ALTERNATIVE ACOUSTIC PULSE ECHO IMMERSION MEASUREMENT SYSTEM DEVELOPMENT FOR NONPOROUS TISSUE MIMICKING MATERIALS

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A thesis submitted in fulfillment of the
requirements for the award of the degree of
Doctor of Philosophy

Faculty of Science
Universiti Teknologi Malaysia

FEBRUARY 2020

DEDICATION

I dedicated this thesis to my beloved parents,

Mat Daud bin Mat Taib and Che Hasnah binti Mat Junoh,

and my wonderful siblings;

Mohd Khairul Ashraf

Mohd Khairul Azreen

Mohammad Afifuddin

Mohamad Aizuddin Amin

Muhamad Ainuddin

Thank you for supporting me throughout this journey.

ACKNOWLEDGEMENT

Alhamdulillah, all praises to Allah for the strengths and His blessing in completing this research. First and foremost, I would like to dedicate my special appreciation to my supervisor, Assoc. Prof. Dr. Md Supar bin Rohani, for his constructive comments and suggestions throughout the experimental and thesis works have contributed to the success of this research.

I also would like to express my appreciation to all staffs of Department of Physics especially Dr. Nurhafizah binti Hasim, Mr. Rashdan bin Rani, Pn. Anisah binti Salikin and Mr. Bakhtiar bin Mat Sari, for their cooperation and contribution throughout this research. Sincere thanks to all my fellow friends, Nurul Wahidah binti Zainal Abidin Sham, Siti Nur Nazhirah binti Mazlan and Siti Rashidah binti Misron, for their kindness and moral support during my study. My deepest gratitude also goes to my beloved parents and also to my siblings for their endless love, prayers and encouragement.

Last but not least, thanks to MyBrain15 scholarship from Malaysia Ministry of Higher Education for the financial support throughout this study.

ABSTRACT

Acoustic properties are important to evaluate the compatibility of tested samples as tissue mimicking materials (TMMs). Common acoustic measurement systems require distilled water as the propagation medium. However, their accuracies are affected by the small change in the medium density and the inaccurate measurement of water temperature. An alternative acoustic pulse echo immersion measurement system for nonporous TMMs is developed in this study. It is developed based on the alternative pulse echo immersion technique (aPEIT) to improve the previous developed system for the noncontact pulse echo immersion technique (PEIT) and specifically designed for the step-shaped nonporous sample. It consists of a pulser/receiver generator, an unfocused transducer, a digital oscilloscope, a temperature controller and a personal computer which are installed with the custom-developed computer program to determine the longitudinal velocity, acoustic impedance, phase velocity and attenuation coefficient of the sample. The precision and accuracy of the developed system are tested for different thickness of sample, temperature of medium, density of medium and center frequency of transducer. The study indicates that developed system for the aPEIT produces the comparable results within 1.16% differences as the previous developed system for the noncontact PEIT, precise results within 6.38% from the average values and accurate results within 0.62% error compared to the reference values. The developed system for the aPEIT offers comparable but more precise results compared to the previous developed system for the noncontact PEIT in measuring the acoustic properties of nonporous TMMs. It can be operated using online and offline analysis modes to measure and differentiate the acoustic properties of specific types of human tissues and TMMs.

