Sensors and Actuators A 203 (2013) 215–224

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Design procedure of ultrasonic tomography system with steel pipe conveyor

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ARTICLE INFO

Article history:
Received 20 February 2013
Received in revised form 13 August 2013
Accepted 13 August 2013
Available online 12 September 2013

Keywords:
Ultrasonic tomography
Ultrasonic sensors
Ultrasonic wave
Non-invasive tomography
Frequency analysis

ABSTRACT

Non-invasive ultrasonic tomography has a dominant role in extracting cross-sectional images of objects. The front-end structure of the proposed ultrasonic tomography system with a steel pipe conveyor is explained in this paper. In the novel ultrasonic tomography system presented, a non-invasive sensing technique is applied for detecting gas bubbles inside the steel pipe. A method of visualising the structure of the steel pipe with finite element software (COMSOL Multiphysics 4.2) is also presented in this paper. An appropriate sensor with 40 kHz resonance frequency, based on simulation results, is selected and experimentally mounted on the periphery of the vessel. Several reviews regarding the common tomography technique proposed and hardware preparation are also discussed. Twelve dual-function (transmitter/receiver) ultrasonic sensors with a fan-shaped beam projection capability are used as the sensory part of the system. Details of the circuitry of the system are also presented, which consists of various parts such as a signal generator, signal conditioning and signal acquisition strategy. Finally, the experimental results of the proposed system, which are useful for further investigation for the application of ultrasonic tomography in industry, are illustrated.

1. Introduction

In the late 1980s and early 1990s, process tomography was investigated in order to determine component concentration in various industries, especially for measurements in the oil industry in Europe and the coal industry in the USA [1]. Some of the studies included the measurement of water content in oil [2] and the visualisation of component distribution in multi-component flow pipelines [3–5]. Ultrasonic tomography (UT) has the advantage of imaging two-component flows, and provides the opportunity to present quantitative and real-time data on chemical media within a full-scale industrial process, such as filtration, without the need for process interruption [6,7]. The major potential benefit of UT systems is their capability of online monitoring for the development of closed-loop control systems [8]. Ultrasonic sensors in UT systems are used to extract the data inside a pipe based on changes in fluid density.

To date, the majority of investigations on UT systems have been done on pipes made from materials such as acrylic, PVC and plastic [9,10]. The main reason why steel pipes are rarely studied as the conveyor of UT systems is their high attenuation of ultrasonic energy and the high influence of bulk waves compared with other kinds of pipe materials. The majority of researchers have concluded that steel pipes have the greatest disadvantage with regard to internal reflections within enclosed pipes [11]. The significant role of steel pipes in industry as the conveyor of liquid/gas has, however, led to alternative solutions, such as the utilisation of UT systems, as proposed in this research.

2. Principles of ultrasonic tomography

Principally an UT system consists of two general parts. The software and hardware elements are shown in Fig. 1. The hardware part of UT systems consists of various elements such as:

- Pulse generator: a microcontroller that produce pulses with a frequency equal to the resonance frequency of the sensor.
- Transmitter circuit: amplifying the pulses generated to actuate the ultrasonic sensor.
- Ultrasonic sensors: applied sensors capable of dual functions, acting as a transmitter and receiver. Ultrasonic transmitter sensors are connected to the amplifier part and they convert the electrical signal to an ultrasonic wave on one side of the pipe, and on the other side an ultrasonic receiver sensor can receive the ultrasonic wave propagated and convert the received ultrasonic wave to an electrical signal.
- Receiver circuit: this part consists of a low noise amplifier, band bass filter, and data acquisition. Reducing the added noise and

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http://dx.doi.org/10.1016/j.sna.2013.08.020

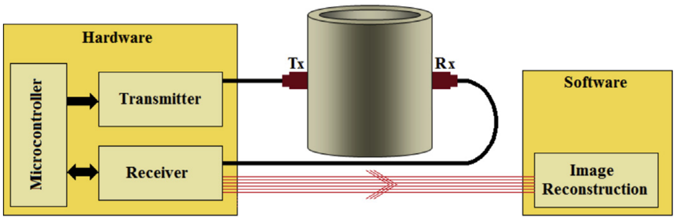

Fig. 1. General block diagram of an ultrasonic tomography system.

amplifying the received signal and finally converting the analogue data into digital data are the procedures carried out by the aforementioned parts in the receiver.
- Image reconstruction: digital data gathered in the software is utilised to construct the cross-sectional image of the pipe by the application of various algorithms such as the linear back projection algorithm.

The first and significant steps in the design approach are to determine the appropriate ultrasonic sensors based on their performance. Ultrasound waves propagate above audible sound; using frequencies from 20 kHz up to several gigahertzes. The twelve ultrasonic sensors applied are mounted on the periphery of the pipe as a ring-shaped structure with an equal distance between the sensors. As the suspended solids' concentration fluctuates, the ultrasonic beam is scattered and the received signal fluctuates in a random manner about a mean value. The continuous signaler pulsed signal can be used to excite the ultrasonic sensors [12]. Since a continuous signal may lead to the formation of standing waves inside the pipe, the pulsed system will be used [13].

