Doppler Spectrogram Calculation using DSP Processor & MATLAB

Harsha Jain, Ashwini Andurkar, Vandana Koli

Abstract— ***Doppler echocardiography is a method for detecting the direction and velocity of moving blood vessels within the heart. It uses Doppler's shift principle that there is change in frequency of ultrasonic waves relative to the motion of moving blood cells. The change in frequency is proportional to the velocity of blood cells. Most of the Doppler ultrasound systems employ quadrature demodulation technique at the detection stage. The information concerning flow direction encoded in the phase relationship between in-phase and quadrature phase channels is not obvious at this stage. A method based on the complex fast Fourier transform (CFFT) and complex wavelet transform (CWT) has been described. It eliminates the intermediate processing stages by mapping directional information in frequency and scale domain respectively. These methods are implemented in real time using commercially available digital signal processors TMS320C6713DSK along with Code Composer Studio 3.1 and also used MATLAB 7.4.0(R2007a) software. This system has been designed as open research platform, which can be programmable with variety of novel algorithms for studying improved and resolved spectrograms to obtain accurate diagnostic details in the future.***

Index Terms- Directional Doppler, Doppler Echocardiography, CFFT, CWT, TMS320C6713DSK

I. INTRODUCTION

Doppler echocardiography is a method for detecting the direction and velocity of moving blood within the heart. This is used for detection of cardiac valvular insufficiency and stenosis as well as a large number of other abnormal flows. Doppler methods extend the use of cardiac ultrasound into the evolution of normal and abnormal flow states and provide quantitative data that are essential in the clinical decision making process concerning patients with heart disease [4].

Most of the Doppler ultrasound systems employ quadrature demodulation techniques at the detection stage. The incoming RF signal from an ultrasonic transducer is multiplied by a 90^0 phase- shifted version of transmitted signal as well as the transmitted signal. After low pass filtering the HF components, in phase and quadrature phase components of the audio Doppler echo signal (DES) are obtained. The information concerning flow direction is encoded in the phase relationship between in-phase and quadrature phase components [9].

The phase relationship is obtained from the spectrogram of DES. Any noise may degrade the readability of the spectrogram and the precision of the clinical indices, so the spectral augmentation plays an important role. Attempts have been made by many biomedical researchers to implement many complex signal processing techniques in order to achieve efficient processing time and highly resolved spectrogram in real time.

This work describes a Doppler ultrasound system for measuring blood velocity and direction of blood flow. The proposed design is implemented and tested using TMS320C6713 DSK and MATLAB 7.4.0 (R2007a). The proposed design employed Complex Fast Fourier Transform (CFFT) as well as Complex Wavelet Transform algorithms to separate and calculate the forward/ reverse flow and Doppler spectrogram from the quadrature demodulated echo signal.

II. DOPPLER ECHOCARDIOGRAPHY

Doppler echocardiography is a non-invasive method for detection and evaluation of the blood flow.

A. Principle of Doppler Echocardiography

These systems use Doppler's Shift principle hence the name Doppler Echocardiography. The Doppler's shift principle states that there is change in frequency of wave relative to the motion of source and receiver.

In Doppler echocardiography, ultrasonic transducer transmits ultrasonic wave incident into the body. The incident waves are scattered by moving blood cells. These scattered waves are received by transducers. There is shift in the frequency of received waves which is proportional to velocity of blood cells. The spectrogram obtained from DES gives distribution of blood velocity in the artery. Fig. 1 shows the Doppler Echocardiography principle.

