Doppler Ultrasound Blood Flow Measurement System for Assessing Coronary Revascularization

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Abstract - *This work describes a Doppler ultrasound system for measuring blood flow. The system is intended to be used for assessing coronary implants and bypass operations. Quantifying the blood flow through these implants/bypasses is an important task to ensure the chirurgical process, thus, reducing both the post-chirurgical and death risks. The system is based on an open architecture that is portable and low-cost, incorporating the advantages of expensive systems with dedicated hardware. It incorporates a pulsed-wave bi-directional Doppler ultrasound flow detector working at 8 MHz. Signal conditioning, detection of direction, signal processing, spectrogram displaying, parameters calculation, and a database handling subsystem complete the system. A graphical user interface is provided for controlling and monitoring the whole system. Doppler signal is processed using both Fourier Transform-based and Parametric Model-based algorithms, having the facility to incorporate alternative higher-resolution spectral estimation methods. The system is being assessed in coronary revascularization.*

Keywords: Blood flow measurement, Doppler ultrasound, signal processing, spectral analysis.

1 Introduction

Ultrasonic techniques have been successfully used in the development of medical diagnostic equipment in obstetrics, cardiology and the peripheral vascular system among others. This equipment may generate the image of an internal structure or the associated spectrogram of an artery's blood flow using external ultrasonic transducers [1,2,3]. Ultrasonic diagnostic is a well-established and widely used technique in almost all medical areas. Although initially its development was focused to obstetrics, very soon several applications were found in cardiology [4].

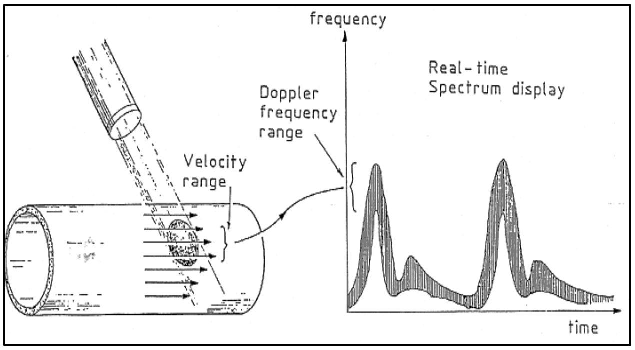
The use of instruments based on the Doppler principle has allowed extracting phase information from the echoes of body moving structures producing images and sonograms which are used to estimate pressure and flow parameters [5]. Development of pulsed Doppler techniques in conjunction with the signal and image processing methods have generated a notorious increment in the use of ultrasound, opening new options and displacing other invasive methods used up to nowadays.

This work describes a Doppler ultrasound system for measuring blood flow. The system is intended to be used for assessing coronary implants and bypasses. Quantifying the blood flow through these implants/bypasses is an important task to ensure the chirurgical process, thus, reducing both the post-chirurgical and death risks. The system is based on an PC architecture that is portable and low-cost, incorporating the advantages of expensive systems with dedicated hardware. It incorporates a pulsed-wave bi-directional Doppler ultrasound flow detector working at 8 MHz. Signal conditioning, detection of direction, signal processing, spectrogram displaying, parameters calculation, and a database handling subsystem complete the system. A graphical user interface is provided for controlling and monitoring the whole system. Doppler signal is processed using both Fourier Transform-based and parametric model-based algorithms, having the facility to incorporate alternative higher-resolution spectral estimation methods based on time-frequency distributions. The system is being assessed in a number of coronary implant and bypass chirurgical operations.

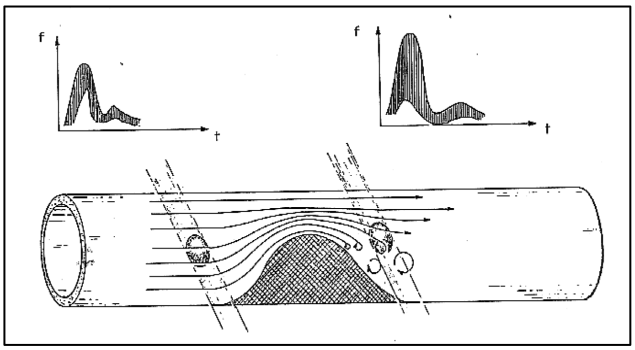
2 Doppler ultrasound

Doppler ultrasound systems either continuous or pulsed are used as a non-invasive method for detection and evaluation of the blood flow [6]. Doppler frequency is proportional to blood velocity in the sampled volume and as the arterial blood flow is pulsed the Doppler signal has a spectrum that constantly varies in the time domain.

