Simulation Research on Frequency Optimization for Oil-Water-Gas Regimes Identification Using Invasive Approach of Ultrasonic Tomography

Abdulrahman Farah Gubran Ahmed Alfareh[1], Mohd Hafiz Fazalul Rahiman[1], Yasmin Abdul Wahab[2*], Leow Pei Ling[3], Ruzairi Abdul Rahim[3], Suzanna Ridzuan Aw[4], Juliza Jamaludin[5], Jaysuman Pusppanathan[6]

[1]Tomography Imaging Research Group, Faculty of Electrical Engineering Technology, Universiti Malaysia Perlis, Pauh Putra Campus, 02600 Arau, Perlis, Malaysia
[2*]Advanced Metrology Sensor Research Group (AMES), Faculty of Electrical & Electronics Engineering Technology, Universiti Malaysia Pahang, 26600 Pekan, Pahang ,Malaysia
[3]Process Tomography Research Group (Protom-i), School of Electrical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia
[4]Faculty of Electrical & Automation Engineering Technology, Terengganu Advance Technical Institute University College (TATiUC), Jalan Panchor, Telok Kalong, 24000 Kemaman, Terengganu, Malaysia
[5]Faculty of Engineering & Built Environment, Universiti Sains Islam Malaysia, Bandar Baru Nilai, 71800, Nilai, Negeri Sembilan, Malaysia
[6]Sports Innovation & Technology Centre (SiTC), Institute of Human Centered Engineering (iHumen), Universiti Teknologi Malaysia 81310 Skudai Johor.

Corresponding author* email: yasmin@ump.edu.my
Available online 20 June 2022

ABSTRACT

This paper presents a simulation study of imaging and visualizing of the three-phase mixture (oil, air, and water) using an invasive ultrasonic tomography approach. Therefore, sound wave propagation phenomena of ultrasonic transducers and its conditions passing through different component have been studied and utilized to simulate and reconstruct the images for the mixture. The change of wave pressure and direction happens when waves go through the interface of two materials boundaries. In this study, 16 transducers have been mounted around the column invasively in order to improve the quality of measurement and spatial resolution of the reconstructed images. Finite Element Method (FEM) has been used to model the system, conduct a feasibility study of the performance, and analysis by simulation using COMSOL Multiphysics simulation software. Transmission mode sensing technique has been proposed in this study. Five different operating frequencies (40 kHz, 250 kHz, 333 kHz, 400 kHz, 500 kHz), reconstructing algorithms were examined to confirm substantially the suitable frequency for imaging three different materials (multiphase mixture) as proposed in this study. Four analytical and statistical image reconstruction algorithms (Linear Back Projection algorithm (LBP), Filter-Back Projection (FBP), Newton's One-Step Error Reconstruction (NOSER), and Tikhonov Regularization algorithm (Tk) were applied to visualize the result for the three-phase mixture. Eventually, evaluation of this study was assessed by using the Mean Structural Similarity Index (MSSIM). The conclusion of this study provided new findings of ultrasonic tomography approach for three-phase mixture research field, where optimum operating frequency is 500 kHz and the suitable image reconstruction algorithms for this study is Tikhonov.

Keywords: Ultrasonic tomography, Three phase mixtures, Invasive

1. Introduction

The multiphase regime such as liquid, solid, and gas are the main concern in industrial applications, where visualized measurement processes vital importance in production increase, state monitoring, and fault prognosis. One of the techniques that can be used is known as ultrasonic tomography (UT).

Ultrasonic tomography is applied to reconstruct the image of the region of interest-based on the spatial distribution of acoustic impedance [1]. A basic structure of an ultrasonic tomogram system consists of a sensor array, data acquisition, and measurement system, as well as image reconstruction algorithms as shown in Figure 1. For flow measurement, the sensor array is normally used as transducers to transmit and receive signals, which is mounted around the pipe or the column for data acquisition propose. The measurement system is dependently upon the core of the system and the type of desired data to be collected. Finally, the image reconstruction algorithms are used to visualize and represent the collected data as an image in the PC.

