



Design and Construction of a Blood Flow Detector Probe for a Continuous Wave Bidirectional Doppler Ultrasound System

M. Fuentes*, A. Sotomayor*, F. García*, E. Moreno** y P. Acevedo*

*DISCA-IIMAS. Universidad Nacional Autónoma de México y

**CENUS, Instituto de Cibernética Matemáticas y Física, La Habana, Cuba

E-mails: martin@uxdea4.iimas.unam.mx, soto@uxdea4.iimas.unam.mx, fabian@uxdea4.iimas.unam.mx, moreno@cidet.icmf.inf.cu y pedro@uxdea4.iimas.unam.mx

(recibido: mayo de 2005; aceptado: noviembre de 2005)

Abstract

The design and construction of a blood flow detector probe for a Continuous Wave (CW) Bidirectional Doppler Ultrasound system is presented. This device is based on two piezoelectric ceramic sensors working in continuous mode and using quadrature phase modulation for detecting the blood flow Doppler signal. The probe generates the I (In phase) and Q (in Quadrature) Doppler signals as audio. These signals are fed to the line in on the PC sound board for further processing. Oscillator-transmitter and detector-demodulator circuits are integrated into a 1.5 x 9 cm printed circuit board (PCB). Piezoelectric ceramics are placed and connected 1 cm apart the PCB, this achieves noise reduction and increases the probe sensitivity. The circuit design allows operation at 4, 5, 8 and 10 MHz depending on the blood flow detection depth in arteries or superficial vessels.

Keywords: *Ultrasound Probe, doppler signals, blood flow detector.*

Resumen

Se presenta el diseño y construcción de una punta detectora de flujo sanguíneo para un sistema Ultrasónico Doppler Bidireccional de Onda Continua. Este dispositivo se basa en dos cerámicas piezoeléctricas operando de modo continuo y utiliza demodulación en cuadratura para la detección de la señal Doppler Ultrasónica del flujo sanguíneo. La punta detectora proporciona como salida las señales Doppler I (In phase) y Q (in Quadrature) en rango audible. Estas señales se alimentan a la entrada *line in* de la tarjeta de sonido en una computadora personal PC para su procesamiento. Los circuitos oscilador-transmisor y detector-demodulador, han sido integrados en una tablilla de circuito impreso de dimensiones 1.5 x 9 cm. Las cerámicas piezoeléctricas están situadas y conectadas a 1 cm del circuito, logrando con una reducción del ruido y un incremento en la sensibilidad de la punta detectora. El diseño del circuito permite operar a 4,5,8 y 10 MHz, dependiendo de la profundidad de la detección del flujo sanguíneo en arterias o en vasos superficiales.

Descriptores: Punta ultrasónica, señales doppler, detección de flujo sanguíneo.

Introduction

In medical application, ultrasound is extensively used as a diagnostic tool. There is a wide range of medical

instruments which are used in this field from simple fetal phones to very sophisticated imaging systems. The main advantage of ultrasound when applied to diagnostic is that it is non-invasive. In Cardiology, the

ultra sonic Doppler probe is a very useful instrument to monitor blood flow.

Blood flow velocity in arteries is periodic in time but its frequency spectrum varies during each cardiac cycle, therefore a blood flow Doppler signal is considered a cycle-stationary stochastic Gaussian signal and in short segments (2-20 ms) is considered a quasi-stationary signal. This signal is commonly analyzed using conventional methods such as the fast Fourier transform (Kay *et al.*, 1981) and also using spectral estimation parametric methods to obtain a better resolution (Ruano *et al.*, 1993).

In this paper the design and construction of a Continuous Wave (CW) blood flow detector probe is presented. This device detects the blood velocity, and flow disturbance by measuring the Doppler frequency shift of an ultrasound beam scattered from the blood flow, using quadrature phase demodulation. Processing the I and Q Doppler signals may provide information about the presence of stenosis and obstruction in arteries (Fish, 1991) (Gosling *et al.*, 1975). Stenosis is a disease that affects blood flow velocity and pressure producing turbulence, due to this the velocity profile changes modifying the frequency spectrum of the signal, these changes determine the stenosis level.

This probe is compact, and includes I,Q quadrature blood flow signal as an output. Total circuit is integrated in 1.5 x 9 cm printed circuit board. This device can operate within 4 to 10 MHz range.

The main advantage of CW systems is that they measure blood flow high velocities with a high accuracy.

Blood Flow Detector Probe

The simplest blood flow Doppler detector probe is the one described by Sotomura (1960). At present this kind of probes are more compact and efficient, they are used as diagnostic tools in cardiovascular diseases more often.

