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A Review on Ultrasonic Process Tomography System

Sallehuddin Ibrahim*, Mohd Amri Md Yunus, Mohd Taufiq Md Khairi, Mahdi Faramarzi

Control and Mechatronic Engineering Department, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

*Corresponding author: salleh@fke.utm.my

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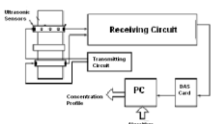
Graphical abstract



Abstract

The advantage of using a tomography system is that it provides visualization of component distributions inside a pipe or a process vessel. Tomography is widely used in the medical field. Due to its non-intrusive nature, tomography has caught the interest of various researchers in process applications. There is an extensive research using ultrasonic tomography for various applications. This paper is a review which expounds the principles of ultrasonic tomography systems, the hardware, and the software used in such systems.

Keywords: Process; sensor; tomography; ultrasound

■1.0 INTRODUCTION

The first practical ultrasonic testing technique was proposed on 1940 when Floyd Firestone applied for a U.S. invention patent. The patent was awarded on 1942 entitled "Flaw Detecting Device and Measuring Instrument". His device can detect inhomogeneities of density or elasticity in materials. If a casting has a hole or a crack within it, the device can detect the presence and location of the flaw although the flaw lies entirely within the casting and no portion of it extends out to the surface. The device operates by sending high frequency signal towards the targeted section, and the computation of the time intervals of arrival of the direct and reflected vibrations at one or more locations on the surface of the object [1]. Since then ultrasound have been widely used for various applications.

In process tomography, tomographic images of concentration distribution inside industrial process pipes are taken in order to be analyzed. This information is beneficial in the design and control of processes. In order to achieve this, sensors are placed around the process vessel and the output from the sensors are combined to reconstruct the images [2].

In general, a tomography system consists of transmitters, receivers, and signal conditioning circuit, data acquisition system (DAS) and a computer. The signal being transmitted passes via the object being measured and is detected by the receiving sensor. Subsequently this signal is amplified, filtered and converted to DC signal. The DAS digitized the signal before sending it to the computer. An image reconstruction algorithm is then utilized in order to display various required information such as the concentration profile and the mass flow rate. The concentration profiles enabled the distinction to be made between the phases in a flow. Several assumptions are made. Among the assumptions are that reflection, scattering and diversion effect are not significant and as such can be ignored. [3].

The potential of ultrasonic process tomography is for imaging processes where distinctions in the density and elasticity of object provide the most significant sensing capability, as an example, for imaging bubbly gas/liquid flows [4]. The utilization of ultrasonic tomography is expanding in the area of imaging for industrial flow. This can be seen in the process involving in liquid borne mixtures. The benefit of using tomography is its usefulness in exploring details of concentration profiles of a pipe or a process vessel. As such data can obtained about the gas, liquid and solid inside a pipe can be obtained and then analyzed. However there is a limitation when sound travels in gas as sound travels effectively only when there is a medium. A high level of noise can also appear when the particle impinged or hits the flow pipe and this must be taken into account when analyzing the data from ultrasonic sensors.

The advantages of using ultrasonic sensors in tomography systems are [5]:

i. It is non-invasive.
ii. It is safe as it does not make use of radioactive materials
iii. It gives a rapid response in a fraction of a second.
iv. Only low energy levels are needed to excite the transducers are very low, and it does not damage the plant or the materials being interrogated

■2.0 ULTRASONIC WAVES

An ultrasonic wave is a wave which has a frequency higher compared to the maximum limit of normal human hearing capability. As such human beings generally cannot hear ultrasound. The limit of human hearing capability is not homogenous. However, the limit is about 20 kHz for adults with normal hearing capability. The frequency range of ultrasonic instruments is from 20 kHz to several GHz [6]. Due to its usefulness ultrasound is applied in various areas. It can be utilized to sense the presence of objects and provide distance measurement. Ultrasonic is also widely used in medicine involving human beings and animals. It can also detect defects and flaws in the area of non-destructive testing. In addition, it can be applied for the purpose of cleaning. Animals such as bats have inbuilt ultrasonic capability which can be used to detect prey as well as obstructions [7].

The science of sound is known as acoustics. Research on acoustics can be traced back to Pythagoras in the 6th century BC, when he investigated the mathematical characteristics of instruments having strings. In 1880, Jacques Curie discovered the piezoelectric phenomenon which can be incorporated in transducers in order to create and detect ultrasound in air and water. A whistle which can create ultrasound was invented by Francis Galton in 1893. Paul Langevin tried to detect submarines using ultrasound in 1917 [8].

