DETECTING MICROCHANGES IN THIN THICKNESS OF LATEX DUCT WALLS WITH 10 MHz ULTRASOUND PULSES

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ABSTRACT

To achieve accurate estimations of thickness changes in thin walls of tubes or ducts, subjected to pulsatile internal flows, could have future interesting applications, when it is applied to human blood vessels, for instance in early medical diagnosis of hypertension or atherosclerosis. Conventional ultrasonic echo-imaging does not provide spatial resolutions with sufficient clinical significance for a convenient thickness evaluation. In this paper, preliminary results of applying a new high-resolution spectral ultrasonic procedure, improved by authors for accurate thickness measurements, are shown. An advanced algorithm for estimating power spectral densities in bi-echo signals is applied and potential resolutions around one micron are shown.

RESUMEN

El lograr una estimación precisa de cambios de grosor experimentados en paredes delgadas de tubos o conductos, sometidos a flujos internos pulsátiles, podría tener usos futuros de gran interés, para aplicarlo a vasos sanguíneos, por ejemplo en diagnóstico precoz de hipertensión o arteriosclerosis. La imagen ultrasónica ecográfica convencional no proporciona resoluciones espaciales con suficiente significación clínica como para facilitar evaluaciones de grosor adecuadas. Se muestran resultados preliminares de aplicar un nuevo procedimiento ultrasónico espectral de alta resolución, mejorado para realizar mediciones muy precisas de espesor en conductos. Se aplica un algoritmo avanzado para estimar la densidad espectral de potencia en señales con dos ecos, y se muestran resoluciones alrededor de una micra.

INTRODUCTION

Research to achieve accurate measures of thickness changes in thin walls (for instance, in the biological field, to analyze blood vessel walls), is a promising R&D line to improve the testing of possible alterations in tubes and ducts. In the case of the medical applications, it would provide means for analyzing new via of attaining with accuracy enough an early diagnosis of diseases like hypertension or atherosclerosis, currently with a strong incidence in the human health, due to they are the more common cause of early mortality. Nevertheless, to attain a sufficiently good estimation of these parameters in a non-invasive way, nowadays still presents many difficulties and new solutions must be searched to overcome them.

The application of high-frequency ultrasonic equipment appears to be a good solution for seeing inner parts in pieces and tissues, in general; and the application of conventional ultrasonic imaging shows good images in many practical cases; but the spatial resolution related to this conventional option is not sufficient for the extraction -from the ultrasonically acquired images- of accurate data to provide a thickness evaluation with high precision when fine details o light alterations in a tube wall must be detected. For instance -in the case of blood vessel diagnosis-, measuring results having sufficient clinical significance (displacements around 10-15 microns) would require to achieve an measurement accuracy of few microns, very far of the maxima ultrasonic imaging resolutions obtainable with the more advanced echographic scanners of rather high working frequency (10-20 MHz), which is ranging in the several hundred of microns.

In order to satisfy these necessities some research lines (in addition to those related to acoustical imaging), arise with the aim of creating new ultrasonic transducer systems working with the reception time of echo-signals and also with theirs spectra in frequency domain. These working lines are intended for providing accurate measurement of determinate physical parameters into specific materials. In particular, the design of new devices in the medical area for early diagnosis is registering an increasing interest. For this last purpose, the application of advanced spectral techniques permits to increase the precision when the ultrasonic echoes coming from those devices must be finely analyzed. The precise measure of early changes in biological membranes like walls in blood vessels [1-2] are possible examples of those activities.

In this paper, some preliminary results obtained with a new broadband ultrasonic procedure, improved by the authors for thickness measuring purposes, are shown. Its performance is analyzed for sub-millimeter walls of a tube made of latex, a material with mechanical properties similar to those of tissues forming the tunicae of the blood vessels. An algorithm for estimating the power spectral density of multi-pulse echo-signals is assessed by means of its application to some experimental echo-traces. It potential capability to provide resolutions around a micron in walls thickness estimation is shown.

