

A NON-INVASIVE AND NON-INTRUSIVE ULTRASONIC TRANSDUCER ARRAY FOR PROCESS TOMOGRAPHY

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Abstract: Ultrasound process tomography is a method for imaging the acoustic impedance or sound velocity distribution within a closed pipe or vessel. It can be used for the determination of process parameters in industrial multi-phase flows. A crucial part of the imaging system is the ultrasonic transducer array. It influences the achievable accuracy as well as the possible application areas. Existing approaches are either invasive, where the transducers are in direct contact with the flow media, or intrusive, where the transducers extend into the flow. To overcome these drawbacks, we present the design of a novel non-intrusive and non-invasive ultrasonic transducer array. Important design parameters are discussed and analyzed using simulations. A prototype transducer arrays is introduced and the feasibility of ultrasound process tomography using a non-invasive and non-intrusive sensor front-end is verified with measurements.

Keywords: flow imaging, process tomography, ultrasound tomography, ultrasonic transducer.

1. INTRODUCTION

The tomographic imaging of multi-phase flows and material distributions in industrial processes, commonly referred to as process tomography, is the subject of considerable research interest. It allows continuous real-time monitoring and control of such processes occurring, e.g., in oil production, food production, pneumatic conveying, filtration, mixing, and chemical processing. An inherent advantage of process tomography is that the process to be imaged is usually not disturbed because the material distribution in the region of interest is reconstructed from measurements taken at the boundary of the region.

Several different sensing principles can be used to acquire the necessary data, leading to, e.g., X-ray, electrical capacitance, electrical impedance, microwave, and ultrasound tomography [1,2]. All of the mentioned methods have their respective advantages and disadvantages. Very accurate images are achievable with X-ray tomography, but at low speed, high cost and stringent safety requirements due to the ionized radiation. The electrical modalities are able to deliver very high frame rates at low cost, but the image resolution is rather low. However, they have shown to be useful in many applications.

Ultrasound tomography has not received as much attention as electrical impedance and electrical capacitance tomography in recent years, but still there have been several authors developing the subject, see, e.g., [1-5] and the references therein. Ultrasonic wave propagation is sensitive to changes in acoustic impedance, acoustic velocity and attenuation. Depending on the used signal processing methods the spatial distribution of one of these parameters can be imaged. The reported process tomography methods are usually based on sensing the acoustic impedance distribution through reflection or transmission measurements of ultrasonic waves. Many industrial processes offer very high contrast in terms of acoustic impedance, e.g. gas-liquid and gas-solid flows. At gas-liquid and gas-solid interfaces virtually all of the acoustic energy is reflected back due to the very small impedance of gases compared to liquids and solids (acoustic mismatch).

A typical setup of ultrasound process tomography consists of a number of ultrasonic transducers that are distributed around the boundary of the imaging region. One transducer at a time is usually excited with a high voltage broadband pulse to transmit a pulse wave into the flow medium. All transducers then act as receivers to collect the transmitted or reflected pulses. The acquired data forms a single projection. Several projections need to be collected by using different transducers as transmitters before an image can be reconstructed.

For many industrial applications it is desirable that the sensors are non-intrusive, i.e. they do not disturb the flow by extending into the process vessel, and non-invasive, i.e. they are not in direct contact with the flow medium. This can circumvent problems like leakage and corrosion. Non-tomographic flowmeters and liquid level meters for single-phase flows that can simply be clamped onto the outer surface of an existing process vessel are readily available and frequently used in industry [6,7].

However, existing approaches to tomographic imaging do not satisfy both demands simultaneously. In [3] a few half-cylindrical transducers that extend into the flow are used as transmitting transducers. Flat transducers are placed between the transmitters and used as receivers. All transducers are mounted invasively. A non-invasive integrated transducer/pipe structure is used in [8]. The sound waves are generated by transducers mounted at the outer pipe surface

and penetrate the wall. However, the pipe wall is deformed in such a way that it acts as acoustic lense at the position of the transducers. So the straight beam of the transducer elements can be transformed into a wide-angle beam. The necessary curvature is so large that a considerable deviation from a circular pipe shape is the result. In addition the maximum possible number of transducers is very limited with this approach due to the required space of the acoustic lenses. The sensor array presented in [9] consists of thin rectangular transducer elements that are accommodated in slots of the process pipe. This design has the advantage that a high number of transducers can be placed around the imaging plane. However, the sensors are in direct contact with the flow medium.

