acústica 2012
VIII Congresso Ibero-americano de Acústica
1-3 outubro
Évora - Portugal

AR PARAMETRIC SPECTRAL ANALYSIS OF ULTRASONIC ECHOES FOR ACCURATE ESTIMATION OF SMALL VARIATIONS IN THIN WALLS & LAYERS

I. Bazan[1], A. Ramos[3], C. Negreira[2], H. Calas[3], T.E Gomez[3], J. Brum[2]

[1]Superior School of Mechanical and Electrical Engineering (IPN). México
{trujilloivonne20@gmail.com}
[2]Dpto. Materiales, Fac. Ciencias, Univ. de la República. Montevideo, Uruguay
{carlosn@fisica.edu.uy}
[3]Lab. “Ultrasonic Signals, Systems & Technologies” (CSIC). Madrid, Spain.
{aramos@ia.cetef.csic.es}

Abstract

Previous auto-regressive authors’ techniques, for evaluating spectral shifts in ultrasonic echo overtones from biological tissues, were adapted for achieving an accurate measure method of thickness changes in thin layers (e.g., blood vessel walls or membrane tissues), which can be useful for detection of cardiac/circulatory accidents and for improving accuracy in the current thickness and velocity measurements in the layered materials. It provides frequency resolutions much more elevated than previous spectral methods (FFT or PSD). Results show the viability of a new spectral technique to estimate physical properties into layers and basic parameters in vessel walls for calculating elastic properties. Thickness data obtained in laboratory, for a latex phantom, show as the spatial resolutions for the vessels analyses could be drastically increased, respect to classic techniques conventionally used for these purposes (time-domain cross-correlation and non-parametric spectral techniques).

Keywords: autoregressive algorithms, spectral analysis, ultrasonic echoes, thickness, overtone shifts

PACS no.: 07.05.kf; 43.35.+d; 07.10.Cm; 43.20.Ks; 43.35.Ns; 43.35.Yb; 43.80.Ev

1 Introduction

The non-invasive estimation of little thickness variations, in layers or thin walls, is an issue of great importance, for instance, in order to make a good characterization for quality control in new layered materials for electronic devices, or well to perform certain early diagnoses in medicine. Nevertheless, there are still not disposable adequate efficient instruments for achieving these objectives with precision enough. The usual non-invasive methods (mainly of the ultrasonic type) employed for the current thickness measurements in pieces of opaque materials, through providing good accuracy (several microns), are not sufficiently precise in many thickness estimation applications, where accuracies around or below one micron could be required in some occasions.

Some auto-regressive parametric frequency-domain techniques, developed by the authors for evaluation of little spectral shifts in the high-order overtones of ultrasonic echo-waveforms with multi-pulse structure, previously applied by us for other finality [7] in biological tissues and phantoms, are now adapted for seeking their applications to an accurate measurement of possible thickness variations appearing on thin walls and layers, encountered in some parts of elastic tubes such as blood vessels or biological membranes in human bodies. This type of estimation tool of internal sizes and distances could be useful in the medical area on the near future, for instance to provide early detection of fatal cardiac or circulatory accidents, or well for improving the effective accuracy resulting of the currently available methods for the measurement of thickness and ultrasonic velocity in material layers.

An analysis of these parametric analytical options will be addressed in this work, showing as they provide distinct levels of accuracy improvement, and always in a considerable amount, enough as for achieving frequency resolutions much more elevated than when conventional non-parametric spectral methods, as Fast Fourier Transforms or typical Power Spectral Densities, are used. The results to be shown, in this article, permit to assure the viability of the innovative application of these spectral techniques to make the estimation of some physical properties into material layers, and also provide precise measurements of the basic parameters needed for calculating some elastic properties in the sanguineous vessel walls. Some thickness estimations so obtained, for a latex phantom (mimicking some vessel properties), are analyzed, showing a clear improvement (in the spatial resolution resulting for vessels characterization purposes), in relation to the classic techniques conventionally employed for it by estimating delays between the pulsed signals coming from the wall interfaces.

