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Optimizing the Frequency of Ultrasonic Tomography System with a Metal Pipeline

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Abstract: Ultrasonic Tomography has an important role in industry to produce scanned images for various propose. In this paper, producing the cross sectional images of pipe for detecting percentage of attendance of solid, liquid and gas inside the metal pipe has been investigated. The correct method of mounting of Ultrasonic sensors and behavior of the ultrasonic wave propagation in different layers has been simulated by the use of finite element software (COMSOL Multiphysics 3.5). To increase in practical nondestructive evaluation and inspection, we should increase our understanding of the basic physics and wave mechanics associated with guided wave inspection. Finding the proper ultrasonic sensor base on its efficiency is the main step of designing an Ultrasonic Tomography system. This is done by estimating the resonance frequency of sensor due to manner of ultrasonic wave propagation in different frequencies shown in simulation results. Optimum frequency of the system is proposed 45 kHz. *Copyright © 2012 IFSA.*

Keywords: Process tomography, Transmission mode, Ultrasonic wave, Ultrasonic tomography, Metal pipeline.

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1. Introduction

The preliminary investigation on determining of the component concentration in flow has been carried out in the late 1980s and early 1990s by applying the capacitance tomography (ECT) [1]. Due to the application of process tomography in industry, especially for measurements in the oil industry in Europe and the coal industry in the USA research on the process tomography have been developed. Some of the studies include measurement of water content in oil [2] and the visualization of component distribution in multi-components flow pipelines [3]. This is a various types of noninvasive tomography for producing the cross sectional images of pipes that in this research Ultrasonic Tomography (UT) has been investigated.

Principally an Ultrasonic Tomography (UT) system is consisted of two general parts, software and hardware parts, which are shown on Fig. 1 as a block diagram. Hardware part of UT systems consists of various parts such as pulse generating, amplifying the generated pulse, sending an amplified pulse to sensors, which are mounted on the periphery of the pipe to data acquisition and receiving the data then reducing added noise, amplifying the received signal and finally converting the analogue data to digital data. Digital gathered data in software part utilize to construct the cross sectional image of pipe by the application of various algorithms.

Identification the concentration of various media inside the pipes in non invasive mode (without making any crash or hole on the pipe) and in non destructive mode (without any contact with the inner fluid) is a challenge among the researchers in recent decades. Due to the done researches and designed systems to date, various type of tomography systems have been designed by the use of various sensors, mounted on the periphery of pipe to achieve the data from inside the pipe and send them to computer for producing cross sectional images and analyzing the concentration profile. In this research proper ultrasonic sensor based on its suitable resonance frequency will be introduced for data collecting of flow regime inside the metal pipe.

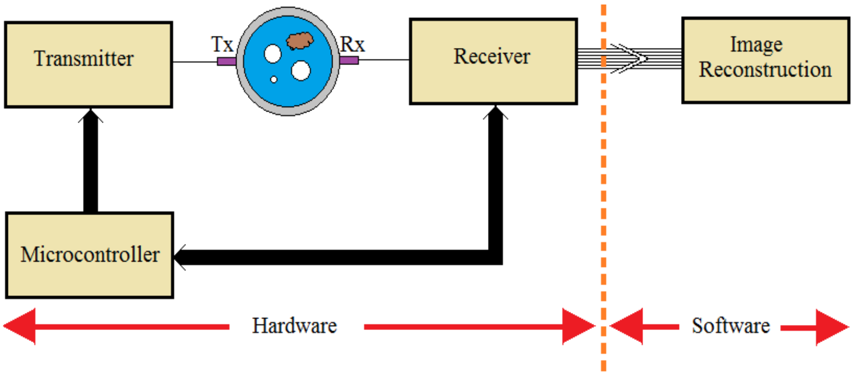

Fig. 1. General block diagram of an ultrasonic Tomography system.

Acoustic impedance of layers is the significant point of designing due to its influence on the manner of ultrasonic wave propagation. The mentioned matter results the most of designed and manufactured UT systems use the pipes with material such as Acrylic, PVC and plastic. Since the large difference of acoustic impedance among liquid and metal pipes and lamb wave disturbance, metal pipe is not investigated as the conveyor of fluent in UT. Majority of designers endorse that it is difficult to collimate and problems occur due to reflections within enclosed spaces, such as metal pipes [4]. The main problems of metal pipes are high attenuation of ultrasonic energy and high influence of bulk waves compares to other kinds of pipes.

