REAL-TIME DIGITAL PROCESSING OF DOPPLER ULTRASOUND SIGNALS

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ABSTRACT

Ultrasound equipment allows an early diagnosis of cardiovascular diseases to be obtained through the appropriate processing of received echo signals.

In this paper a real time digital implementation of processing algorithms dedicated to investigate both the hemodynamic and mechanic properties of large human arteries is described. In particular, an FFT analysis is used to obtain the information about the blood flow, and an autocorrelation-based procedure is applied to estimate the tissue movements. Furthermore, a real-time software approach for audio processing is shown capable of generating directional Doppler signals and of reproducing them on a standard personal computer (PC).

Finally, a summary of the system capabilities is presented by showing the results of application of the above procedures to common carotid artery investigation.

1. INTRODUCTION

Ultrasound (US) diagnostic systems typically transmit short bursts of acoustic energy into the human body. Each tissue inhomogeneity met by the traveling wave generates an echo which goes back to the same transducer used for US transmission.

The echo signals received from subsequent depths are extremely rich of information. When appropriately processed, such signals can provide details not only about the morphology of the region of interest (ROI), but also on its hemodynamic and mechanic properties [1]. Commercial equipment can now provide B-mode images of the ROI, Doppler waveforms describing the blood flow behavior in such region and, more recently, even elastograms reporting the tissue elasticity.

In this paper we describe how the backscattered echo-signals can be processed in real-time to detect both the blood velocity profile and the wall movements in human arteries. Echoes generated from the walls are characterized by high amplitudes and low Doppler frequencies, while those from red blood cells have low amplitudes and relatively high Doppler frequencies. While the classic FFT is shown to be adequate to describe the blood velocity profiles, time-domain auto- and cross-correlation algorithms are used to detect the slower arterial wall movements.

Finally, a novel real-time software procedure based on the Hilbert transform for generating stereo audio signals corresponding to directional blood velocity components is reported.

2. DOPPLER ULTRASOUND SIGNAL PROCESSING

The experimental set-up implemented for this work consists of an echographic machine (Megas, Esaote SpA, Florence, Italy) and a custom made acquisition-processing board [2] housed in a PC (Fig. 1).

The echograph is first used in B-mode to explore the ROI and to choose a single (M-mode) line of sight across the image (Fig. 2). Such line can be set at different angles with respect to the vessel, depending on the type of information that has to be extracted. Then, the US machine is switched to PW-mode. In this modality, US bursts, focussed along the selected line, are periodically transmitted at the pulse repetition frequency (PRF). The received echo-signals are amplified and coherently demodulated to baseband quadrature channels.

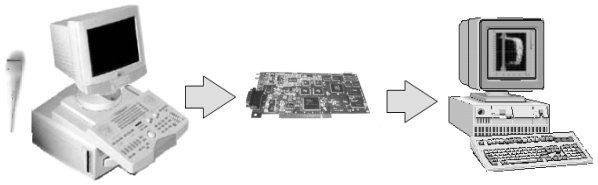

Fig. 1. Experimental setup. From left to right, the echograph, the acquisition/processing board, the host PC.

The acquisition board is fed with the demodulated (I and Q) signal components, and the transmission synchronism (PRF pulse). After a section dedicated to analog signal conditioning, the I and Q signals are converted to digital through two 10 MSPS 14-bit ADCs. Such a high resolution is justified by the need of preserving the high signal dynamic range due to the

possible simultaneous presence of strong and weak echoes. For each transmitted pulse, 128 samples of the received echoes, corresponding to 128 subsequent depths along the beam, are acquired and stored into a SDRAM circular buffer.

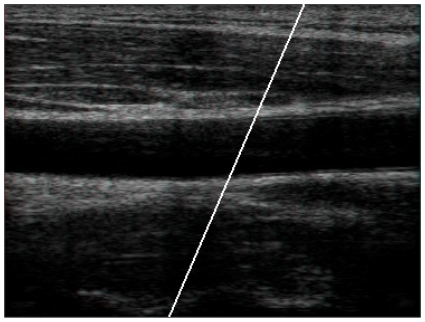

Fig. 2. Longitudinal view of a common carotid artery obtained in B-mode. In PW-mode, only the echo-signals backscattered along the selected line are considered.

Real-time digital processing is carried out in a TMS320C6202 (Texas Instruments, Austin, Texas) 32-bit fixed point Digital Signal Processor (DSP). The results of the elaboration are sent to the PC through the PCI bus.

The host PC runs a dedicated software written in Visual C++ (Microsoft Corp., Redmond, Washington) which allows the storage in a file of input raw data and the real time display of processed data.

