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Sound Propagation and Signal Quality of Ultrasonic Sensors in Dependency on the Distance of the Transducers

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Abstract: In applications with ultrasonic clamp-on sensors measurement accuracy and repeatability are significantly worse when compared to ultrasonic inline sensors in spite of both sensor types using the same measurement principle. The positioning of the ultrasonic transducers of clamp-on sensors has a determining influence on the precision and accuracy of the measurement results. A study was made of sound propagation and receiver signal quality as they vary depending on the distance between the ultrasonic transmitter and the ultrasonic receiver. If the positioning of the ultrasonic transducers can be optimized, then the precision of the measuring in clamp-on applications is improved. As a result of studying transducer sensitivity it was possible to implement an automatic positioning system for ultrasonic clamp-on sensor applications. The positioning system automatically finds an optimal transducer position for a particular application, this allows a user to operate a clamp-on sensor without having any special knowledge of the application procedure or needing to set any parameters of the system in advance. *Copyright © 2016 IFSA Publishing, S. L.*

Keywords: Ultrasonic clamp-on sensor, Receiver signal quality, Propagation of sound, Dependency on distances of transducers, Automatic transducer positioning.

1. Introduction

This is an extended paper of a study, which was presented and discussed in some details at the conference ALLSENSORS 2016 [1].

1.1. State of the Art

Today, a well-known application area for ultrasonic clamp-on sensors is in the flowmeters which are used in many industrial processes [2-7].

Ultrasonic clamp-on sensors offer the opportunity to measure other parameters, for example density and the concentration of ingredients in fluids [8-11].

Other kinds of ultrasonic clamp-on sensors allow detection of the composition of homogenous alloys or can distinguish synthetic materials without any chemical analysis [12]. Such systems are used where non-destructive material control is required.

The main advantage of all these kinds of ultrasonic clamp-on measurements is the possibility to measure non-invasively. Parameters can be detected offline or online, so one does not have to disconnect a running system. This advantage led to successful development and deployment of clamp-on transducers for more than twenty-five years [13].

There are also some disadvantages of using ultrasonic clamp-on sensors particularly in comparison to ultrasonic sensors with fixed-mounted transducers in a complete sensor system. The main functional components, transducers and electronics of these different ultrasonic sensors generally operate in the same way. Only the positioning of the transducers is significantly different [14]. The greatest signal amplitudes and the best signal to noise ratio are expected when the transmitter and the receiver are located in an optimal relative position.

Thus, the proposal is the following: if the positioning of the ultrasonic transducers can be optimized, then the precision of the measuring in clamp-on applications is improved.

1.2. Aim of the Study

This study concentrates on flowmeter applications and finding an optimal relative position between an ultrasonic transmitter and an ultrasonic receiver when placed on a water-filled pipe. Without the influence of any flow, the signal quality of the receiver was measured as solely dependent on the distance between the transducers. The maximum amplitude for the envelope curve of the receiver signal is a sure indicator of an optimal distance between transmitter and receiver. An automatic transducer positioning system for clamp-on flowmeter applications was developed using this criterion.

1.3. Structure of the Paper

The paper is subdivided into five main sections. According to this instruction, some relevant theoretical basics are elucidated and illustrated in section ‘Theory’. The theoretical basics are described in this section in more details than in [1], representations of [15] were included. The section ‘Measurements’ contains a description of the experimental setup, the measurement results and an interpretation of the represented series of receiver signals.

In section ‘Automatic Transducer Positioning System’, such a system for clamp-on ultrasonic transducers is briefly depicted. In a last section, a summary and an outlook are written.

2. Theory

2.1. General Basics

Two general kinds of ultrasonic clamp-on sensors for measuring flows are known.

The first group is based on the Doppler-effect. Flowmeters of this group are not an object of consideration here, because they work much more inaccurately than the other ones. Furthermore, such flowmeters are only usable if there are enough reflecting particles or gas bubbles in the flowing fluid. They do not function to measure the flow of a homogeneous liquid like e.g. oil or clear water.

Clamp-on flowmeters of the second group are based on exact the same measurement principle like the inline ultrasonic flowmeters.

Both, inline and clamp-on sensors, function on the so called transit-time differential method. The main functional components, transducers and electronics, of these different ultrasonic flowmeters generally operate in the same way. Also the accuracy and resolution of transit time measurements depend on the signal quality in all kinds of contrapropagating transit time flowmeters.