Despite the mentioned problems of metal pipe as a conveyor of UT systems, it is investigated to find the solution in this paper. Installing method of ultrasonic sensors and behavior of ultrasonic wave propagation in different layers is simulated by the means of finite element software. Bulk wave propagation of ultrasonic wave on the wall of metal pipe depends on the frequency of ultrasonic wave. According to the simulation results of ultrasonic wave propagation in various frequencies of ultrasonic wave, the optimum frequency for the ultrasonic sensors is estimated.

In this paper, the fundamental physics of ultrasonic wave propagation and essential mathematic for simulating in mathematical software will be presented in second and third units, respectively. Then followed by demonstrating the simulation results and finally the conclusion are presented.

2. Propagation of Ultrasonic Wave

Ultrasonic tomography is based on time-varying and amplitude of reached wave in receiver face, which it is generally referred to as acoustic wave distribution. All material substances are made of atoms, which may be forced into vibration motion in their fixed positions. There are many different patterns of vibration motion at the atomic level. Acoustics is focused on particles that contain many atoms that move in unison and cause to produce a mechanical wave. The particles of material have elastic oscillations when it is not stressed in tension or compression beyond its elastic limit and internal (electrostatic) restoration forces arises when the particles of a medium are displaced from their equilibrium positions. It is the mentioned elastic restoring forces between particles, combined with inertia of the particles, which leads to the oscillatory motions of the medium [5].

The first layer is metal pipe and its material principally is solid. In solids, ultrasound waves can propagate in four principle modes, which are based on the way the particles oscillate. Ultrasound can propagate as longitudinal waves, shear waves, surface waves, and in thin materials as plate waves. Longitudinal and shear waves are the two modes of propagation most widely used in ultrasonic testing. The modes of ultrasound wave propagation are illustrated in Fig. 2 [6].

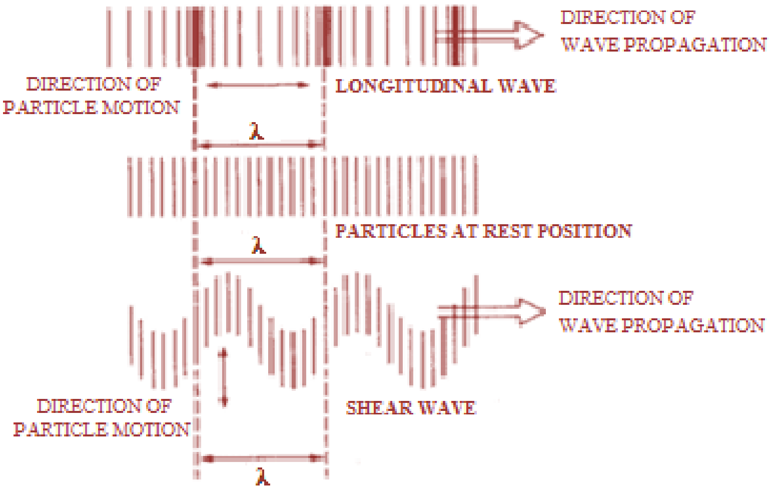

Fig. 2. Longitudinal and shear waves of wave propagation mode.

In longitudinal waves, the oscillations occur in the direction of wave propagation. The longitudinal wave is also called pressure or compressional waves because of compressional and dilational forces are active in these waves. They are also sometimes called density waves due to their particle density fluctuate as they move. In liquids also longitudinal waves can be propagated as well as solids because the energy travels through the atomic structure by a series of compressions and expansion (rarefaction) movements [6].

In the transverse or shear wave, the particles oscillate at a right angle or transverse to the direction of ultrasonic wave propagation. Shear waves for an effective propagation require an acoustically solid material and therefore, are not propagated in some materials such as liquids or gasses, effectively.

Shear waves in compare with longitudinal waves are relatively weak. Actually, shear waves are usually generated in materials using some of the energy of longitudinal waves.
The Table 1 summarizes many of the possible wave modes in solids [5].

Table 1. Ultrasonic propagation modes in solids.