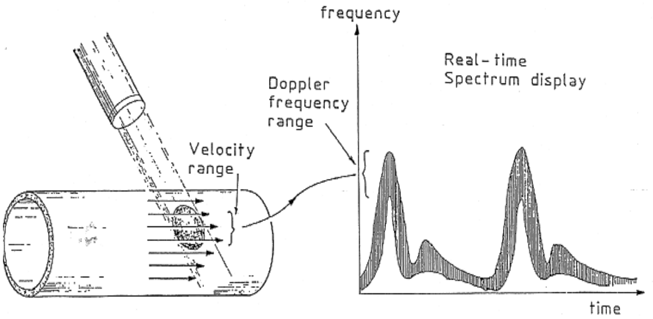

Fig. 1 Doppler Echocardiography Principle [3]

III. SPECTROGRAM CALCULATION ALGORITHMS

A. Complex Fast Fourier Transform (CFFT) Algorithm

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The CFFT is a straight forward method for detection of directional information as no other extra signal-processing is required to produce frequency domain information. The complex timing signal is given as input to CFFT algorithm. In-phase component of DES is taken as real part of the complex time signal and quadrature phase component is taken as imaginary part of it. The properties of the CFFT states that if the complex input time signal is in quadrature i.e. the phase difference between the real and imaginary parts is 90^0, the output is directional and output spectrum is dual sided. Fig. 2 shows block diagram of the CFFT algorithm.

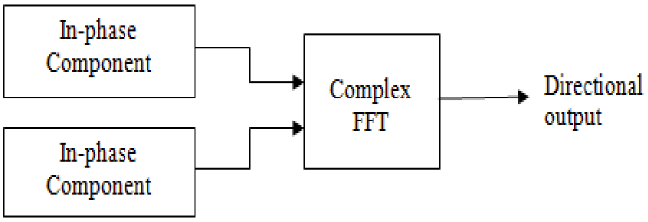

Fig. 2 Block diagram of CFFT algorithm

The complex Fourier transform has some useful properties which allow the detection of the direction of blood flow when it is applied to quadrature signals. Consider a complex time signal; if its real part is even and its imaginary part is odd, then the CFFT is real. If its real part is odd and its imaginary part is even, then the CFFT is imaginary. The method of extraction of directional output using CFFT is explained below [7].

Consider a discrete Doppler quadrature signal $s(n)$ given by eq. 1, containing information of forward channel and reverse channel signals.

$$S(n) = I(n) + jQ(n) \qquad (1)$$

$I(n)$ and $Q(n)$ are given by eq.2 and eq. 3.

$$I(n) = Sf(n) + H[Sr(n)] \qquad (2)$$

$$Q(n) = H[Sf(n)] + Sr(n) \qquad (3)$$

Where, $H[\,]$ stands for Hilbert Transform of

Therefore,

$$S(n) = Sf(n) + H[Sr(n)] + j\{Sr(n) + H[Sf(n)]\}$$

$$S(n) = \{Sf(n) + jH[Sf(n)]\} + j\{Sr(n) - jH[Sr(n)]\} \qquad (4)$$

By taking the Fourier transform of eq. 4,

$$S(w) = \begin{cases} 2\,Sf(w) & 0 \le w < \pi \\ j\,2\,Sr(w) & -\pi \le w < 0 \end{cases} \qquad (5)$$

It is clear that the positive frequencies of $S(w)$ contain only the spectrum of the forward channel signal $Sf(n)$, and its negative frequencies contain only the 90^0 shifted spectrum of the reverse channel signal $Sr(n)$. The directional time domain outputs can then be obtained by taking inverse FFTs.

B. *Complex Wavelet Transform (CWT)*

The Wavelet transform (WT) is performed by projecting a signal $s(t)$ onto a family of zero-mean functions deduced from an elementary function (wavelet) $\psi(t)$ by translations and dilations. It is given by eq. 6.

$$Ws(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} s(t)\,\psi^*\!\left(\frac{t-b}{a}\right) dt \qquad (6)$$

The variables *a* and *b* control the scale and position of the wavelet, respectively. The WT is a linear transformation and covariant under translations and dilations. It creates a two dimensional representation of a one dimensional signal, with the horizontal axis as time and vertical axis as scale. The third dimension is the amplitude of the WT coefficients which is represented by different intensity level. This allows exact localization of any abrupt change, or an exact time and duration of a short signal.