Parametric algorithms previously developed by us for spectral ultrasonic evaluation of biological multi-echo waveforms are adapted and improved here in order to achieve a more elevated frequency resolution. Finally obtained methods and results have permitted to study in detail the possible future application of our auto-regressive spectral technique, in order to estimate internal properties like wall thickness changes, with accuracy enough. These sophisticated ultrasonic measurements in blood vessels have an increasing interest as a tool to estimate basic parameters for calculating elastic properties in the vessel walls. The thickness data obtained in the phantom provide a promising expectative for this new estimation technique in vessels characterization. This option constitutes a diagnostic tool of growing attention by part of the researchers in this field. First calculated data suggest clear improvement in spatial resolution, over the classic estimation of delays between pulsed signals, well a) by time-domain cross-correlation, or well b) by non-parametric spectral techniques.

Some research publications have reported laboratory techniques for the ultrasonic estimation of thickness and elastic parameters in blood vessels walls (e.g., in carotid or femoral), with the aim of obtaining an early diagnostic of vascular problems [1-5] related to certain diseases due to arterial hypertension and atherosclerosis, which alter the physical properties of vessels of large length. This specific research topic becomes nowadays of growing attention from the medical sectors for its potential application in advanced vascular diagnosis. Some research lines in this direction include ultrasonic measures of radial displacements in arterial walls as a function of cardiac pulse. And, by the estimation of mechanical displacements of the vessel walls as a function of internal pressure variations, the biomechanical behavior of the vessel walls could become to be conveniently studied on phantoms and human arteries [6]; as an interesting result, it was observed that when atheroma plaques are present in an artery, a modified Young modulus appears quite different than in healthy vessels.

By applying this characterization of biomechanical properties in certain human arteries, an early diagnosis of certain cardiovascular diseases, as arteriosclerosis or atherosclerosis, would be possible.

Though, some ultrasonic procedures have already been proposed and applied for evaluating tube wall parameters, more accurate methods are still needed. In this paper, a new procedure is analyzed for detecting arterial wall thicknesses with an enhanced spatial resolution. The procedure uses a modified parametric spectral technique (of the auto-regressive type) for wall thickness measurements from ultrasonic echoes acquired in sanguineous vessels, improving and extending a technique previously proposed by the authors [7] for distinct medical objectives. Our technique, for early diagnoses of some diseases, is based on detecting changes on the overtones frequency location of the echoes spectra.

2. Analysis of ultrasonic information with multi-echo structure by using time and frequency domain signals processing methods

Processing methods of the ultrasonic echoes, acquired from human tissues, have been largely explored for possible non invasive diagnosis of certain diseases for instance in liver [8-10], which are based on the digital processing of pulsed ultrasonic signals acquired from the analyzed media (biological phantoms or tissues). In this way, useful information about the analyzed media can be extracted in order (for instance) to facilitate the diagnostic of some viral or degenerative diseases, by using new diagnosis ways, as v.g. a non-invasive analysis of the internal thermal distribution into tissues. The main parameters employed for it are: ultrasonic velocity, echo flight-times, spectrum amplitude & phase, changes of stiffness, and variations of scatters distances. Specific procedures for data extraction from inside of the tissues were proposed to improve the simple direct-time procedure, for instance: the conventional time cross-correlation, and the parametric spectral analysis. This last spectral method was successfully applied to study some kinds of multi-echo broadband signals [7, 11] acquired in biological tissues or phantoms, for the aim of extracting clinical information hidden inside them.

The echographic ultrasonic information acquired from biological media uses to be composed by broad-band pulses whose nature depends on the tissue internal structure. In general, time-patterns of the raw ultrasonic echo-signals are rather complex, and the multiple information contained in them is difficult to be directly interpreted with a certain accuracy. Possible noise and speckles added to the acquired echoes difficult the localization of the real medium information among the undesirable perturbations masking the searched echoes.