The aim of the present work is to investigate the feasibility of an ultrasound process tomography sensor array that is both non-invasive and non-intrusive. The sensor requirements have to be carefully addressed because they are very different from conventional flowmeters, which is discussed in the following section. After that our novel sensor design is presented and the influences of major design factors are studied using simulations. Finally, some measurements from a prototype sensor array are reported to demonstrate the validity of the approach.

2. DESIGN REQUIREMENTS

One essential demand on process tomography systems is real-time performance with regard to the occurring flow rates. A disadvantage of ultrasound in this context is its slow propagation compared to electromagnetic waves. The speed of sound in water, e.g., is $c_w \approx 1500$ m/s at room temperature. To achieve real-time image reconstruction for an acceptable flow rate it is crucial to capture as much data as possible in a single measurement cycle. The most promising configuration to achieve this goal is a large number of transducers evenly distributed along the boundary of the imaging plane, as depicted in Fig. 1, where 16 transducers are used. The transducers should have a beam profile that is diverging over a wide angular range in the imaging plane and narrowly confined normal to it [3-5]. This ensures that a large portion of the region of interest is illuminated with the ultrasonic wave emitted by a single transducer so that a maximum amount of projection data can be measured. The beam profile in axial direction determines the slice of the pipe cross-section that is imaged. It should be as thin as possible to have a clearly defined measurement region and to neglect averaging effects.

A single projection measurement consists of exciting a transducer with a short high voltage pulse. After that all transducers, including the transmitter, act as receivers. After the sound field has died down due to attenuation the next transducer is used to emit a pulse, and so on. Measurement frame rates of 200 frames/second have been reported using this principle [4,5]. The received signals depend on the material distribution in the measurement plane. In our case of discrete gas-liquid or gas-solid flows it is often assumed that perfect reflection of ultrasonic waves occurs at material interfaces due to the striking difference in acoustic impedance. The pressure reflection coefficient of an acoustic wave incident on the interface between a propagation medium

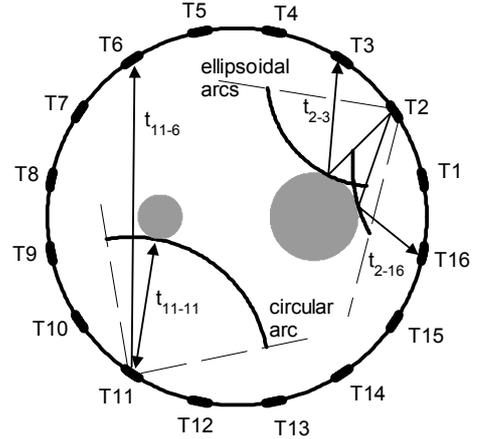


Fig. 1. Principle of a sensor array for ultrasound process tomography with 16 transducers T1 – T16 mounted around the pipe circumference. The transducers have a fan-shaped beam in the imaging plane. The measured pulse travel times can be used to determine through-transmission, circular and ellipsoidal backprojected arcs.

with impedance Z_1 and a medium with impedance Z_2 is:

$$R_p = \frac{Z_2 - Z_1}{Z_1 + Z_2} \quad (1)$$

At a water-air interface, e.g., the reflection coefficient is 99.8% [10].