The WT for processing quadrature Doppler signals can be implemented in such a way that only the coefficients resulting from the forward flow components are obtained when the scale is positive, and only the coefficients resulting from the reverse flow components are obtained when the scale is negative. This is attained by the sine-cosine formulation. This is naturally exists in some common wavelets such as the Morlet Wavelet, which is obtained by taking a complex sine wave and localizing it with a Gaussian envelope [9]. The waveform of Morlet wavelet is shown in fig. 3.

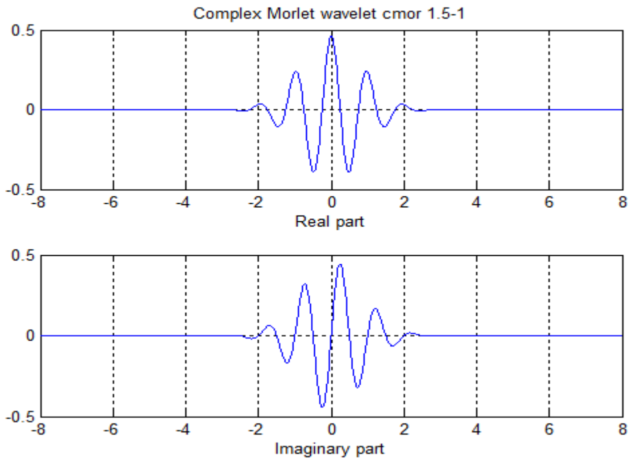

Fig. 3 Waveform of Morlet Wavelet

Ignoring the translation parameter b, the scale dependent Morlet wavelet is given by eq. 7.

$$\psi\left(\frac{t}{a}\right) = \pi^{-\frac{1}{4}}\, e^{i\left(\frac{w0t}{a}\right)}\, e^{-\frac{t^2}{2a^2}} \qquad (7)$$

Where w0 is the non-dimensional frequency and usually assumed to be 5 to 6 to satisfy the admissibility condition. The FT of eq. 7 is given by eq. 8.

$$\psi(w) = \begin{cases} \sqrt{2}\,\pi^{1/4}\,|a|\,e^{-\frac{(aw-w0)^2}{2}}\,H(w), & if\ a > 0 \\ \sqrt{2}\,\pi^{1/4}\,|a|\,e^{-\frac{(aw+w0)^2}{2}}\,H(-w), & if\ a < 0 \end{cases} \qquad (8)$$

Where H stands for the Heaviside step function

It is clearly observed that a frequency spectrum of an upper analytic signal $s(t)$ is obtained for a > 0 and a frequency spectrum of a lower analytic signal is obtained for a < 0.

The WT of a signal with the Morlet wavelet is given by

$$Ws(a,b) = \frac{\pi^{-\frac{1}{4}}}{\sqrt{|a|}} \int_{-\infty}^{+\infty} s(t)e^{iw0\left(\frac{t-b}{a}\right)}\, e^{-0.5\left(\frac{t-b}{a}\right)^2} dt \quad (9)$$

If the number of scales is J, a complete set of directional wavelet coefficients can be mapped over the scales from a= -J to a=J, excluding a=0. Thus, using Complex Morlet wavelet for the analysis of Doppler signal can extract the directional information [4].

IV. SPECTROGRAM USING CFFT AND DSK

The spectrogram is a plot of distribution of spectral content of signal the time. This is two dimensional plot in which horizontal axis represents time and vertical axis represents frequency. While the FFT coefficients are shown by different color intensity levels. In this system FFT coefficients are calculated using DSP Processor TMS320C6713 DSK and Code Composer Studio (CCS). While the calculated FFT coefficients are plotted using MATLAB software. Data exchanged between MATLAB and DSK is done with RTDX (Real Time Data Exchange) Channels. The block diagram of system is shown in fig. 4.

