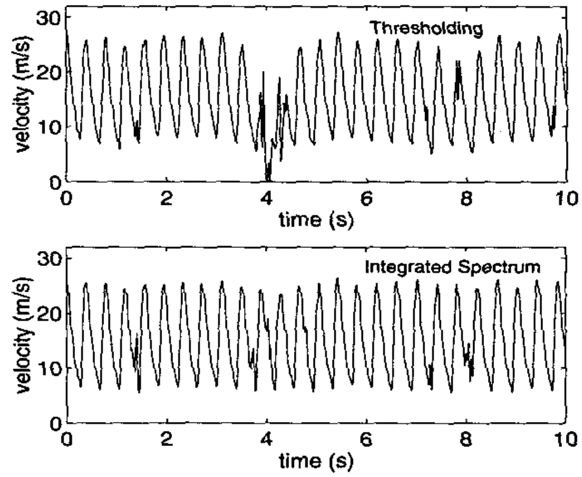

Figure 2: Comparison of maximum blood velocity waveforms of real signals.

to the variation of the instantaneous noise level.

IV. CONCLUSION

Reliable estimation of the frequency components are difficult using thresholding algorithms when the instantaneous SNR varies with the environment. The algorithm presented in this paper is adaptive to the environmental noise levels and is less impacted by the changes of noise density. Furthermore, it is easier to implement this algorithm than currently available methods since there are no *ad hoc* parameters to be chosen. The rotated-integrated spectrum method outperforms the thresholding method and has the potential to provide more robust and accurate medical diagnostic information from maximum blood flow velocity waveforms than presently used algorithms.

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