The interaction between ultrasonic waves and reflecting objects depends on the ratio of the object dimensions to the acoustic wavelength. Specular reflection can be assumed if the wavelength is small compared to the object size. This allows the use of specialized reconstruction algorithms that are particularly simple [5,11]. The reconstruction principle based on backprojections is illustrated in Fig. 1. A pulse emitted from T11 is partly reflected back to T11 from the first obstacle, leading to a measured time of flight t_{11-11} . A circular arc can be backprojected with its center at T11 and a radius of:

$$r_a = \frac{c}{2t_{11-11}} \quad (2)$$

The arc is confined according to angular width of the transducer beam and indicates that a reflector is located somewhere on that arc. Part of the wave emitted from T11 reaches receiver T6, which records a travel time t_{11-6} . This transmission information can be used to track down regions that contain no reflecting objects. A different case is illustrated for the case of T2 acting as transmitter. Parts of the pulse are reflected to T3 and T16. From the recorded arrival times ellipsoidal arcs can be backprojected, with the focii at the transmitting and receiving transducer. The final image is obtained by summing up the contributions from all projection measurements.

If the acoustic wavelength is in the order of the obstacle dimensions, incoming waves are partly scattered back and forward at geometrical obstacles, which seriously complicates the imaging process. Therefore it is tried to use a frequency high enough to obtain specular reflections.

Another issue is the attenuation of ultrasound in a propa-

gation medium. For most fluids the attenuation due to viscous loss is proportional to the square of the frequency. For water the attenuation is 0.2 dB/m at 1 MHz, 1.2 dB/m at 2.5 MHz and already 4.9 dB/m at 5 MHz. So lower frequencies would be favourable. However, the achievable spatial image resolution is improved as the frequency increases due to more accurate travel time measurements. A second factor contributing to the total attenuation is the dispersion of the fan-shaped beams. As the acoustic energy is distributed over a larger region as the beam diverges the local attenuation is inversely proportional to the distance from the source.

3. PROTOTYPE SENSOR DESIGN

3.1. Fan-shaped beam transducers

A crucial aspect of an ultrasound tomography sensor array is the generation of fan-shaped beams. There are basically four methods to generate a wide beam angle in the measurement plane. One is to use a curved transducer materials of half-cylindrical shape, as sketched in Fig. 2(a). The acoustic waves are emitted normal to the front surface and will thus diverge over a wide angle. Curved active materials are available from some manufacturers of piezoelectric materials but are rather uncommon compared to flat elements.

Another method to achieve beam spreading is the use of an acoustic lens placed on a transducer with a flat front surface emitting a straight beam. This situation is illustrated in Fig. 2(b). The acoustic lens has the shape of a half-cylinder and must be made from an acoustically transparent material. It works similar to an optical lens and widens the initially narrow beam. Such acoustic lenses have been applied in [3,8]. A disadvantage of acoustic lenses and also of curved transducers is that they usually are intrusive regarding the process vessel and also rather bulky. Therefore they may disturb the flow inside the vessel.

A third possibility to produce a diverging sound beam is to take transducers producing a straight beam and use masks to force diffraction [12]. The acoustically opaque mask is put on the front surface of the transducer and has to contain a thin slot, as shown in Fig. 2(c). Significant diffraction of the sound waves occurs if the width of the slot is in the order or smaller than the used acoustic wavelength. The thinner the slot, the wider is the beam spreading. As a disadvantage of this method only a small part of the produced sound intensity passes the slot and can be used to insonify the measurement plane.

The fourth method for generating wide beams is to use flat active elements with a width in the order of the acoustic wavelength [5,9]. The height of such elements is bigger than

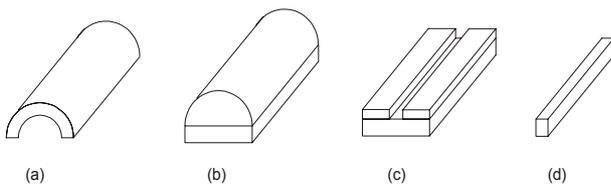


Fig. 2. Different possibilities for generating a fan-shaped ultrasonic beam. (a) Curved transducer material; (b) acoustic lens on top of a flat transducer; (c) Mask with a thin slot on top of a flat transducer; (d) Flat transducer with a width in the order of the used acoustic wavelength.