ABSTRAK

Sifat-sifat akustik adalah penting untuk menilai kesesuaian sampel-sampel yang diuji sebagai bahan-bahan menyerupai tisu (TMMs). Sistem-sistem pengukuran akustik yang biasa memerlukan air suling sebagai medium perambatan. Akan tetapi, kejituan sistem-sistem tersebut dipengaruhi oleh perubahan kecil yang berlaku pada ketumpatan medium dan ketidaktepatan pengukuran suhu air. Satu sistem pengukuran akustik alternatif bagi TMMs tidak poros telah dibangunkan dalam kajian ini. Sistem ini dibangunkan berdasarkan teknik rendaman pantulan gema alternatif (aPEIT) untuk menambah baik sistem terdahulu yang dibangunkan bagi teknik rendaman pantulan gema (PEIT) tanpa sentuh dan direka khusus untuk sampel berbentuk tetangga yang tidak poros. Sistem ini terdiri daripada satu penjana pendenyut/penerima, satu transduser tidak berfokus, satu osiloskop digital, satu pengawal suhu dan satu komputer yang dipasang dengan perisian komputer yang dibangunkan sendiri untuk menentukan halaju gelombang membujur, impedans akustik, halaju fasa dan pekali pengecilan akustik sampel. Kepersisan dan kejituan sistem yang dibangunkan diuji untuk ketebalan sampel, suhu medium, ketumpatan medium dan frekuensi pusat untuk transduser yang berbeza. Kajian ini menunjukkan bahawa sistem yang dibangunkan bagi aPEIT menghasilkan keputusan yang setanding dalam julat perbezaan 1.16% seperti sistem terdahulu yang dibangunkan bagi PEIT tanpa sentuh, keputusan yang persis dalam julat 6.38% daripada nilai-nilai purata dan keputusan yang tepat dalam julat selisih 0.62% berbanding dengan nilai-nilai rujukan. Sistem yang dibangunkan bagi aPEIT menawarkan keputusan yang setanding tetapi lebih persis berbanding sistem terdahulu yang dibangunkan bagi PEIT tanpa sentuh untuk mengukur sifat-sifat akustik TMMs yang tidak poros. Sistem ini boleh dikendalikan dengan menggunakan mod dalam dan luar talian untuk mengukur dan membezakan sifat-sifat akustik bagi tisu-tisu manusia dan TMMs yang khusus.

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LIST OF ABBREVIATIONS

aPEIT	-	Alternative pulse echo immersion technique
AVF	-	Aluminium volume fraction
BSA-PAG	-	Bovine serum albumin-polyacrylamide hydrogel
FFT	-	Fast Fourier Transform
GPIB	-	General Purpose Interface Bus
GSa/s	-	Gigasamples per second
GUI	-	Graphical user interface
IP	-	Internet Protocol
KGM	-	Konjac Glucomannan
KC	-	Konjac-Carrageenan
NDT	-	Nondestructive testing
PAA	-	Polyacrylamide
PDMS	-	Polydimethylsiloxane
PMMA	-	Polymethyl methacrylate
TPX	-	Polymethyl pentene
PVA	-	Polyvinyl alcohol
PVC	-	Polyvinyl chloride
PVCP	-	Polyvinyl chloride plastisol
PPI	-	Pore per inch
PEIT	-	Pulse echo immersion technique
PET	-	Pulse echo technique
R	-	Receiving transducer
TT	-	Through transmission technique
TMM	-	Tissue mimicking material
TCPIP (VICP)	-	Transmission Control Protocol/Internet Protocol (Versatile Instrument Control Protocol)
T	-	Transmitting transducer
UIT	-	Ultrasonic insertion technique

LIST OF SYMBOLS

A	-	Amplitude
D	-	Diameter
d	-	Thickness
E	-	Elastic properties
f	-	Frequency
f_c	-	Center frequency of transducer
G	-	Shear modulus
I	-	Intensity
k	-	Wavenumber
L	-	Separation distance between transducer and reflector
m	-	Mass
N	-	Length of the Fresnel zone
p	-	Number of data points
P	-	Pressure
RC	-	Reflection coefficient
T	-	Temperature
t	-	Time
TC	-	Transmission coefficient
V	-	Volume
v_g	-	Group velocity
v_L	-	Longitudinal velocity
$v_L(T)$	-	Temperature dependent longitudinal velocity
v_p	-	Phase velocity
$v_p(f)$	-	Frequency dependent phase velocity
$v_p(T)$	-	Temperature dependent phase velocity
v_S	-	Shear velocity
W	-	Width of beam divergence
Y	-	Magnitude

Z	-	Acoustic impedance
$Z(T)$	-	Temperature dependent acoustic impedance
α	-	Attenuation coefficient
$\alpha(f)$	-	Frequency dependent attenuation coefficient
$\alpha(T)$	-	Temperature dependent attenuation coefficient
θ_F	-	Fraunhofer divergence angle
λ	-	Wavelength
ρ	-	Density
υ	-	Poisson's ratio
ϕ	-	Phase
ω	-	Angular frequency