Only the positioning of the transducers is realized extremely different and therefore the calibration opportunities are significantly different, too.

In case of inline sensors every functional detail of the ultrasonic sensor is optimal designed. The material of the measuring pipe is well-chosen by the developers of the sensor. The distance between the ultrasonic transmitter and receiver and the acoustical contact with the measuring pipe are realized by the producer of the sensor.

But in the case of clamp-on sensors the pipe of the process is used as the measuring pipe although it was not designed for this function. The mounting of the ultrasonic transducers depends significantly on the knowledge and skills of the installer. The installer has to organize an acoustical contact and he needs to find out the optimal distance of the transmitter and receiver. Often there is not enough or not correct information available on several parameters. Therefore a suboptimal distance of the ultrasonic transducers is realized.

Thus, the idea must be: if the positioning of the ultrasonic transducers is brought under optimized automatic control, then the precision of the flow measuring in clamp-on applications becomes better.

Optimized automatic control of the positioning of ultrasonic clamp-on transducers has to operate only with objective parameters of the application. It has to find out which parameters are important and which are negligible. That is why the measurement principle’s dependency on parameters was theoretically and experimentally studied.

2.2. Measurement Principle

First, one has to look at the known basics of the measurement principle in transit time flowmeters, which are illustrated in Fig. 1 and Fig. 2.

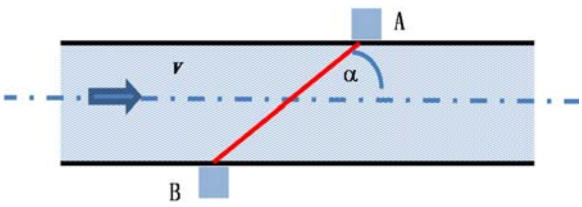


Fig. 1. Up-and down signals (z-model arrangement).

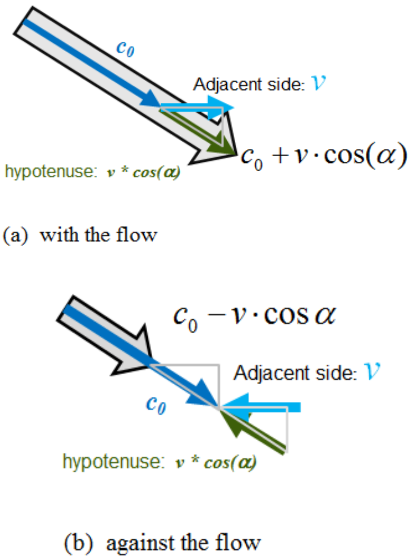


Fig. 2. Addition of velocity vectors in both directions.

Like shown in Fig. 2, the transit times of the traveling ultrasonic signals from A to B and also from B to A can be calculate:

$$t_{AB} = \frac{l}{c_0 + v \cdot \cos(\alpha)}, \tag{1}$$

$$t_{BA} = \frac{l}{c_0 - v \cdot \cos(\alpha)} \tag{2}$$

Comparing both directions, more time is needed against the flow. The transit times both up- and downstream, t_{BA} and t_{AB}, are indirectly proportional to the velocity.

Moreover, they depend on the sound velocity of the fluid. On the one hand the sound velocity is much greater than the flow velocity $c_0 >> v$ and on the other hand the change of the sound velocity by parasitic influences like temperature or density of the flowing fluid may be greater than the measuring effect by the velocity of the flow ($\Delta c_0 = f(T,\rho)$; $\Delta c_0 > \Delta v$).

By calculating the difference Δt and the sum Σt or alternatively by calculating the difference Δt and the product Πt of the measured transit times (with: $\Delta t = t_{BA} - t_{AB}$; $\Sigma t = t_{BA} + t_{AB}$; $\Pi t = t_{BA} \cdot t_{AB}$) the following equations are deduced:

$$v \approx \frac{2l}{\cos(\alpha)} \cdot \frac{\Delta t}{(\Sigma t)^2}, \tag{3}$$

$$v \approx \frac{l}{2 \cdot \cos(\alpha)} \cdot \frac{\Delta t}{\Pi t} \tag{4}$$

The flow velocity is directly proportional to the difference of the transit times v~Δt and the dependency of the sound velocity is eliminated there.

While the absolute transit times of the z-arrangement (Fig. 1) are in the µs-range, the difference of the transit times behaves only ps. According to this the time measurement has to be realized with a high resolution.