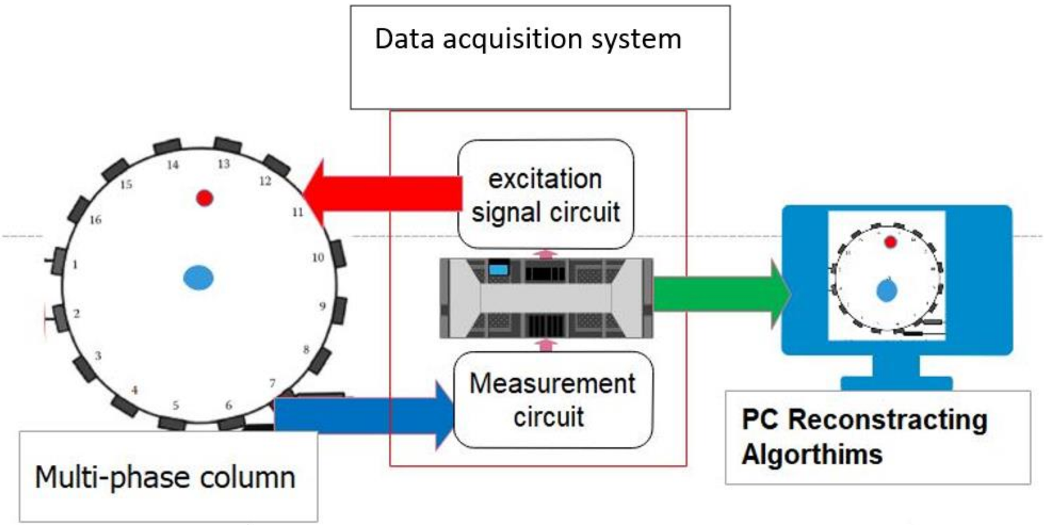


Figure 1. Basic structure of ultrasonic tomography system

Moreover, ultrasound is a branch of acoustics with sound wave above 20 KHz that utilize the mechanical pressure wave above the human hearing range [2]. The monitoring of the fluid in the pipeline of the oil industry has importance to measure the fluids produced from oil wells accurately for efficient oil exploitation and production. Fluids are widely well-known in the oil industry, chemical plant, and other engineering fields. Normally, oil field exploitation produces a complex mixture of oil, water, gas, and other fluids that made a difficult to measure the multi-phase fluids. The conventional technique is to separate components individually and measurement can be applied to each component using a single-phase measurement. Thus, the cost, time, and efforts will be increased. Besides, there has been wide research of ultrasonic tomography in identifying multiphase regimes but mostly focus on two-phase regimes like water-oil, water-air, or oil-air as in Ref. [1], [3]–[6]. Therefore, looking for another approach that can measure internal acoustic distribution in three phase regimes is highly recommended, which is capable of extracting information such as mixture concentration and mass of flow for each component, without separation.

Besides, the frequency is the main factor when dealing with ultrasonic solutions in fluids. Thus, transmitted signals by the transducers play a great role when it comes to accuracy depends on the media properties. Normally, liquids have sonic velocity for approximation 1000\ m/s. Therefore, transducer with a greater frequency of more than 1 MHz can resolve objects less than 1mm [7]. However, the cost is high and the equipment is difficult to find. Besides, the greater the frequency the smaller the angle of transmission, where the smaller the angle of transmission leads to an increase in the number of transducers to view the object from as many angles as possible to obtain complete information of the phantoms for each mode [8]. Therefore, this article aims to investigate the optimize frequency of identifying three phase regimes with suitable reconstruction algorithms through finite element model simulation approach. The oil will be the main medium in the pipe while water and air become the obstacle.

In addition, the ultrasonic tomography consists of either transmission mode or reflection mode whereas a straight line is assumed in the transmission mode [9]. In the same way, the transmission and reflection of signals through two materials from the transducer penetrates through the different layers (multiphase mixture). When propagating a signal from high acoustic impedance to low acoustic impedance media, reflection and scattering phenomena normally occurred, which called the boundaries interfacing of acoustic impedance. Hence, this paper will consider the transmission mode with the invasive ultrasonic technique in water, gas and oil mixtures and propose the solution to cater to the problems. The invasive technique and transmission mode is applied compared with non-invasive of ultrasonic tomography is to improve the spatial resolution of the ultrasonic tomography system.

2. Fundamental of Ultrasonic Tomography

Ideally, the sound pressure (signal amplitude) diminishes with distance during traveling through materials due to wave pervasion (see Figure 2). The sound of amplitude is weakened due to the scattering effect and absorption process of sound, where the reflection of sound in the opposite direction of wave propagation direction. The concept of scattering is the effects on wave propagation due to an inhomogeneous medium. The abruptly changes of the acoustic impedance at the boundary interaction will occurred if the material is not totally homogeneous. Alternately, the absorption is the conversion of sound pressure energy to other forms of energy due to wave splitting into various reflections, that repeatedly happen for each wave and divided into partial waves that gradually converted into heat.

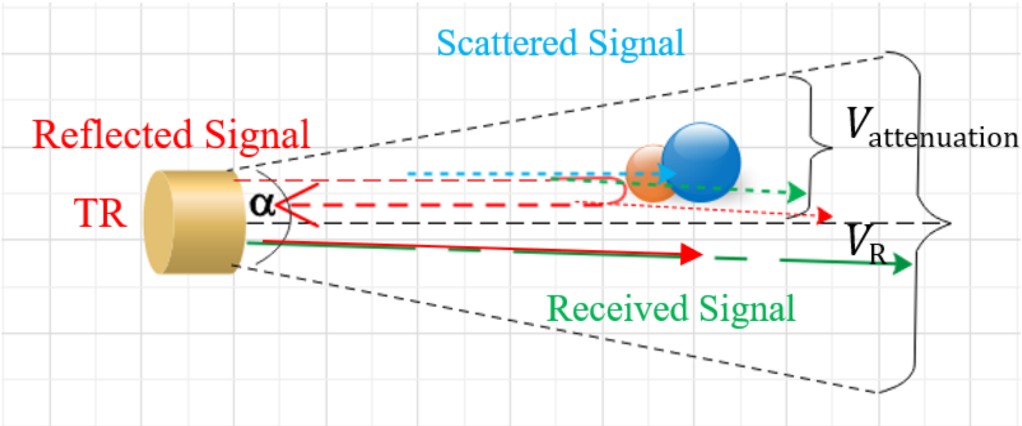


Figure 2. Attenuation modelling of an ultrasonic signal

The amplitude change of a decaying plane wave can be expressed as in Eqn. 1 [10]. The A_0 is known as initial (unattenuated) amplitude, α is the attenuation coefficient of the object field, and x is the distance of transmission.