Wave Types in Solids	Particle Vibrations
Longitudinal	Parallel to wave direction
Transverse (Shear)	Perpendicular to wave direction
Surface - Rayleigh	Elliptical orbit - symmetrical mode
Plate Wave - Lamb	Component perpendicular to surface (extensional wave)
Plate Wave - Love	Parallel to plane layer, perpendicular to wave direction

Between all of the demonstrated modes in Table 1, lamb wave is the undesirable wave mode and makes a problem in measuring process. Plate waves are similar to surface waves except that lamb wave can only be generated in materials a few wavelengths thick. Lamb waves are the most commonly plate waves which are used in NDT. Lamb waves are complex vibrational waves that propagate parallel to the pipe surface throughout the thickness of the material. Propagation of Lamb waves in the thickness of the pipe wall depends on the density and the elastic material properties of a component. Lamb waves propagation is also influenced a great deal by the test frequency and material thickness. Lamb waves are generated at an incident angle in which the parallel component of the velocity of the wave in the source is equal to the velocity of the wave in the metal pipe. Lamb waves will travel several meters in steel and so are useful to scan the surface of the plate, wire, and tubes [6].

With generating of Lamb waves, various modes of particle vibration are possible but the two most common are symmetrical and asymmetrical which are shown in Fig. 3 [6]. The complex motion of the particles is similar to the elliptical orbits of particles for surface waves. Symmetrical Lamb waves move in a symmetrical fashion about the median plane of the pipe. Since the lamb wave is “stretching and compressing” the plate in the wave motion direction so it is sometimes called the extensional mode. When the exciting force is parallel to the plate then wave motion in the symmetrical mode is most efficiently produced. Since a large portion of the motion moves in a normal direction to the plate, and a little motion occurs in the direction parallel to the plate so the asymmetrical Lamb wave mode is often called the “flexural mode”[5].

In this paper a transmission-mode of ultrasonic wave propagation is investigated and the receiver amplitude and the arrival time analysis are emphasized. Arrival time analysis is based on the ultrasonic propagation manner that it takes some finite time for an ultrasonic disturbance to move from one position to another inside the experimental pipe. In the other hand, another mode of ultrasonic wave, which is mentioned as a lamb wave makes disturbance in analyze the time of flight of straight path signal. Basically, the longitudinal mode of ultrasonic wave could penetrate through the pipe from the transmitting sensor to the receiving sensor within a low acoustic impedance media such as liquid. For example, the penetration of longitudinal waves from the transmitting sensor of Tx4 to the receiving sensor of Rx7 is shown in Fig. 4. However, there is another wave generated due the complex vibrational effects, which was mentioned as Lamb waves. The Lamb wave is also shown in Fig. 3 that propagates and travels within the pipe boundary.

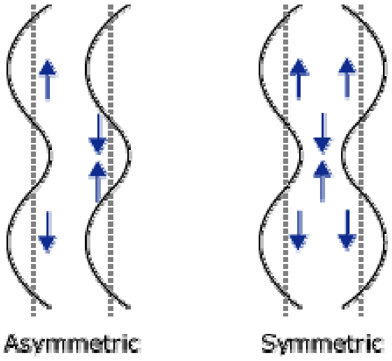

Fig. 3. Two most modes of vibration of particles.

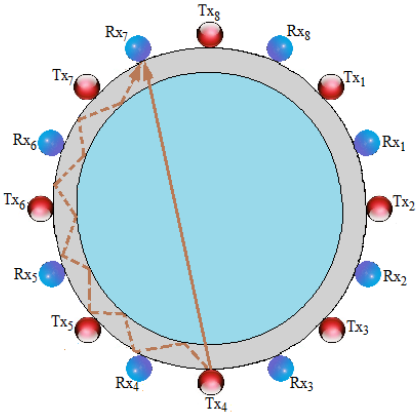

Fig. 4. Two modes of ultrasonic wave propagation in the cross section view of the pipe.

As consequences of using transmission-mode method, the amplitude of receiving wave in the receiver should relates to just the longitudinal mode not the Lamb mode. The Lamb waves do not provide any information of ultrasonic disturbances caused by the object obstruction inside the pipe because the lamb wave propagates within the pipe boundary. Finite element simulations with COMSOL software, is used for detecting the receiving time of the longitudinal waves and lamb waves. It is possible to diagnosing the manner of ultrasonic wave propagation on the pipe and finding any way to reduce the lamb wave affection by changing the frequency. The simulations with COMSOL are discussed in next section.