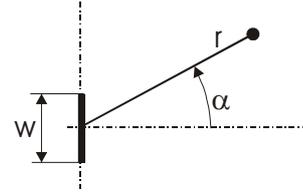


Fig. 3. Coordinate system used for calculating the beam profile of an infinitely long transducer.

their width, as depicted in Fig. 2(d). The resulting transducers are very compact and are suitable for non-intrusive sensor designs. The full sound intensity can be radiated. However, as the elements get thinner to achieve a wider beam the sensitivity of the transducers is reduced. Due its advantages over the other methods the thin rectangular transducer elements are also the basis of our sensor design.

Our prototype sensor is intended to image objects with dimensions down to around 10 mm. So a transducer center frequency of 1 MHz, giving a wavelength of 1.5 mm in water, was found to be sufficient to assume specular reflection. Other systems reported in the literature used frequencies between 1.5 and 3 MHz [3,5,8,9,12]. The beam profile of an infinitely long flat rectangular transducer depends on its width w and the acoustic wavelength λ in the medium. The normalized pressure in the far field as a function of the distance from the source r and the observation angle α , as defined in Fig. 3, can be approximated as (derived from [10]):

$$\left| \frac{p(r, \alpha)}{p_0} \right| = \frac{w}{\sqrt{r\lambda}} \frac{\sin\left(\frac{\pi w}{\lambda} \sin \alpha\right)}{\frac{\pi w}{\lambda} \sin \alpha} \cos \alpha \quad (3)$$

The beam profiles of transducers with varying width are illustrated in Fig. 4, where a frequency of 1 MHz, giving a wavelength of $\lambda = 2.4$ mm in PVC, was assumed. In water the decline of the curves would be steeper due to the smaller wavelength. The curves were normalized to the maximum amplitude under the assumption of constant total beam intensity. The maximum amplitudes of the different transducers decrease with increasing beam divergence and therefore with decreasing transducer width. The variation of the beam angle Φ with respect to the transducer width is sketched in

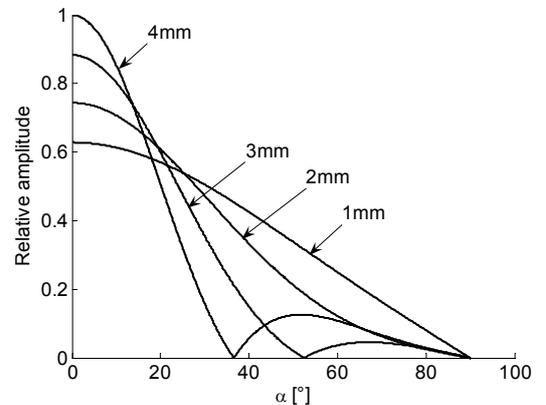


Fig. 4. Beam profiles (normalized sound pressure assuming constant total beam intensity) of rectangular transducers of infinite length of different width (1 to 4 mm) at a wavelength of 2.4 mm.

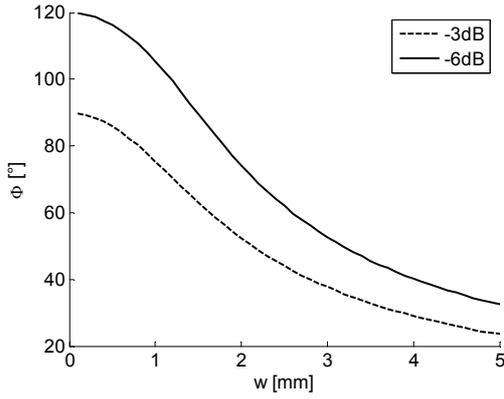


Fig. 5. Beam angle Φ (at a decay of -3dB and -6dB, respectively) of a rectangular transducer of infinite length for a wavelength of 2.4 mm as a function of its width w .

Fig. 5. The beam angle is defined as the total angular range of the sound beam with an amplitude decay of less than -3dB and -6dB, respectively. A maximum -3dB beam angle of 90° and a -6dB beam angle of 120° can be achieved for a transducer width approaching zero. The beam angle is quickly decreasing with increasing width in the region of about one wavelength. A width of 1 mm was chosen for our design since it represents a reasonable compromise between wide beam, high sensitivity and ease of machinability. A length of 9 mm is used to generate a narrow beam normal to the measurement plane.

