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Resonant Ultrasound Spectroscopy

Analysis of thickness resonances to characterise a material

Master Thesis Project

16.01.2017 – 03.07.2017

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1. Introduction

The aim of this project was to establish reliable setup to characterise a living material using resonant ultrasound spectroscopy. In the first stage of the project, the solid materials such as aluminium, glass and plastics were tested to prove that setup is well tested and ready to switch to a living materials such as plants. The experiments were performed with aluminium, glass and plastic due to existing elastic constants, hence it is straightforward to compare datasheet values to analysed data.

The main reason why exactly ultrasound resonant spectroscopy was used is that that by measuring transmission coefficient of a sample, RUS can infer parameters like thickness, density, attenuation coefficient, speed of sound and first order resonant frequency. Moreover, this technique is non-destructive, non-invasive, rapid and relatively inexpensive. Therefore, there is no damage on a sample which is significantly important for a plant samples, while running the experiment.

Coefficient of transmission of sound at normal incidence through each sample in the frequency range 0.6 MHz – 1.7 MHz was measured. For all cases, at least one thickness resonance was observed. From these measurements density, sound velocity, and attenuation of ultrasonic longitudinal waves were obtained and compared to available data provided in an articles or by manufacturers.

The method is based on frequency-domain analysis, by using the Fast Fourier transform, of pulse transmitted through a sample.

All the experiments were conducted in Biology department of Albert-Ludwig's University of Freiburg city in Germany. And the required equipment, except oscilloscope (listed below) were transported from Heriot-Watt University, Edinburgh:

- Transducer
- Hydrophone
- Water tank
- Pulser/receiver
- DC coupler
- Oscilloscope

Results reveal that these resonances are strongly sensitive on different parameter changes which are discussed further in the report.

This report goes through all the steps and problems which are faced during the experiments and gives suggestions for further improvements.

All the needed information such as analysed data, Matlab and Python codes, setup instruction, the report can be provided via GitHub control system.

2. Literature review and theory

2.1. Fundamentals of ultrasound

2.1.1. Ultrasound

The sound waves with frequencies above 20 kHz is called ultrasound and they are not in range for human hearing (William, 2012). Ultrasound is broadly used technique in different applications of medicine, food industry, factories and non-destructive testing. Sending and receiving of transmitted or reflected ultrasonic pulses allows ultrasonic devices to detect objects, defects and measure distances.

Ultrasound imaging (sonography) is mostly used in medicine to identify a health or gender of baby. In the non-destructive testing of materials or structures, ultrasonic waves are used to detect flaws. Industrially, ultrasound is used for cleaning, mixing and to accelerate chemical processes. In living environment, animals like bat and porpoises use ultrasound to locate prey and obstacles.

Table I. Frequency classification of Ultrasound

Frequency (Hz)	Classification
20 – 20.000	Audible sound
20.000 – 1.000.000	Ultrasound
1.000.000 – 30.000.000	Diagnostic ultrasound

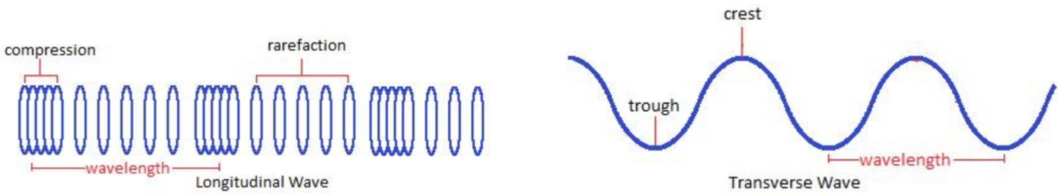
2.1.2. Ultrasonic waves

In ultrasound, high-frequency sound waves travel through the material being tested and information about parameters of a material are then obtained by measuring the type and interaction angle between the sound wave and the testing sample. When the sound waves are introduced within a sample, alternating molecular compression and rarefaction takes place. There are 2 modes of waves which propagates through a solid material:

- Longitudinal waves (pressure waves)
- Transverse waves (shear waves)

Longitudinal waves, where oscillation happens in the same direction as the wave is moving. This type of wave can be generated in liquids, solids and gases. In transverse wave, the oscillation occurs perpendicular to the direction that the wave is travelling in. This type of wave is propagated in solid structures only. Figure 1 represents these types of waves.

