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A Digital Method for the Detection of Blood Flow Direction in Ultrasonic Doppler Systems

Método digital para la detección de la dirección de flujo sanguíneo en sistemas doppler ultrasónicos

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Abstract

Doppler ultrasound systems are widely used to study blood flow and diagnosis of vascular diseases. An important characteristic of these systems is the ability to detect the direction of the blood flow. Most Doppler ultrasound systems apply a quadrature demodulation technique on the ultrasonic transducer output signal. Therefore additional treatment is necessary to separate forward and reverse flow signals. This work presents a digital method to convert signals in quadrature into directional signals using a Fast Fourier Transform (FFT) approach. Validation of the method has been achieved using simulated Doppler ultrasound signals.

Keywords: Signal analysis, direction detection, Dopper ultrasound.

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Resumen

Los sistemas Doppler ultrasónicos se utilizan ampliamente para el estudio del flujo sanguíneo y el diagnóstico de enfermedades vasculares. Este tipo de instrumentos cuenta con una característica muy importante que es la de poder detectar y discriminar la dirección del flujo sanguíneo. Por lo general, estos equipos utilizan la técnica de demodulación en cuadratura de la señal proveniente de un transductor ultrasónico, por lo que es necesario un tratamiento adicional para separar completamente las señales de flujo directo e inverso. Se presenta un método digital para la conversión de señales en cuadratura a direccionales, basado en la Transformada Rápida de Fourier (FFT), que es utilizada para la detección de la dirección del flujo sanguíneo en sistemas Doppler Ultrasónicos. El método ha sido validado utilizando señales Doppler ultrasónicas sintetizadas.

Desciptores*: análisis de señales, detección de dirección, ultrasonido Doppler.*

Introduction

At present Doppler ultrasound systems are widely used to study blood flow and diagnosis of vascular diseases. The wide use of these systems is mainly due to their noninvasive characteristics and their relative low cost. An important characteristic of the modern Doppler instruments is that these are able to obtain the direction of the blood flow in a accurate manner for which there are several proposed techniques. These equipments mainly use the demodulation in quadrature technique of the signal from the ultrasonic transducer (Evans *et al.*, 2000). The result of this demodulation is two signals in quadrature which are filtered to eliminate the high frequency components. These signals known as signals in phase and in quadrature require an additional processing to be able to extract the blood flow direction (Evans *et al.*, 2000) (Nizamettin, *et al*., 1994). Analogue methods have been typically used to perform this decodification basing its operation in the treatment of the signal in the phase and frequency domains. Diverse and novel algorithms have been proposed, showing the advantages of the digital techniques over the analogue techniques (Nizamettin and Evans, 1994, 1996), (Marple, 1999).

This work presents a digital method to convert signals in quadrature into directional signals (forward and reverse flows) using a FFT and IFFT transforms to implement the Complex Discrete Fourier Transform (CDFT) and the Inverse Complex Discrete Fourier Transform (ICDFT) respectively as shown in figure 1. The advantage of having on one side a signal in phase and on the other side a signal in quadrature is that we have the possibility to store the information of the forward and reverse flows in an independent form in the time domain, allowing to perform a detailed study of the behavior of the blood circulation within the

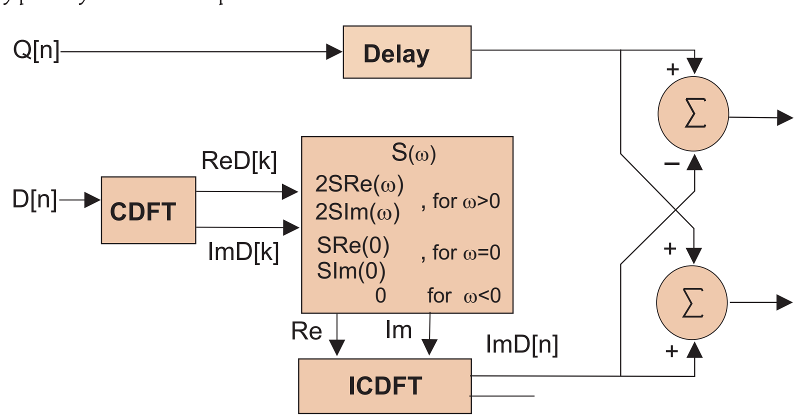

Figure 1. Block diagram of the algorithm in the time domain

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irradiated zone and to show in an independent way the flow in each direction.