In the different ultrasonic measurement procedures explained in this paper, the time and frequency domains options can be considered as alternative tools for attaining an improved estimation.
- In the time domain, the conventionally used tool, with better results, has been the time cross-correlation between echo-signals taken at different instants of the cardiac pulse [6]. This processing option is quite robust against possible signal deformations and also in presence of moderate SNR levels, but any time-domain digital processing method has an inherent limitation in that related to the obtainable resolution for the estimation of small delays, which is related to the sampling period.
- In some types of frequency-domain analyses, the study of ultrasonic echo-signals seems an adequate via to properly detect little changes, with a good resolution, on other physiological parameters, like temperature, which usually results to be directly related with variations in the echo-delays.

2.1. Some related signal processing Operators and Procedures

An interesting fact to be noted is that the changes on the delays between echoes, for distinct situations of the specimen under study, can be reflected in the peaks locations appearing into the corresponding frequency spectra, which provides a better resulting resolution than the previous time options. This section shows distinct analysis tools to be comparatively assessed to estimate wall thickness changes in our phantom, which are implemented both in the time and frequency domains.

For instance, in order to find in the time domain an estimation of the delay existing between two similar echo-signals *a*, *b* (one delayed respect to the other) in an analytical way, a cross-correlation operation can be performed between them. In the case addressed in this paper, the delays estimated by a cross correlation operator, of two ultrasonic waveforms acquired in distinct times, would be related to the echoes shifts produced by possible changes experimented in the thickness of a specific wall.

The cross-correlation sequence is a statistical function defined in this way:

$$CC_{ab}(m) = E[a_n \,.\, b^*_{n-m}] = E[a_{n+m} \,.\, b^*_n] \qquad (1)$$

where a_n and b_n are the stationary sequences related to the signal sampling in a digitizing process , m is the lag existing between both signals, expressed in samples number, and E [.] is the operator known as *expected value*.
Respect to practical calculation aspects, a common estimation, based on N samples of a_n and b_n , is the deterministic cross-correlation sequence [11]. By measuring the displacement between the maxima of CC_{ab} and CC_{aa}, a measure of the delay registered between the *a* and *b* signals can be obtained.
With the aim of estimating the thickness of thin membranes or walls, a possible option in the frequency domain (alternative to the cross-correlation operator) is the Power Spectral Density (PSD), which is used commonly to analyze the frequency components contained in complex echo signals.
In consequence, it can be employed to detect the signal changes associated to echoes temporal shifts.
The PSD of a continuous signal can be expressed as the Fourier transform of the autocorrelation function. And for the discrete case, the PSD of a stationary sequence a_n is related to the autocorrelation sequence (CC_{aa}) by the discrete Fourier transform:

$$PSD_{aa}(\omega) = \frac{1}{2\pi} \sum_{-\infty}^{\infty} \left[CC_{aa}(m)\, e^{-j\omega m}\right] \qquad (2)$$

where: ω is the angular frequency ($2\pi f/f_s$, where f_s is the sampling frequency).

There are two main classes of spectral estimation methods: of the “parametric” and “non-parametric” styles. Among the non-parametric methods, the periodogram is perhaps the more used when to find the power spectrum in a simple way is a priority. It is defined as:

$$Pdgr\left(e^{j\omega}\right) = \frac{1}{2\pi N} \left\{\sum_{1}^{N} a_n\, e^{-j\omega n}\right\}^2 \qquad (3)$$

where a_n represents the N samples of the signal to be transformed.

The operator described by the expression (3) could be used to measure displacements on frequency harmonics related to time-delays in an echo-signal, by analyzing its frequency spectrum, but it presents limitations in the resulting resolution that could be attained with its use, which are derived from those typically associated to the FFT algorithm in which the periodogram function is based. In order to avoid this resolution constraint, parametric methods must be used.
Parametric methods are based on a time-series model of the random process x(n). In this paper, auto-regressive (AR) modeling is assumed for our parametric analysis. The Power Spectrum Density of the time-series model is a function of the model parameters, at difference of that occurring in the cross-correlation and non-parametric methods. And the model parameters can be obtained by means of an autocorrelation sequence.
An interesting approach for autoregressive PSD estimation is based on using the Yule-Walker option, which employs the autocorrelation estimates matrix to found the AR parameters:

$$\begin{bmatrix} r_{xx}(0) & r_{xx}(-1) & \cdots & r_{xx}(-p) \\ r_{xx}(1) & r_{xx}(0) & \cdots & r_{xx}(-p+1) \\ \vdots & \vdots & \ddots & \vdots \\ r_{xx}(p) & r_{xx}(p-1) & \cdots & r_{xx}(0) \end{bmatrix} \begin{bmatrix} 1 \\ \alpha_1 \\ \vdots \\ \alpha_p \end{bmatrix} = - \begin{bmatrix} \sigma_w^2 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \quad (4)$$

The PSD of the data sequence is defined by the expression:

$$PSD_{xx}(f) = \sigma_w^2 \frac{1}{|A(f)|^2} \quad , \quad (5)$$

where σ_w^2 is the variance of the input driving process in the time series model, and $A(f)$ is defined by:

$$A(f) = 1 + \sum_{k=1}^{p} \alpha_k e^{-j\omega n} \quad (6)$$

A second approach for PSD estimation, that has been adopted by us for the applications considered here, is based on the Burg method, which provides a better resolution in the spectral estimate [11], because it is based on a least squares criterion in order to determinate the required model parameters.

3. Experimental Ultrasonic Data and Estimation Results for Wall Thickness

For obtaining the multipulse echo signals needed to calculate the thickness variation of a phantom, a specific experimental setup was constructed. The sample, a tube with walls made of elastic latex, is placed in a variable pressure circuit consisting in a perfusion line made of polyethylene and silicone, with a mechanism for inducing different pressures (to simulate those ones produced by the cardiac cycle), and being interrogated by broadband ultrasonic pulses. The measure of the wall displacement was made in this case by means of using a broadband ultrasonic probe of nominal frequency centred around 10 MHz, and working in the pulse-eco mode. The resulting ultrasonic beams were generated perpendicularly to the tube wall, giving us multipulse echoes (A-Scans) as those shown in Figure 1.

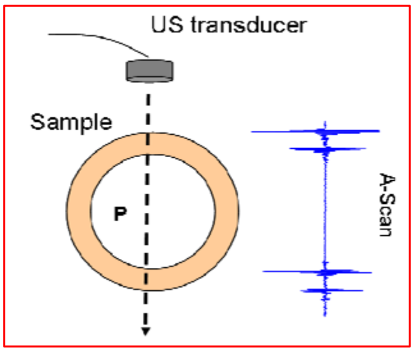

Figure 1. Scheme of the walls displacements measurement in a cylindrical tube.
Each A-Scan contains 4 echoes, from the four sample-fluid interfaces.

A collection of A-scans was acquired at different pressure values of liquid into the tube, which were digitized at a sampling frequency of 80 MHz.
In the Figure 2, a family of 150 echo acquisitions, taken from one of the walls of this tube, is shown, where the internal pressure in the tube was periodically varied, in order to create successive wall displacements similar to those encountered in the real blood vessels.

By measuring the delays between echoes, for each of the obtained A-Scans, by the application of the different algorithms to be analyzed, the successive wall displacements (originated by the pressure changes) were calculated.