$$A = A_0 e^{-\alpha x} \quad (1)$$

Subsequently, the attenuation is also known as the loss in acoustic energy of transmitted waves [11], which caused by decrement exponentially when traveling through distance and this loss is following Newton's law conservation of energy. Where a part of the acoustic energy is converted to thermal energy as heat. In this study, the measured voltage can be expressed as in Eqn. 2. The v_{Rx} is the ultrasonic receiver voltage, v_{Tx} is the ultrasonic transmitted voltage, and z is the distance of the transmission.

$$v_{Rx} = v_{Tx} e^{-\alpha z} \quad (2)$$

Besides, the boundaries interfacing of acoustic impedance is an important factor, in terms of reflection and transmission of signals between two materials. The transmitted signal from the transducer penetrates through the different materials layers and reflection is excessive when the propagating signal from high acoustic impedance to low acoustic impedance. The impedance and velocity properties of the material are an essential part of the signal behaviour during penetration through the materials and interfacing with different materials. The acoustic impedance (Z) is formalized as in Eqn. 3 [12]. ρ is density of the medium, and c is the speed sound in the medium.

$$Z = \rho\, c \quad (3)$$

Table 1 shows the material properties of sound speed, density, and the calculated acoustic impedance of the applied material in this research based on Eqn. 3.

Table 1. Material properties

Material	Speed of sound [m/s]	Density [kg/m3]	Acoustic Impedance [Mkg/m2s]
Water	1500	1000	1.5
Oil (Crude Oil)	1200	800	0.96
Glycerol	2730	1190	3.25
Air	340	1	0.00034

In addition, Eqn. 4 and 5 indicate the reflection and transmission relationship that corresponds to the acoustic impedance for the mediums involved[6]. The Z_1 rand Z_2 representing the acoustic impedance of the first and second material, respectively.

$$\text{Reflection coefficient , } R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (4)$$

$$\text{Transmission coefficient , } D = \frac{2Z_2}{Z_2 + Z_1} \quad (5)$$

According to these relations, the example of ratio between transmission and reflection at the boundary interaction is shown in Table 2. It can be observed that the reflection of sound waves is dependent on interfacing impedance of interacted materials which is the density of material multiplied by the speed of sound. Significantly, the penetration of transmission ultrasonic signal is bigger for water - oil interaction but very small for the medium of oil-air interaction or air-water interaction.

Table 2. Ratio between transmission and reflection at boundary interaction

Interaction	Medium 1 [Mkg/m^2s]	Medium 2 [Mkg/m^2s]	Transmission (%)	Reflection (%)
Water – Oil	1.5	0.96	78.05	-21.95
Oil – Air	0.96	0.00034	0.07	-99.93
Air – Water	0.00034	1.5	0.05	99.95

Ultrasonic tomography has offered quantifiable images of acoustical parameters such as density, the speed of sound, attenuation by utilizing the pressure field measurements[13]. he tomogram of the region of interest can be reconstructed in the inverse problem part. There are a variety of types of image reconstruction algorithms implemented in the ultrasonic tomography system. The most popular algorithm is the linear back-projection algorithm (LBP). The simplicity and straightforward of the LBP algorithm make it an easy choice for image reconstruction in a few fields of tomography. Although its reconstruction accuracy is not that perfect, LBP has the advantage of being quite fast, in practice requiring only the multiplication of a fixed reconstruction matrix times the vector of measurements as in Ref. [14], [15]. The LBP algorithm can be applied by using Eqn. 10 as detailed explain Ref. [14]. Another non-iterative algorithm implemented in this research is filter back projection algorithm (FBP). As explained in Ref. [16]. Besides, the comparison also had been carried out by using iterative algorithm such as Newton's One-Step Error Reconstruction (NOSER) and Tikhonov Regularization as in Ref. [17].

3. Methodology

The modelling ultrasonic system had been done by using finite element software which is Comsol Multiphysics software. The authors implemented 16 ultrasonic transducers that mounted around the pipe invasively but non-intrusive. It means that the sensor is only placed in the inner part of the pipe but not protrudes into the medium[18]. The reason for using the invasive approach is because the emitted ultrasound waves will be focused on the mixture directly.

Figure 3 illustrates the transducer arrangement of the ultrasonic tomography model. In this modeling, the geometry of the system includes the inner diameter and circumference of the pipe is 60 mm and 188.5 mm, respectively. Simultaneously, the 16 transducers had been placed equally around the pipe with the degree of rotation is 22.5 degrees, and the transducer diameter is 11.78 mm each.

The divergence angle of the transducer depends totally on frequency propagation as detailed explained in Ref. [19]. Consequently, different frequencies were tested included 40 KHz, 250 KHz, 333 kHz, 400 kHz, and 500 kHz. Figure 4 shows an example when TxR1 becomes a transmitter when all channel becomes a transmitter and meshing of the model of ultrasonic tomography with existing obstacles. Here, the divergence angle of the transducer becomes 110 °. The fan beam projection had been applied. When channel 1 becomes a transmitter, other channels become the receiver. This complete cycle will be done when all transducers become transmitters and receivers. The continuous sound wave approach has been utilized in designing and evaluating the system to investigate and analyze the internal interaction and distribution of the mixture. The sensor readings performance was then analyzed and used for the image reconstruction part.