SOME ANTECEDENTS

Non-invasive measurements "in vivo" of small internal distances in biological ducts requires a good estimation of scarcely measurable parameters, which results very difficult from the current "state of the art" in ultrasonic technology. In fact, the commercial echographic equipment have serious limitations to discriminate, from the final tissue images, echoes coming from two reflectors very close between them, due to their resolutions use to be worse than 0.5 mm, in spite of that their technologic complexity [3] is quite high (more than a hundred of ultrasonic channels are normally involved, having each channel a wideband ultrasonic transducer and the electronic modules for the E/R of the pulsed signals).
Some analysis improvements can be made by means of some types of additional processing of the ultrasonic images in commercial imaging units, for instance using segmentation algorithms [4-5], which improve in some account the measurements in blood vessels; but the enhancement in spatial resolutions obtained in this way, after applying advanced processing for image segmentation, is still insufficient, because the final resolution results worse than 200-300 µm. These discrimination levels are yet very coarse as to permit a thickness measurement with the precision required for an early diagnosis of problems in artery walls, where changes in walls thickness so small as 10 µm have a clear clinical interest. Other options use a direct processing, in time or frequency, of the pulsed waveforms acquired from the analyzed medium, but searching alterations in other tissue parameters as the elasticity [6-7] which are more sensible to certain pathologies than the conventional changes on the tissue densities values, used for echography (conventional echo-scanner medical units).
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To attain an added resolution improvement for performing a more precise analysis of the arteries walls, without for it adding an excessive complexity (and the subsequent cost) in the related technologies, is a difficult aim. It should be possible only by generating a new specific technique that implicitly reduce the whole system costs, for instance by using one unique ultrasonic emitter-receiver specifically designed for an efficient analysis of thin biological layers. Logically, in order to compensate this rather simple topology, a sophisticated signal processing, focused on improving the final spatial accuracy, must be performed with the aim of obtaining measurement resolutions ranging around few microns. This innovative solution to ultrasonically

estimate very small spatial distances, in comparison with the current state of the art, would be applicable to achieve non-invasive early diagnoses [3]. The application of single and array ultrasonic transducer systems to obtain high-resolution detection in similar detection problems of other diagnosis areas, has been explored, searching solutions for non invasive diagnoses of some human diseases [3, 7-11]. Some of these applications [3, 10-11] uses the above commented option of employing a single transducer but including a posterior phase of advanced spectral processing in the high frequency range, by finding a very precise pattern of the power spectral density contained into the ultrasonic echoes.

METHODS AND EXPERIMENTS

In order to perform the estimation of the power spectral density (PSD) of the traces coming from the ducts wall zones, autoregressive (AR) parametric methods based on the extrapolation of signal autocorrelation values have been used for processing. In this type of methods, it is required to know “a priori” certain information about how the signal to be processed was generated, and in consequence a modeling about the signal generation must be constructed based on certain AR parameters, which must be estimated from a study of the signal data. Our analytical procedure looks for the achieving of a higher frequency resolution that that obtainable with more conventional spectral approaches (periodogram, Yule Walker based estimation, etc.). In our solution, the high resolution in frequency is obtained by applying and adapting, to the present estimation problem, a short-time windowing of the echo-traces, and then decomposing the echo-traces in many fractional time-windows, artificially extended in their digital lengths, before to be parametrically analyzed with precision in the power spectrum domain, by means of the Burg method. In our estimation of the AR parameters by this method, a minimization of the direct and inverse errors in the linear predictors is made, taken into account the restriction of that the AR parameters should satisfy the recursion know as Levinson-Durbin.