Description of the method

The blood flow Doppler signal *x(t)* has flow information in the forward and reverse direction for two signals in perfect quadrature and balanced in amplitude (Nizamettin and Evans, 1994).

$$x(t) = d(t) + jq(t) \quad (1)$$

$$x(t) = (\cos\omega_f t + \sin\omega_r t) + j(\sin\omega_f t + \cos\omega_r t) \quad (2)$$

therefore:

$$d(t) = \cos\omega_f t + \sin\omega_r t \quad (3)$$

$$q(t) = \sin\omega_f t + \cos\omega_r t\ . \quad (4)$$

The Doppler discrete signal can be modelled as a complex signal analytic (Vaitkus *et al*., 1988) as follows:

$$X[n] = D[n] + jQ[n], \quad (5)$$

where $D[n]$ and $Q[n]$ are the real signals in phase and in quadrature respectively in discrete time. Under conditions of stable flow, forward and reverse flow components can be implemented using the algorithm shown in figure 1, calculating the CDFT can be expressed as:

$$D[k] = \mathrm{Re}[k] + j\,\mathrm{Im}[k] \quad (6)$$

$$D[k] = \frac{1}{N}\sum_{n=0}^{N-1} D[n](\cos(2\pi kn/N) - j\sin(2\pi kn/N)) \quad (7)$$

where

$$\mathrm{Re}\,D[k] = \frac{1}{N}\sum_{n=0}^{N-1} D[n]\cos(2\pi kn/N) \quad (8)$$

$$\mathrm{Im}\,D[k] = -\frac{1}{N}\sum_{n=0}^{N-1} D[n]\sin(2\pi kn/N). \quad (9)$$

An analytic signal *s(t)* in continuous time corresponding to a real signal of finite energy is defined in the frequency domain (Papoulis, 1977) as:

$$S(\omega) = \begin{cases} 2S(\omega), \text{for } 0 \le \omega < \pi \\ S(0), \text{ for } \omega = 0 \\ 0, \quad \text{for } \omega < 0 \end{cases}$$

Calculating the ICFDT to obtain $D[n]$:

$$D[n] = \mathrm{Re}\,D[n] + j\,\mathrm{Im}\,D[n] \quad (11)$$

$$D[n] = \sum_{k=0}^{N-1} \mathrm{Re}\,D[k](\cos(2\pi kn/N) + j\sin(2\pi kn/N)) \quad (12)$$

$$-\sum_{k=0}^{N-1} \mathrm{Im}\,D[k](\sin(2\pi kn/N) - j\cos(2\pi kn/N))$$

$$\mathrm{Im}\,D[n] = -\sum_{k=0}^{N-1} \mathrm{Im}\,D[k](\sin(2\pi kn/N) + j\cos(2\pi kn/N)). \quad (13)$$

In the time domain:

$$\mathrm{Im}\,d(t) = -\sin\omega_f t + j\cos\omega_r t, \quad (14)$$

from equations (4) y (14). Applying the proposed algorithm we have:

$$F[n] = Q[n] - \mathrm{Im}\,D[n] \Rightarrow \sin\omega_f t + j\cos\omega_r t + \sin\omega_f t - j\cos\omega_r t$$

$$F[n] \Rightarrow 2\sin\omega_f t \ \textit{forward flow}. \quad (15)$$

$$R[n] = Q[n] + \mathrm{Im}\,D[n] \Rightarrow \sin\omega_f t + j\cos\omega_r t - \sin\omega_f t + j\cos\omega_r t$$

$$R[n] \Rightarrow 2\cos\omega_r t \ \textit{reverse flow}. \quad (16)$$

Simulation

To evaluate the performance of the implemented algorithm it was necessary to simulate a simple signal which includes the forward and reverse flow components:

$$D(n) = \cos(\omega_f n) + \cos(\omega_r n)$$
$$Q(n) = \sin(\omega_f n) - \sin(\omega_r n), \quad (17)$$

where ω_f and ω_r represent the forward and reverse flow components, respectively. The reverse flow component was kept as a constant varying only the forward flow component (from 150 Hz to 8000 Hz) calculating the level of separation using the following expression:

$$level\_dB = 20\log_{10}\left(\frac{RMS_{reverse}}{RMS_{forward}}\right). \quad (18)$$

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Figure 2 shows the plot of the level of separation obtained with the implemented algorithm within the wideband under study. It is clearly seen that for frequencies under 1 KHz the level of separation is within –54 and –40 dB, this is due to the method which introduces frequency components to the output signal due to the discontinuities caused by the effects of the borders of the applied window before the FFT calculation. However as the level of these signals and their harmonics are lower than –40 dB the effect on these are negligible.

To display the corresponding spectrum of the signal under study a 2-D spectogram representation like the one shown in figure 3 was used, since this is the typical method used in ultrasonic Doppler systems.