The basic elements that build the probe are shown in figure 1. This probe is a Continuous Wave (CW) device with coherent demodulation to obtain the I (In phase) and Q (in Quadrature) blood flow Doppler signals.

It is worth to mention that the blood flow Doppler signal is actually formed by two components which are the direct and inverse flow. Therefore it is necessary to have two signals in quadrature I_{out} and Q_{out} to be able to separate the flow direction, this is achieved using signal digital processing in the frequency domain (Evans *et al.*, 2000).

The transmitter produces an ultrasonic signal that can be defined by the following expression:

$$T(t) = B \cos(\omega_0 t) \tag{1}$$

where;

$\omega_0 = 2\pi f_0$ = angular frequency, and f_0 = operation frequency of the ultrasonic transducer.

Considering that the ultrasonic signal received $S(t)$, it is formed by the carrier and the two resultant blood flow signals (forward and reverse), it is possible to express it as:

$$S(t) = A_0 \cos(\omega_0 t + \phi_0) + A_f \cos(\omega_0 t + \omega_f t + \phi_f) + A_r \cos(\omega_0 t - \omega_f t + \phi_r) \tag{2}$$

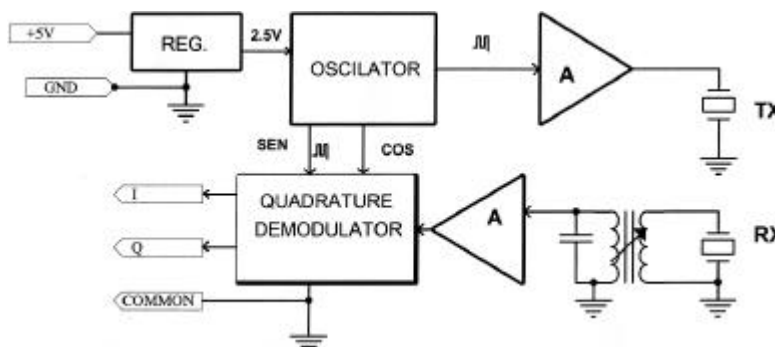


Figure 1. Schematic diagram of the blood flow detector probe

where A , ω y ϕ are the amplitude, angular frequency and phase of each signal respectively. ϕ_o , ϕ_r are the carrier, the forward signal and the reverse flow signal respectively.

With the aim of preserving the real and imaginary components of the Doppler signal, the signal $S(t)$ is demodulated in quadrature.

This demodulation consists in multiplying by a signal of the same frequency from the transmitter $\cos(\omega_0 t)$ and its signal in quadrature $\sin(\omega_0 t)$.

$$I(t) = S(t) \cos(\omega_0 t) \quad (3)$$

$$I(t) = \frac{1}{2} A_o [\cos(\phi_o) + \cos(2\omega_0 t + \phi_o)] + \frac{1}{2} A_r [\cos(\omega_r t + \phi_r) + \cos(2\omega_0 t + \omega_r t + \phi_r)] \quad (4)$$

filtering high frequency and eliminating the d.c. components we obtain:

$$I(t) = \frac{1}{2} A_r \cos(\omega_r t + \phi_r) + \frac{1}{2} A_r \cos(\omega_r t - \phi_r) \quad (5)$$

similarly the signal in quadrature is obtained,

$$Q(t) = S(t) \sin(\omega_0 t) \quad (6)$$

$$Q(t) = -\frac{1}{2} A_r \sin(\omega_r t + \phi_r) + \frac{1}{2} A_r \sin(\omega_r t - \phi_r) \quad (7)$$

then

$I_{out} = I(t)$ is the *In phase* signal and

$Q_{out} = Q(t)$ is the signal in *Quadrature*.

Description of the Elements of the Probe

Transducer

The transducer used in the design of this probe as it is shown in figure 2, it was constructed using two piezoelectric discs PZT-5 with D form, one working as a transmitter and the other as a receiver. The frequency range depends on the

application, for example for fetal phones 2 MHz, for blood flow detection in veins and arteries 4–5 MHz and for detection of blood flow in superficial veins 8–10 MHz.