3.1. Non-invasive and non-intrusive configuration

Non-invasiveness can be a very important requirement for industrial sensors. There may be special demands on purity, like in food production, or the flow may contain aggressive and hazardous substances, like in the chemical industries. Fig. 6(a) shows an example of a non-invasive transducer as proposed in [8]. The sensor element is not in direct contact with the flow. However, the configuration is intrusive as the pipe wall is formed to act as an acoustic lens spreading the sound beam.

Non-intrusiveness may also be of importance in order to not disturb the flow, leading to pressure drops and turbulences. Such a setup is depicted in Fig. 6(b) and was used, e.g., in [9]. The process vessel contains slots through which the transducer elements are brought into direct contact with the flow medium. This approach avoids potential problems like attenuation of the pipe material, reflection loss due to acoustic mismatch, and coupling between neighboring transducers through structure-borne sound. However, it is prone to problems like leakage and corrosion of the trans-

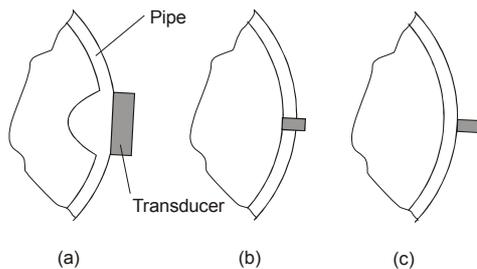


Fig. 6. Invasiveness and intrusiveness of different sensor configurations: (a) Non-invasive but intrusive principle; (b) Non-intrusive but invasive principle; (c) Non-intrusive and non-invasive principle.

ducers.

A main feature of our novel sensor array is both its non-invasiveness and non-intrusiveness. The arrangement of a single transducer element is shown in Fig. 6(c). The piezoelectric plate is bonded to the outer surface of the pipe. We use a standard industrial-grade PVC as the basis of our sensor design since this is a commonly encountered material. Depending on the application other pipe materials like metals could also be used.

The acoustic waves generated at the transducer-pipe interface have to propagate through the pipe wall and pass the PVC-water interface, where refraction occurs. The effects of a PVC layer on the beam spreading are illustrated in Fig. 7, where the transmission and reflection angles at the transition from PVC to water and vice versa are shown as functions of the angle of incidence. The curves were obtained using Snell's law [10], assuming plane wave conditions and a plane interface. When transmitting through a PVC-water interface, the maximum angle to the interface normal that can be achieved for the transmitted wave is 39.1° . Conversely, when receiving a wave across a water-PVC interface there is also a critical angle of 39.1° for the incident wave. At angles greater than the critical angle there is no through-transmission and only a wave parallel to the interface can propagate. So there is a theoretical limit for the beam angle Φ of 78.2° .

In addition the transmission coefficient at the PVC-water interface depends on the incident angle. At normal incidence 86% of the beam intensity are transmitted into the water, but the figure is rapidly decreasing for incident angles larger than 60° . So to obtain the effective beam profile in water both the relative intensity of the beam, as shown in Fig. 4, and the transmission coefficient have to be considered. The resulting intensity profile is depicted in Fig. 8. Transducer elements of different width are compared, where the curves have been individually normalized to their respective maximum amplitudes. The presented simulations are based on plane wave conditions. This is a simplification because the acoustic impedance of cylindrical waves is complex close to the origin. However, it approaches the plane wave impedance with increasing distance from the origin [10]. Only longitudinal wave propagation is considered since the effect of shear waves is small for excitation with longitudinal wave

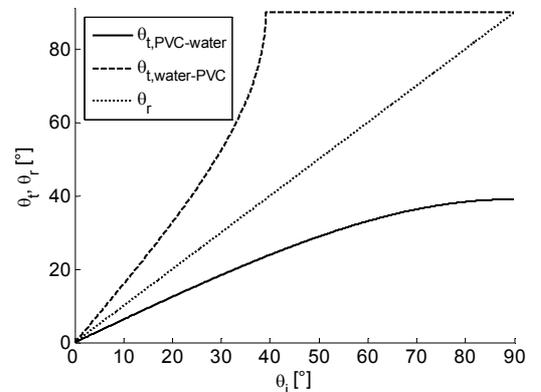


Fig. 7. Transmission and reflection angles θ_t and θ_r of sound waves at PVC-water and water-PVC interfaces as a function of the angle of incidence θ_i .

