Simulation of the Bubble Gas Detection inside the Fluids based on Transmission and Reflection of Ultrasonic Waves

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Abstract

The appearance of gas bubbles in veins inside the body is the primary cause of decompression illness. Preliminary research has conducted to develop the gas bubble detection system in the both mediums of water and blood with an oxygen and nitrogen gas bubbles. In this research, we use a computer simulation approach based on the analysis of the ultrasonic signal alteration that was received by the transmission and reflection signal mode. The result shows that the attenuation is caused by the absorption of the medium was very small, which the reduction of the amplitude for the medium of blood and water, respectively 1.1% and 0.012%. The existence of gas bubbles within the medium drives the amplitude reduced by 4% to 5% from the initial amplitude and the intensity percentage that was reflected by the bubbles for the medium of blood is greater than the medium of water. The selected frequency of the ultrasonic signal source influences the ability to detect the diameter of the bubbles

Keywords: *attenuation, gas bubble, ultrasonic wave, simulation.*

1. Introduction

Decompression illness is a condition which is suffered by divers who move fast from the deep-sea with higher ambient pressure to the lower ambient pressure [1]. The condition was indicated by the appearance of gas bubbles which has collected in the body tissues. Gas bubbles can be formed in the whole of the body, and they are also frequently observed in the bloodstream [2]. It can cause potentially fatal effects such as paralysis or even death for the divers. Therefore, early detection of the presence of bubbles in the body is an important in order to avoid its impacts.

During the time, the detection of the presence of bubbles has been done through capacitive method [3] and optic method [4]. Both methods have limitations and less precise when they are applied to detect the bubbles either in the tissues or in the blood stream. The bubble is known as a reflector for the acoustic waves due to the difference in acoustic impedance which is large enough between gas and liquid [5] and ultrasonic waves are mechanical waves which have the largest penetrating power characteristics than other mechanical waves. Based on these characteristics, ultrasonic waves can be applied for bubble detection. Recently, Rahiman was performing a bubble detection test inside a chemical column with a medium of water through the transmission wave measurement system [6]. In this paper, we present the detection system of nitrogen and oxygen bubbles that presence in the water and blood medium using ultrasonic sensor. Simulation approach was conducted to analyze the influence of the bubble to the signal attenuation that received by the detector.

2. Theory

2.1 Medium Attenuation

In the propagation, acoustic waves need a medium. The existence of the medium causes attenuation due to the absorption of wave energy [7]. The attenuated amplitude A_1 which caused by the medium with the thickness d is [8]:

$$A_1 = A_0 \, e^{-\alpha d} \tag{1}$$

where A_0 is an initial amplitude, and α is a attenuation coefficient that depend on the frequency. This coefficient is measured in Nepers per length unit (Np/l) or in decibels per length unit (dB/l) with the conversion factor ($\alpha_{dB/l} = 8.636\, \alpha_{Np/l}$). In the liquid medium is influenced by the factors of viscosity and thermal conduction which are described by classical absorption constant (α_C).

$$\alpha_c = \frac{\omega^2 \eta}{2\rho_0 c^3}\left(\frac{4}{3} + \frac{(\gamma-1)}{Pr}\right) \tag{2}$$

where µ is an angular frequency (2®*f*), η is viscosity coefficient, γ is the specific heat ratio, *Pr* is Prandtl number, ρ_0 is medium density, and *c* is wave propagating velocity through the medium [9]. In the fluid, the absorption of acoustic waves depends on the frequency, and it is expressed in the α_c/f^2 form, where frequency (*f*) in Hz. The acoustic wave absorption coefficient for water medium, nitrogen and oxygen gas at the room temperature, respectively 25 x 10^{-15} Np/m, 1.35 x 10^{-11} Np/m, and 1.61 x 10^{-11} Np/m [7]. And for the blood medium is about 0.18 dB/cm [10].