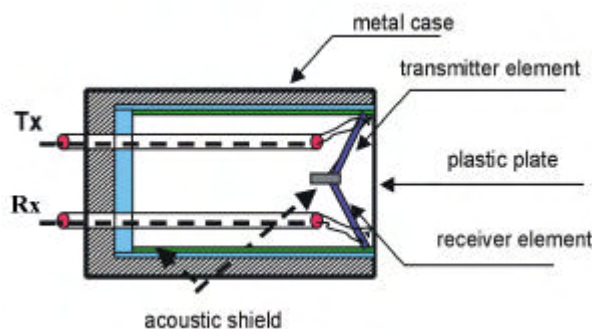


Figure 2. Ultra sonic Transducer

Oscillator-transmitter

In this stage an ultrasonic continuous wave at the operation frequency is generated (4, 5, 8 or 10 MHz). Also in this stage the signals in quadrature $\cos(\omega_0 t)$ and $\sin(\omega_0 t)$ at the same operation frequency of the transducer are generated. Figure 3 shows a schematic diagram of the circuit, it is worth to mention that when designing the transmitter it is convenient to take into account some characteristics such as power and matching impedance and these must fulfill the security levels recommended by the American Institute of Ultrasound in Medicine (AIUM) (Fish, 1991).

Receiver – Demodulator in Quadrature

The recuperated Doppler signal is very small, therefore it is necessary an RF amplification. Figure 4 shows the schematic diagram of this section. It consists of a RF transformer tuned to the operation frequency of the ultrasonic transducer, a FET transistor used as an RF amplifier in cascode configuration with two bipolar transistors which function is to mix the received signal with the signal in quadrature $\cos(\omega_0 t)$ and $\sin(\omega_0 t)$, advantage is taken of the RC components to limit the frequencies forming a low-pass filter cutting the high frequencies (Equation 4) leaving alone the blood flow Doppler signal. Two miniature trimmers are included in this section to balance I_{out} and Q_{out} , compensating small errors due to the variation of the electronic components.

Design and Construction of a Blood Flow Detector Probe for a Continuous Wave Bidirectional ...

*Figure 3. Schematic Diagram of the Oscillator-transmitter. Components marked with an * are dependant on the frequency operation of the ultra sonic transducer*

*Figure 4. Schematic Diagram of the Receiver-Demodulator in Quadra ture. Components marked with an *, must be tuned up at the ultra sonic trans ducer's frequency*

M. Fuentes, A. Sotomayor, F. García, E. Moreno y P. Acevedo

If we consider that the human blood flow velocity profile has a range of 20-700 mm/s, and the ultrasonic velocity in tissue is about 1540-1600 m/s (Fish, 1991) (Atkinson, 1975) (Vaitkus *et al.*, 1988), using ultrasonic transducers within 2–10 MHz we are able to estimate the range of the recovered blood flow Doppler signal.

The Doppler signal is given by:

$$F_d = (2v / c) f_0 \quad (8)$$

So the blood flow Doppler signal lies within 200–10,000Hz, that is the audible range and it is relatively easy to divide the high frequencies from the signal of the detector.

Experiments and Results

To verify the performance of the probe (Figure 5) the I and Q outputs were connected to an amplifier and filter of two channels. The filters used were fifth order band-pass filters with a cut frequency of 300 and 8000 Hz and an amplification of 40–50 dB per channel.

These filters and the probe were designed and constructed as an integral section of a bi-directional blood flow Doppler system at DISCA-IIMAS-UNAM laboratory.

Using MATLAB 6.1 tools, I, Q blood flow signals coming from the probe were acquired using a PC Pentium III audio board, these signals were stored as WAV files. Figure 6 shows these signals.

To verify the frequency spectrum of the acquired I, Q signals, an specific software was developed to display the spectrogram of the blood flow signal as shown in figure 7.



Figure 5. Detector probe with printed circuit board, ultra sonic trans ducer (probe), PVC container and connector cable (scale is in cm)

Design and Construction of a Blood Flow Detector Probe for a Continuous Wave Bidirectional ...