2.1. Spectral Profile Detection

For flow investigation, the DSP elaborates the samples generated from the different depths, by computing for each depth the corresponding power spectral density through an optimized 128-FFT algorithm. This operation is performed after an appropriate rearrangement of input data that have been stored in the buffer over subsequent repetition intervals. Data blocks corresponding to a same depth are extracted, with an overlap which depends on the PRF. Each data block is weighted by a Hanning or Blackman-Harris window before being processed through a complex FFT. The result of the elaboration is the so called "spectral profile" [2], a matrix of 128×128 spectral data that is computed every 20 ms. Subsequent spectral profiles are transmitted to the PC and displayed in real-time. The blood velocity profile can be extracted by evaluating the mean or the maximum frequencies from the spectra [3].

2.2. Tissue Motion Estimation

Tissue velocity may be measured by appropriately processing the clutter signal, which consists of the strong echoes coming from quasi-stationary targets. The slow movements cause Doppler shifts of low frequency (from a few to some tens of Hz), which must be estimated using a short time window, typically 10 ms. This task is performed by an autocorrelation algorithm that uses a 2D estimation window [4] comprising 2M+1 Doppler samples along the beam (depth range), and over a set of NP subsequent transmitted pulses (time window):

$$\hat{R}_w(m,n) = \sum_{i=-M}^{M-m} \sum_{j=0}^{NP-n-1} w(i,j) w^*(i+m, j+n)$$

where w(i,j) is the i-th complex echo sample taken at the j-th pulse.

This autocorrelation sum provides both the average Doppler shift (m=0, n=1), and the average received pulse frequency $\hat{f}_0$ (m=1, n=0). The latter is used to compensate for frequency-dependent tissue attenuation [5], allowing the proposed acquisition/processing system to be used with wide bandwidth US equipment.

The instantaneous tissue velocity is evaluated through:

$$\hat{v} = PRF \frac{c}{2\hat{f}_0} \frac{\angle \hat{R}_w(0,1)}{2\pi}$$

in which c is the sound propagation velocity. The tissue displacement is finally estimated by time-integrating the measured velocity.

We have implemented the above procedure to estimate the change in diameter (distension) of the common carotid artery (CCA), which provides significant information about the vessel elasticity. CCA walls are preliminarily found by searching for the high level signal due to the strong echoes from the blood/wall interface. Then, the described procedure is applied to estimate the movements of the two walls and to track them. The distension waveform is finally calculated as the difference between the anterior and posterior wall positions.

2.3. Audio signal processing

The Doppler shift frequencies lie within the human audible range. If adequately processed, the echo signal from a given depth can be listened through a pair of stereo audio speakers dedicated to the separate reproduction of forward (Fw) and Reverse (Rv) signal components. These components correspond to positive and negative Doppler shifts, respectively, and thus provide directional information about blood velocity. The availability of this audio output is important in clinical applications since it provides a useful help to get an immediate although qualitative estimation of flow behavior in the vessel.

The Fw/Rv Doppler components can be obtained from the I/Q echo components through the classic Hilbert transform [6,7], which has been traditionally implemented through dedicated hardware. The high performance of currently available CPUs makes now possible a software implementation of such a processing in real-time.

Moreover, PC sound cards can be used for audio reproduction, but it has to be taken into account that their output data rate (e.g. 48 kHz) is constant and independent from the variable input data rate (PRF, typically ≤ 15 kHz).

The steps implemented to fully exploit the available PC resources for this application are represented in Fig. 3. The program was written in Visual C++ as a stand alone class. Fw and Rv components are first separated through a 121-point Hilbert filter. The sample rate conversion is carried out through a bandlimited interpolation filter [8]. Since the input data rate is variable, depending on the vessel depth [9], a variable sample rate conversion has been achieved by implementing an automatic feedback control that regulates the resampling factor. A digital filter is finally applied to remove the low frequency components (clutter), which do not add useful information to the audio output.

The output latency has been kept short (i.e. less than 100 ms) to avoid that the audio output were appreciably delayed with respect to the real-time PC display.

The audio samples can also be stored in a standard uncompressed WAV file or in the popular MP3 compressed format [10].

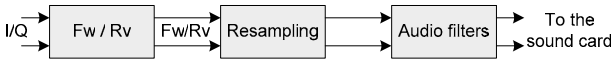

Fig. 3. Digital processing of audio Doppler signals.

3. RESULTS

The described system is currently employed in a research project funded by the Italian Ministry of Education, with the aim of reaching a better knowledge of regional hemodynamics in humans. For this goal a systematic characterization of common carotid artery (CCA) flow profiles of a healthy subject population is being made.