The inclination angle α has to be chosen small to get longer absolute transmission times t_{AB} (1) and t_{BA} (2). Instead of the z-model arrangement a v- or w-model arrangement (Fig. 3) is useful to get longer signal ways in the fluid, longer transit times and in consequence of it better measurement resolutions:

Methods of gate measurement or cross-correlation are typically used for measurement of the transit times in such ultrasonic flowmeters.

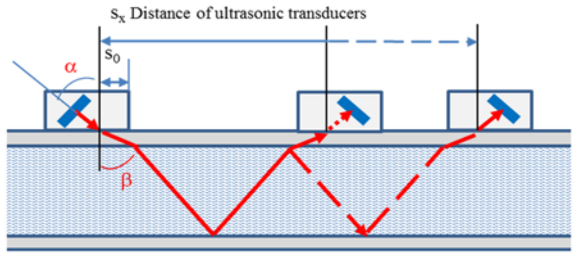


Fig. 3. Arrangements of ultrasonic transducers (v- and w-model).

2.3. Law of Reflection

One of these optimal relative positions results from the v-model arrangement of the transducers. The way of the ultrasonic signal in a v-model arrangement is illustrated in Fig. 4.

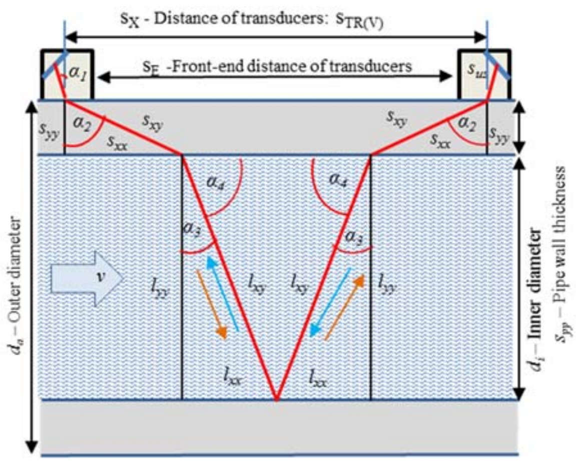


Fig. 4. Path of the ultrasonic jet in a v-model arrangement.

The basic of this representation is the SNELLIUS-law of reflection. It describes the change of the direction of propagation at boundaries between mediums with different sound velocities [16]. In general it applies:

$$\frac{c_1}{c_2} = \frac{\sin(\alpha_1)}{\sin(\alpha_2)}, \quad (5)$$

$$\alpha_2 = \arcsin\left(\frac{c_2 \cdot \sin(\alpha_1)}{c_1}\right) \quad (6)$$

If SNELLIUS-law of reflection (6) is used repeatedly then multiple reflections at all boundaries of the measuring setup are considered. The following equations are deduced from this:

$$\alpha_2 = \arcsin\left[\frac{c_{pipe} \cdot \sin(\alpha_1)}{c_{transducer}}\right], \quad (7)$$

$$s_{xy} = \frac{s_{yy}}{\cos(\alpha_2)}, \quad (8)$$

$$s_{xx} = \sin(\alpha_2) \cdot s_{xy}, \quad (9)$$

$$\alpha_3 = \arcsin\left[\frac{c_{fluid} \cdot \sin(\alpha_2)}{c_{pipe}}\right], \quad (10)$$

$$l_{xy} = \frac{d_a - 2s_{yy}}{\cos(\alpha_3)}, \quad (11)$$

$$l_{fluid} = 2 \cdot l_{xy}, \quad (12)$$

$$l_{xx} = \sin(\alpha_3) \cdot l_{xy} \quad (13)$$

Optimal distances of the transducers can be calculated for the z-, v- and w-arrangement:

$$s_{transducer-Z} = 2s_{xx} + l_{xx}, \quad (14)$$

$$s_{transducer-V} = 2s_{xx} + 2l_{xx}, \quad (15)$$

$$s_{transducer-W} = 2s_{xx} + 4l_{xx} \quad (16)$$

2.4. Fault Effects

The influence of incorrect parameterizing of sound velocities or the inclination angle is shown in Fig. 5 and Fig. 6.

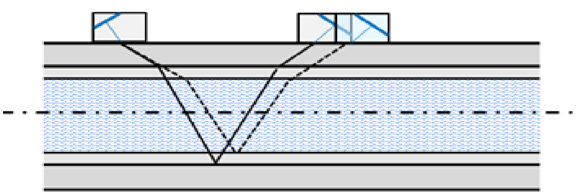


Fig. 5. Optimal distance of transducers depending on the diameter or on the pipe wall thickness.