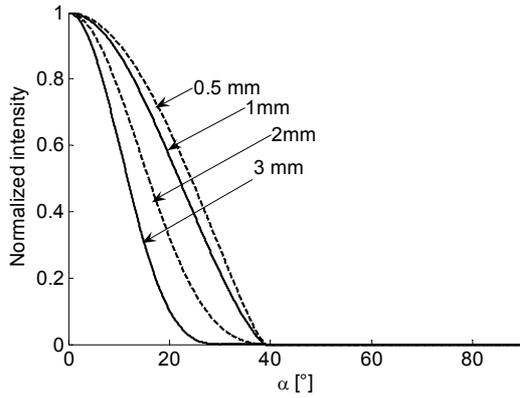


Fig. 8. Beam profiles of thin rectangular transducers at a frequency of 1 MHz of varying width in water with a PVC layer inserted between the transducer and the water. The curves have been individually normalized

transducers. The figure shows that there is only a small difference in the achievable beam angle between a transducer width of 0.5 and 1 mm. It is however rapidly decreasing as the width is increased, justifying the use of 1 mm wide elements for our prototype sensor.

A Finite Element Method (FEM) simulation of the beam profile generated by such a transducer when emitting through a 1 mm thick PVC pipe wall of 60 mm inner diameter is shown in Fig. 9. Only one half of the configuration is discretized due to its symmetry. The Helmholtz equation with suitable boundary conditions is used to model the problem. The simulation shows that the sound beam is spreading with an angle 35° in a region with significant excess pressure. This is in agreement with the results obtained from the analysis of the transmission coefficients. Although the ultrasound is emerging from a very thin element outside the pipe it enters the water across a wider area. This is attributed to the divergence of the beam inside the pipe wall. Parts of the beam emitted at large angles travel sideways before they hit the interface and enter the water at the critical angle. This effect is amplified through the curvature of the pipe at small pipe diameters. The sound field inside the pipe wall is quickly dying down due to attenuation and transmission of the energy into the water.

Further simulations revealed that the beam angle is re-

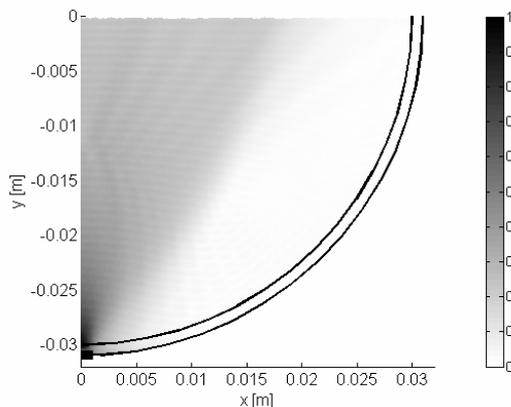


Fig. 9. FEM simulation of the beam profile generated by a 1 mm wide transducer transmitting into water through a 1 mm thick PVC pipe wall at 1 MHz. The transducer is attached to the lower left part of the pipe. The image shows the normalized maximum excess pressure.

duced as the pipe wall thickness increases. With a thicker wall more of the acoustic energy travels along the wall and is absorbed. This behavior has also been confirmed with measurements, where a usable angular range of 35° for 1 mm wall thickness, 30° for 2 mm, and only 15° for a thickness of 4.7 mm were achieved.

3.3. Transducer material

A serious issue when transmitting ultrasound through a solid is structure-borne sound. This problem is worsened in our case since a significant part of the acoustic energy in the wide beam will be reflected at the inner pipe wall and propagate along its circumference. A further problem is the small width of the transducer. With typical transverse wave speeds of commonly used PZT material, this would give an unwanted lateral resonance at around the desired working frequency of 1 MHz. To reduce the sensitivity of the sensor array to lateral modes we use a piezocomposite material for the transducers. It consists of thin PZT rods in longitudinal direction arranged with a random pitch embedded in an epoxy matrix [13]. This configuration gives a good immunity to lateral resonances.

