Biomedical Signal Processing and Control 40 (2018) 454–461

Contents lists available at ScienceDirect

Biomedical Signal Processing and Control

journal homepage: www.elsevier.com/locate/bspc

Research Paper

Examination of a spectral-based ultrasonic analysis method for materials characterization and evaluation

Jeremy Stromer[a,*], Leila Ladani[b]

[a] Department of Mechanical Engineering, University of Connecticut, Storrs, CT, United States
[b] University of Texas at Arlington Research Institute, Institute for Predictive Performance Methodologies, Mechanical and Aerospace Engineering, University of Texas at Arlington, United States

ARTICLE INFO

Article history:
Received 24 October 2016
Received in revised form 6 October 2017
Accepted 15 October 2017

Keywords:
Ultrasound
Materials characterization
Imaging
Signal processing

ABSTRACT

Ultrasonic analysis has long been used as a diagnostic tool for materials and medicine, and measurements that are able to detail internal structure are often desirable. Peak density has previously been used as an assessment for tissue pathology. This quantity has potential for use in the study of tissue and soft materials. However, the use of this parameter is still in its early stages, and the signal processing techniques used are limited. In this work, other signal processing methods commonly used in ultrasonic measurement are applied to the resulting ultrasound pulses transmitted through a soft phantom material to study their effects on peak density calculations. This study examines the outcomes due to the selection of pulse width, the use of standard window functions, and spectral normalization using a reference spectrum. The consequences are assessed through the inspection of individual frequency spectra as well as two dimensional images based upon the peak density parameter. It was found that peak density was highly dependent on the window function employed and was also subject to the pulse width. Spectral normalization was found to have little effect on peak density calculations.

1. Introduction

Ultrasonic measurement plays an essential role in nondestructive evaluation and testing in industrial, structural and medical settings. As opposed to most other nondestructive methods commonly used, ultrasonic analysis may allow for the detection well below the sample surface and presents little hazard to operators and patients [1,2]. This practicality has led researchers to continue to improve and develop new approaches to fully utilize the propagation of ultrasonic waves as a means of measurement.

Typical ultrasonic measurements, as performed in hospitals and thickness gauging, reveal little information about the underlying material characteristics. The examination of the amplitude or time-of-flight of the received ultrasound pulse reveals internal interfaces and flaws [3–5]. This is useful for mapping large-scale differences in structure but provides little additional information. Furthermore, these measurements are not necessarily absolute and require skilled operators to fully understand the results. This suggests that measurements which are able to quantify particular material attributes would be beneficial, since the values would reveal additional information and would be less dependent on operator input.

Several quantifiable methods have been employed to use ultrasound to study the intrinsic properties of materials. Standard material based parameters used in most fields of ultrasonic evaluation include the measurement of sound speed, attenuation and the elastic properties [6–18]. Pulse-echo measurements based off of aspects of the frequency spectrum have also proven fruitful. These measurements have given insight into the internal composition of tissue. Analyses of this nature were first studied by Lizzi et al. and Feleppa et al. [19–21]. In their work they correlated specific spectral features, namely spectral slope and 0 MHz intercept, to the more tangible quantities of scatterer size, concentration, and acoustic impedance. They note that frequency-based measurements are less vulnerable to external influences introduced by the experimental setup when normalized with a reference spectrum. These methods have been utilized in characterization of rat models along with several different types of human tissues including ocular, liver, renal, and breast tissue [19–24]. Several analogous values exploit the properties of the waveform's frequency spectrum and include other parameters such as midband fit and also estimates of the scatterer spacing [23]. Issues with these frequency-based

* Corresponding author at: Department of Mechanical Engineering, University of Connecticut, 191 Auditorium Road, Unit 3139, Storrs, CT, 06269, United States.
E-mail addresses: jeremy.stromer@uconn.edu (J. Stromer), Leila.Ladani@uta.edu (L. Ladani).

https://doi.org/10.1016/j.bspc.2017.10.010

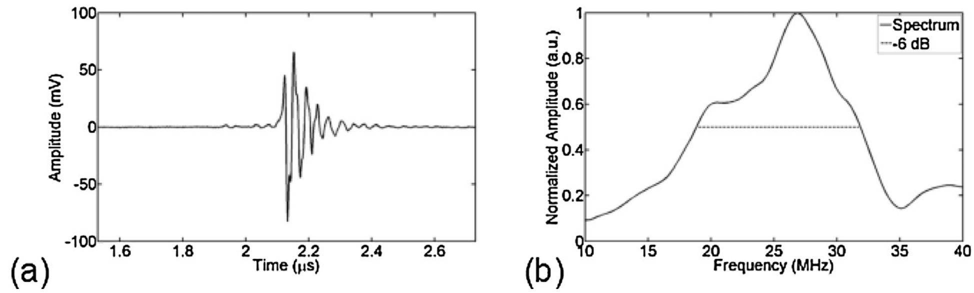

Fig. 1. The ultrasonic pulse through a small amount of ultrasonic coupling gel in through-transmission mode (a). The normalized power spectrum for the received pulse (b). The standard −6 dB bandwidth is shown and corresponds to 18.6–32 MHz for a bandwidth of 52.5%.

measurements often include the necessity of more complex mathematics and the use of theoretical models.