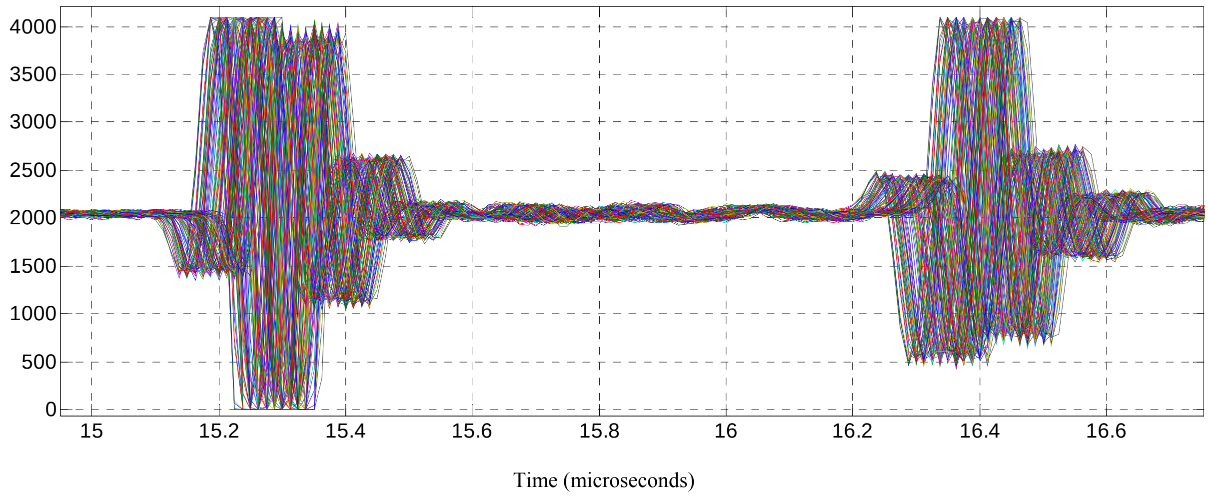

Figure 2. Waveforms of 150 echoes coming from the first wall of a latex tube, for distinct pressures.

3.1 Delay results between wall echoes estimated by time-domain techniques

Here, time domain analyses are comparatively applied between two particular waveforms (extracted from the echoes family in Figure 2) belonging to A-scans at instants of maximum widening and narrowing in tube diameter.

Results of simple direct-time estimation and cross-correlation methods will be considered. By a direct time-estimation of delays between the first peaks or the maxima of both wall pulses, certain uncertainly (in the order of 50 ns) is registered for the estimation of delays between these two echoes [11] coming from the first tube wall (for distinct cycle moments), which corresponds to spatial resolutions worse than 35 microns, clearly insufficient for our necessities.

But, some more sophisticated techniques will be applied in the following, with the attempt of increasing the resulting spatial resolution, so making possible a clear discrimination of little changes in the wall thickness.

The first attempt was performed by means of performing a time cross-correlation (1) between the two A-Scans belonging to the waveforms which correspond to the instants of maximum widening and narrowing in the tube diameter of the latex tube used as phantom of blood vessel in our experiments.
Between these two extreme cases in the wall thickness changes points (A-Scans for maximum and minimum tube diameters), the time-shifts and spatial-displacements detected by correlation were:

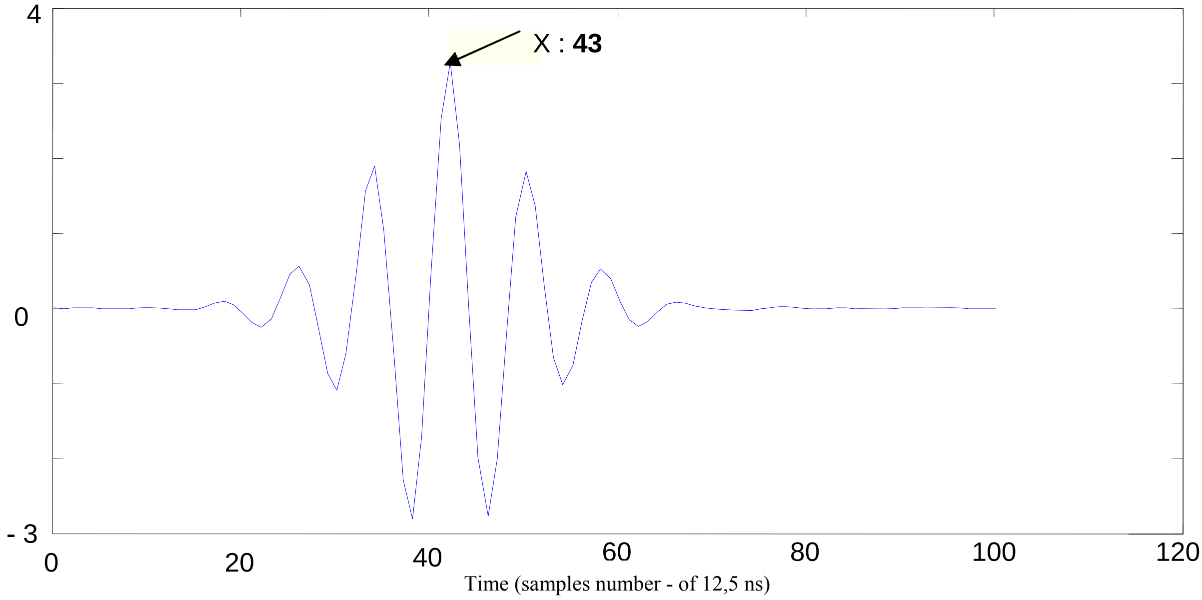

Figure 3. Cross-correlation of first echoes in the two A-Scans (coming from the interface fluid-wall)

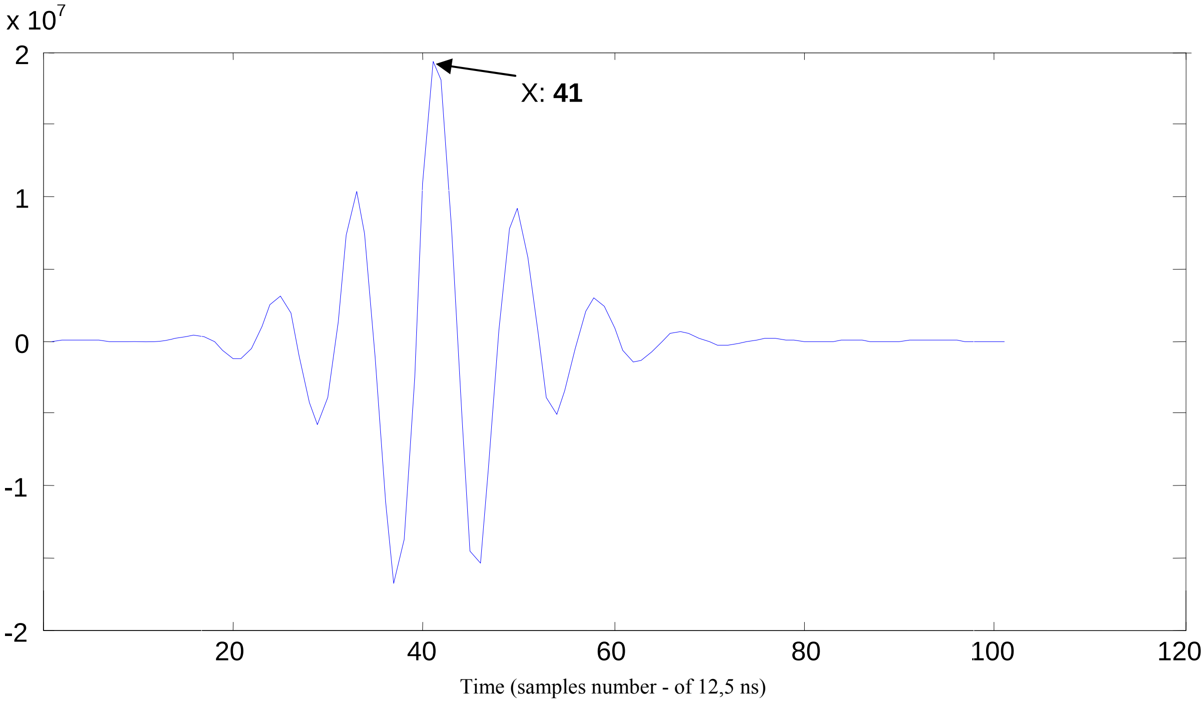

Figure 4. Cross-correlation of second echoes in the A-Scans coming from the interface wall-fluid.

- In the wall external face: 8 digital samples (51-43) at 80 Mhz, equivalent to 100 ns (with a resolution of 12,5 ns). And the equivalent spatial displacement is: 100/2 ns x1,8 Km/s = 90 micrometers (with 12,5% of resolution, i.e.: 11,2 µm).
- In the wall internal face: 10 samples (51-41), equivalent to 125 ns, and the related spatial displacement is: 125/2 ns x1,8 Km/s = 112 µm (with resolution of 10%: 11,2 µm).