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Tissue mimicking materials (TMMs) refer to materials that mimic the acoustic properties of human tissues (Zell, *et al.*, 2007; Maggi, *et al.*, 2009). TMMs are important for the performance testing of medical ultrasonic systems and the development of new ultrasonic transducers or diagnostic systems. TMMs can be categorized into two main types; soft and hard TMMs. Soft tissues consist of muscles, tendons, ligaments, fascia, fat, fibrous tissue, synovial membranes, nerves and blood vessels while hard tissues consist of cortical bone, trabecular bone, dental, enamel and dentin. Soft TMMs are usually prepared from agar, gelatin, polyacrylamide (PAA) and polyvinyl alcohol (PVA) while hard TMMs are developed from epoxy, plastics and ceramic (Culjat, *et al.*, 2010).

Recently, researchers studied the potential of alternative samples as TMMs like polyvinyl chloride plastisol (PVCP) (Fonseca, *et al.*, 2015; Vogt, *et al.*, 2016), gellum gum hydrogel (Cortela, *et al.*, 2015), Konjac-Carrageenan (KC) hydrogel (Kenwright, *et al.*, 2014) and Konjac Glucomannan (KGM) gel (Mat Daud, *et al.*, 2017). The compatibility of a tested sample as a TMM is confirmed by comparing its acoustic properties with the acoustic properties of real human tissues. There are four common techniques of ultrasonic method for the acoustic characterization of TMMs; through transmission technique (TT), pulse echo technique (PET), ultrasonic insertion technique (UIT) and pulse echo immersion technique (PEIT).

The TT and PET are the common techniques for determining the acoustic properties of a material. However, both techniques involve the direct application of couplant gel at the surface of the tested sample. Thus, the acoustic properties of the sample could be changed as the applied couplant on the surface is absorbed into the sample (Green Jr., 2004; Yochev, *et al.*, 2006; Kadem, 2011). Therefore, the UIT and PEIT are employed by previous researchers as they replace the couplant gel with the aqueous medium to acoustically couple the sample with the transducers. The UIT and PEIT are the common techniques used to determine the acoustic properties of TMMs. There are two types of UIT; contact and noncontact UIT, and PEIT; contact and noncontact PEIT.

Since the TT, PET, contact UIT and contact PEIT involve the direct contact between the transducer and the sample, the soft TMMs may be compressed during the experiment and it will cause some errors in the acoustic properties measurement. Meanwhile, the TT, contact UIT and noncontact UIT require the alignment of two identical transducers in a line facing each other. Thus, all three techniques require the accessibility of two sides of the sample. Furthermore, the sample should be carefully inserted between transducers to ensure that both sides of the sample are perpendicular to transducers (Fahr, 2013; Mat Daud, *et al.*, 2017; Mat Daud, *et al.*, 2018).

Meanwhile, the contact UIT, noncontact UIT, contact PEIT and noncontact PEIT require the distilled water as the propagation medium to acoustically couple the sample with the transducers. However, only the contact UIT, noncontact UIT and noncontact PEIT involve two measurement steps of ultrasonic pulse transmission in a single sample to determine its acoustic properties. Therefore, all three techniques require the ultrasonic pulse transmission in distilled water as the calibration procedure (Ghoshal, *et al.*, 2011; Cortela, *et al.*, 2013; de Carvalho, *et al.*, 2016; Rabell-Montiel, *et al*., 2016). The techniques also involve the measurement of water temperature to calculate the acoustic properties of samples (Maggi, *et al.*, 2011; Cortela, *et al.*, 2013; de Carvalho, *et al.*, 2016).

The acoustic properties of tested samples can be calculated from the transmitted or reflected acoustic signals in it. The acoustic signals can be analysed using the time domain analysis to calculate the longitudinal velocity, acoustic impedance and attenuation coefficient of samples at the center frequency value of a transducer. The signals also can be analysed using the frequency domain analysis to determine the frequency dependent phase velocity and attenuation coefficient of samples. The frequency dependent phase velocity of a sample is important to determine its acoustic dispersion characteristic while its frequency dependent attenuation coefficient is essential to determine the effects of scattering and absorption with the change of frequency (He, 1999; Lee, *et al.*, 2007).