When sound hits a solid surface it will be reflected resulting in an echo. The same situation will occur when sound travelling in water hit an obstruction. If the velocity of sound is known, the distance to the obstruction can be determined. This requires the determination of time required by sound to travel towards the obstruction and then returned. The distance is obtained by multiplying speed and time as follows:

$$\text{Distance} = \text{speed x time} \tag{1}$$

In order to determine the one-way distance, the distance in equation (1) has to be divided by two. Echoes are utilized for sonar (sound navigation and ranging). For this to be effective, the sound pulse should be short and it is better to use high frequencies since they can propagate further without suffering from absorption. For sonar the frequencies are in the MHz range. The speed of sound will change according to the material. Factors such as temperature and pressure will influence the speed of sound. In air, it is 330 m/s, in water it is 1500 m/s whereas in metal it is 5000 m/s [9].

For the ultrasonic tomography systems, there are three modes namely the transmission, reflection and diffraction modes [10]. In the transmission mode, measurement is based on the characteristics of the transmitted wave, which depends on the material forming the measuring medium. This is normally used for forward scattering where the parameter of interest is the amplitude and/or the time of flight. Besides it is assumed that the wave propagate in a straight line in order to simplify the image reconstruction algorithm. Absorption by the media and the complex sound field are the two main limitations when applying the transmission mode [11]. By measuring the location and the change of the physical characteristics of the ultrasonic wave, the reflection mode can be implemented. In the case of the diffraction mode, measurement is based on the diffraction of ultrasonic waves at the interface.

Most of the research on ultrasonic tomography utilized the transmission mode. Fazalul Rahiman *et al.* [12] used the transmission mode for imaging the gas/liquid which constitutes a strongly inhomogeneous medium. The research was based on the transmission and the reception of ultrasonic sensors which were installed circularly on the surface of a process vessel. Nor Ayob *et al.* [13] designed a system which is intended for the imaging of two component flows (such as gas/water) inside pipes. Abdul Wahab *et al.* [14] used transmission mode system to identify the multiphase flow regime consisting of liquid, gas and solid. The system was designing non-invasively by using offline method. The transmission mode with fan shaped beam back projection had been implemented for using 8×8 projections. Steiner *et al.* [15] constructed a transmission system using 16 transducer elements. To decrease the sensitivity of the sensor array to lateral modes they utilized a piezocomposite material for the transducers which comprises thin PZT rods in longitudinal direction configured with a random pitch embedded in an epoxy matrix. They claimed this arrangement provided a good immunity to lateral resonances.

Ultrasonic reflection tomography has been applied for an aluminium rod smaller than the wavelength [16]. The use of low frequency resulted in a lower resolution. To restore resolution, they used a signal processing method based on the Papoulis deconvolution. Ultrasonic reflection tomography using Bayesian filtering has been investigated for binary material distributions [17]. The results showed that blurring and artifacts were inherently removed, enabling for more reliable and accurate images. Another investigation using reflection mode made use of 16 transducers to image gas in water [18]. They utilized iterative model-based algorithm. However, the results showed that blurring, artifacts and noise pixels cannot be avoided. Brancheriau *et al.* [19] developed an ultrasonic reflection tomography system to image green wood using a non-parametric imaging algorithm. The images obtained were geometrically accurate considering the internal inclusions.

Ultrasonic diffraction tomography has been applied to allow ray bending correction for imaging of scattering material [20]. They claimed that diffraction tomography can include scattering effects into algorithms so as to enhance image resolution. Pintavirooj *et al.* [21] made use of diffraction mode using phantoms made from gelatin having the refractive index close to the water. The diameter of the phantom is 60 mm. The object to be image is insonified by a plane wave and the transmitted ultrasonic pulse is measured along a line perpendicular to the direction of propagation of the incident ultrasonic wave. It is assummed that the weak scattering of the ultrasonic wave as it traverses through the object. The diffraction mode was also applied to cross-hole seismic data [22]. Images were obtained within both the first Born and Rytov's approximation. The results showed that Rytov's approximation attained good resolution of the lower wavenumber components of the object, whereas the first Born approximation achieved good results if the object is discontinuous. Shekhar [23] developed an ultrasonic diffraction tomography system to detect defects in large pipe lines and cylindrical structures. Multiple defects of diameter as small as 50 mm were accurately detected.

■3.0 HARDWARE

One of the most important hardware components in an ultrasonic system is the ultrasonic transceiver which is a transducer that converts electrical energy into sound and also converts sound back to electrical energy. A transceiver consists of a combination of a transmitter and a receiver which share a single housing. It has piezoelectric crystal materials that can transform mechanical energy into electrical energy and vice versa. Various commercial ultrasonic transceivers are available. Each transducer is distinguished by its dimension, center frequency, sensitivity to temperature fluctuations, beam angle, driving voltage, sound pressure level and other parameters. As the transceiver is placed at the first stage of an ultrasonic tomography system, it is vital to use the right type of transceiver is very important [24].