The minimum square error can be calculated from the expression:

$$\varepsilon_m = \sum_{n=m}^{N-1}[|f_m(n)|^2 + |g_m(n)|^2] \tag{1}$$

And the corresponding direct and inverse errors, f_m(n) and g_m(n), are defined as:

$$\begin{aligned} f_m(n) &= x(n) - \hat{x}(n) \\ g_m(n) &= x(n-m) - \hat{x}(n-m) \end{aligned} \tag{2}$$

The estimated of the direct linear prediction can be defined in this way:

$$\hat{x}(n) = -\sum_{j=1}^{m} p_m(j)x(n-j)$$

where p_m(j), 0 ≤ j ≤ m-1, m=1,2,…,l, are the prediction coefficients.
And $\hat{x}(n-m)$ is the inverse linear prediction [3]

ε_m can be minimized, by properly selecting the prediction coefficient according to the conditions imposed by the Levinson-Durvin recursion:

$$p(j) = p_{m-1}(j) + K_m p_{m-1}^*(m-j);\quad 1 \le j \le m-1 \ and \ 1 \le m \le l \tag{3}$$

In (3), $K_m = p_m$ is the m reflection coefficient of the predictor lattice filter [3]

Burg algorithm calculates the reflection coefficients of the equivalent lattice structure, and the Levinson-Durvin algorithm is employed here to obtain the AR model parameters. Based on the estimation of AR parameters, the Power Spectrum can be estimated as:

$$PSD_{xx}^{BU}(f) = \frac{\hat{E}_i}{\left|1+\sum_{j=1}^{p}\hat{p}_i(j)e^{-j2\pi fj}\right|^2} \tag{4}$$

where, $\hat{E}$ is an estimated of the total square error E_m.

The main advantages of employing the Burg method with the aim of estimating AR model parameters are: to provide a higher frequency resolution, to produce a stable AR model, and to have better computation efficiency.

A single ultrasonic transducer working in pulse-echo mode was used for laboratory experiments. The experimental scheme is shown in Figure 1. It includes: a) an ultrasonic transmitter excited by a pulsed driver generating high-voltage spikes [12]; b) a wideband matching & tuning network; c) a stage for analogical treatment of the echo-signals, with circuits for the decoupling between the HV spikes [13] and the low-voltage echoes and for wideband amplification.

The ultrasonic echo-responses acquired from blood vessels are of multi-pulse structure and containing certain level of speckles; in consequence, a direct interpretation from them about the tissue configuration becomes quite difficult. For this reason, it is necessary to perform a sophisticated signal processing, in this case based on spectral estimations of the echo-traces. This option probes to be an effective way to obtain data hidden inside noisy ultrasonic echoes coming from the internal structures to be analyzed. Besides, this via for analyzing ultrasonic echo-signals constitutes a low-cost tool to detect very small changes originated on the duct geometries, because they modify the observed frequency peaks in the overtones of the echographic information produced by reflections of the emitted pulses from the laminar walls.