From these data, the cross-correlation method applied to our problem, already can estimate that, at the same time when the tube is inflating, their walls result compressed; but the so estimated value (≈ 22 µm) for this compression, still presents an important error of up to ≈ ± 11,2 µm, i.e.: a error of ± 51%. As a conclusion, this quite improved resolution of 11,2 µm (12,5 ns) -respect to a direct time estimation- does not result, still, sufficiently high for our purpose of analyzing with accuracy thickness changes in some vessel walls.

3.2 Delay results between the wall echoes estimated in the frequency domain

As a second attempt to increase spatial resolutions, we will apply some methods based on performing analyses defined in the frequency domain. The more simple options in this domain are based on non-parametric spectral analysis methods, being the Periodogram one of the most used. As typical example using this option, a spectral result for a particular A-Scan line on Figure 2, is shown in Figure 5.

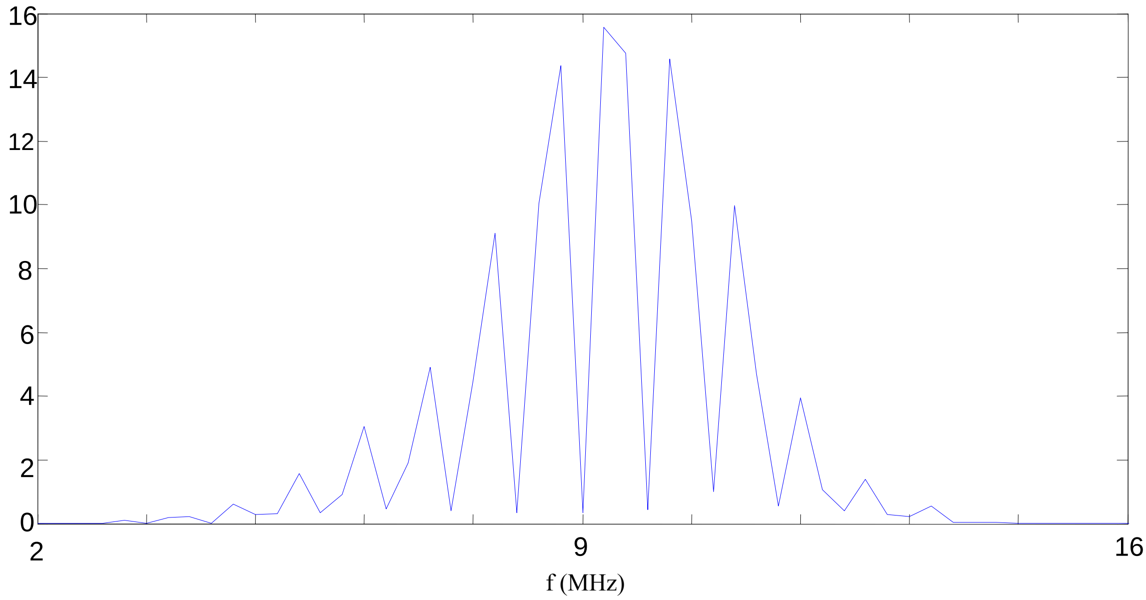

Figure 5. Periodogram of echoes coming from the same tube wall considered in previous figures

In this case, the peak results truncated and 310 KHz of the curve are lost, equivalent to a spatial resolution of 405 µm in the main resonance), which can be substantially improved by analyzing the 10^{th} overtone (ranging around transducer band center); but, even in this case, final resolution will be of 40 µm, even worse than when the correlation method is used to this thickness estimation purpose.
In the other hand, it is well known that non parametric methods are affected by windowed effects, which produced a low resolution spectra.

For this reason, other more complex spectral techniques, but of the parametric kind, were analyzed looking forward achieving the required resolution, and one of the first results is detailed in the Figure 6, where the power spectral density (PSD) related to the same time-waveform as in Figure 5 is shown, but now calculated by means of one of our new procedures based on parametric spectral analysis methods, in this case the so called Burg method
The resulting spectrum peaks by applying this particular parametric method are clearly narrower than in the non parametric case.