To obtain this representation the Short Time Fourier Transform (STFT) was evaluated using 10 ms Hanning windows over consecutive segments of the signal. To minimize the effects of the data segmentation an overlap technique between windows was used

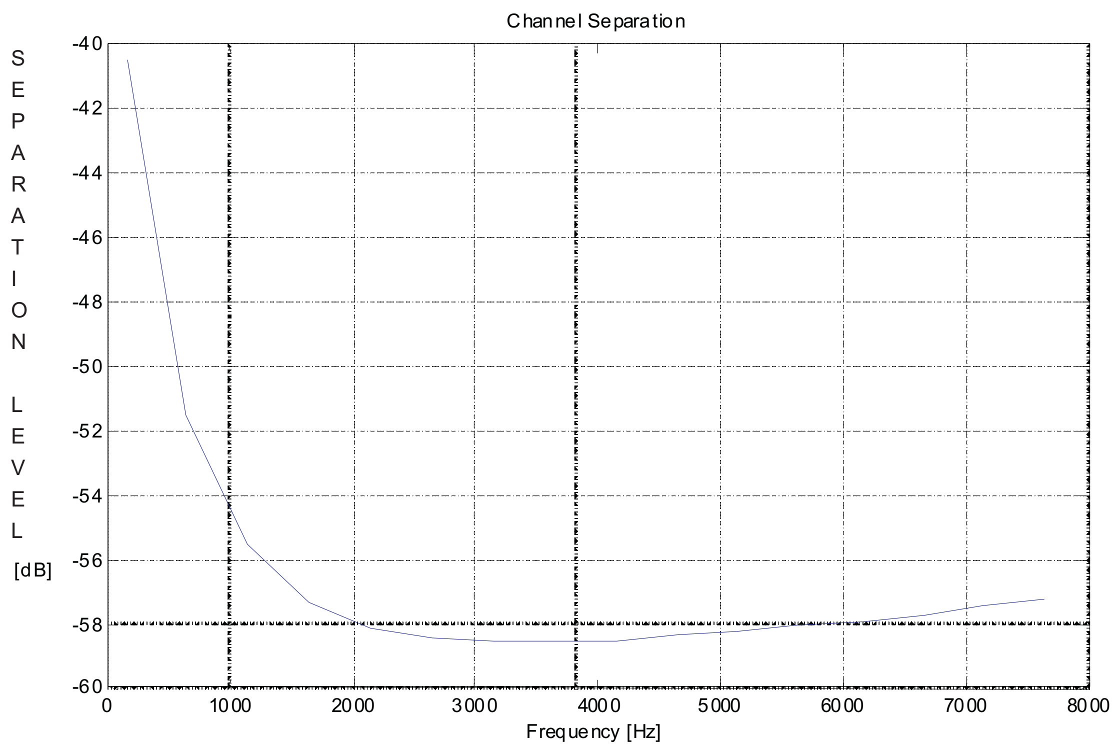

Figure 2. Level of separation of simulated signal

Table 1. Characteristics of the simulated signal using the FIELD II program

Sample frequency (fs)	8 MHz
Transducer central frequency (fo)	2 MHz
Pulse Repetition Frequency (PRF)	5 kHz
Resolution	16 bits
Number of scatterers	4990
Vessel central position	60 mm
Vessel radius	4 mm

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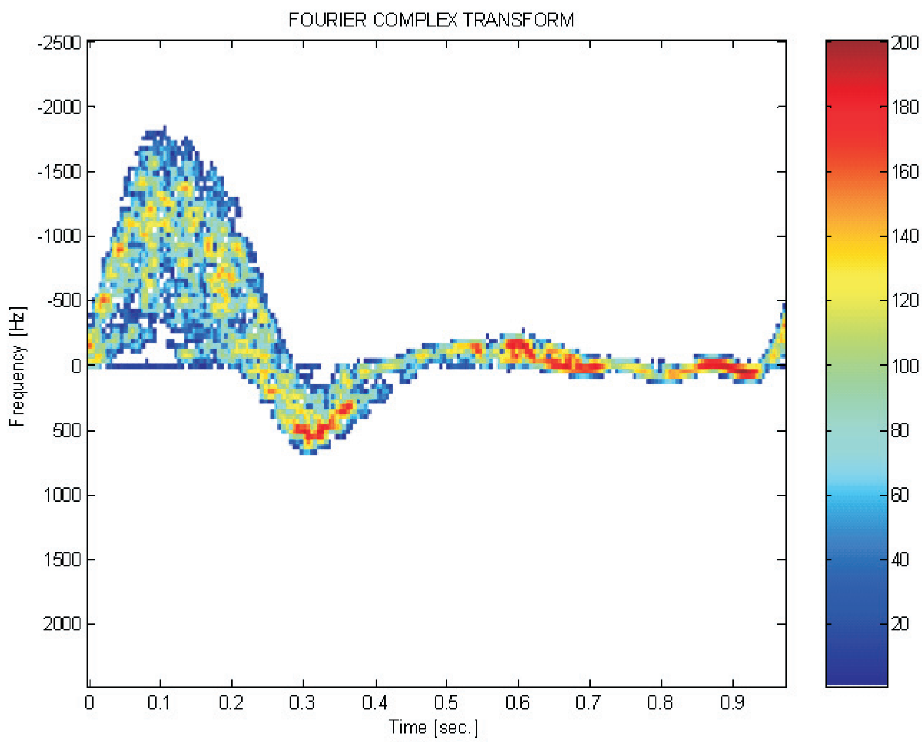