Many research made use of ultrasonic transceivers having 40 kHz resonance frequency. Rahim *et al.* made use of a 40 kHz transceiver which is capable of driving up to 15 Vrms with a divergence angle of 125º [24]. Such angle enables a wide coverage of the object under investigation. In order to provide suitable mounting and coupling, a plated metal housing is used. Other types of housing can cause unwanted air to be trapped in the housing. The air between the sensor surface and the surface of the pipe can affect the signal thus causing error [25]. Ibrahim *et al.* [3] developed an ultrasonic tomographic system using the transmission mode method utilizing 40 kHz transceiver. It used fan beam projection technique. The system consists of 8 ultrasonic transmitters and 8 receivers. Each transducer is separated at an angle of 22.5º. This type of transducer arrangement will measure the concentration flowing objects in a pipe of 100 mm diameter. The ultrasonic system topology is shown in Figure 1.

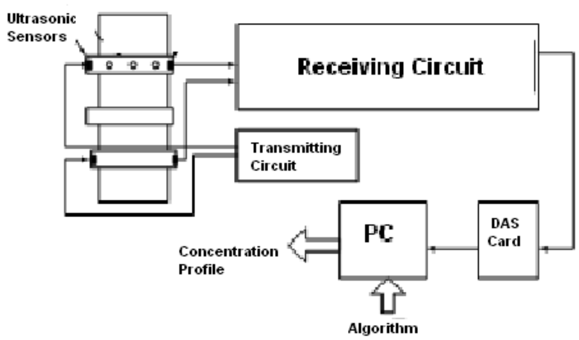


Figure 1 Ultrasonic system topology

Nor Ayob *et al.* [13] use ultrasonic transceivers having resonant frequencies of 333 kHz. The transmission of ultrasonic wave requires the impedance matching of the sensor to that of the column in order to maximize the transmitted energy [13].

Since the area or the object under investigation is confined to a specific region, the number of ultrasonic sensors that can be used is limited. For example, Rahiman *et al.* [26] used 16 pairs of transceivers which are arranged equally-spaced around the periphery of a pipe due to limited diameter of the pipe. The limited number of transceiver used means that it affects the resolution of the tomographic images.

In several investigations, a microcontroller is used. For example Zakaria *et al.* [25] used a microcontroller (PIC18F452) as a signal generator to generate and control the a 40 kHz signal. The block diagram of the whole system is shown in Figure 2. Analog switches were used to switch the transceiver either to the transmitter or the receiver.

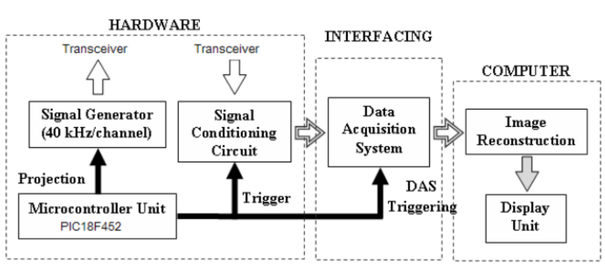


Figure 2 An ultrasonic tomography system designed by Zakaria *et al.* [26]

The ultrasonic transmitters are usually connected to an amplification circuitry which transform the electrical signals into ultrasonic signals. These ultrasonic signals are then propagated towards the ultrasonic receivers which transform the ultrasonic signals into electrical signals. The ultrasonic receiver is connected to a signal conditioning circuit (SCC). The function of the SCC is to process the raw data from the sensors. It would normally contain a filter for noise reduction purpose and several amplifier stages in order to amplify the signal. The output of the SCC is the form of analog signals. These signals have to be digitzed before being sent to the computer. In order to achieve this, the signals have to be sampled. There are several methods used to sample the signals. Among them is the peak detection method and using a sample and hold circuit [13].

Peak detection involved the use of a peak detector circuit. The circuit determines the peak voltage on an ac signal and transforms it into a dc voltage. This method has the advantages of having a faster response time, easier integration into the system and can fit into a more compact board. The sample and hold circuit (SHC) holds the analog value steady for a short duration [27]. The analog voltage is stored by a capacitor and the capacitor is alternately connected and disconnected from the analog input using a digital switch. The advantage of using SHC is that is guarantees improved data collection that the peak detection method. However, SHC requires more components to be utilized which means more space is needed resulting in bigger board [13].

The use of digital signal processing (DSP) can reduce the image reconstruction task by providing more powerful computing nodes [28]. Schlaberg *et al.* [29] made use of a DSP incorporated in an ultrasonic tomography system applied to hydrocyclones. The DSP processed the time-of-flight information and sent the results to a PC through a serial link. The DSP has sufficient time between sampling periods to perfom data conversion which transforms the stored values of the 16 transducers (one per sensor) digital outputs from the transducers into data packets having the format composed of transmitter, receiver, time-of-flight. Thus the amount of data transmitted to the host is reduced and the processing needed for image reconstruction is also reduced.