Various interactions may be used to gain information relating to the internal nature of the process. These possibilities yield a variety of sensor configurations which may provide raw data for processing, in order to yield both one- and two-dimensional scalar and three-dimensional vector tomographic results. These techniques are categorised in three distinct modes: transmission mode, reflection mode, and diffraction mode. The transmission-mode technique is the acquisition of data due to the measurement of forward scattering and the reconstruction algorithm used based on the inverse solution of the wave equation. The amplitude and/or time of flight, and a reconstruction algorithm based on the assumption of straight line propagation, are the only significant issues that should be considered in transmission mode [14,15].

The reflection-mode technique is based on the measurement of the position and change in physical properties of a wave or a particle reflected on an interface. Similar to the reflection-mode technique, there are some techniques based on the diffraction or refraction of a wave at a discrete or continuous interface in the object space [14].

3. Design approach of sensory part

Piezoelectric-based ultrasonic transducers have the ability to transform mechanical energy into electrical energy, and vice versa. If the frequency of the applied signal equals the resonance frequency of the piezoelectric transducer, it will result in an ultrasonic wave of similar frequency [16]. Ultrasound can propagate as longitudinal waves, shear waves, surface waves, and in thin materials as plate waves [17]. Longitudinal and shear waves are the two modes of propagation most widely used in ultrasonic testing [18,19]. Since the transmission-mode technique is selected as the sensing mode for the proposed UT system, a straight-line signal is considered as the data signal. In other words, the longitudinal mode of ultrasonic wave propagation is the desired mode and the other modes of propagation are neglected.

Table 1
Pressure levels of received ultrasonic wave on opposite side of the transmitter at 42 μs for different frequencies.

Frequency (kHz)	Pressure level (pa)
40	0.17
80	0.42
120	1.76

Since the steel pipe is used as the conveyor of the UT system, the appropriate ultrasonic sensor should be chosen with regard to its performance. As a consequence of using the transmission-mode, the amplitude of the receiving waves with the receiver sensor should only relate to the longitudinal mode and not the Lamb mode. The Lamb waves do not provide any information on the ultrasonic disturbances caused by object obstruction inside the pipe, because the Lamb wave propagates within the pipe boundary. Finite element simulations with COMSOL software are used to determine the optimum frequency of the ultrasonic sensor and to determine the receiving time of the longitudinal waves and Lamb waves.

It is possible to diagnose the manner of ultrasonic wave propagation in the pipe and find a way to reduce the Lamb wave effect by changing the frequency. The travelling rate of the longitudinal mode and Lamb wave are detected and compared with each other using this software.

For a better demonstration of ultrasonic wave propagation in different layers, a 2D simulation is investigated. The pipe material and the fluid inside the pipe are considered to be steel and water, respectively. The geometry of the simulated pipe is: inner diameter = 10 cm, pipe wall thickness = 0.8 cm.

Based on the simulation results, the frequency of the ultrasonic wave plays an important role in the manner of the ultrasonic wave propagation. Fig. 2 shows 3D views of the scattered ultrasonic pressure at different frequencies. The transient mode of simulation was carried out and the simulation results for each frequency at three different times: 15 μs, 30 μs and 45 μs are shown in Fig. 2. High pressures are denoted by peaks (red) while low pressures are represented by troughs (violet).

From the simulation results shown in Fig. 2, it can be concluded that the Lamb wave reaches the receiver (opposite side of transmitter) before the longitudinal wave. The Lamb wave exists for the whole of the propagation time, which causes disturbance in receiving the longitudinal wave and acts as a noise effect. As can be seen in Fig. 2, the pressure levels of the ultrasonic wave in the receiver (opposite side of transmitter) at 42 μs are completely related to the Lamb wave. The pressure levels of the ultrasonic wave at the receiver point at 42 μs are given in Table 1. From these pressure levels, it can be seen that increase of frequency leads to increase of the pressure level of the Lamb wave. The observation time of the longitudinal wave (time-of-flight) is 78 μs. The pressure levels obtained at different frequencies at 78 μs, for the case of the receiving ultrasonic wave devote to the longitudinal wave and lamb wave is neglected, are presented in Table 2. The pressure levels in Table 2 show the increase of frequency leading to the decrease of the pressure level of the longitudinal wave. It is obvious from a comparison of the results that the amplitude of the pressure wave on the boundary of the pipe (Lamb wave) will increase as the frequency increases. On the other hand, as the frequency increases

Table 2
Pressure levels of longitudinal wave on opposite side of the transmitter at 78 μs for different frequencies.

Frequency (kHz)	Pressure level (pa)
40	0.18
80	0.15
120	0.11