Figure 1. Longitudinal and transverse waves (http://www.keywordsuggests.com/)

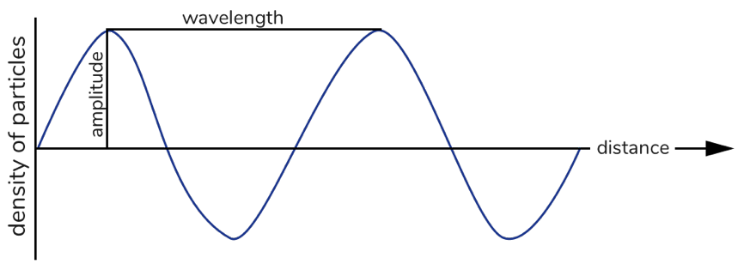


Wave characteristics

An area of compression and a neighbouring zone of rarefaction identify one cycle of an ultrasound wave. A wave cycle can be depicted as a graph of local pressure in the medium versus distance l along the direction of the wave (Figure 2). The wavelength is the distance covered by one cycle. The number of cycles per unit time introduced in the medium each second is referred to as the frequency, and measured in unit of hertz, kilohertz or megahertz, where 1 Hz is 1 cycle per second. The maximum height of the wave cycle is referred to amplitude of the ultrasound wave. And the multiplication of the frequency (v) and the wavelength (λ) is the velocity of the wave and expressed as below (William, 2012):

$$c = v\lambda \tag{1}$$

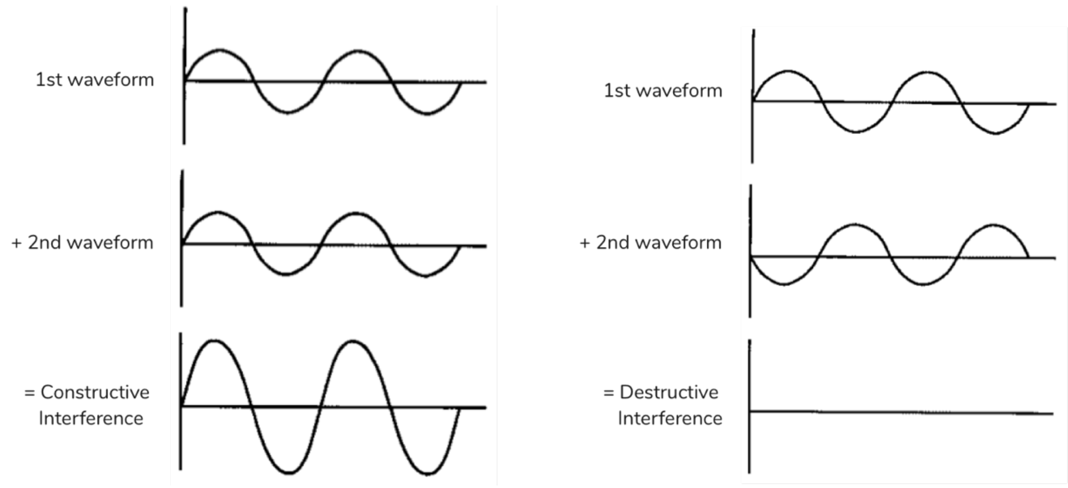
Figure 2. Characteristics of an ultrasound wave



Interaction of waves

Interference of waves occurs when to waves meet. There are two extremes of waves' interference: constructive and destructive. In constructive interference peak meets with other peak, they are said to "in phase" and in destructive interference the waves are "out of phase", hence two waves cancel each other out. Waves experience constructive interference when their amplitudes added, whereas waves undergoing destructive interference can completely nullify each other (Figure 3).

Figure 3. Interference of two waves



Reflection and Transmission

The part of incident energy reflected from the surface directly depends on the different in acoustic impedance of the material on opposite sides of the interface. The acoustic impedance can be expressed as follows:

$$Z = \rho c = \frac{\omega\rho}{k} \qquad \text{(X)}$$

where Z is acoustic impedance of medium, ρ is density of the medium and c is the speed of sound in the medium, ω is angular frequency and k is wavenumber (explained below).

In a case of one layer material the reflection coefficient α_R is shown below (ultrasound wave incident perpendicular):

$$\alpha_R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 \qquad \text{(X)}$$

where Z_1 and Z_2 are the acoustic impedances of two different media. The fraction of the incident energy is transmitted through the media and can be described by transmission coefficient:

$$\alpha_T = \frac{4Z_1Z_2}{(Z_1+Z_2)^2} \qquad \text{(X)}$$

Therefore, it is clear, that:

$$\alpha_R + \alpha_T = 1 \qquad \text{(X)}$$

A large impedance mismatch occurs at an interface, when the most of energy if reflected, and only small portion is transmitted across the interface. For instance, ultrasound energy is significantly reflected at air-

tissue and air-water interfaces, because the air impedance is much less than tissue or water.