3. Mathematic of Simulation

Since this software is mathematic software that it can solve wave equations, so we should have an introduction to mathematics of ultrasound wave and its equations and assumptions that they are considered in my simulations. Sound waves in a lossless medium are governed by the following equation for the acoustic pressure, p (with SI unit Pa) [7]:

$$\frac{1}{\rho_0 c_s^2}\frac{\partial^2 p}{\partial t^2} + \nabla \cdot \left(-\frac{1}{\rho_0}(\nabla p - \mathbf{q})\right) = Q ,$$

here ρ0 (kg/m3) refers to the density, and cs (m/s) denotes the speed of sound. The dipole source q (N/m3) and the monopole source Q (1/s2) are both optional. The combination ρ0 cs2 is called the adiabatic bulk modulus, commonly denoted K (Pa) [7].

An important special case is a time-harmonic wave, for which the pressure varies with time as

$$p(\mathbf{x}, t) = p(\mathbf{x})e^{i\omega t},$$

where ω = 2π f (rad/s) is the angular frequency, with f (Hz) denoting the frequency. Assuming the same harmonic time dependence for the source terms, the wave equation for acoustic waves reduces to an inhomogeneous Helmholtz equation [8]:

$$\nabla \cdot \left(-\frac{1}{\rho_0}(\nabla p - \mathbf{q})\right) - \frac{\omega^2 p}{\rho_0 c_s^2} = Q$$

In lossy media, it is necessary to introduce an additional term of first order in the time derivative to account for attenuation of the sound waves [8]:

$$\frac{1}{\rho_0 c_s^2}\frac{\partial^2 p}{\partial t^2} - d_a\frac{\partial p}{\partial t} + \nabla \cdot \left(-\frac{1}{\rho_0}(\nabla p - \mathbf{q})\right) = Q$$

For transient analysis, the damping term in Equation 3.9 is absent from the standard PDE formulations in the Pressure Acoustics application modes. The intensity distribution, I(r), can be obtained from p(r) via the equation [9]:

$$I(r) = \frac{p(r)^2}{2\rho c}$$

Equation 3.8 is homogeneous and so can be solved using separation of variables. Thus, the final solution can be written as [9]:

$$p(r,t) = Ae^{i(\omega t - k \cdot \tau)}$$

The analytical treatment here shows that a sinusoidal function is obtained as the solution to homogeneous Helmholtz equation. This is in contrast with results obtained elsewhere [8] that showed an exponential decay solution with high intensity regions just below the horn tip [7]. The homogeneous Helmholtz equation 3.8 is solved using FEMLAB using the finite element method. It is imperative that while solving by numerical techniques, the node length (h) should satisfy the following [9]:

$$\frac{\Delta h}{\lambda} \leq 1$$

where λ is the wavelength while κ is the magnitude of the wave vector and is equivalent to ω/c. This condition is indicative of the accreion of errors in the finite element solution associated with increases in wave number and is termed as pollution effect [10]. To circumvent this problem, one would use as fine a mesh as possible, which has been followed in this paper and also elsewhere [11].

4. Simulation Results

The conveyor of ultrasonic tomography system is cylindrical metal pipe with simple geometry (outer diameter=20 cm, inner diameter 18 cm, height=40 cm) with ultrasonic sensors (diameter=1.5 cm), which are implemented on the surface of metal pipe. The 3D geometry of pipe with the sensor holder ring and implemented sensors are shown in Figs. 5 and 6, respectively. 2D simulating of process has been done to view the manner of propagation on the boundary of pipe and inside the pipe, precisely. The degree of freedom of meshing in this process equals to 18220 with the maximum meshing size 0.012 due to the ultrasonic wavelength.

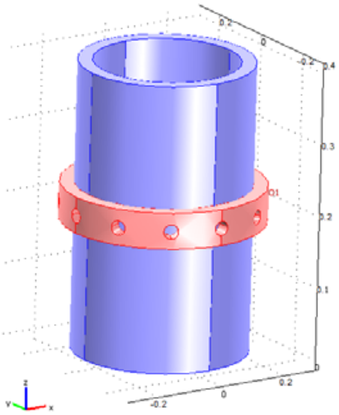

Fig. 5. 3D view of metal pipe with sensor holder ring.

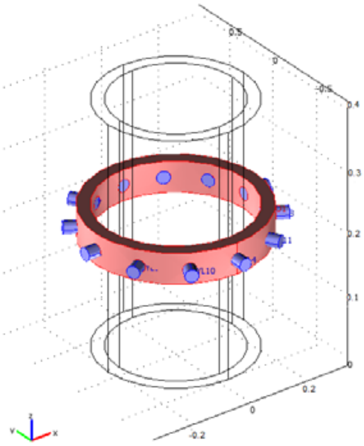

Fig. 6. Implementation of sensors on the surface of metal pipe.