■4.0 IMAGE RECONSTRUCTION ALGORITHMS

Many tomographic images made use of the linear back projection (LBP) algorithm. Most of the work in process tomography has focused on the back projection technique. Initially it was invented for use in X-ray tomography [30]. It has the benefit of providing low computation cost. In the back projection algorithm, solution of the forward problem must be obtained initially and then the inverse problem is solved [31]. The forward problem provides the predicted output of each sensor when the sensing region is considered to be two-dimensional. The forward problem can be determined by utilizing the analytical solution of sensitivity maps that resulted in the sensitivity matrices [28]. By computing the attenuation of the ultrasonic signal at each receiver the sensitivity distribution can be obtained. The inverse problem involved obtaining from the sensitivity matrices, a transformation matrix for converting the measured sensor values into pixel values that constitute the tomographic images. To reconstruct the image, each sensitivity matrix is multiplied by its corresponding sensor reading. The voltage distribution obtained using the LBP algorithm can be expressed as [3]:

$$V_{LBP}(x, y) = \sum_{Tx=0}^{8} \sum_{Rx=0}^{8} S_{Rx,Tx} M_{Tx,Rx}(x, y) \qquad (2)$$

where $V_{LBP}(x, y)$, voltage distribution obtained using LBP algorithm (concentration profile in unit volt) an $n \times m$ matrix where n equals to dimension of sensitivity matrix, $S_{Rx,Tx}$, is the signal loss amplitude of the receiver Rx-th for transmitter projection Tx-th in unit of volt, and $M_{Tx,Rx}(x, y)$ is the normalized sensitivity matrices for the view of Tx–Rx.

The Hybrid Reconstruction (HR) algorithm combines the knowledge of sensor reading and the LBP in order to improve the accuracy of the image reconstruction [31]. It determines the condition of projection data and enhances the image reconstruction by taking into account when there is no material.

Filtered Back Projection (FBP) algorithm requires less computational resources compared to algorithms such as the Iterative Reconstruction (IR) algorithm. In FBP, by filtering the projections before backprojection it is hoped that the objective of recovering the original object can be attained. FBP is among the most widely used algorithm in tomography. As the FBP is a linear, shift-invariant method, the variances of the reconstructed pixel values are fairly uniform spatially. FBP needs a lot of of integral measurement data to get a reliable accuracy and yet the images are still susceptible to noise [32]. The noise is due to unmodelled processes occurring in the production and capture of the real signal. The sources of noise might be due to the variations in the detector sensitivity, environmental fluctuations, the discrete nature of radiation, transmission or quantization errors, etc. Noise in images appears in various ways and can result in results which are not acceptable. Noise makes analysis and data interpretation difficult. Utomo *et al*. [33] used iterative filtered backprojection (IFBP) technique to analyze distributions of gas and solid in slurry bubble column using ultrasonic tomography. They showed that IFBP is better than FBP in reconstructing the images.

The Hybrid Binary Reconstruction (HBR) algorithm can improve the stability and repeatability of image reconstruction. It can be implemented by multiplying each sensor output to its related sensitivity map. If output value of the sensor is larger or identical to the threshold voltage, then its projection path which is represented by the sensitivity map is set to a maximum pixel value or else it is set to a minimum pixel value [33].

Rahim *et al*. [34] employed three image reconstruction algorithms namely LBP, HR and HBR for imaging liquid and gas flow which is a strongly inhomogeneous medium. Their ultrasonic tomography system is based on the transmission-mode. The algorithms used to reconstruct the concentration profile for the two-phase flow incorporated a fan-shaped beam scanning geometry. They claimed that the results are acceptable. LBP smears out the images and resulted in blurry images. As such, it is difficult to get quantitative data from this image. This advantage of LBP however was improved by using HR. From the reconstructed images, it shown that blurry image by the smearing effects has been reduced. The uses of HBR manage to eliminate almost all the smearing effects.

In order to enhance the images, thresholding can be used. This can be done by discarding the noise pixels. A linear threshold can only process images which have homogenous populations because it takes into account of all pixels in an equal manner. Actually the intensity profile covering the whole reconstruction relies on the width of the divergence beam angle of the ultrasonic sensors. The reconstruction will have a higher intensity and a more uniform contour near the middle region of the images if there is a reflector in that location. As the reconstruction depends on intensity, a nonlinear threshold can be an alternative [35].

8.0 CONCLUSIONS

There is an extensive research using ultrasonic tomography system. Current and future research attempt to fine tune the system and use it for multifarious applications. Many investigations are still confined to the laboratories. More research should be carried out to apply the ultrasonic tomography system to industrial plants.

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