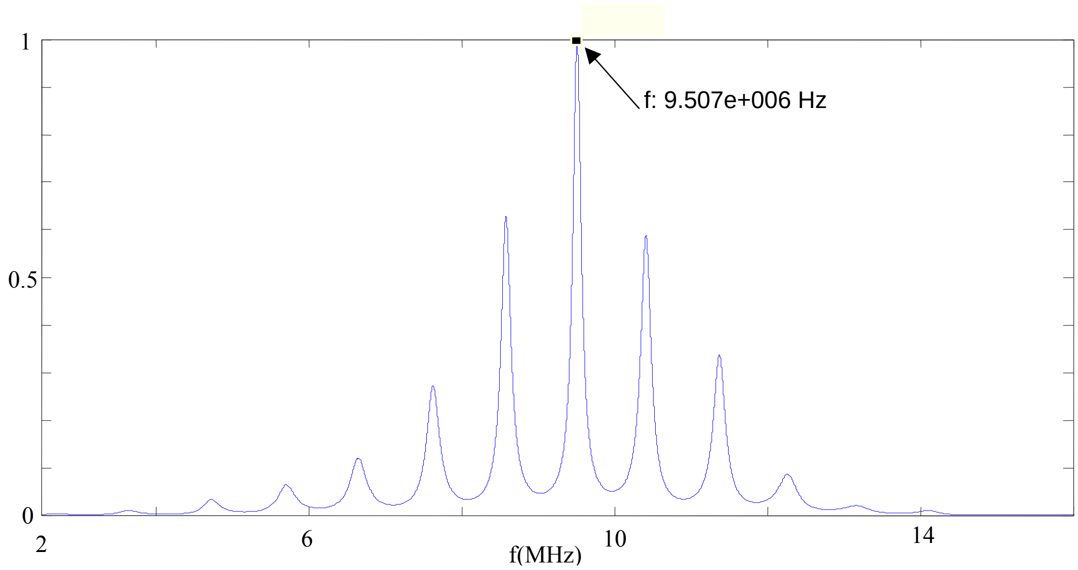

Figure 6. PDS calculated with our procedure and using the parametric Burg method.

And by analyzing the 10th overtone, as it was also considered for the case of the Figure 5, a frequency resolution of 19,5 KHz is attained, which provides that a spatial resolution closed to ± 1 µm could be achieved, strongly improving (in more that one magnitude order) the value of 12,5 µm obtained with the cross-correlation based delay estimation method.

4. Conclusions

By means of new advances that improve the performance of a parametric algorithm of autoregressive type, developed by the authors, its resulting frequency resolution was drastically elevated, confirming the application viability of our new spectral technique to accurately estimate wall thickness changes in certain blood vessels. Thickness results, calculated with this improved estimation technique, from some ultrasonic multi-echo measurements acquired in a laboratory phantom of a blood vessel (made of an elastic latex material), show a very good resolution close to one micron. This spectral option can be also applied for calculating some elastic properties in vessel walls, clearly improving the resulting resolution, over the current cross-correlation and non-parametric techniques. By means of further efforts, the potential resolution of this new procedure could be still optimized, perhaps in one order of magnitude. In particular, rigorous analyses of ultrasonic echo-responses acquired from well-controlled sanguineous tissues phantoms would be needed, to extract the maximum potential resolution of this new thickness measurement procedure, and also for evaluating its possible clinic limitations.

Acknowledgments

Work developed in the frame of the Project CONACYT-FOMIX (Estado de Veracruz) Nº 128572, Mexico, and in part sponsored by the Spanish National Plan (Project PN - DPI2011-22438). Our acknowledgment also to the ALFA European program (projects Petra and Biosenintg, with stays of I. Bazan in the CSIC lab.), to CYTED, and to R&D institutions in which laboratories these research works have been developed: IPN (México), CSIC (Spain) and URU (Uruguay).

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