In ideal conditions the Doppler power spectrum has a similar form to a blood flow histogram in the sampled volume. This is depicted in figure 1a. The analysis of the Doppler signal gives relative information to the evolution of the distribution of the blood particle velocity in the artery [7]. An increment in the Doppler frequency range as a result of some type of turbulence in the blood flow is typically used to detect artery occlusions and other vascular problems, see figure 1b.



(a)



(b)
Figure 1.- Doppler ultrasound measurement

3 System description

The system is based on an PC architecture that is portable and low-cost, incorporating the advantages of expensive systems with dedicated hardware. It incorporates a pulsed-wave bi-directional Doppler ultrasound flow detector working at 8 MHz. Flow direction, signal processing, spectrogram displaying, parameters calculation and a database handling subsystem complete the system. A graphical user interface is provided for controlling and monitoring the whole system. Figure 2 shows the complete system. The system described in this work introduces some modifications in order to optimize its size, cost and operation.

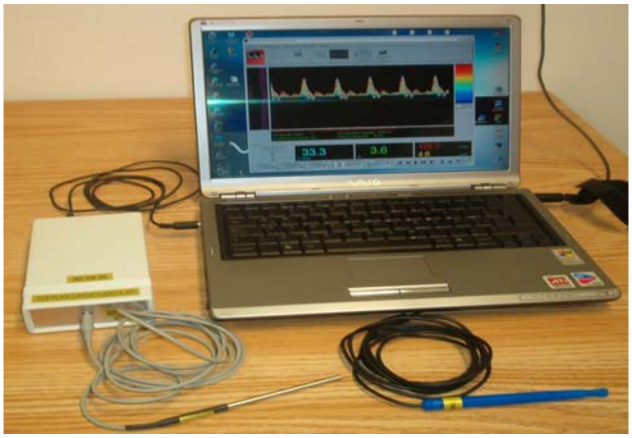


Figure 2.- Doppler ultrasound blood flow system

4 Pulsed wave flow detector

The design of a pulsed wave bi-directional Doppler Ultrasound blood flow detector is presented. The system includes a piezoelectric transducer operating in pulsed wave mode at 8 MHz of frequency. It uses a quadrature phase demodulation for detecting the Doppler signal produced by the blood flow. The Doppler detector generates audio signals I (in phase) and Q (in quadrature). These audio signals in quadrature are used as an input for further processing.

4.1 Sensing probe

The system described in this work incorporates in a sensing probe, the transducer and the detector of the ultrasonic Doppler signal. Figure 3 shows a diagram of this sensing probe. This device has two piezoelectric ceramics, which are excited in a continuous mode, using demodulation in quadrature to detect the ultrasonic Doppler signal and giving as output the I and Q signals. The oscillator–transmitter and the detector–demodulator circuits are integrated in a printed circuit board. These PZT-5 ceramics with a ‘‘D’’ shape are connected 1 cm away from the circuit for noise reduction and a higher sensitivity. System includes an ultrasound 8 MHz probe, however the circuit design allows the use of 4, 5, 8 and 10 MHz piezoelectric ceramics.

4.2 Filters

Considering that the blood flow velocity profile in humans is within the 20–750 mm/s range and the ultrasound velocity in tissue is 1540–1600 m/s [8,9], we may estimate the resulting Doppler signal bandwidth (Fd), and use ultrasonic transducers in the 2–10 MHz range. This Doppler signal may be calculated using the expression; $Fd = (2v/c)\ f0$, where v is the blood velocity [m/s], c is the ultrasound velocity in the medium and f0 is the transducer frequency, using this expression and the values given, the Doppler signal is within the 200–10,000 Hz range. Quadrature signals (I, Q outputs) from the blood flow-sensing probe are connected to a two channel amplifying and filtering module, a schematic diagram of this module is shown in Figure 4. Filters are dynamic analogue, fifth order band-pass and with 300 and 8000 Hz cut frequencies, and a 40–50 dB amplifier per channel.