According to time harmonic analyzing and assuming the resonance frequency of ultrasonic wave as 20 kHz then the simulation result is shown in Fig. 7.

High pressures are denoted by peaks (red) while low pressures are represented by valleys in (violet).

The propagation of ultrasonic wave inside the pipe after a lot of reflection with the boundaries is demonstrated in Fig. 7. As can be seen in this figure lamb waves can also propagate on the boundary of the pipe considerably. According to this figure the percentage of lamb wave in rate to the total amount of ultrasonic wave is notable amount, which can make a problem in measuring process. The amplitude of the propagated ultrasonic pressure on the boundary of the metal pipe and inside the pipe is shown as a trend from in Figs. 8 and 9, respectively. These trends can be useful to denote the affection of frequency varying in lamb wave and longitudinal wave propagation.

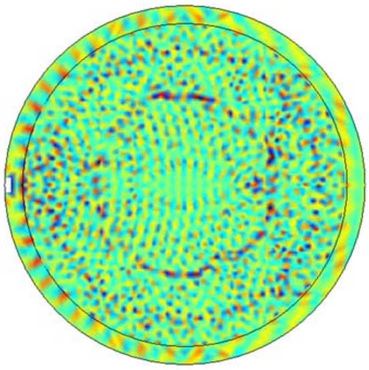

Fig. 7. Ultrasonic wave propagation in 20 kHz.

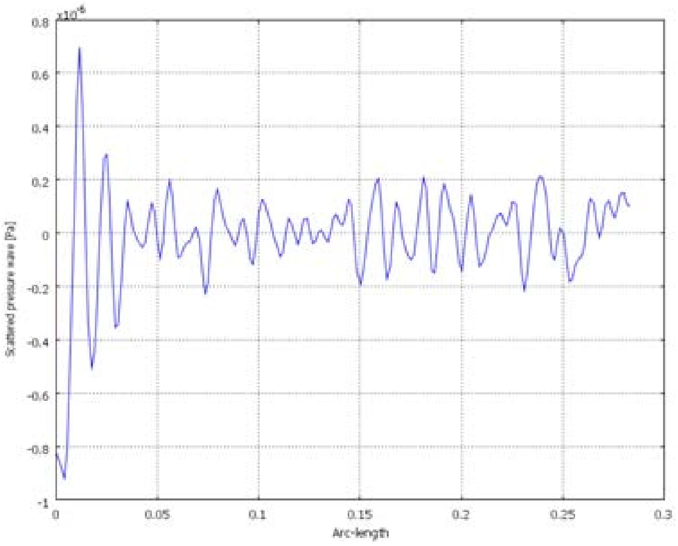

Fig. 8. Distribution of ultrasonic wave on the boundary of the metal pipe in 20 kHz.

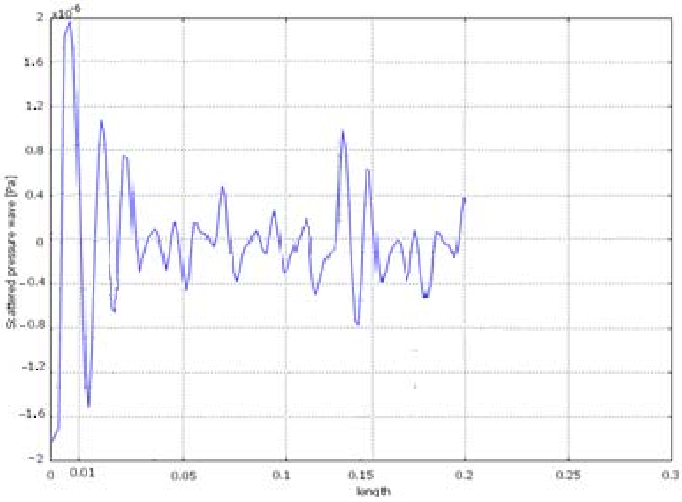

Fig. 9. Distribution of ultrasonic wave inside the metal pipe in 20 kHz.