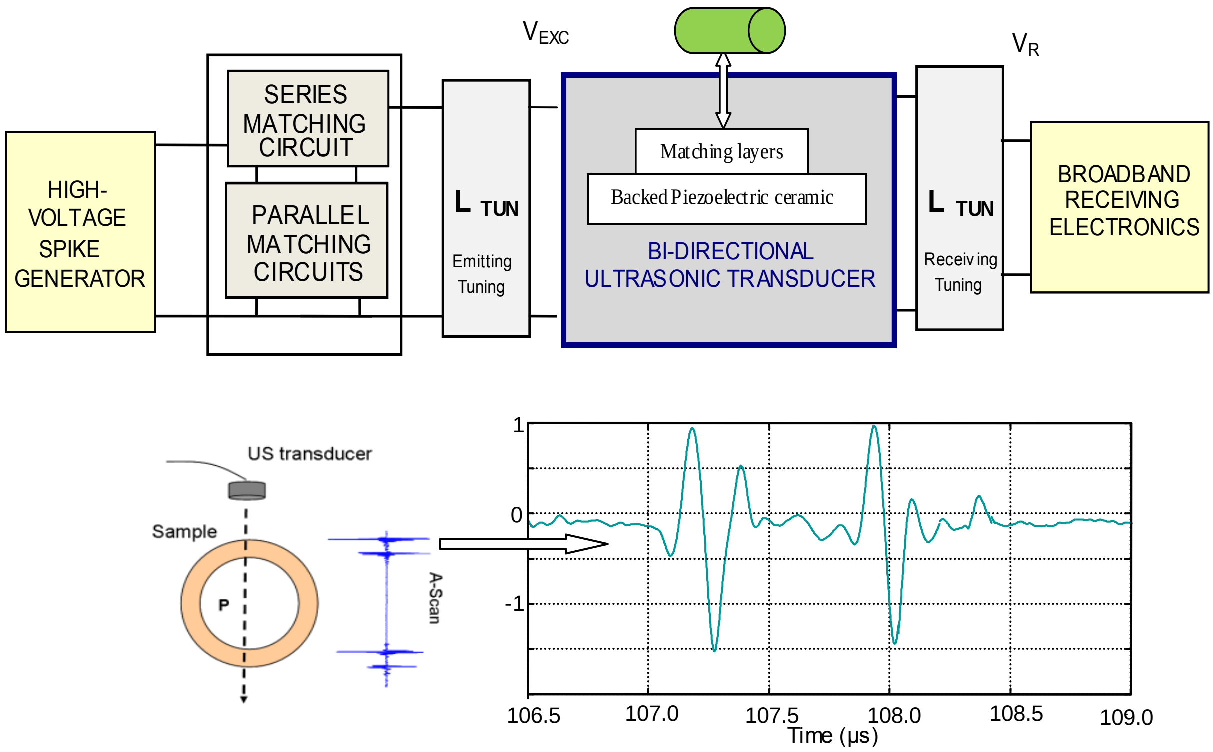

Figure 1. Pulsed ultrasonic transceiver with electrical matching & tuning, and mechanically matched to the inspected latex tube, to acquire echoes from duct interfaces with internal & external media. A typical laboratory echo-signal, from latex-water interfaces is also shown.

Our approach is that the spatial changes considered here, could estimated by applying our spectral procedures, due to the changes in wall thickness appear reflected on certain time and frequency changes appearing between a normal tube echo-trace and those acquired from an externally modified tube wall (related to the subsequent micro-changes in its wall thickness). In fact, some variations -mainly in phase- of the spectral peaks in the echoes and their harmonics could be caused by variations in the state of the tube walls, emulating those due to diseases as atherosclerosis or atheroma plaque formation.

The dependence of particular changes in the peak frequencies of the calculated spectra from measured echo-traces, in regard to variations experimented in the wall thickness was analyzed for a latex tube with an internal pulsed flow. A sophisticated method of the parametric type for

spectral estimation will be used in this article. It is based on Burg algorithm [3]. The advantage of the parametric methods for PSD estimation is to assure high-resolution in frequency domain, avoiding the distortion by the windowing influence related to the time based methods.
In our case, for achieving sufficiently high resolution, as needed in thickness estimation, an adaptation of the echo-trace registers is performed before applying the parametric processing, splitting the time-traces by means of a selective windowing associated to each tube wall interface, and then extending their time-lengths with a number of samples without information.
In this way, the frequency resolution is improved without paying secondary effects, and maintaining the time content, and avoiding the use of any type of interpolation technique for intercalating estimated samples into the searched information.

RESULTS OF SPECTRAL ESTIMATION OF DUCT WALL THICKNESS

In a preliminary ultrasonic analysis made in time domain, the “visible” movements suffered by the duct structure, caused by artificially induced tube inflations (as it happen in real vessels), overlap the very small changes induced on the thickness of the wall, causing that these last (of at least one order de magnitude smaller) cannot be detected by insufficient spatial resolution.