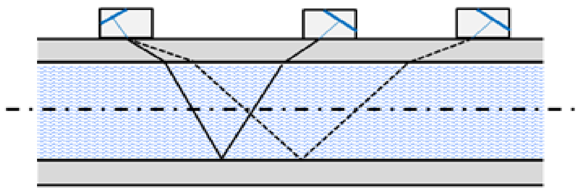
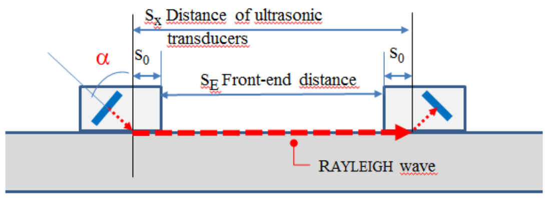


Fig. 6. Optimal distance of transducers depending on the inclination angle or the sound velocities.

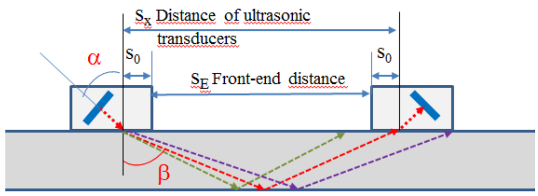
The optimal distance of transducers depends on the diameter of the pipe, the pipe wall thickness, the inclination angle and the sound velocities of the transducer material, the pipe material and the fluid in the pipe.

2.5. Sound Propagation

The sound propagation between an ultrasonic transmitter and an ultrasonic receiver (see Fig. 7 and Fig. 8) takes place by Rayleigh waves (surface acoustic waves) and by transversal and longitudinal waves.



(a) Direct Rayleigh waves (0. Order)



(b) Reflective waves (1. Order)

Fig. 7. Paths of ultrasonic waves at the wall of the pipe.

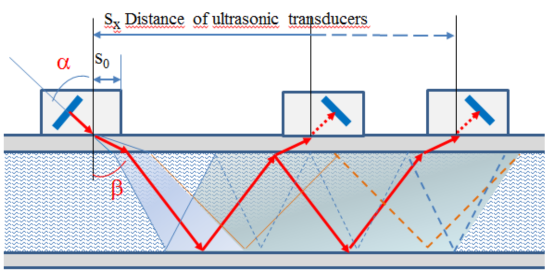


Fig. 8. Sound propagation with beam spread instead of supersonic jets.

Furthermore, as is generally known, ultrasonic sound velocity depends on material properties [17]. In solids, the ultrasonic sound propagation is a result of volumetric deformation and shear deformation. All kinds of waves propagate in solid materials like the wall of the pipe. The sound velocity depends on the bulk modulus, the shear modulus and the density of the material in which the ultrasonic wave is travelling. Fluids do not transmit shear forces therefore only longitudinal waves have the capability to spread in liquids and gases. Typically, longitudinal waves travel faster in materials than do transversal waves [18]. Furthermore, the sound velocity of Rayleigh waves is less than the sound velocity of transversal waves [19].

$$c_{RAYLEIGH} < c_{transversal} < c_{longitudinal} \quad (17)$$

Fig. 7 depicts the relevant distances, the inclination angle α, the shortest path of surface acoustic waves (Rayleigh waves) and the path of reflective waves at the wall of the pipe.

Another aspect of sound propagation is the superposition of different orders in the pipe through the fluid (Fig. 8 and Fig. 9).

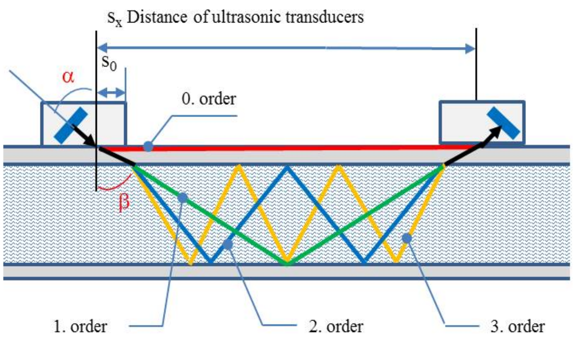


Fig. 9. Definition of different order parts of an ultrasonic signal.

A widespread beam is really propagated instead of a supersonic jet. Such a widespread beam has a similar effect like an instability or uncertainty of the inclination angle.