According to previous researches, all techniques can be employed to measure the acoustic properties of TMMs at the center frequency value of a transducer. However, only UIT and PEIT were utilized to determine the frequency dependent attenuation coefficient of TMMs. Furthermore, the noncontact UIT was the common technique to determine the frequency dependent phase velocity of TMMs (Lee, 2011; Zhang, *et al.*, 2011; Lee, 2015). It requires the accessibility of two sides of the sample and the alignment of two identical transducers in a line facing each other. Hence, the sample should be carefully inserted between transducers to ensure that both sides of the sample are perpendicular to transducers. Thus, the noncontact PEIT can be used as an alternative technique to determine the frequency dependent phase velocity of soft TMMs as it involves the accessibility of one side of the sample and a single transducer.

Most previous researchers studied the frequency dependent phase velocities of hard TMMs; normal bone (Chen & Chen, 2006), calcaneus bone (Chen & Chen, 2006), trabecular bone (Lee, 2011; Lee, 2015) and osteoporotic bone (Chen & Chen, 2006). The variation of frequency dependent phase velocities of hard TMMs could be due to the size and distribution of porosity in the samples as confirmed by previous studies (Lee & Choi, 2007; Zhang, *et al.*, 2011). Previous researchers also measured the frequency dependent phase velocities of soft TMMs. However, they only discussed the frequency dependent phase velocities of soft tissue (Rajagopal, *et al.*, 2015) and tendon (Garcia, *et al.*, 2003) TMMs.

Previous researchers also studied the temperature dependent acoustic properties of TMMs. However, only several previous studies discussed the effect of scatterer on the temperature dependent longitudinal velocities and attenuation coefficients of TMMs (Ortega, *et al.*, 2010; Cortela, *et al.*, 2013; Maggi, *et al.*, 2013). Furthermore, most of them utilized graphite powder as scatterer in TMMs (Cortela, *et al.*, 2013; Maggi, *et al.*, 2013). Meanwhile, the effect of modifier on the temperature dependent acoustic properties of TMMs was solely studied by Maggi, *et al.* (2013). Besides, they only investigated the effect of modifier on the temperature dependent longitudinal velocities of TMMs.

Therefore, a technique is proposed to improve the established techniques for the acoustic characterization of TMMs. Then, the acoustic measurement system is developed for the proposed technique to perform time and frequency domain analysis to determine the acoustic properties of TMMs. The developed system can be employed to study the factors affecting the temperature and frequency dependent acoustic properties of TMMs.

1.2 Problem Statement

Acoustic properties are important to confirm the compatibility of a tested sample as a TMM by comparing its acoustic properties with the acoustic properties of real human tissues. The noncontact UIT is the common technique used to determine the frequency dependent phase velocity of TMMs (Lee, 2011; Zhang, *et al.*, 2011; Lee, 2015). However, it requires the alignment of two identical transducers in a line facing each other and the accessibility of two sides of the sample. Therefore, the noncontact PEIT can be used as an alternative technique for the acoustic characterization of soft TMMs as it requires the accessibility of one side of the sample and a single transducer to measure its acoustic properties.

However, both techniques involve two measurement steps to determine the acoustic properties of a single sample; the measurement of ultrasonic pulse transmission with and without sample immersed in the distilled water. Therefore, they require the distilled water as the medium of ultrasonic pulse propagation to acoustically couple the sample with the transducer. Thus, the measurement of ultrasonic pulse transmission in distilled water is compulsory as the calibration procedure (Ghoshal, *et al.*, 2011; Cortela, *et al.*, 2013; de Carvalho, *et al.*, 2016; Rabell-Montiel, *et al*., 2016). Both techniques also require the measurement of water temperature to calculate the acoustic properties of samples (Maggi, *et al.*, 2011; Cortela, *et al.*, 2013; de Carvalho, *et al.*, 2016). The acoustic properties of TMMs are also highly dependent on the water temperature (Ghoshal, *et al.*, 2011; King, *et al.*, 2011; Dunmire, *et al.*, 2013; Parisa, *et al.*, 2013; Souza, *et al.*, 2018). Hence, the fluctuation and inaccurate measurement of water temperature could affect the accuracy of acoustic properties measurement of TMMs.