Figure 3. Spectogram of the simulated signal using the FIELD II program

allowing to minimize discontinuities present in the time domain.

Figure 3 shows the spectogram of the ultrasonic Doppler signal in a cardiac cycle.

Results

Figure 4 shows signals in quadrature $D(n)$ and $Q(n)$ for a cardiac cycle. These signals are obtained using demodulation in quadrature of the signal from the transducer (both signals are filtered to eliminate the high frequency components). Figure 5 shows the signals already separated after applying the described method, it is clearly observed the moment when the direction of

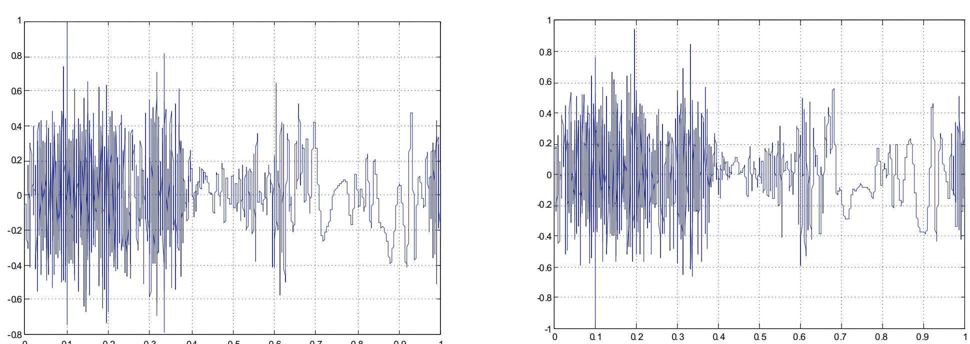

Figure 4. Simulated signals in quadrature

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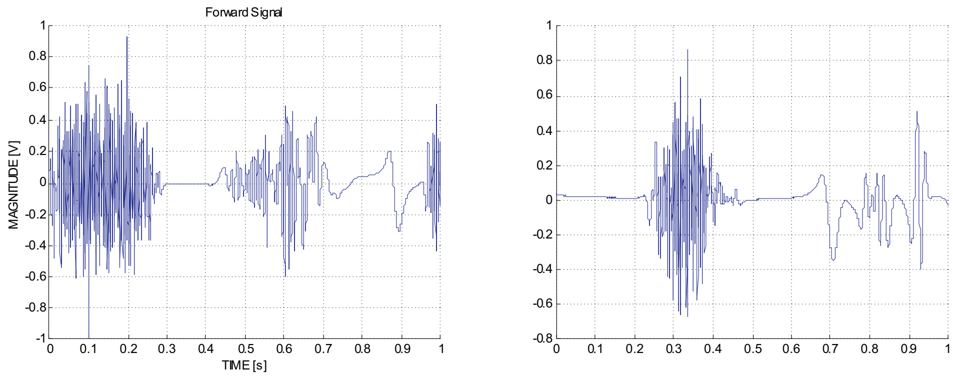

Figure 5. Forward and reverse flow signals obtained using the method

the flow changes in the time axe (0.25 to 0.4 seconds in figure 3). It is worth mentioning that the level of separation was approximately –56 dB within the bandwidth under study, this level is higher than ones reported in previous works.

Conclusions

The method described in this work requires basically the evaluation of a Fast Fourier Transform (FFT) and an Inverse Fast Fourier Transform (IFFT), therefore, this method can be implemented in a very efficient way on Digital Signal Processor (DSP) based architectures. It is worth mentioning that the level of separation of the forward and reverse flow signals obtained was around –56 dB within the operation bandwidth, this result is a higher value than the values recently reported. It is also worth mentioning that the method was implemented on a bi-directional ultrasonic Doppler system based on a personal PC which is capable of processing and displaying in real time the forward and reverse flow signal spectograms in two independent windows as well as supplying this information in two separate audio outputs.

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