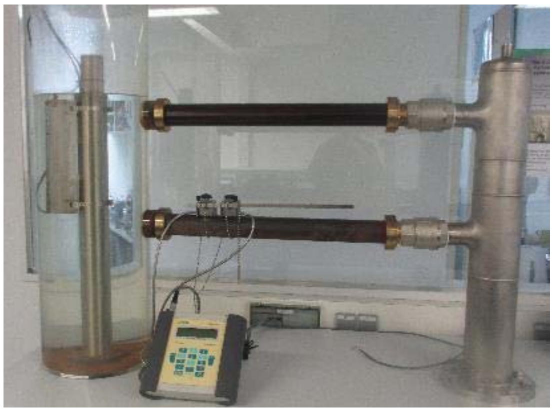
Both the breadth of the real beam spread and the superposition of multiple reflections constitute reasons why there is a measurement effect in nearly every distance between the ultrasonic transmitter and receiver (Fig. 8).

If the distance between the transducers is immovable, ultrasonic receiver signal consist of the superposition of different signal parts, too. By analogy to Fig. 7, the signal part of the shortest direct path between the transducers is the zero-order part, the v-reflection is defined as the first-order part, the w-reflection represents the second-order and so on. Fig. 9 depicts the first to the third orders in a fluid filled pipe, while the zeroth order results from the path at the wall of the pipe. Note, there is a different between the higher orders through the fluid and the higher orders at the wall of the pipe (compare Fig. 7 and Fig. 9).

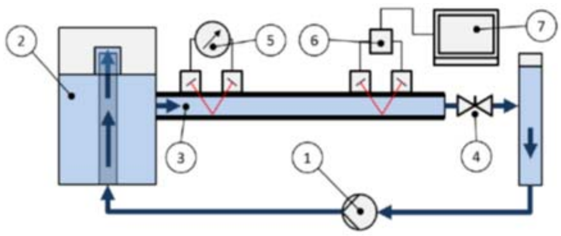
3. Measurements

3.1. General Description of the Experimental Setup

The experimental setup is shown in Fig. 10 to Fig. 13. Each horizontal pipe (Fig. 10) consists of a different material. The pipes are filled with water. Ultrasonic clamp-on transducers can be mounted on these pipes. Usually, this is achieved by pipe clamps such as those used by the transducers of the reference clamp-on flowmeter F601 from the Flexim GmbH company (Fig. 10(a)).



(a) Photographic image



(b) Schematic drawing [20]

Fig. 10. Setup with water filled pipes for testing ultrasonic clamp-on sensors.

Fig. 10 shows the main parts of the experimental setup. The experimental setup (Fig. 10 (b)) consists of:

- (1) A pump;
- (2) A cylindric fluid reservoir;
- (3) Two pipes with a flowing fluid (water);
- The upper one consists of pertinax;
- The lower one consists of steel;
- (4) A valve (manual adjustability);
- (5) A reference clamp-on flowmeter (F601 from the Flexim GmbH company);
- (6) A test clamp-on system;
- (7) Oscilloscope (DSO) or PC with ADC.

In the test case, a pair of ultrasonic clamp-on transducers was mounted with only the force of permanent magnets on a pipe of rusty steel (Fig. 11).

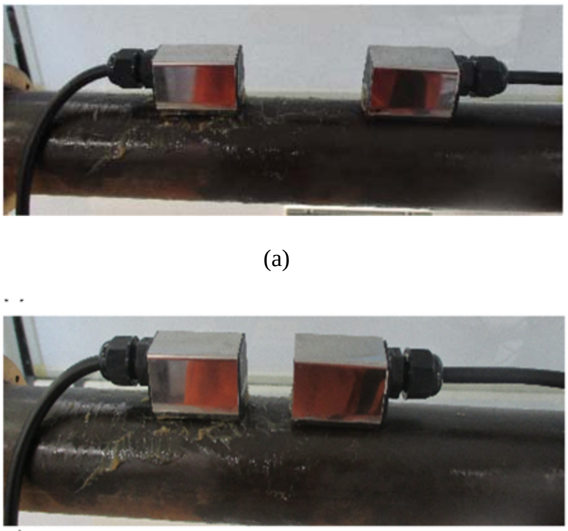
This made it very simple to change the distance between the transducers in the test scenario.

To study how the received signal quality depends on the distance between the transducers, the distance between the front-ends of the housings of the ultrasonic transmitter and the ultrasonic receiver was measured. The front-end distance of the housings is smaller than the real transducer distance.