The frequency and temperature dependent acoustic properties of TMMs depend on the modifier, scatterer and porosity. However, previous researchers only studied the effect of porosity on the frequency dependent acoustic properties of bone (Lee & Choi, 2007) and cancellous bone (Zhang, *et al*., 2011) TMMs. Meanwhile, previous researchers also only discussed the effect of scatterer on the temperature dependent attenuation coefficients of TMMs (Ortega, *et al.*, 2010; Cortela, *et al.*, 2013). The findings were important to develop the specific type of TMMs as their acoustic properties can be manipulated by the addition of modifier and the presence of scatterer and porosity in the samples. However, previous researchers did not investigate the effect of modifier on the frequency dependent phase velocities and temperature dependent attenuation coefficients of TMMs. Previous researchers also did not determine the effect of scatterer on the frequency dependent phase velocities of TMMs.

Based on the limitations of previous researches, this study proposes the development of an acoustic measurement system for time and frequency domain analysis to measure the acoustic properties of nonporous TMMs. The developed system employs an alternative technique, which is adapted from the noncontact PEIT to eliminate the requirement of the distilled water as the propagation medium, the ultrasonic pulse transmission in distilled water as the calibration procedure and the water temperature measurement to calculate the acoustic properties of TMMs. Then, the developed system is employed to measure the acoustic properties of two types of nonporous TMMs and study the effect of modifier and scatterer on their temperature and frequency dependent acoustic properties.

1.3 Objectives of Study

The objectives of this study are:

(a) To develop the alternative acoustic pulse echo immersion measurement system for nonporous tissue mimicking materials.

(b) To evaluate the precision and accuracy of the alternative acoustic pulse echo immersion measurement system for nonporous tissue mimicking materials.

(c) To measure the temperature and frequency dependent acoustic properties of agar-based and Konjac Glucomannan-based samples using the developed system.

(d) To determine the effects of modifier and scatterer on the temperature and frequency dependent acoustic properties of agar and Konjac Glucomannan samples using the developed system.

1.4 Scope of Study

This study is carried out to develop an alternative acoustic pulse echo immersion measurement system for TMMs. The developed system employs the alternative pulse echo immersion technique (aPEIT), which is adapted from the noncontact PEIT and specially designed for the step-shaped sample. It is particularly developed for nonporous TMMs. Therefore, the developed system could not be used to determine the acoustic properties of porous and multilayered TMMs.

The system is developed to calculate the acoustic properties of a TMM from the reflected acoustic signals through the thin and thick sections of the sample using time and frequency domain analysis. In this study, the acoustic signals are analysed using the time domain analysis to calculate the longitudinal velocity and acoustic impedance of the sample. The acoustic signals are also analysed using the frequency domain analysis to calculate its phase velocity and attenuation coefficient. The other acoustic properties such as shear velocity, backscatter coefficient and nonlinear parameter are not included in this study.

The precision and accuracy of the developed system are evaluated to validate whether it can produce comparable or better results compared to the noncontact PEIT. In this study, the precision of the developed system is determined by comparing the results obtained from the developed system for the aPEIT and the previous developed system for the noncontact PEIT for four parameters; thickness of sample (the thin section of the sample is one third, half and two third of its thick section), temperature of medium (25.0^{o}C, 30.0^{o}C and 35.0^{o}C), density of medium (1000 kg m^{-3}, 1003 kg m^{-3} and 1007 kg m^{-3}) and center frequency of transducer (2.25 MHz, 4.00 MHz and 5.00 MHz). Meanwhile, its accuracy is determined by comparing the results obtained from the developed system for the aPEIT, the previous developed system for the noncontact PEIT and the reference values.

Then, the developed system is used to determine the temperature and frequency dependent acoustic properties of agar-based and KGM-based samples. In this study, the temperature dependent acoustic properties of both samples are determined within the range of 25.0^{o}C and 33.0^{o}C temperatures of distilled water at 5.00 MHz frequency. Meanwhile, the frequency dependent acoustic properties of samples are determined within the range of 4.00 MHz and 6.00 MHz frequency at 25.0^{o}C temperature of distilled water.