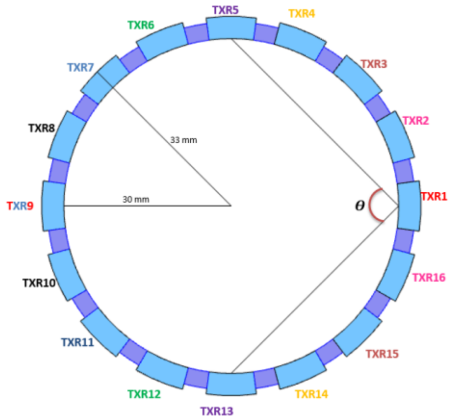


Figure 3. Transducer arrangement

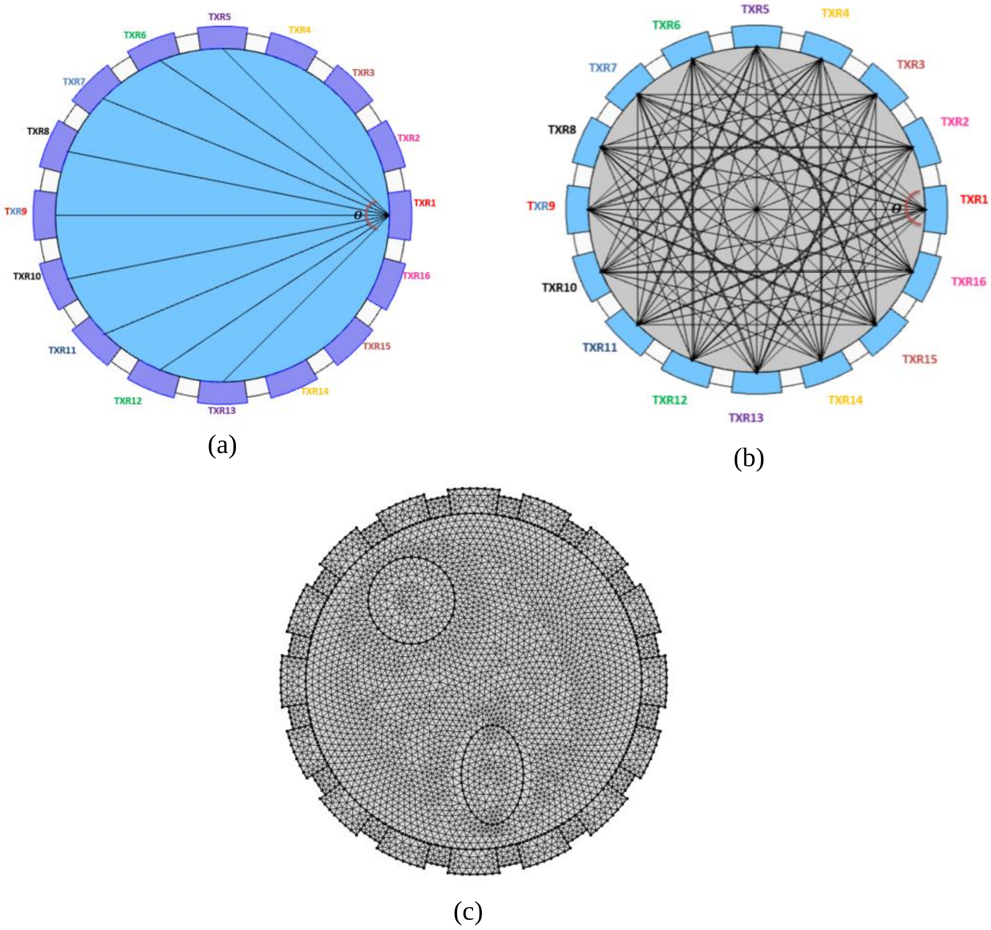
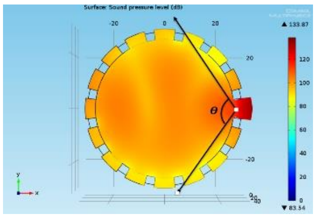
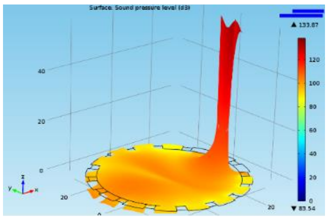
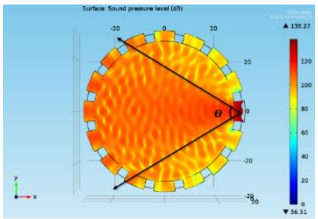
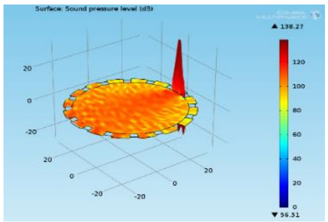
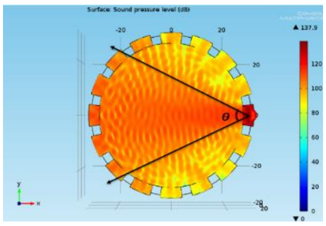
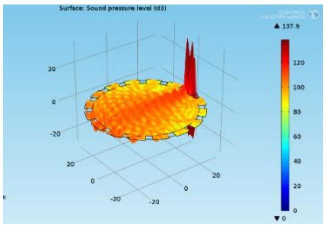
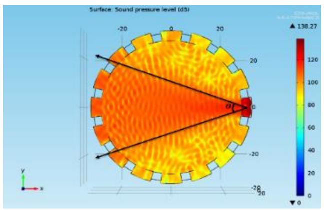
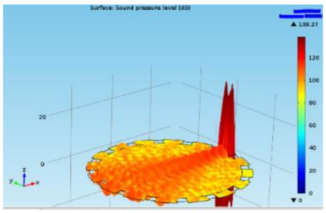
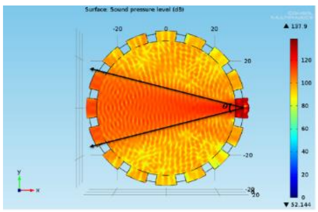
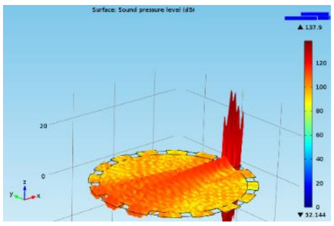