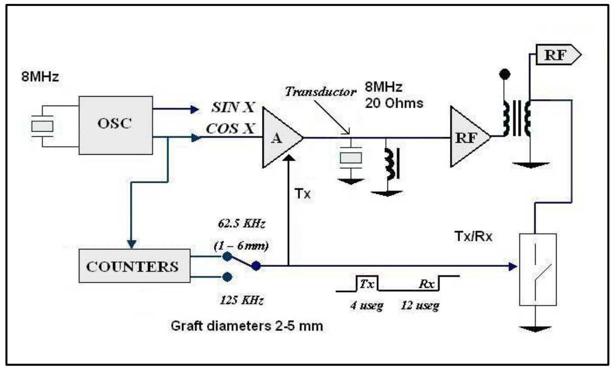


Figure 3.- Sensing probe diagram

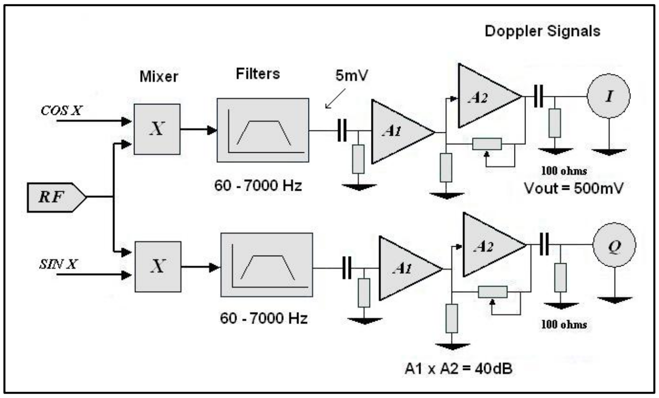


Figure 4.- Amplifying and filtering module

4.3 Flow direction

Blood flow signals I(t) and Q(t) are filtered and amplified giving as a result signals I'(t) and Q'(t) These signals are input and then are transform into quadrature signals d(n) and q(n) to be digitally processed. There are several methods to transform quadrature signals d(n) and q(n) into flow directional signals f(n) (forward flow) and r(n) (inverse flow). The phasing filter [1] was selected to transform the signals. This has the advantage that the processing time is around milliseconds. Figure 5 shows the block diagram of the algorithm. Here Hilbert transform was implemented using FFT in order to achieve efficiency.

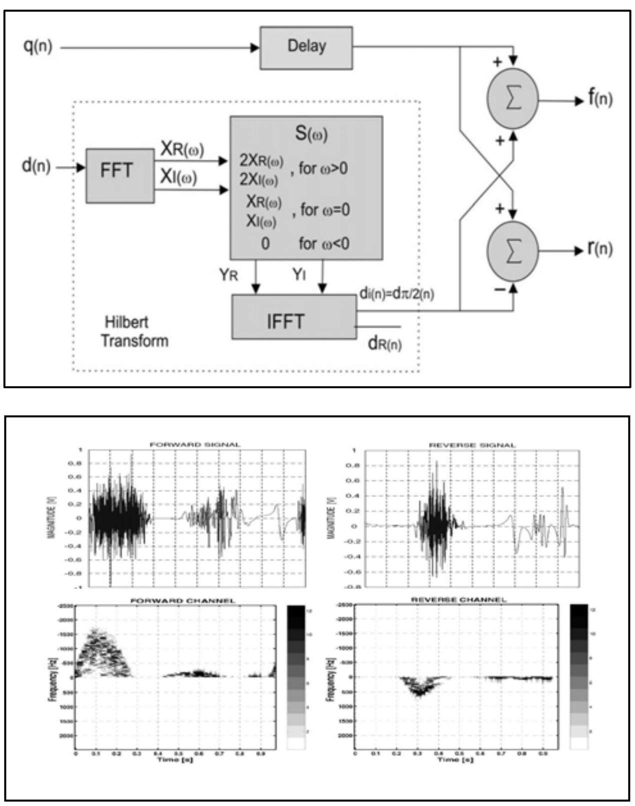
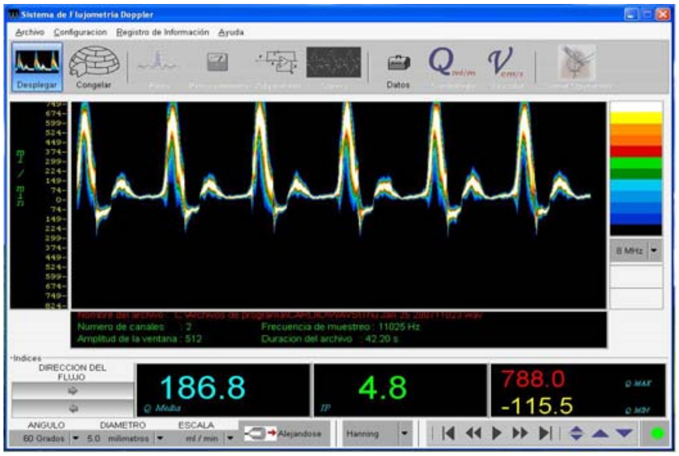