Piezocomposites have a significantly lower acoustic impedance than pure PZT crystals (19 MRayls in our case, compared to 33.7 MRayls for PZT-5A). This allows the pipe wall in principle to act as a matching layer since its impedance lies between that of water and the piezocomposite. However, the diverging waves are not reflected back to the transducer in the wide-beam setup so that resonances can not build up.

4. MEASUREMENT RESULTS

A picture of our prototype sensor array with 16 transducer elements is shown in Fig. 10. The PVC pipe has an inner diameter of 60 mm and is machined to a wall thickness of 1 mm at the transducer positions. The inner electrodes are conductively bonded to the outer pipe surface with silver-loaded epoxy that serves as ground connection. The top electrode connections have been soldered. The sensor is fitted into an aluminium casing holding the electrical connectors.

The waveform obtained from transmitting a pulse at one side of the water-filled pipe and receiving on the opposite



Fig. 10. Prototype sensor array with 16 transducer elements of 1 mm width mounted on the outer PVC pipe surface. The pipe is built into a casing holding the electrical connections.

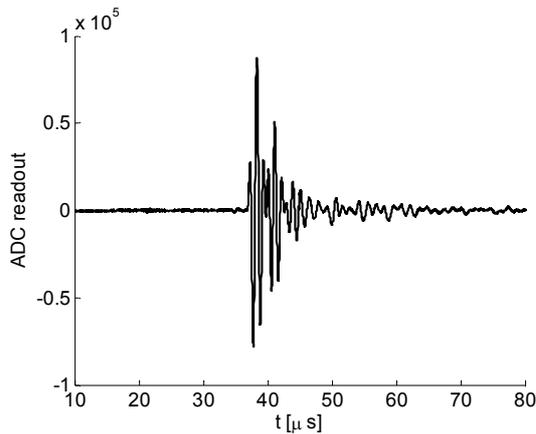


Fig. 11. Received waveform of a transducer element after transmitting a pulse on the opposite side of the pipe.

side is illustrated in Fig. 11. The received signal has a reasonably high bandwidth of around 400 kHz.

The pulse travel times recorded by the receivers after pulsing the first transducer are shown in Fig. 12. The values have been obtained from thresholding the received waveforms. Times of zero indicate that no signal has been detected. The dashed curve shows the travel times theoretically calculated from the distances of the transducers. It can be seen that there is an excellent agreement with the measured values for transducers 7 to 9, which are opposite to the transmitter. The other transducers can not detect a signal due to the finite beam angle. The receivers adjacent to the transmitter detect signals that are attributed to cross-coupling through the pipe wall.

5. CONCLUSION

Process tomography offers the possibility to measure internal process parameters from boundary measurements. Sensors that are non-intrusive and non-invasive may be desirable in many industrial applications. Therefore we presented the design of a novel non-invasive and non-intrusive ultrasonic transducer array for industrial imaging applications. The major design issues for ultrasound process tomography sensors have been discussed. Simulation studies showed the influence of design parameters on the sensor performance. Based on these results a prototype sensor array with 16 transducers has been manufactured. Measurement results demonstrate the validity of the approach. So the developed sensor array is able to capture projection data

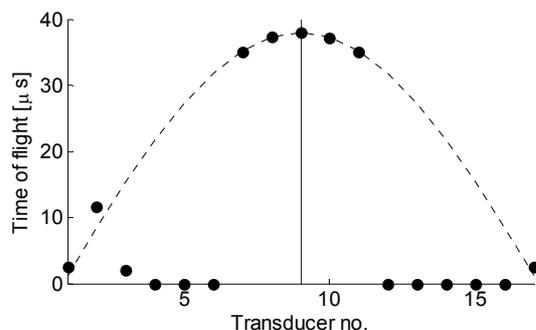


Fig. 12. Recorded pulse travel times of the receivers for transmitting at transducer 1. The dashed curve are the arrival times expected from the geometrical distance between the transducers.

without interfering with the flow or process to be imaged.

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