Figure 4. Projection model:(a) Single projection, (b) Full projection, (c) Example mesh with existing of obstacle

4. Results and Discussion

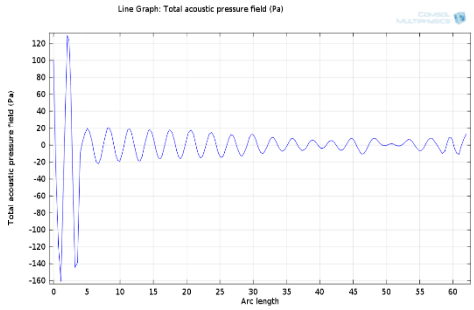
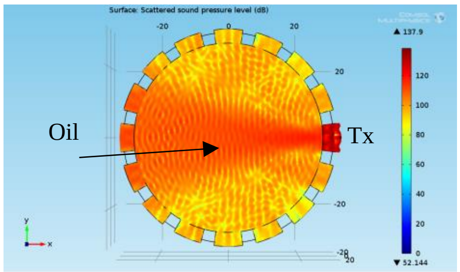
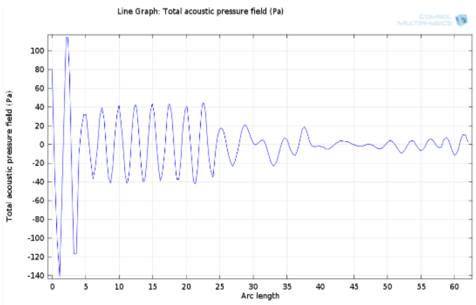
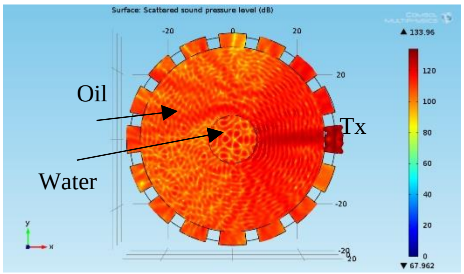
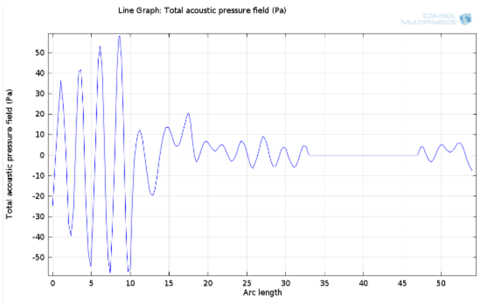
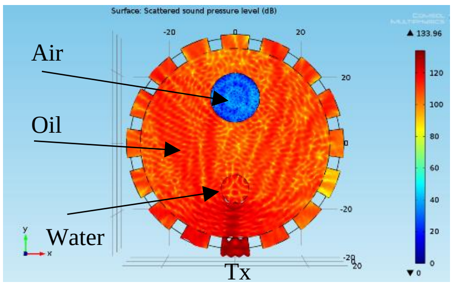
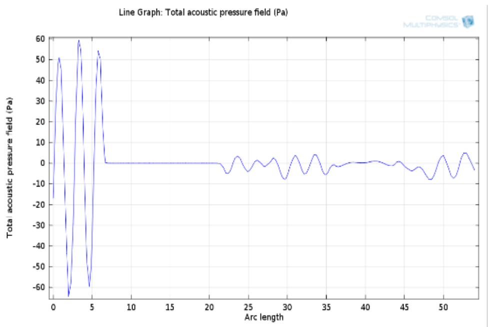
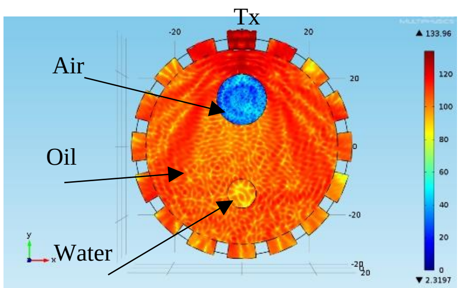
The frequency is an impact factor when dealing with ultrasonic solutions in fluids. Thus, transmitted signals by the transducers play a great role when it comes to accuracy depending on the media properties. Normally, liquids have sonic velocity for an approximation of 1 mm/us. Therefore, a transducer with a greater frequency more often than 1 MHz can resolve objects less than 1mm[7]. Table 3 shows the projection angle with a different value of frequencies. It can be seen that; the increment of frequency will decrease the beam angle for each of the transmitters. The 500 kHz has a smaller angle and 40 kHz has a wider angle.