As an example, the following figures show the results of the real-time processing carried out by positioning the US beam on the CCA of a 31 year-old male volunteer.

In Fig. 4 the spectral profile obtained with an FFT computed over a 20 ms time slot is reported. The magnitude of the power spectral densities (grey scale) are shown with frequency in horizontal axis and depth in vertical axis. The vertical line in correspondence of zero frequency is due to the analog chain dc level, which has not been removed since such line provides an useful reference. Over the same line, the clutter signals received from the vessel walls are visible as wider, high intensity regions at the boundaries of the spectral profile.

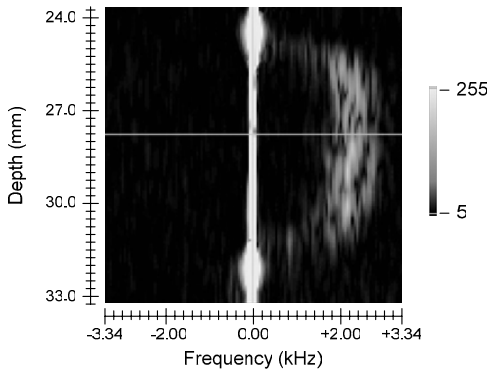

Fig. 4. Spectral profile. The power spectral densities are reported in grey scale as a function of frequency and depth. The horizontal line indicates the depth (~ 28 mm) selected for audio reproduction.

The procedure described for wall movement detection has also been applied. Fig. 5 reports the velocity waveform detected from the near vessel wall, the corresponding displacement and the distension, over two cardiac cycles.

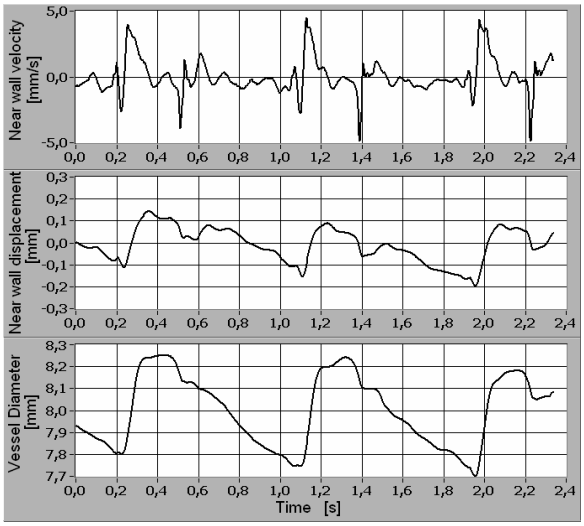

Fig. 5. Near vessel wall (far wall omitted) velocity and displacement waveforms, and vessel diameter vs. time (distension).

The audio signal processing was carried out at the depth indicated by the horizontal line visible in Fig. 4. The time evolution of the spectrum (sonogram) for the selected depth is shown in Fig. 6a. The spectral amplitude is grey scale coded as a function of time (x axis) and frequency (y axis). The spectrum lies in the positive frequency range, corresponding to a mostly mono-directional blood flow. The same behaviour can be noticed from the time waveforms shown in Fig. 6b-c

where the audio signal has a significant amplitude only in the Fw channel.

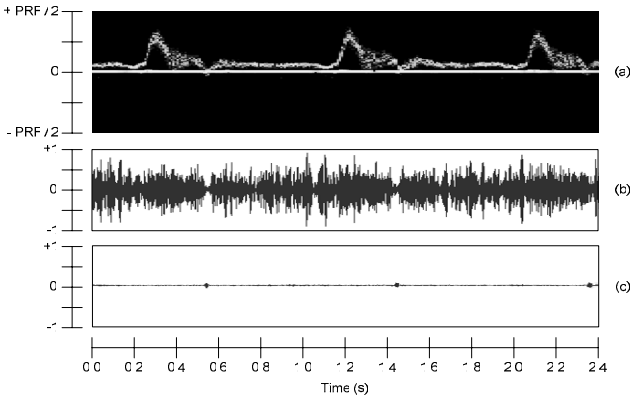

Fig. 6. Audio output waveform, evaluated at the depth selected in Fig. 5: (a) Sonogram, (b) Forward channel, (c) Reverse channel.

4. CONCLUSION

In this paper the implementation of signal processing procedures dedicated to Doppler US signals elaboration has been discussed.

The proposed system has been shown capable to perform in real time all the tasks required to get a complete scenario of the hemodynamics and mechanics in human large arteries.

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5. REFERENCES

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