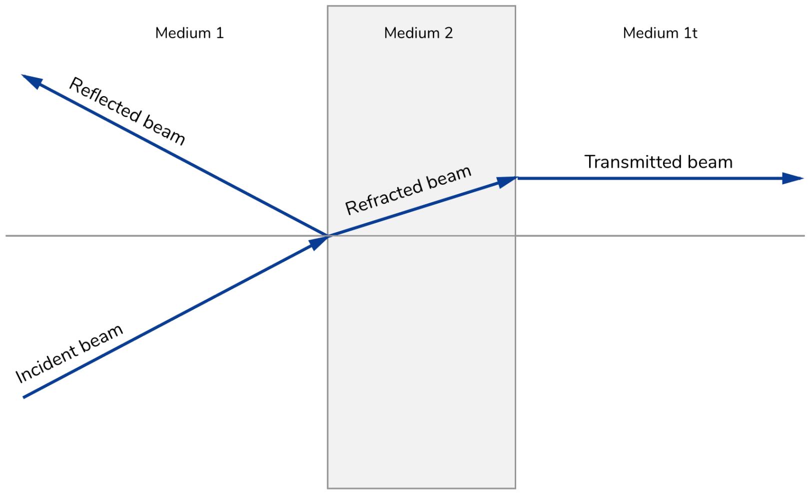
Refraction

The direction of incident beam is changed once it crosses an interface obliquely between two media. If the velocity of ultrasound is higher in a second medium, then the beam enters this medium at less steep angle. This behaviour of ultrasound beam is called refraction. The relationship between incident angle and refracted angle can be described by Snell's law:

$$\frac{sine\ of\ incident\ angle}{sine\ of\ refractive\ angle} = \frac{velocity\ in\ incidence\ medium}{velocity\ in\ refractive\ medium}$$

$$\frac{sin\theta_i}{sin\theta_r} = \frac{c_i}{c_r} \quad \text{(X)}$$

Figure 4. Reflection, refraction and transmission of ultrasound



Note to Figure 4: The beam hits the medium 2 at an angle of θ_i. A portion of the energy is reflected at an angle of θ_r and part of energy goes through at an angle of θ_{ref}.

2.1.3. Ultrasound intensity

As an ultrasonic waves pass through a medium, it transfers energy through the medium. The amount of energy transport is called "power".

The rate of flow of energy (power) per unit of cross sectional area is called intensity. Intensity is commonly described relatively to another intensity; for example, the intensity of ultrasonic waves transmitted through medium may be compared with that of the ultrasound sent into the

material. The intensity is measured in a logarithmic scale, since it is the most appropriate for recording data over a range of many orders of magnitude. The decibel scale is used in acoustics:

$$dB = 10log\frac{I}{I_0} \qquad \text{(X)}$$

where I_0 is the reference intensity. Due to intensity is power per unit area and power is energy per unit time, it is possible to write above expression as:

$$dB = 10log\frac{Power}{Power_0} = 10log\frac{E}{E_0} \qquad \text{(X)}$$

Ultrasound wave intensity is allied to maximum pressure (P_m) in the medium by the following expression:

$$1 = \frac{P_m^2}{2\rho c} \qquad \text{(X)}$$

where ρ is the density of the medium and c is the speed of sound in the medium. When we substitute Eq. (X) for I and I_0 in Eq. (X):

$$dB = 10log\frac{P_m^2/2\rho c}{(P_m^2)_0/2\rho c} = 10log\left[\frac{P_m}{P_{m0}}\right] = 20log\frac{P_m}{P_{m0}} \qquad \text{(X)}$$

While comparing two pressure waves, Eq. (X) can be used directly; the pressure does not have to be converted into intensity to find dB value.

2.1.4. Ultrasound velocity

The speed of an ultrasonic wave through a medium changes and it depends on the physical properties of the medium. The velocity of an ultrasonic wave is relatively low in low-density media such as air and gases, since the molecules in them move over relatively large distances before they impact neighbouring molecules. In solids, the molecules are limited in their motion, and the ultrasound velocity is relatively high. In another hand, liquids demonstrate ultrasound velocities in-between those, gases and solids.

Table II. Approximate velocities in different medium

Nonbiological material	Velocity (m/s)	Biological material	Velocity (m/s)
Aluminium	6400		

Plastic	2680	
Water (degassed)	1480	
Glass	5640	
Air	330	

2.1.5. Ultrasound attenuation

As an ultrasound beam penetrates a medium, energy decreases due to absorption, reflection and scattering, so to say, the attenuation of ultrasound is when sound intensity decreases exponentially with distance from the source.

Donation to attenuation of an ultrasound beam can include:

- Reflection
- Absorption
- Scattering
- Refraction
- Diffraction
- Interference

Ultrasound energy is absorbed by a medium when the fraction of the beam's energy turned into other forms energy, like an increase in the arbitrary motion of molecules. Ultrasound is reflected back when the angle of reflection is same as incident angle. If the part of beam changes direction in a less orderly manner, this phenomenon is called "scattering".

The attenuation of ultrasound in a medium is expressed by attenuation coefficient α in units of dB/cm or Nepers per meter(1 Np = 8.686 dB). The attenuation coefficient is the total amount of individual coefficients for scattering and absorption and can be expressed as follows:

$$A = A_0 e^{-\alpha x} \quad \text{(X)}$$

where α is attenuation coefficient, A is amplitude of the ultrasound wave, A_0 is the initial amplitude and x is the distance the wave has travelled through the medium. (McClements and Gunasekaran, 1997)

Table III. Attenuation coefficient α for 1 MHz ultrasound

Medium	**α (dB/cm)**
Blood	0.18
Fat	0.16
Muscle	3.3
Water	0.0022
Bone	20
Brain	0.85

Note to Table III: The given figures in table are relative and may vary with both the origin and condition of the biological sample.