Table 3. Projection angles of different frequencies

	2D Projection	3D Projection
40 KHz		
250 KHz		
333 KHz		
400 KHz		
500 KHz		

Furthermore, the analysis of the signal propagation for each medium also has been done. The behavior of the signals during the penetration of different phases or layers can be shown in Table 4. The 500 KHz had been used as a reference for this simulation analysis. The medium oil (see Table 4 (a)) was used as the main medium in this research. It can be observed that the penetration of the signal in oil was without fluctuations compared to the medium that exists of air and water interfacing. The signal showed different patterns because of the change in the density of different mixtures. Moreover, when the different channel was set as the transmitter, Tx, it can be seen that the signal passes through the air as shown in Table 4.2 (c) and Table 4.2 (d) showed the lowest amplitude compared when it passes through water or oil. It shows that the signal in a low-density medium has low fluctuated amplitude.

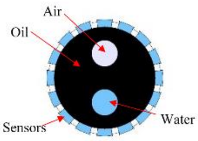
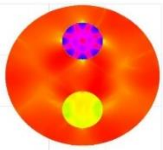
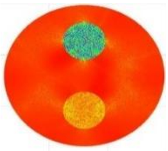
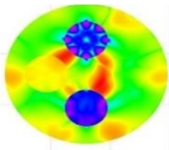
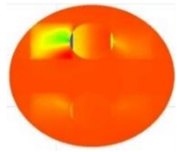
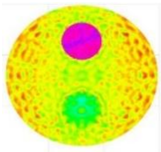
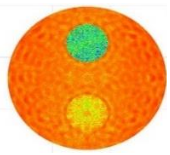
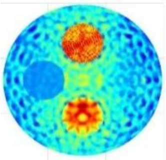
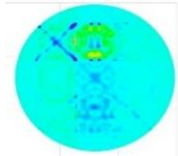
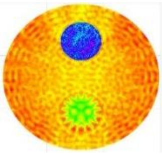
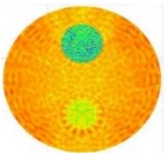
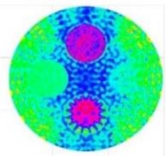
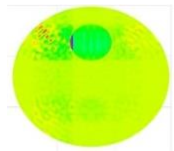
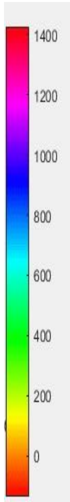
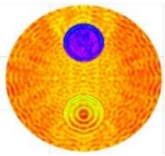
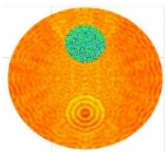
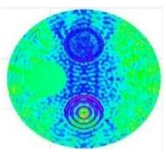
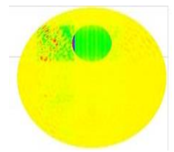
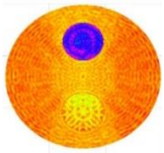
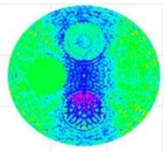
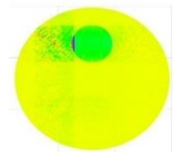
Table 4. Ultrasonic propagation signal in different medium

	Ultrasonic Propagated signals	Surface result at 500 KHz
(a) Oil only		
(b) Oil /Water		
(c) Oil/Water /Gas		
(d) Oil/ Gas/ Water		

The 128 x 128 pixels of tomograms using the LBP algorithm for distinguishing conditions had been carried out in this research to observe the performance of the optimization frequency obtained. Moreover, the other three algorithms named FBP, NOSER, and Tikhonov are also introduced and used to compare the result with the Linear Back projection (LBP).

Table 5 illustrates the tomograms of phantom A that can be assumed in the vertical position with different frequencies and image reconstruction algorithms. The size of air and water is 7 mm in diameter. It is indicated that the reconstructed image clarity and similarity to the real phantom were depending on the frequency applied and image reconstruction algorithm. The reconstructed images in Table 5 at 250 kHz using filter back projection (FBP) are clearer and it easy to distinguish the three phases.