The same pressure of ultrasonic wave is applied to the ultrasonic transducer in different frequencies by varying the frequency from 20 kHz to 250 kHz. Increasing the frequency from 20 kHz to 250 kHz leads to decreasing the lamb wave pressure level as demonstrated result in 250 kHz in Fig. 10. As shown in Fig. 10, the length of the lamb wave propagation is not longer than 20 kHz mode. This phenomenon satisfies the transmission mode measuring in ultrasonic tomography because its amplitude in receiver part is so weak and it cannot affect on the straight path signal. Disadvantage of increasing the frequency is that the longitudinal wave is decayed very fast and it cannot travel a long distance. The mentioned problem is a significant matter because in transmission mode ultrasonic tomography, the longitudinal wave has the main role to show the information of the concentration of inside the pipe. The related trends to the amplitude of wave propagation in 250 kHz, inside the pipe and on the wall of the pipe also are demonstrated on Figs. 11 and 12. If we compare these trends with previous trends, the affection of frequency varying in longitudinal wave and lamb wave is clear.

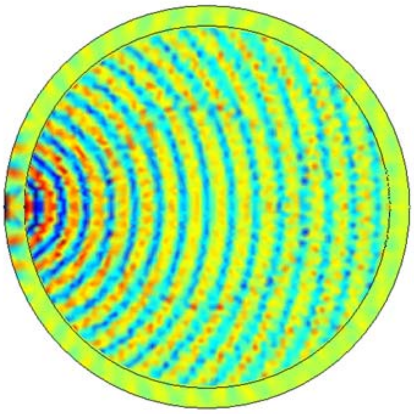

Fig. 10. Ultrasonic wave propagation in 250 kHz.

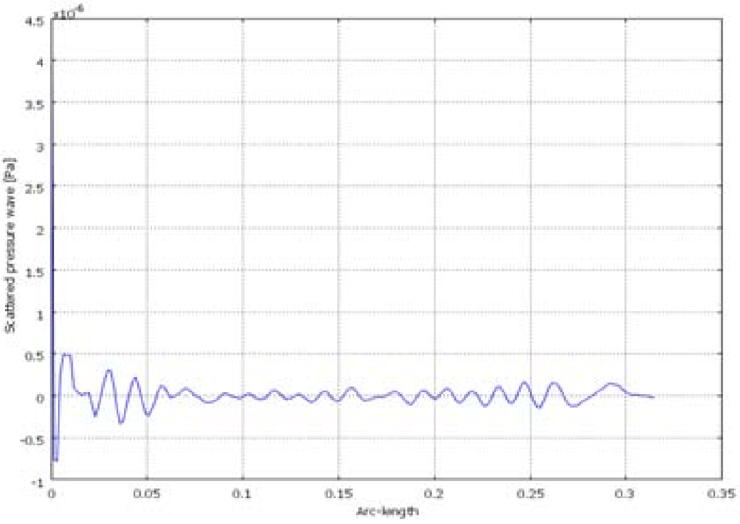

Fig. 11. Distribution of ultrasonic wave on the boundary of the metal pipe in 250 kHz.

Duo to the comparison of the ultrasonic wave propagating manner in 20 kHz with 250 kHz, it is concluded that if the frequency of ultrasonic wave increase, the lamb wave propagation length will decrease. Where increasing the frequency cause to reduce the affection of ultrasonic lamb wave in the receiver part and it is our desire. In the other hand, increasing the frequency of ultrasonic wave results the fast decaying of the longitudinal wave.

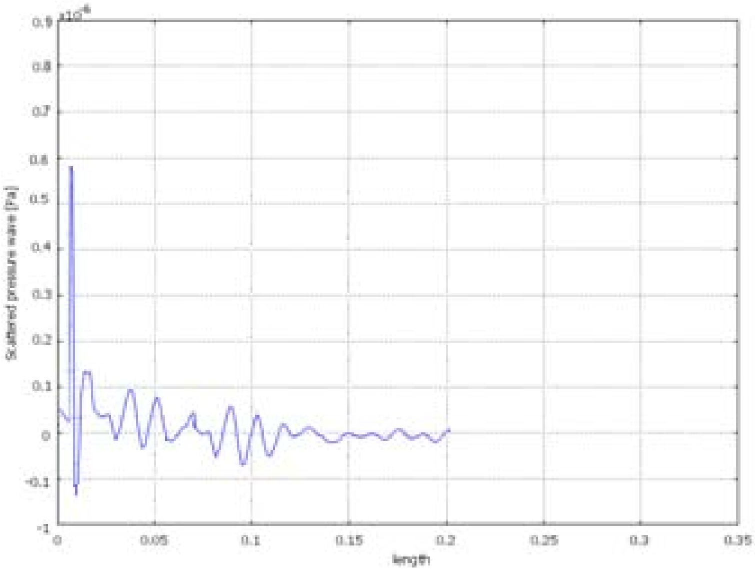

Fig. 12. Distribution of ultrasonic wave inside the metal pipe in 250 kHz.