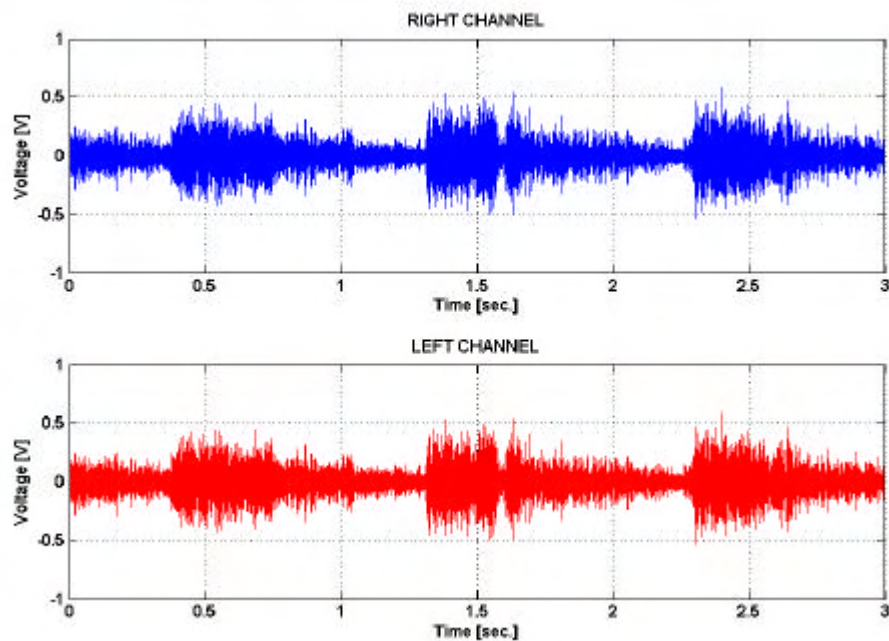


Figure 6. Segments of a blood flow ultrasonic Doppler signal (I and Q), from a carotid artery acquired using 4 MHz probe and a PC audio board with a 22 KHz sample frequency

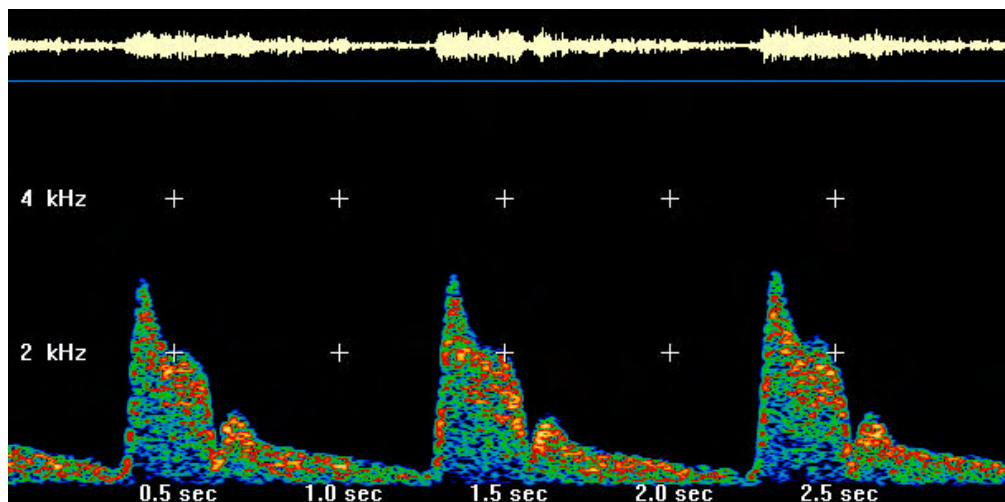


Figure 7. Spectrogram of one of the signals in figure 6. A method based on the Short Time Fourier Transform (STFT), with a 512 points sampling window was used

Conclusions

The blood flow Doppler detector probe has a good performance, having the transmitter and receiver at a short distance from the piezoelectric discs and also having a good shield gives to the probe good sensibility and low noise. The design of the circuit allows the probe to operate within a range of 4 to 10 MHz depending on the depth of

the blood flow detection in veins and superficial blood vessels. Validation of the performance of the probe has been made acquiring real signals associated to the blood flow in arteries, and also processing and displaying these signals as spectrograms. Comparison of these spectrograms with spectrograms produced with commercial equipment has shown the good performance of the detector probe.

M. Fuentes, A. Sotomayor, F. García, E. Moreno y P. Acevedo

Acknowledgements

The authors acknowledge the support of DGAPA-UNAM (PAPIIT-IN120103) (PAPIIT-IN111303).