2.2 Transmission and Reflection Waves Intensity

In the propagation of a wave through boundary mediums, the wave will be reflected and transmitted as shown in Figure 1. Transmission and reflection in the boundary surface are depending on the medium acoustic impedance. If the discrepancy of acoustic impedance (Z) between the two mediums is large, it’s indicated that most of the incidence wave energy will be reflected. In other hand, if the discrepancy is small, most of the incidence wave energy will be transmitted [11].

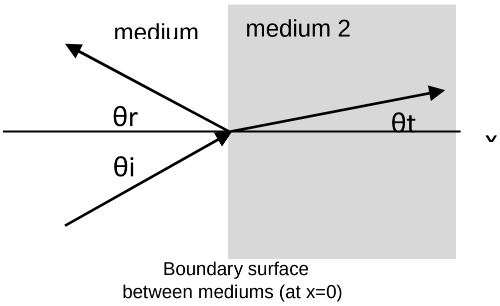

Figure 1 Schematic of reflection and transmission of the incidence waves on the boundary surface (modified from Kinsler, 2000).

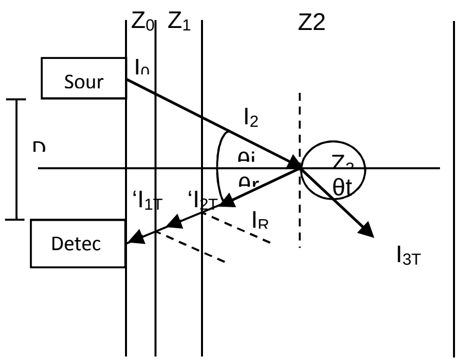

Figure 2 Schematic model of detection bubble with a reflection mode (modified from Rahiman et.al, 2013).

The intensity of the reflected (I_R) and transmitted (I_T) waves in the oblique incidence is determined by the following equation:

$$I_R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 \quad (3)$$

and

$$I_T = \frac{4Z_1 Z_2}{(Z_2 + Z_1)^2} = 1 - I_R \quad (4)$$

where $Z_1 = \frac{\rho_1 V_1}{\cos\theta_1}$ and $Z_2 = \frac{\rho_2 V_2}{\cos\theta_2}$ are the acoustic impedances for two mediums, θ is the angle incidence wave to the normal line of the plane, ρ and v are respectively a medium density and the wave velocity through the medium [7]. The density and velocity of wave propagation in each medium are shown in Table 1.

Table 1 Density and velocity of the sound wave propagation [9]

Type of Medium	Density (kg/m^3)	v (m/s)
Glycerin	1.26x10^3	1920
Acrylic	1.40x10^3	2680
Water	1x10^3	1498
Air	1.2	331
Blood [12]	1.06x10^3	1570

2.3 The Effect of The Source-Detector Geometry Arrangement

Due to obstruct by the presence of another organ or tissues between the source and the detector it is difficult to set up the transmission measurement mode. Therefore, the reflection measurement was setup in order to detect the bubble as shown in Figure 2. In the reflection mode, the geometric arrangement of the source-detector will effect to the received wave intensity. Based on the analysis of the Figure 2, the value of angle θ or θ_i can be determined by the following equation:

$$\theta = sin^{-1}\left(\frac{r}{\sqrt{r^2 + l^2}}\right) \quad (5)$$

where r is a distance between the horizontal axis lines to the source, l is a distance between the surface wave to the detector surface, and D is a distance between the source and detector. The detection requirement of the minimum size of a detected bubble is determined based on the ratio of the bubble peripheral size to the source wavelength, as represented by the equation 6 [6].

$$\frac{2\pi a}{\lambda} \ll 1 \quad (6)$$

where a is bubble radius, k is a wave number. In order to the scattering of waves as well as reflections on the flat surface, the required value of ka is 2 [6].

3. Method

This study was conducted a computer simulation approach to analyze the signal attenuation, which caused by the presence of the bubble. The simulation was performed on water and blood medium which contained in the acrylic tube with 3 cm diameter and ultrasonic frequency source is about 40 kHz. The bubbles model was described in the spherical and in it's filled with nitrogen and oxygen gas. Schematic model of detection bubble was shown in the Figure 2. The source-detector (D) distance variation was setup from 1 cm to 6 cm to obtain the percentage of the received intensity by the detector. The percentage of receiving intensity for water medium will be compared with to the blood medium.