According to the mentioned problem, we should find the suitable frequency satisfies either longitudinal mode or lamb mode propagation. As the simulation results in different frequencies, 40 kHz is the suitable one, which the resulted trends for the boundary of the metal pipe and inside the pipe are shown in Figs. 13 and 14. It is obvious that in 40 kHz both of the cases are satisfied and this frequency can be selected as the resonance frequency of sensor. The applied sensor on the periphery of the metal pipe should be wide beam angle to cover the wide area of inside the pipe, can support high amplitude voltages due to the attenuation affect of metal pipe and the resonance frequency of sensor should be around 40 kHz.

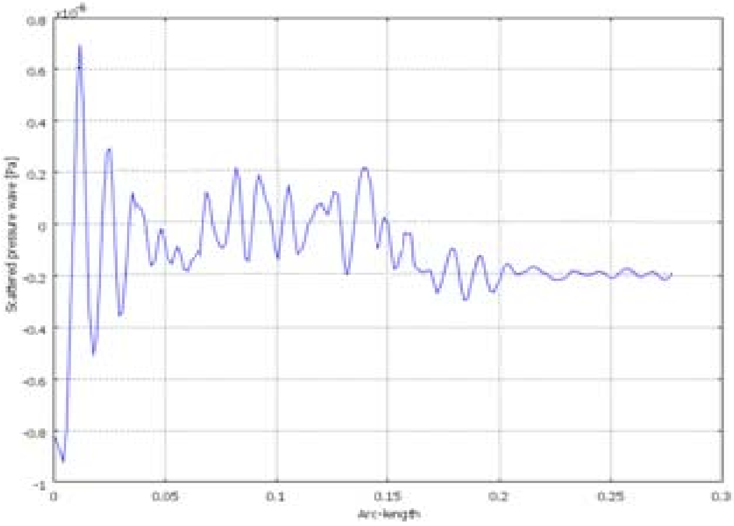

Fig. 13. Distribution of ultrasonic wave on the boundary of the metal pipe in 40 kHz.

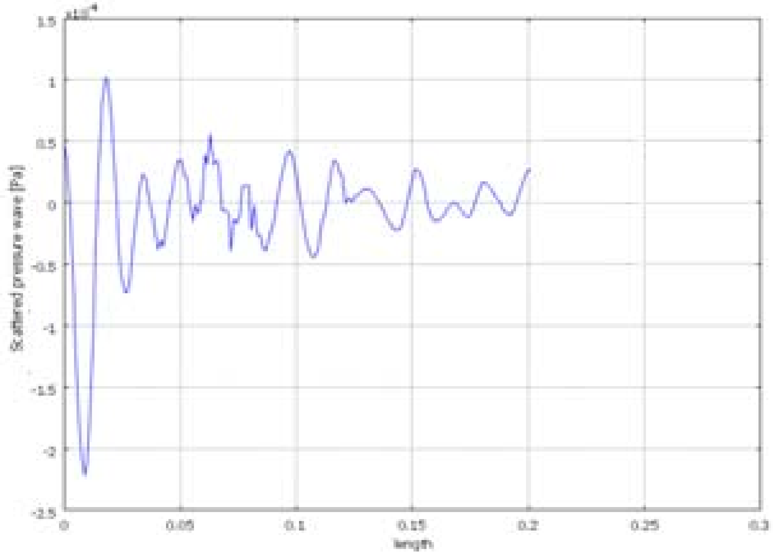

Fig. 14. Distribution of ultrasonic wave inside the metal pipe in 40 kHz.

5. Conclusion

Different methods in ultrasonic tomography systems used for extracting the scanned cross sectional images to be informed about the concentration of liquid/gas/solid inside the pipe, noninvasively. A popular method, which is used in recent decays is the transmission mode method. In this method extracting the concentration profile of inside the pipe is done by the use of straight path signal, which penetrates from the wall of the pipe to inside the pipe.