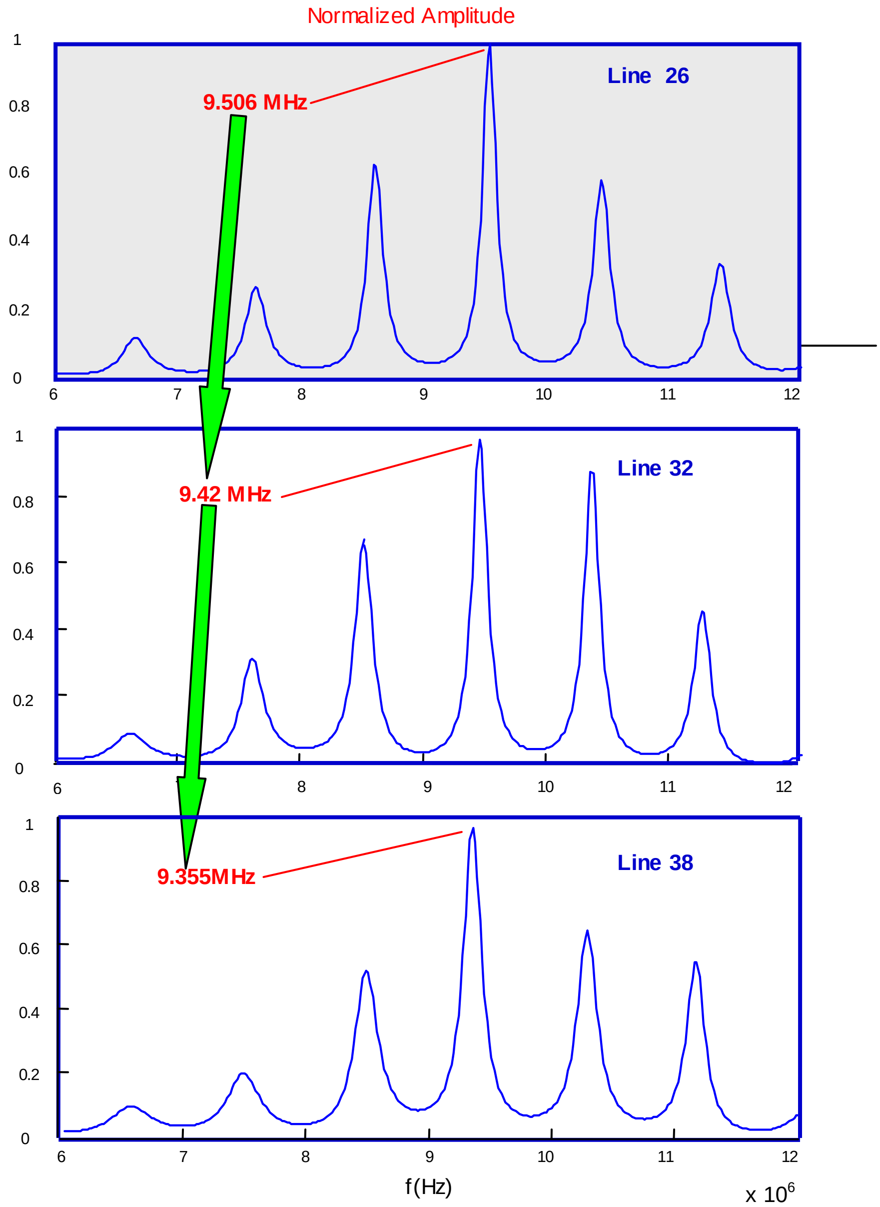

Fig. 2. PSD curves calculated with a parametric spectral procedure that applies the Burg algorithm to the echoes acquired at three inflation levels in the latex tube.

But, by using a fine quantification of the frequency peaks variations at the harmonics of the resonance band related to the wall thickness dimension, this last parameter can be measured with sufficient accuracy Our spectral procedure uses an autoregressive parametric procedure based in the Bug algorithm, which provides good spatial resolutions during the estimation of very-small thickness variations in the dynamically modified walls of a latex duct mimicking the behavior of arterial vessels. This solution for our estimation problem produces a better resolution than the classical cross-correlation or non parametric estimation spectral methods.

Three curves showing the Power Spectral Densities (PSD), calculated with the above mentioned estimation procedure (based on a autoregressive parametric method) for three two-pulse echoes acquired with a 10-MHz transducer (with real working band centered at 9,5 MHz), are depicted in the Figure 2·

A detailed peaks analysis of this type of curves was conducted, which is based on spectral calculations for three significant thickness situations, that corresponds to three specific received A-scans (number: 26, 32 and 38, of a total of 150 ultrasonic traces) which are related to the cycle situations coincident respectively with the minimum, intermediate, and maximum wall thicknesses. Its aim was to analyze the performance of our thickness estimation procedure under distinct duct inflation conditions.