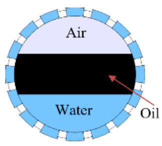
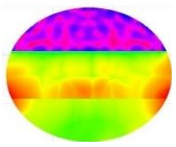
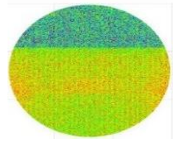
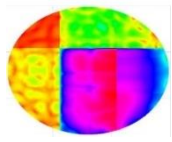
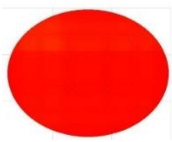
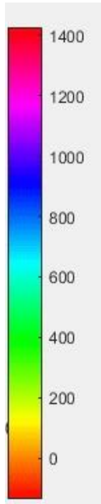
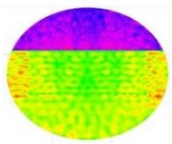
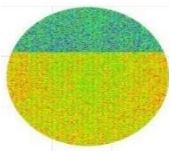
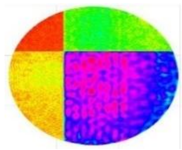
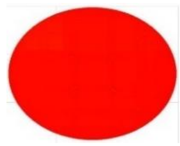
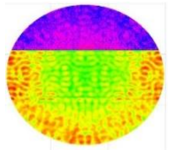
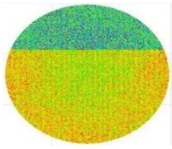
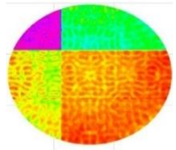
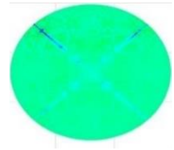
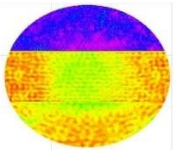
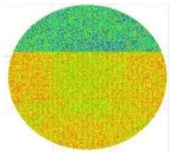
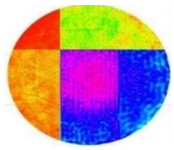
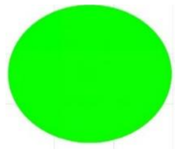
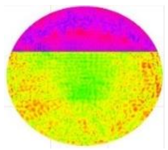
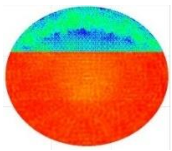
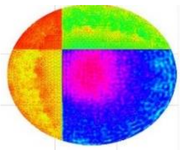
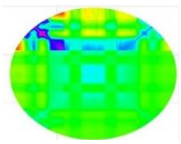
Table 5. Tomograms of phantom A at a different frequency and image reconstruction algorithm for vertical pipe

Phantom A	Freq (KHz)	LBP	FBP	NOSER	Tikhonov	
	40					
	250					
	333					
	400					
	500					

Subsequently, Table 6 illustrates the tomograms of phantom B in the pipe at the horizontal position. The results can be concluded that the reconstructed images clearness was also depending on the frequency applied to the phantom and the image reconstruction algorithm used. As shown in Table 6, the reconstructed image at 500 kHz using linear back projection (LBP) is distinguished as the three-phase mixture compared to other frequencies and algorithms.

Later, the mean structural similarity index for measurement (MSSIM) as introduced by Zhou Wang *et al.* [20]–[23] had been applied to know how much the tomogram is similar to the reference image. The MSSIM results in between 0 and 1. If the value is near 1, it means that the image is almost similar to the reference image. Figure 5 and Figure 6 show the MSSIM values for both phantom A and phantom B. Generally, even though the conclusion made from the visualization of tomograms were not the same as what obtained in Table 5 and Table 6, the Tikhonov algorithm showed the highest value of MSSIM for all frequencies and other algorithms applied. It is because the basic algorithm was based on the LBP algorithm. Thus, the smearing effect exists from the LBP algorithm influence the results obtained for others algorithm. Also, the 500 KHz gave the highest value of MSSIM for both phantom A and phantom B.

Table 6. Tomograms of phantom B at a different frequency and image reconstruction algorithm for horizontal pipe

Phantom B	Freq (KHz)	LBP	FBP	NOSER	Tikhonov	
	40					
	250					
	333					
	400					
	500					

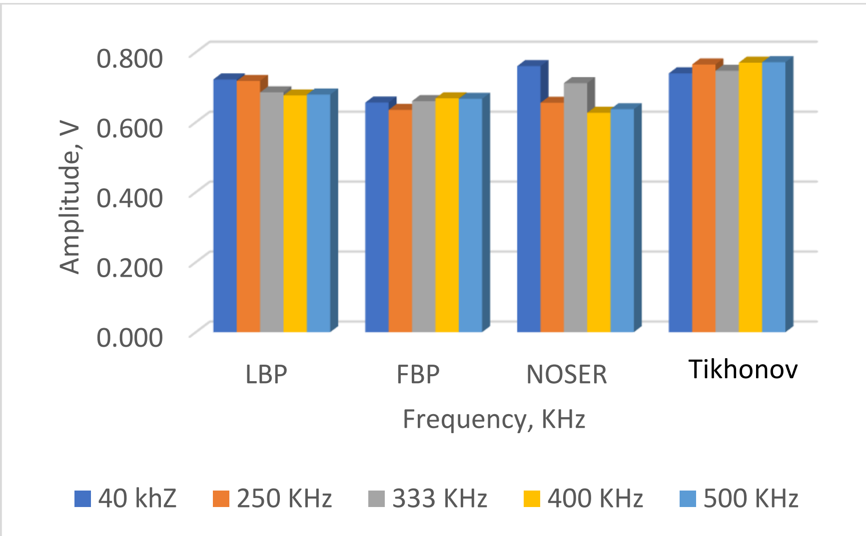


Figure 5. MSSIM of phantom A

Figure 6. MSSIM of phantom B

5. Conclusion

In short, the demonstrated results of the simulation of different frequencies have been applied for different models with different phantoms. It can be concluded that the higher the frequency the higher the spatial resolution. Moreover, this finding is dependently limited to the size of the transducer and the media of propagation (accuracy condition). The result of image reconstructing for different algorithms and frequencies shows that the Tikhonov algorithm has the highest value over all the algorithms at the frequency of 500 kHz for the same algorithm. The Tikhonov algorithm has repeatedly the highest value according to the MSSIM evaluation and suitable for visualizing a three-phase mixture. Future research will include different testing of phantom conditions and a thresholding approach to improve the tomograms of the region of interest.