Figure 5.- Phasing filter and flow direction case study

5 Doppler signal processing

In order to measure blood velocity and to monitor is flow, it is necessary to estimate the Doppler signal spectrum. A conventional method to determine and display the spectral information is real time spectral analyzer, see Figure 6. The frequency information of the signal may be display as an amplitude graphic of the signal spectral components versus frequency (frequency spectrum) for each sample interval. Due to the blood velocity in arteries is periodic, the Doppler signal is cycle-stationary, therefore, the Doppler spectrum of each sample interval show variations in the mean frequency and shape along the cardiac cycle. Then, it is necessary to use very short intervals (5–10 ms) where the Doppler signal may be considered as a stationary signal. Spectral power density estimation of a Doppler signal is achieved using methods based on the Fourier transform (FT). However, several research studies present spectral estimation alternative methods such as parametric methods [10-16]. Processing module includes different processing capabilities and calculates automatically the Pulsatility Index, Resistance Index and volumetric flow. The software can also process the Doppler signal using a CFFT (Complex Fast Fourier Transform) algorithm [3,4] or an AR-Modified Covariance algorithm [10] in order to visualize the spectral broadening due to possible stenosis. Doppler blood flow signal is typically represented by a spectrogram where the horizontal axis is time [s], the vertical axis is frequency [Hz] or Volumetric Flow [ml/min] and the Amplitude is represented with a color proportional to its magnitude. The software was developed using C++ programming language and Open GL for graphics display. The Graphical User Interface (GUI) has been developed using GTK. Figure 6 shows examples of spectrograms displaying 512 point windows at 11025 S/seg sampling rate. Hanning windows are used with a 5 ms overlap to reduce the numeric noise due to windowing. The complete spectrogram is build with all the consecutives spectra, scaling the amplitude to a dynamic range 1 – 12 (1 being at 25 dB and 12 at 37 dB). Doppler signal was divided into 2-20 ms overlapped windows and processed.

(a)



(b)

Figure 6.- Spectrograms corresponding to 6 cardiac cycles using (a) FT and (b) AR-modified covariance based methods (over zero values-direct flow, below zero-inverse flow)

6 Tests and results

The testing of the detection device in the laboratory was conducted using a blood flow "phantom" system which includes an electronic controlled pump that emulates different flows and heart rates through 2–4 mm diameter vessels as is shown in figure 7. A mimic blood fluid was used to produce the Doppler effect in the fluid passing through the vessels. The system was also tested in real open-heart surgeries in 10 patients that had coronary implanted grafts, see figure 8.

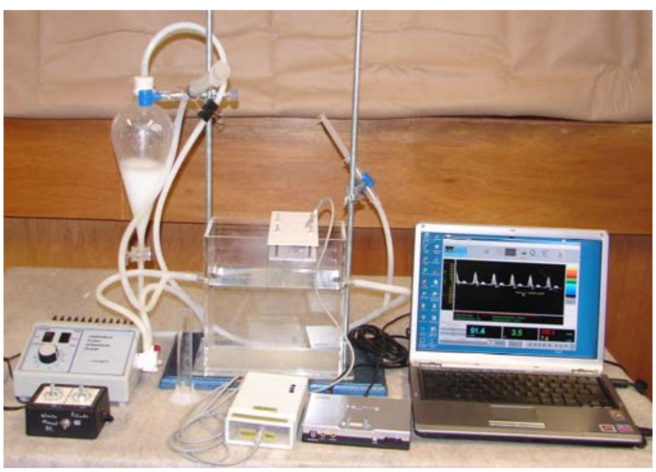


Figure 7.- Doppler ultrasound system *in vitro*

The application software allows the user to select the diameter of the artery, the frequency and angle of the ultrasound probe. It also allows de user to select the amplifier gain, threshold, dynamic range and processing approach (CFFT or Modified Covariance) so the surgeon can visualize the spectrogram according to predefined patterns of the signal. The software incorporates a stand-alone data base that will capture all single or sequential grafts done in each operation and that can be uploaded or downloaded from a general distributed database system connected via internet.