The spatial results calculated from ultrasonic echo-traces received by the wideband transducer (in 5–10 MHz range) from this latex duct (initial wall thickness of 0.95 mm), showed resolutions better than 1 µm. These results were obtained for a wall lightly modified in its thickness dimension, up to 15 microns, by using periodic pressure changes applied to the internal liquid.

ROBUSTNESS OF THE ULTRASONIC DETECTION IN NOISY CONDITIONS

The accuracy obtained by means of ultrasonic estimation of distances inside biological materials, membranes and blood vessels, when our spectral approach is used, depends directly on the resolution and accuracy finally obtained for the location of the peak frequency value related to the selected overtone of the fundamental resonance associated to the distance being estimated. Thus, possible alterations, in the finally calculated spatial results, could appear when the non-ideal echoes, coming from the real tissues and vessels, are considered.

In order to obtain an estimation of estimation procedure robustness under rather unfavorable conditions, distinct PSD distributions were calculated for simulated echoes, with different levels of added corrupting noise, for a rather thin wall and a more difficult frequency range.

Signal to noise ratios ranging of 40 dB to 3 dB were added to typical echo-traces related to a thin wall having a thickness of 100 µm, considering a wideband transducer having a bandwidth of 70% around a central working frequency of 30 MHz.

Table I	(1)				
Harmonic Number	Without Noise	SNR = 3 dB	SNR = 6 dB	SNR = 20 dB	SNR = 40 dB
4	30.868.100	30.877.300	30.874.500	30.904.600	30.882.100
5	39.355.000	39.410.100	39.336.400	39.459.500	39.424.600
	(2)				
		SNR = 3 dB	SNR = 6 dB	SNR = 20 dB	SNR = 40 dB
4		−0.030%	−0.021%	−0.118%	−0.045%
5		−0.140%	0.047%	−0.266%	−0.177%

1 - Values obtained by our spectral estimation method for the 4th and 5th harmonic peaks of the Power Spectrum Density (expressed in Hz);

2 - Error en % observed between the signals with different level of signal-to-noise ratios and a patron signal without any noise.

The obtained simulated results show that for signal-to-noise ratios higher that 3 dB, the noise influence in the thickness estimation results, obtained with our procedure, could be neglected, as it is summarized in the Table I.

CONCLUSSIONS

An autoregressive parametric spectral procedure, proposed by the paper authors, was applied to estimate shifts in the overtones of the power spectrum density calculated for the echoes acquired with a 10-MHz ultrasonic transducer, in a latex duct mimicking a human artery.

The parametric procedure was improved specifically for this application (searching an accurate thickness measurement), by means of an elevation in its digital sampling frequency. A good spatial resolution was attained (of an order of the micron). These results are clearly better than with non-parametric spectral techniques or with time cross-correlation options.

It was shown that the here proposed option, using the Burg PSD estimates, seems to provide the narrowest frequency lobes in the overtones (respect other options), so optimizing the spectral discrimination for the peak locations, and finally the final spatial resolution.

As future perspective for a further procedure improvement, if a finer frequency step were used, a better spatial resolution could be achieved, improving in that way the, good value here found (0.9 μm), and penetrating in the nanometric field.

New research efforts and analyses must be made in this technological field, with more realistic ultrasonic echoes, acquired from real vessel tissues, to confirm the potential resolution of this thickness estimation approach. And its clinical limitations must be evaluated with "in vivo" measured signals. Finally, additional studies of measuring distortions must be performed, searching secondary factors in the spectral algorithms, lightly affecting the peak location, depending on the algorithm internal parameters and on the chosen overtone.

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REFERENCES

[1] P. Pignoli, E. Tremoli, A. Poli, P. Oreste and R. Paoletti. "Ultrasound imaging intimal plus medial thickness of the arterial wall: a direct measurement with ultrasound imaging". ISSN: 1524-4539. American Heart Assoc.. Print ISSN: 0009-7322. Online 72514. *Circulation* (American Heart Association), 74: pp. 1399-1406. (1986).