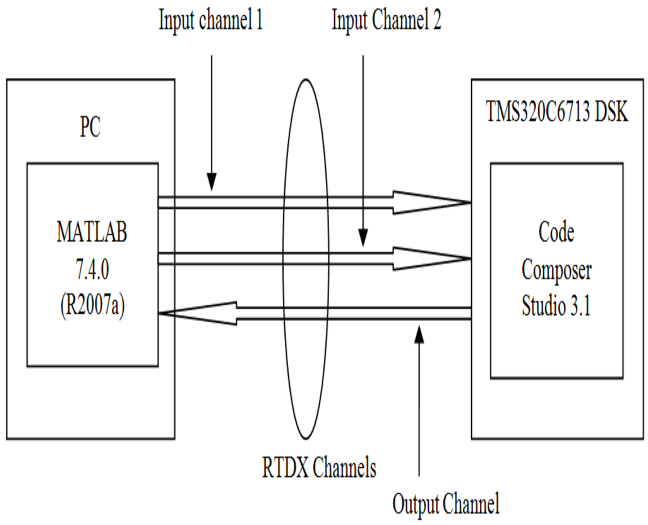

Fig. 4 Block Diagram of Proposed System

The audio DES is obtained from Doppler echo machine is read into the MATLAB. Fig. 5 shows the waveform of DES.

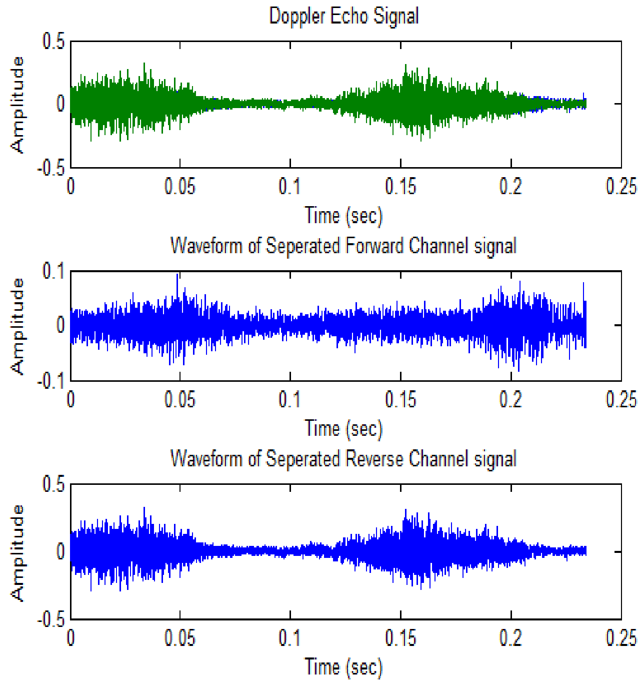

Fig. 5 Waveform of Doppler Echo Signal

The in phase component of the input signal is sent to DSK through RTDX input channel 1 while the quadrature phase component is sent to DSK through RTDX input channel 2. Spectrogram is obtained by windowed Fourier transform. That means only small part of input signal is taken into consideration at a time whose FFT is calculated. As the sampling frequency of input signal is 44.1 kHz and the DES is assumed to be stationary for 5-10ms, we are taken 256 samples of input signal at a time. Further calculation of CFFT algorithm is done in CCS.

The RTDX channels are configured in both MATLAB and CCS software. The configuration of RTDX channel is done by adding DSP/BIOS configuration (.cdb) file to the project in CCS. Fig. 6 shows DSP/BIOS configuration file.

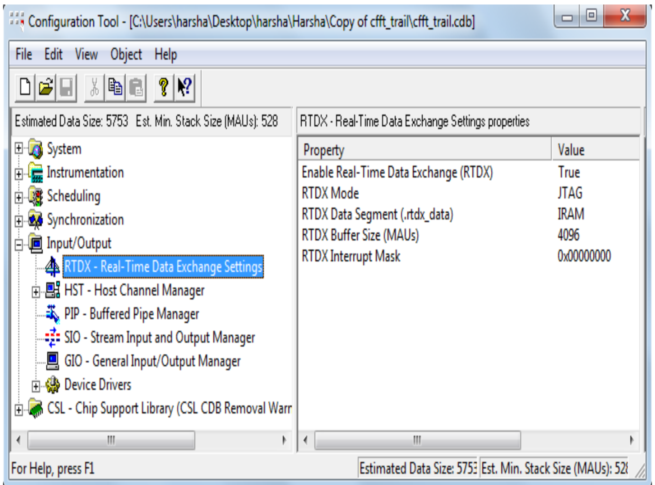

Fig. 6 DSP/BIOS configuration file to configure RTDX channels

The 256 samples obtained from input channel 1 are taken as real part of complex input signal while the samples obtained from input channel 2 are taken as imaginary part of it.