Another ultrasound parameter of interest, peak density, was first used by Doyle et al. at high frequencies to distinguish malignant and benign breast tissue samples [25]. This parameter, using through-transmission ultrasound, was found to relate to the pathology and thereby the internal structure as well. This measurement could be of particular interest to the entire field of nondestructive evaluation due to its relation to the internal material characteristics.

Peak density looks to be a suitable measurement parameter for assessing material characteristics, but the nature of the journal in which the authors' results were published did not allow for many of the details of the analysis to be included [25]. This paper explores the inclusion of several standard signal processing procedures in peak density calculations and evaluates the effects in the resulting measurements. We conduct a systematic experiment to study the effects of pulse width selection, window functions, and spectral normalization on peak density calculations. Section 2 illustrates our sample preparation and experimental operation procedures. Section 3 details the peak density calculation and discusses the signal processing techniques considered in this study. The results of our different peak density measurements are given in Section 4. We analyze our findings through the comparison of distinct waveforms and show two dimensional images as well for a more instinctive examination method. Concluding remarks are given in Section 5.

2. Experimental setup

2.1. Sample preparation

In order to carry out ultrasonic measurements in soft materials, a phantom was constructed. The phantom material was created using gelatin (Kraft Foods Global, Northfield, IL, USA) and psyllium fiber powder (Equate, Walmart, Bentonville, AR, USA) [26]. The gelatin based phantom provides a cheap and simple alternative to agar based phantoms and has been used in numerous phantom studies [27–29]. Inclusions were added to give contrast to adjacent measurements and included a hard pepper seed and soft pepper flakes. The addition of the inclusions allowed a more intuitive evaluation of the signal processing techniques by visualizing our resulting two-dimensional mappings of the phantom. The phantom was 2.1 mm tall which was measured with Vernier calipers.

2.2. Ultrasonic acquisition

Ultrasonic measurements were taken using two high frequency pachymeters (TransducerWorks, Centre Hall, PA, USA) operated in through-transmission mode. The transducers are small in diameter (2 mm) and are centered at 25 MHz. A typical non-attenuated pulse is shown in Fig. 1(a). The transducers were excited with a 50 ns, 100 V square pulse using a UTEX UT340 pulser-receiver (UTEX Scientific Instruments Inc., Mississauga, Ontario, Canada), and the received signals were amplified by 20 dB. The signals were digitized at 1.25 GS/s using a Tektronix DPO3052 oscilloscope (Tektronix, Inc., Beaverton, OR, USA). Waveform acquisition was automated through the use of LabVIEW (National Instruments, Austin, TX, USA). To facilitate two-dimensional mapping, a micrometer stage was constructed to position the sample as shown in Fig. 2. The measurements were taken in 1 mm steps and were carried out in a standard raster pattern. A total of 100 individual measurements were taken across the phantom covering an area 1 cm^2. Coupling of the transducers to the phantom was accomplished using ultrasound coupling gel (Sonotech Clear Image, Magnaflux INC, now NEXT Medical, Branchburg, NJ).

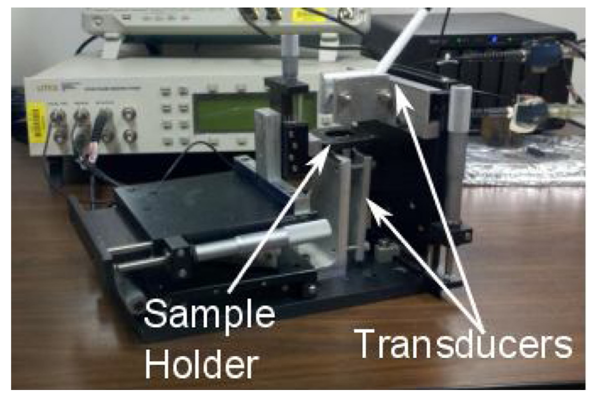

Fig. 2. Photograph showing the micrometer testing stage built for this experiment.

2.3. Velocity

To help characterize the phantom, velocity measurements were taken for the phantom in the top left quadrant of the phantom in which there were no inclusions present. Velocities were found based on the time of flight. The average of the 25 measurements was determined, and the speed of sound of the phantom was found to be 1389 ± 10 m/s.

3. Signal processing

3.1. Peak density

According to Doyle et al., the density of peaks, or peak density, is defined as the number of resulting peaks and valleys in a waveform's power spectrum [25]. In their paper, the ultrasonic pulses were windowed, zero padded and then had a Fourier transform applied. The number of peaks and valleys was counted by determining the number of times the derivative of the power spectrum