[2] I. Wendelhag, O. Wiklund, and J. Wikstrand. "Arterial Wall Thickness in Familial Hyper-cholesterolemia Ultrasound Measurement of Intima-Media Thickness in the Common Carotid Artery". *Arterioscler Thromb Vasc Bio.* 1992, 12: pp. 70-77 (1992).

[3] A. Ramos, I. Bazán, C. Negreira, J. Brum , T. Gómez, H. Calás, A. Ruiz and J. M. de la Rosa. "Estimation of PSD Shifts for High-Resolution Metrology of Thickness Micro-Changes with Possible Applications in Vessel Walls and Biological Membrane Characterization". *Sensors* 2012, 12, pp. 15394 - 15423; doi:10.3390/s121115394. 2012.

[4] Ž.N. Savić et al.. "Comparison between Carotid Artery Wall Thickness Measured by Multidetector Row Computed Tomography Angiography and Intimae-Media Thickness Measured by Sonography". *The Scientific World Journal,* 11, pp. 1582–1590. ISSN 1537-744X; DOI 10.1100 / tsw. 2011. 147. (2011).

[5] F. Zhang et al. "Evaluation of Segmentation Algorithms for Vessel Wall Detection in Echo Particle Image Velocimetry". In *Proceedings of 2009 IEEE International Ultrasonics Symposium*, Rome, Italy, 20–23 September 2009; pp. 2476–2479.

[6] L. Cui, J. Shao, J. Wang, J. Bai, Y. Zhang, "Ultrasound Elastography of Ethanol-induced Hepatic Lesions*:* In Vitro Study", *Chinese Medical Sciences Journal* Vol. 24, No. 2, pp. 81-85. (2009).

[7] B. Boozari, A. Potthoff, I. Mederacke, A. Hahn, A. Reising, K. Rifai, H. Wedemeyer, S. Kubicka, M. Manns, M. Gebel. "Evaluation of a novel ultrasound method for the detection of liver fibrosis - Prospective comparison with transient dynamic elastography and histology", *Journal Hepatology,* Vol. 52, pp S404. (2010).

[8] S. Dasarathy, J. Dasarathy, A. Khiyami, R. Joseph, R. Lopez, A. J. McCullough, "Validity of real time ultrasound in the diagnosis of hepatic steatosis: A prospective study". *Journal Hepatology,* 51, 1061–67. (2009).

[9] N. Goyala, N. Jaina, V. Rachapallia, D.L. Cochlina, M. Robinsonb, "Non-invasive evaluation of liver cirrhosis using Ultrasound". *Clinical Radiology,* 64, pp. 1056–1066. (2009).

[10] I. Bazan, M. Vazquez, A. Ramos, A. Vera, L. Leija. "A performance analysis of echographic ultrasonic techniques for non-invasive temperature estimation in hyperthermia range using phantoms with scatterers", *Ultrasonics*, Vol. 49, No. 3, March 2009, pp. 358–376. (2009).

[11] I. Bazan, A. Ramos, H. Calas, A. Ramírez, R. Pintle, T. E. Gómez, C. Negreira, F. J. Gallegos, and A. J. Rosales. "Possible Patient Early Diagnosis by Ultrasonic Noninvasive Estimation of Thermal Gradients into Tissues Based on Spectral Changes Modeling". *Computational and Mathematical Methods in Medicine*, Volume 2012, Article ID 275405, 14 pages. doi:10.1155/2012/275405 (2012).

[12] A. Ramos, J.L. San Emeterio and P.T. Sanz. "Dependence of pulser driving responses on electrical and motional characteristics of NDE ultrasonic probes". *Ultrasonics,* Vol. 38, nº 1-8, pp. 553-558, (2000).

[13] A. Ramos, J.L. San Emeterio. "Interface Electronic Systems for Broadband Piezoelectric Ultrasonic Applications. Analysis of Responses by means of Linear Approaches". Chapter 6 in book "Piezoelectric Transducers and Applications". *Springer-Verlag,* pp. 187–203 (ISBN 978-3-540-77507-2), doi.10 1007 /978-3-540-77508-9_6. Berlin. (2008).