In this paper metal pipe is applied as the conveyor of the liquid. Due to our investigation in transmition mode measuring method for ultrasonic tomography system then we should be confirmed about the received straight path signal. Due to simulations, which are done by the means of finite element software (COMSOL), it is found that plate wave as the lamb wave make a disturbance in receiving signal. Increasing the frequency of ultrasonic wave causes the lamb wave has the different behaviors. It is concluded that by increasing the frequency the percentage of lamb wave propagation was decreased. But, frequency increasing causes to fast decaying of straight path signal, which is undesirable event. Finally a suitable frequency, which can satisfy the both modes is found as 40 kHz. The resonance frequency of selected sensor, which install on the periphery of metal pipe for generating the ultrasonic wave should equals to 40 kHz.

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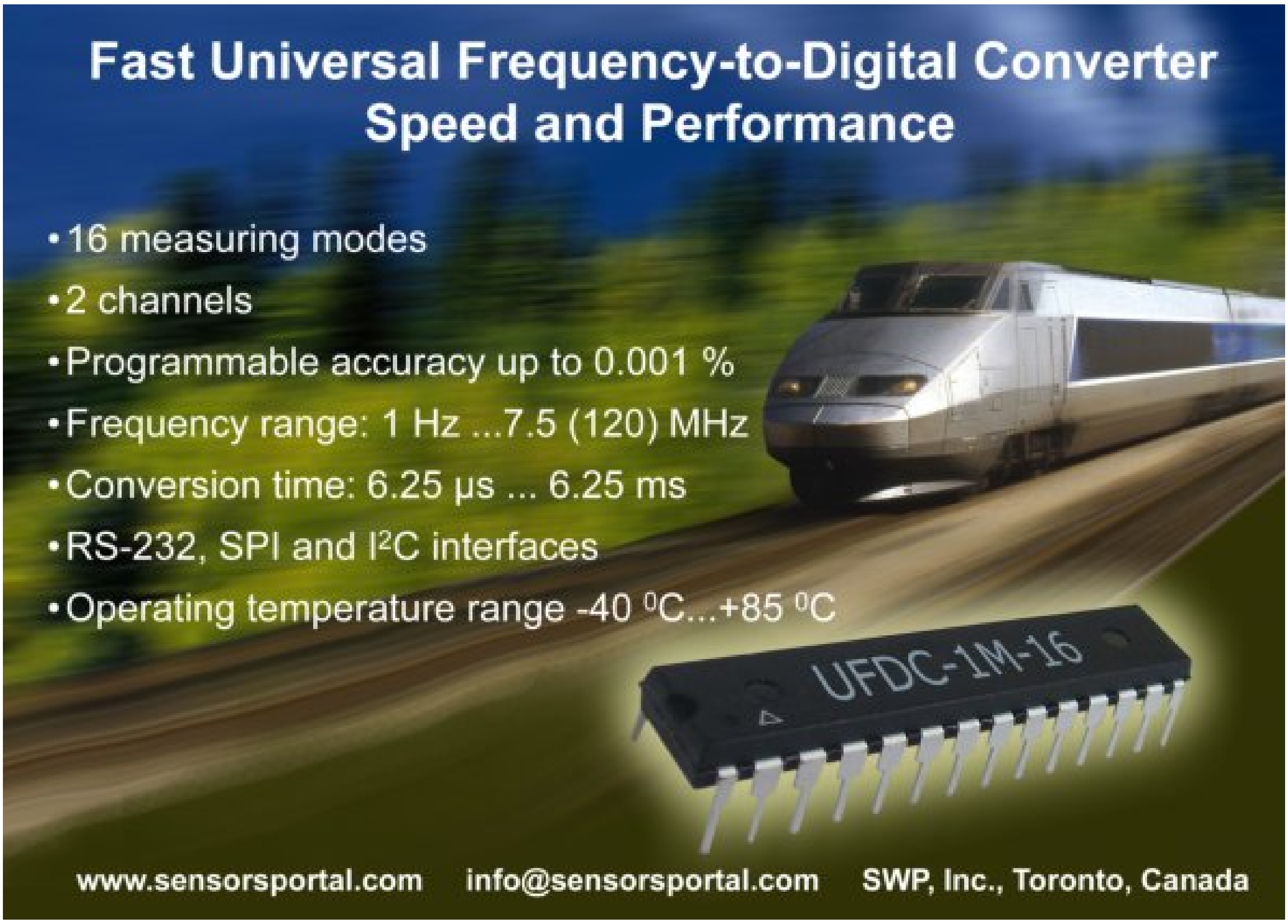

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