These samples are multiplied with the Hanning window coefficients to avoid spectral leakage. Then FFT is calculated. The Calculated FFT coefficients are received in MATLAB through RTDX output channel. The process of sending input channel coefficients and receiving FFT coefficients is done throughout the input Doppler audio signal. Lastly the spectrogram is plotted in MATLAB. Fig. 7 shows the spectrogram obtained. To avoid spectral leakage at side lobes overlapping samples are taken. Fig. 8 & fig. 9 shows the spectrogram with overlapping samples at 50% & 90% respectively.

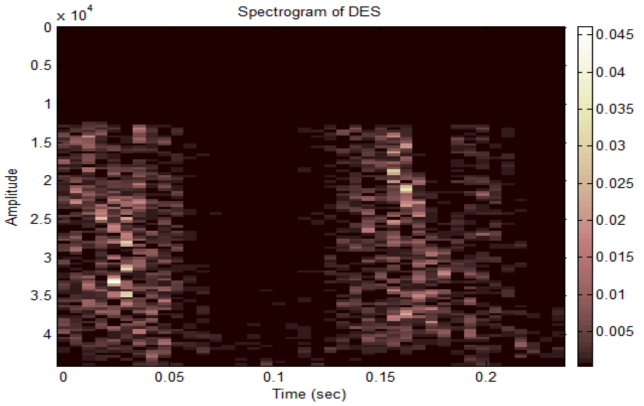

Fig. 7 Spectrogram obtained using CFFT with no overlapping

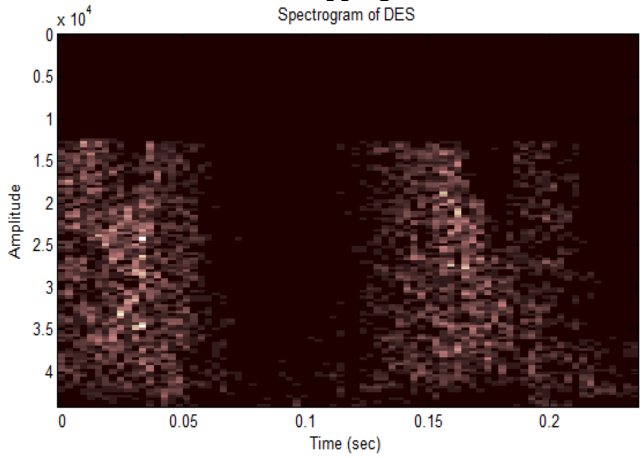

Fig. 8 Spectrogram obtained using CFFT with 50% overlapping

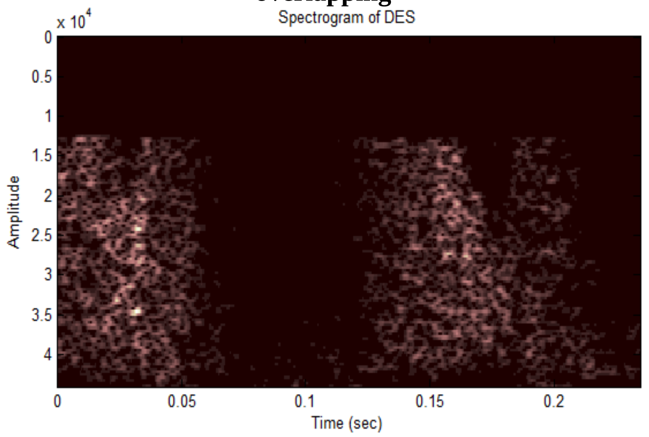

Fig. 9 Spectrogram obtained using CFFT with 90% overlapping

V. SCALOGRAM USING CWT

The audio DES obtained from Doppler Echo Machine consists of in phase component as well as quadrature phase component. The complex input signal is obtained by taking in phase and quadrature phase components as real and imaginary parts respectively. This complex input signal is given to the CWT algorithm. The whole algorithm is developed in MATLAB. The scalogram is plot of CWT coefficients obtained at different scales over the time. For each scale number of CWT coefficients equal to the input signal length. If we take scale equal to -16 to 16, excluding 0 number of CWT coefficients obtained are very large. The memory required to store such large number of coefficients is also large which is not available in DSK. So processing is done MATLAB only.