Then, the temperature and frequency dependent acoustic properties of agar-based and KGM-based samples are analysed to determine the effects of modifier and scatterer on the temperature and frequency dependent acoustic properties of agar and KGM samples. In this study, the temperature dependent acoustic properties of agar-based and KGM-based samples are analysed to determine the effects of modifier and scatterer on the temperature dependent longitudinal velocity, acoustic impedance, phase velocity and attenuation coefficient of agar and KGM samples. Meanwhile, the frequency dependent acoustic properties of agar-based and KGM-based samples are analysed to determine the effects of modifier and scatterer on the frequency dependent phase velocity and attenuation coefficient of agar and KGM samples.

1.5 Significance of Study

This study is important for researchers who are involved in the development of TMMs. Since the common acoustic measurement system adapts the noncontact UIT and PEIT, both techniques require the distilled water as the propagation medium, ultrasonic pulse transmission in distilled water as the calibration procedure and water temperature measurement to calculate the acoustic properties of a sample. Therefore, the developed alternative acoustic pulse echo immersion measurement system in this study is significant to improve the accuracy of common acoustic measurement of human tissues and TMMs.

The acoustic properties of human tissues also highly depend on temperature and frequency. Thus, the temperature and frequency dependent acoustic properties of TMMs can be manipulated by the addition of modifier and the presence of scatterer and porosity to mimic the acoustic properties of human tissues. However, previous researchers only studied the effect of modifier on the temperature dependent longitudinal velocity of TMMs and the effect of porosity on the frequency dependent phase velocity of TMMs. Therefore, this study is significant to determine the effects of modifier and scatterer on the temperature and frequency dependent acoustic properties of TMMs.

This study is also important for researchers who are involved in the medical field. The abnormal human tissues have different acoustic properties compared to the normal tissues. According to the previous researches, the TMMs with modifier and scatterer may mimic the abnormal human tissues. However, previous researchers only studied the frequency dependent attenuation coefficient of abnormal TMMs. Therefore, this study is significant to differentiate the temperature and frequency dependent acoustic properties of normal and abnormal human tissues and TMMs.

1.6 Thesis Organization

This thesis is divided into five chapters. The first chapter, chapter 1 covers the background of study, problem statement, objectives of study, scope of study and significance of study. Meanwhile, chapter 2 describes the literature review related to the acoustic measurement techniques of human tissues and TMMs, their acoustic properties and factors affecting the temperature and frequency dependent acoustic properties of TMMs. Then, chapter 3 explains the measurement procedure for aPEIT, development of alternative acoustic pulse echo immersion measurement system for nonporous TMMs and sample preparation. Meanwhile, chapter 4 discusses the performance of the developed system and the temperature and frequency dependent acoustic properties of agar-based and KGM-based samples. Finally, chapter 5 covers the conclusion and recommendation for further study.

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LIST OF PUBLICATIONS

Journal with Impact Factor

1. **Anis Nazihah Mat Daud**, Rosly Jaafar, Shahrul Kadri Ayop, Mohd Ikhwan Hadi Yaacob & Md Supar Rohani (2017). Elastic constant determination of hardwoods using ultrasonic insertion technique. *Ultrasonics, 75*, 194–198 **(Q1, IF: 2.377)**.
2. **Anis Nazihah Mat Daud**, Rosly Jaafar, Shahrul Kadri Ayop, & Md Supar Rohani (2018). A computerized system based on alternative pulse echo immersion technique for acoustic characterization of non-porous solid tissue mimicking materials. *Measurement Science and Technology*, *29* (4), 045902 **(Q2, IF: 1.685)**.

Indexed Journal

1. **Anis Nazihah Mat Daud**, Md Supar Rohani & Rosly Jaafar (2017). Acoustic characterisation of Konjac Glucomannan Gel as a medical phantom. *Solid State Phenomena*, *268*, 379–383 **(Indexed by SCOPUS).**
2. **Anis Nazihah Mat Daud**, Md Supar Rohani & Rosly Jaafar (2018). A computerized time domain and spectral analysis system for acoustic characterization of tissue mimicking materials. *Journal of Physics: Conference Series*, *1083*, 012016 **(Indexed by SCOPUS).**

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Indexed Conference Proceedings

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