4. Result and Discussion

The existence of the bubble in the medium acts as a barrier to the propagation, so that pressure exerted by the wave source causes vibrations of gas molecules in a bubble. The incident drives the scattering and absorption of incidence wave that will affect the intensity of the detected waves. Figure 3 shows the simulation result of the attenuation amplitude by water medium, and due to the presence of nitrogen and oxygen gas bubbles.

The attenuation discrepancy of acoustic wave due to absorption by the water medium, and absorption due to the presence of oxygen or nitrogen bubble is very small. The amplitude loss is about 0.0121%. Therefore, the attenuation due to wave absorption by the medium can be ignored. In addition, the presence of oxygen and nitrogen bubbles respectively, decreases the amplitude about 6.25% and 5.47%.

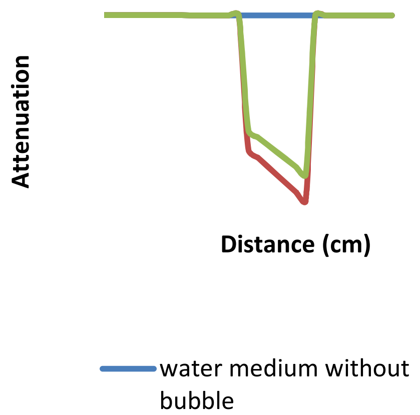

Figure 3 The simulation result of wave attenuation due to water medium absorption, and when there are nitrogen and oxygen bubbles.

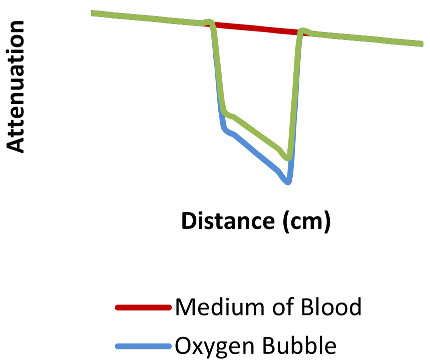

Figure 4 The simulation result of acoustic wave attenuation due to blood medium absorption, and when there are nitrogen and oxygen bubbles.

Similarly, the absorption by the blood medium (Figure 4) without any bubble amplitude loss is about 1.1%. Meanwhile, the presence of oxygen and nitrogen bubbles in the medium, the attenuation respectively decreased 5.38% and 4.61%. The intensity value of the wave at each boundary medium is determinate using equation (3) and (4) at a distance (D) 1 cm as shown in Table 2.

Table 2. The intensity of the reflection and transmission waves at the boundary medium

Acoustic Impedance	Boundary Medium	Intensity	
		I_R	I_T
$Z_2 - Z_3$	Water-*Bubble*	0.999	0.001
$Z_2 - Z_1$	Water-Acrylic	0.202	0.798
$Z_1 - Z_0$	Acrylic-Glycerin	0.037	0.963
$Z_{2'} - Z_3$	Blood-*Bubble*	0.999	0.001
$Z_{2'} - Z_1$	Blood-Acrylic	0.165	0.835

The percentage value of receiving wave intensity detector for water and blood mediums at 1 cm distance was determined based on the wave intensity that led to the detector i.e. I_R, $'I_{2T} = I_{2T}$ and $'I_{1T} = I_{1T}$.

(a) For water medium

$$\%I = (I_R \times 'I_{2T} \times 'I_{1T}) \times 100\%$$
$$\%I = (0.998992 \times 0.797862 \times 0.963174) \times 100\%$$
$$\%I = 76.770\%$$

(b) For blood medium

$$\%I = (I_R \times 'I_{2T} \times 'I_{1T}) \times 100\%$$
$$\%I = (0.999092 \times 0.834637 \times 0.963174) \times 100\%$$
$$\%I = 80.317\%$$

According to the intensity results, detector receiving more intensity of the ultrasonic waves that reflected by bubbles in the blood medium than in a water medium. Table 3 shows the percentage intensity ultrasonic waves which are received by the detector.