Acknowledgment

The authors would like to thank the Collaboration Research Grant (CRG-UTM) RDU182304 and CRG 05G04 for support the research.

References

[1] Jiang, Y., Soleimani, M. & Wang, B. (2019). Contactless electrical impedance and ultrasonic tomography: Correlation, comparison and complementarity study. *Measurement Science and Technology, 30 (11)*.

[2] Duck, F. & Leighton, T. (2018). Frequency bands for ultrasound, suitable for the consideration of its health effects. *The Journal of the Acoustical Society of America*, *144 (4)*, 2490–2500.

[3] Liang, G., Dong, F., Kolehmainen, V., Vauhkonen, M. & Ren, S. (2020). Nonstationary Image Reconstruction in Ultrasonic Transmission Tomography using Kalman Filter and Dimension Reduction. *IEEE Transactions on Instrumentation and Measurement*, *70*, 1–1.

[4] Zielińska, M. & Rucka, M. (2020). Detection of debonding in reinforced concrete beams using ultrasonic transmission tomography and hybrid ray tracing technique. *Construction and Building Materials, 262*.

[5] Liu, H., Tan, C., Ren, S. & Dong, F. (2020). Real-Time Reconstruction for Low Contrast Ultrasonic Tomography Using Continuous-Wave Excitation. *IEEE Transactions on Instrumentation and Measurement*, *69(4)*, 1632–1642.

[6] Qorbani, O. & Aghdam, E.N. (2020). Two-phase flow measuring with ultrasonic tomography. *Archives of Acoustics*, *45(3)*, 459–465.

[7] Williams, R.A. & Beck, M.S. (2012). *Process tomography: Principles, techniques and applications*. Elsevier Ltd.

[8] Rahiman, Ruzairi, H. (2011). Gas Hold-Up Profiles Measurement Using Ultrasonic Sensor. *IEEE Sensors Journal*, *11(2)*, 460–461.

[9] Zhang, W., Tan, C. & Dong, F. (2020). Wide Angle Ultrasonic Transmission Tomography by Sparse Preimaged OMP Algorithm. *IEEE Transactions on Instrumentation and Measurement*, *69(9)*, 6262–6270.

[10] Fazalul Rahiman, M.H. et al. (2014). Gas Hold-Up Profiles Determination by means of Ultrasonic Transducer.

Jurnal Teknologi, 69(8), 81–84.

[11] Chai, H.K., Momoki, S., Kobayashi, Y., Aggelis, D.G. & Shiotani, T. (2011). Tomographic reconstruction for concrete using attenuation of ultrasound. *NDT & E International*, *44(2)*, 206–215.

[12] Khairi, M.T.., Ibrahim, S., Faramarzi, M., Sean, G.P., Pusppanathan, J. & Abid, A.(2019). Ultrasound comptuted tomography for material inspection: Principles, design and applications. *Measurement: Journal of the International Measurement Confederation, 146*, 490–523.

[13] Mamou, J. (2013). *Quantitative Ultrasound in Soft Tissues*.

[14] Li, N., Cao, M., Xu, K., Jia, J. & Du, H. (2018). Ultrasonic transmission tomography sensor design for bubble identification in gas-liquid bubble column reactors. *Sensors (Switzerland)*, *18(12).*

[15] Li, N., Xu, K., Liu, K., He, C. &Wu, B. (2019). A Novel Sensistivity Matrix Construction Method for Ultrasonic Tomography Based on Simulation Studies. *IEEE Transactions on Instrumentation and Measurement, 68(10)*, 3548–3562.

[16] Wahab, Y.A. et al. (2017). Inverse Problem : Comparison between Linear Back- Projection Algorithm and Filtered Back-Projection Algorithm in Soft-Field Tomography. *International Journal of Integrated Engineering*, *9(4)*, 32–36.

[17] Du, Q., Bai, B., Pang, P. & Ke, L. (2012). An improved reconstruction method of MIT based on one-step NOSER. in: *Proceedings - 2012 International Conference on Biomedical Engineering and Biotechnology*, *1*, 723–726.

[18] Abdul Wahab, Y. et al. (2018). Optimisation of electrode dimensions of ERT for non-invasive measurement applied for static liquid–gas regime identification. *Sensors and Actuators, A: Physical*, *270*, 50–64.

[19] Abbaszadeh, J., Rahim, H.A. & Rahim, R.A.(2012). Optimizing the Frequency of Ultrasonic Tomography System with a Metal Pipeline. *Sensors & Transducers*, *140(5)*, 53–64.

[20] Wang, Z. (2011). Applications of objective image quality assessment methods. *Signal Processing Magazine, IEEE*, *28(6)*, 137–142.

[21] Wang, Z. & Bovik, A.C.(2009). Error : Love It or Leave It ?. *IEEE Signal Processing Magazine*, *26 (January)*, 98–117.

[22] Wang, Z., Bovik, A.C., Sheikh, H.R. & Simmoncelli, E.P.(2004). Image Quality Assessment: From Error Visibility to Structural Similarity. *IEEE Transactions on Image Processing*, *13(4)*, 600–612.

[23] Wang, Z., Bovik, A.C. & Lu, L. (2002). Why is Image Quality Assessment So Difficult?. in: *Proceedings of the 2002 IEEE International Conference on Acoustics Speech and Signal Processing, 303*, 3313–3316.