References

- Atkinson P. (1975). *A Fundamental Interpretation of Ultrasonic Doppler Velocimeter*. *Ultrasound in Med. Biol.*, 2, pp. 107-111.
- Evans D.H and Mc Dicken W.N. (2000). *Doppler Ultrasound, Physics, Instrumentation and Signal Processing*. John Wiley & Sons, LTD. Second Edition, pp. 101-104.
- Fish P.J. (1991). *Non-Stationary Broadening in Pulsed Doppler Spectrum Measurements*. *Ultrasound in Medicine & Biology*, Vol. 17, pp. 147-155.
- Gosling R.G. and King D.H. (1975). *Ultrasonic Angiography in Arteries and Veins*. (Eds. A.W. Hascus and L. Adamson). Edinburgh, pp. 61-98.
- Kay S.M. and Marple S.L. (1981). *Spectral Analysis a Modern Perspective*. Proc. of the IEEE, 69, pp. 1380-1419.
- Ruano M.G., García-Nocetti D.F., Fish P.J. and Fleming P.J. (1993). *Alternative Parallel Implementations of an AR-Modified Covariance Spectral Estimator for Diagnostic Ultrasonic Blood Flow Studies*. *Parallel Computing*, 19, pp. 463 - 476.
- Sotomura, S. (1960). *Ultrasonic Doppler Method for the Inspection of Cardiac Functions*. *Acoust. Soc. Am.*, Vol. 29, pp. 1181-1185.
- Vaitkus P. and Cobbold R. (1988). *A Comparative Study and Assessment of Doppler Ultrasound Spectral Estimation Techniques, Part 1*. *Ultrasound in Medicine & Biology*, 14, pp. 661-672.

Semblanza de los autores

Martín Fuentes. Es ingeniero mecánico electricista (área de electrónica), egresado de la Facultad de Ingeniería de la UNAM. Labora en el IIMAS desde 1983. Ha colaborado en diferentes proyectos institucionales dentro y fuera de la UNAM, tales como: Instituto de Ciencias del Mar y Limnología, Instituto de Biología, Instituto de Geofísica, Museo Universum, Instituto Mexicano del Petróleo y el Departamento de Ultrasonía del ICIMAF-CUBA. Ha realizado estancias de trabajo en España, Cuba y Brasil. Sus áreas de especialidad son la instrumentación sismológica, oceanografía, meteorología y monitoreo atmosférico, así como ultrasonía médica e industrial.

Alejandro Sotomayor. Es licenciado en ingeniería electrónica y maestro en ciencias por el Instituto Superior Politécnico de la Habana, Cuba, desde 1992. Ingresó al Instituto de Cibernética Matemática y Física de Cuba, en el Centro de Ultrasonía en 1994. Para el año de 2001, ingresó al Instituto de Investigaciones en Matemáticas Aplicadas y en Sistemas, UNAM. Las líneas de investigación que desarrolla actualmente son el diseño de transductores, instrumentación ultrasonía y procesamiento de señales para medicina y Pruebas No Destructivas (PND).

Fabián García. Egresó en 1984 de la Facultad de Ingeniería de la UNAM con mención honorífica. Recibió los grados de maestro y doctor en el área de sistemas de cómputo por la Universidad de Gales, Bangor, Reino Unido, en 1988 y 1991, respectivamente. Recibió el Premio Nacional de Ingeniería "Emilio Rosenblueth 1996", otorgado por la Academia Nacional de Ingeniería, así como el Premio "Ciencia e Ingeniería de la Computación" en el año 2000. Se especializa principalmente en cómputo de alto desempeño, procesamiento de señales e imágenes, imagenología ultrasonía, tomografía de procesos, computación móvil y redes inalámbricas. Actualmente es investigador titular "B" del IIMAS.

Eduardo Moreno. Es físico por la Facultad de Ciencias de la Universidad de la Habana, Cuba. Desde 1980, labora en el Centro de Ultrasonía (CENUS-ICIMAF), Cuba, con categoría de investigador. En 1994, obtuvo su doctorado en ciencias físicas por la Academia de Ciencias de Cuba, y para mayo de 2000 a mayo de 2002, se desempeñó como investigador del IIMAS-UNAM, así como profesor en el Posgrado en Ciencia e Ingeniería de la Computación de la UNAM. Actualmente es jefe de proyecto en el CENUS-ICIMAF. Las áreas de investigación que estudia son el procesamiento de señales e imágenes, así como imagenología ultrasonía.

Pedro Acevedo Es egresado de la Facultad de Ingeniería de la UNAM en 1984. Recibió los grados de maestro (Instrumentación) y doctor (Ultrasonido) por la Universidad de Gales, Bangor, Reino Unido en 1987 y 1992, respectivamente. Actualmente es investigador titular "A" y jefe del Departamento de Ingeniería de Sistemas Computacionales y Automatización del IIMAS. Asimismo, es profesor de asignatura en la Facultad de Ingeniería de la UNAM. Sus líneas de investigación son el procesamiento de señales e imágenes, imagenología ultrasonía, diseño, modelado, construcción y caracterización de transductores ultrasonía. También pertenece al Sistema Nacional de Investigadores del CONACYT.