Table 3. Percentage of the received wave intensity of detector for water and blood medium with different source-detector distance

Source-Detector Distance, D (cm)	Intensity Percentage (%)	
	Water Medium	Blood Medium
1	76.770	80.317
2	73.810	77.626
3	68.909	72.920
4	62.881	66.924
5	56.588	60.524
6	50.582	54.323

The result shows an inverse correlation between distance and wave intensity that was detected by a detector. The received wave intensity will be decrease when the distance between source and detector increase as shown in the Figure 5. In Figure 5, it appears that the percentage of the reflection intensity for blood medium is greater than water medium. I can be explained that the acoustic impedance of blood is greater than the acoustic impedance of water. Similarly to the density and velocity of acoustic waves pass through the blood medium is greater than in the water medium.

Additionally, the simulation was conducted to determine the minimum diameter of the bubble that can be detected with a ka constant value 2 and using a various frequency of ultrasonic waves i.e. 40 kHz, 100 kHz, 200 kHz, 300 kHz, 500 kHz, and 1 MHz. The calculated results are shown in the graph of Figure 6. As shown in Figure 6, the capabilities of bubble detection depend on the frequency of the ultrasonic wave source. If the frequency of the ultrasonic waves used increasingly large, the minimum diameter of the bubble which can be detected will be smaller. It can be observed from the analysis results for the frequency resources using of 40 kHz, 100 kHz, 200 kHz, 300 kHz, 500 kHz, and 1 MHz respectively, are 23.84 mm, 9.53 mm, 4.77 mm, 3, 18 mm, 1.91 mm, and 0.95 mm. Hence, for the detecting bubble purposes, especially in the arteries is required ultrasonic frequency source with minimum frequency 1 MHz.

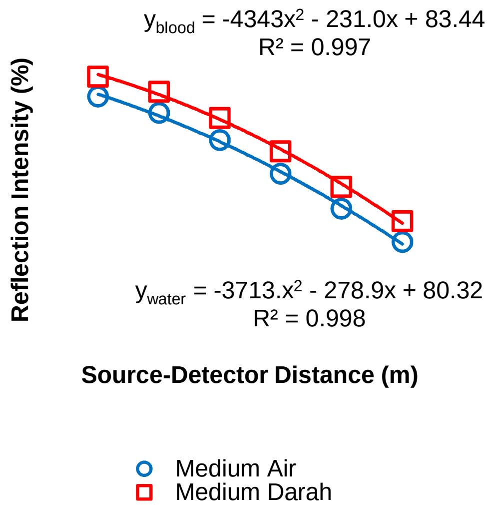

Figure 5 **The percentage of the received wave intensity detector for water medium and blood medium.**

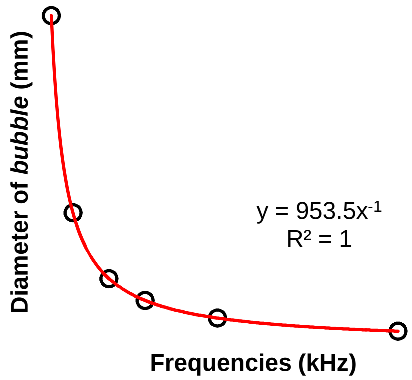

Figure 6 **The minimum bubble size that can be detected using different frequencies.**

5. Conclusion

The simulation results show that the attenuation of the ultrasonic signal intensity detected was influenced by several factors, including the medium characteristics, the presence and characteristics of gas bubble, and the distance of signal source-detector as a receiver. Attenuation due to medium absorption is very small, in which the amplitude loss for medium blood and water are respectively 1.1% and 0.012%. The existence of the bubbles in the medium can cause a loss of amplitude about 4% to 5%. Attenuation which caused by the presence of oxygen bubble is greater than the nitrogen bubble. In addition, the bubble detection capabilities depend on the source frequency usage. For the future work, a low-cost portable bubble detection instrument will be made for the application of early detection of decompression illness.

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