The scalogram plot obtained at scale 8 and 16 is shown in fig. 10 and fig. 11 respectively.

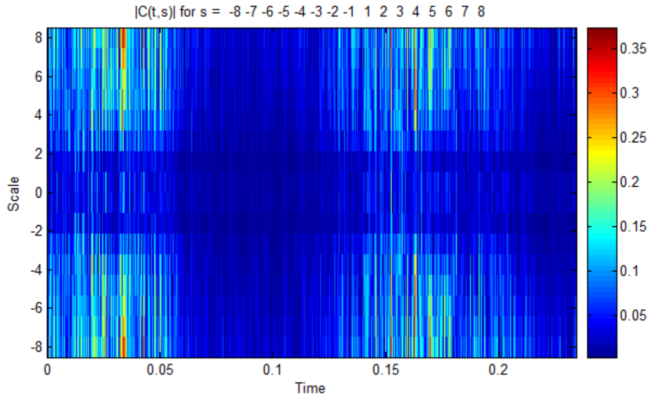

Fig. 10 Scalogram of DES at scale=8

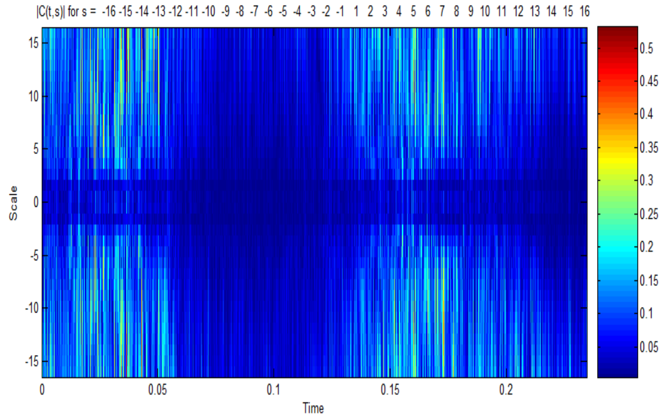

Fig. 11 Scalogram of DES at scale=16

VI. RESULT

These methods for separation of forward and reverse flow signals in an ultrasonic Doppler system have been implemented by CCS and MATLAB software. The processing platform was a powerful 32-bit floating point digital signal processor capable of processing Doppler signals at several hundreds of kHz in real time.

The processing time required for CFFT simulation in MATLAB is listed in table 1. The time period required for overlapping samples is more as the number of iterations are more. The overlapping sequence is used to reduce the spectral leakage at side lobes.

Table 1 Processing time required for CFFT algorithm

Overlapping Ratio	Processing Time (sec)
0%	0.043
50 %	0.086
90 %	1.274

The processing time required for CWT simulation in MATLAB is listed in table 2. As the scale is increased, the number of calculations increased so time required to process is more. Increased scales give well resolved plot.

Table 1 Processing time required for CWT algorithm

Scale	Processing Time (sec)
8	1.370
16	2.804

From Table 1 and 2 it is clearly observed that time required to process CWT is more than CFFT.

VII. CONCLUSION

The directional Doppler ultrasound methods used to separate forward as well as reverse flow. Processing time required to obtained spectrograms with overlapped data is more but the spectrogram plot is more accurate in CFFT. While CWT required more time to process. CFFT and CWT separate the directional information in positive & negative frequencies and positive & negative scales respectively. Also this system has been designed as open research platform, which can be programmable with variety of novel algorithms for studying improved and resolved spectrograms to obtain accurate diagnostic details in the future.

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