Figure 8.- Doppler ultrasound system *in vivo*

7 Conclusions

A Doppler ultrasound system for measuring blood flow has been presented. The system is intended to be used in coronary implants and bypasses, aiming to verify the quality of flow in coronary grafts which is essential for the success of a heart surgery and the recovery of a patient with heart disease. Quantifying the blood flow in these implants/bypasses is an important task to ensure the chirurgical process, thus, reducing both the post-chirurgical and death risks. The spectrogram output and estimated parameters generated by the system provides important quantitative and qualitative information of the blood flow and can even detect possible errors during surgery or even internal stenosis or "flaps" in the new implanted grafts.

The system is based on an architecture that is portable and low-cost, incorporating the advantages of expensive systems with dedicated hardware. A graphical user interface has been provided for controlling and monitoring the whole system. Doppler signals are processed using both Fourier Transform-based and Parametric Model-based algorithms, having the facility to incorporate alternative higher-resolution spectral estimation methods.

The system has been tested successfully in the laboratory (with synthetic signals in a "phantom") and during real surgery, separating effectively the direct and inverse flow components of the Doppler signal and giving important information about the quality of blood flow, providing the cardiovascular surgeon with an suitable tool for detecting anomalies during the coronary graft surgery. Further work is being carried out, aiming to provide higher-resolution spectral estimation methods together a number of software tools that can help in the interpretation of the Doppler grafts signals database.

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8 References

[1] D.H. Evans, W.N. McDicken, Doppler Ultrasound, Physics, Instrumentation, and Signal Processing. Second edition, John Wiley & Sons Ltd.,2000.

[2] P. Atkinson, J.P. Woodcock, Doppler Ultrasound and its use in Clinical Measurement, Academic Press Inc. London Ltd., 1982.

[3] J.A. Jensen, Estimation of Blood Velocities Using Ultrasound, Cambridge Univ. Press, UK, 1996.

[4] M.D. Cavaye, R.A. White, Arterial Imaging – Modern and Developing Technology, Chapman & Hall Medical, London, 1993.

[5] R.L. Powis, W.J. Powis, A Thinker's Guide to Ultrasonic Imaging, Urban and Schwarzenberg, 1984.

[6] S. Marple Lawrence, Computing the discrete-time ‘‘analytic’’ signal via FFT, IEEE Trans. Signal Process. 47 No. 9 (1999) 2600–2603.

[7] P.J. Fish, Physics and Instrumentation of Diagnostic Medical Ultrasound, John Wiley & Sons, Chichester, UK, 1990.

[8] P.J. Fish, Non-stationary broadening in pulsed Doppler spectrum measurements, Ultrasound Med. Biol. 17 (1991) 147–155.

[9] P. Atkinson, A fundamental interpretation of ultrasonic Doppler velocimeter, Ultrasound Med. Biol. 2 (1975) 107–111.

[10] M.G. Ruano, D.F. Garcıa Nocetti, P.J. Fish, P.J. Fleming, Alternative parallel implementations of an AR-modified covariance spectral estimator for diagnostic ultrasonic blood flow studies, Parallel Comput. 19 (1993) 463–476.

[11] J. Solano, D.F. Garcia Nocetti, M.G. Ruano, High performance parallel-DSP computing in model-based spectral estimation, Microprocess. Microsyst. 23 No. 6 (1999) 337–344.

[12] J. Solano, K. Rodrıguez, D.F. Garcıa Nocetti, Model-based spectral estimation of Doppler signals using parallel genetic algorithms, J. Artif. Intell. Med. 19 No.1 (2000) 75–89.

[13] M.M. Madeira, S.J. Bellis, L.A. Beltran, J. Solano, D.F. Garcia Nocetti, W.P. Marnane, M.O. Tokhi, M.G. Ruano, High performance computing for real time spectral estimation, IFAC J. Control Eng. Pract. 7 No.5 (1999) 679–686.

[14] J.Y. David, S.A. Jones, D.P. Giddens, Modern spectral analysis techniques for blood flow velocity and spectral measurements with pulsed Doppler ultrasound, IEEE Trans. Biomed. Eng. 38 (1991) 589–596.

[15] F. Garcıa Nocetti, J. Solano Gonzalez, E. Rubio Acosta, E. Moreno Hernandez, Parallel computing in time–frequency distributions for Doppler ultrasound blood flow instrumentation, Mex. J. Biomed. Eng. XXII, 1 (2001) 12–19.

[16] J. Solano, M. Vazquez, E. Rubio, I. Sanchez, M. Fuentes, F. García-Nocetti, Doppler ultrasound signal spectral response in the measurement of blood flow turbulence caused by stenosis, Physics Procedia, 3 (2010) 605-613.