The relationship between the distances is illustrated in Fig. 4, Fig. 7 and Fig. 12.

Ultrasonic transducers of a TUF2000-Clamp-on flowmeter were used for the experiments (Fig. 11 and Fig. 12).

In Fig. 12 the pipe-sided design of the transducers used is photographed.



(a)

(b)

Fig. 11. A pair of magnetic ultrasonic clamp-on sensors mounted at different distances.

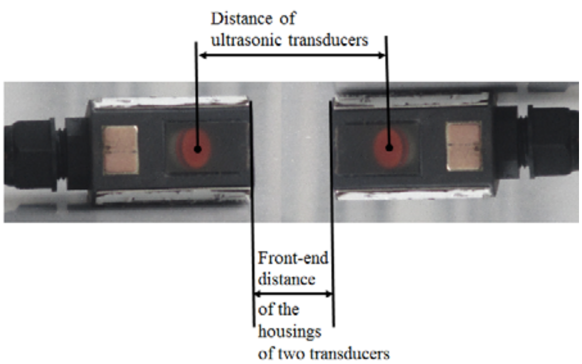


Fig. 12. Distance between the ultrasonic transducers.

3.2. Technical Specifications

The experimental setup used in the presented studies of ultrasonic signal quality considered paths without any flow (v=0 m/s). So, it was not necessary to use the installed clamp-on reference flowmeter (F601) for the presented studies.

The ultrasonic transmitter is driven by an electronic burst generator. Every burst consists of 10 single pulses. While the frequency of the burst sequence is 1 kHz, the frequency of the single pulses in the bursts is about 1 MHz.

The signals of the transmitter and the receiver were observed with an oscilloscope (DSO PM3394, 200 MHz, 200 MS/s, 16 bit ADC), a typical screen is shown in Fig. 13. The oscilloscope-channels may be read out by a LabVIEW-program.

In the detected signals of the receiver the transmitting burst is also observed (Fig. 13). This is a helpful effect of electromagnetic crosstalk.

Because of the observed parasitic crosstalk it is possible to detect absolute transmitting times of the ultrasonic signal passing the distance between the transmitter and the receiver by analyzing the data of only one channel (Fig. 7).

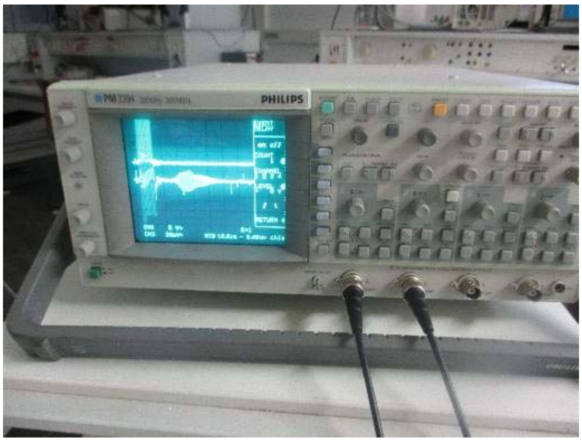


Fig. 13. Typical visualization of the transmitter and the receiver signal with electromagnetic crosstalk.

The main parameters of the experimental setup, which were varied, are (Fig. 4):

- The outer diameter d_a of the pipe;
- The thickness of wall s_{YY} of the pipet;
- The distance of ultrasonic transducers s_X.

For the distance of the transducers s_X obtains (Fig. 7 and Fig. 8):

$$s_X = s_E + 2*s_0, \quad (18)$$

$$s_X = s_E + 2*12\ mm, \quad (19)$$

where s_E = Front-end distance, s_0 = 12 mm [20].

3.3. Real Signals

It has been proved that the form and quality of the signal depends on geometrical pipe parameters and on the distance of the ultrasonic transducers.

In a first study, two different pipes (Table 1) were filled with water. There was no flow in the pipes during the measurements (v= 0 m/s).

Table 1. Geometrical pipe parameters of the test Cases I and II.

	Case I	Case II
Outer diameter of the pipe	33.2±0.1 mm	60.0±0.1 mm
Wall thickness of the pipe	3.2±0.1 mm	2.0±0.1 mm
Distance of transducers	104±0.1 mm	96.5±0.1 mm
Material of the pipe	Steel	Steel

Fig. 14 depicts scope-screenshots of the test Cases I and II [20].

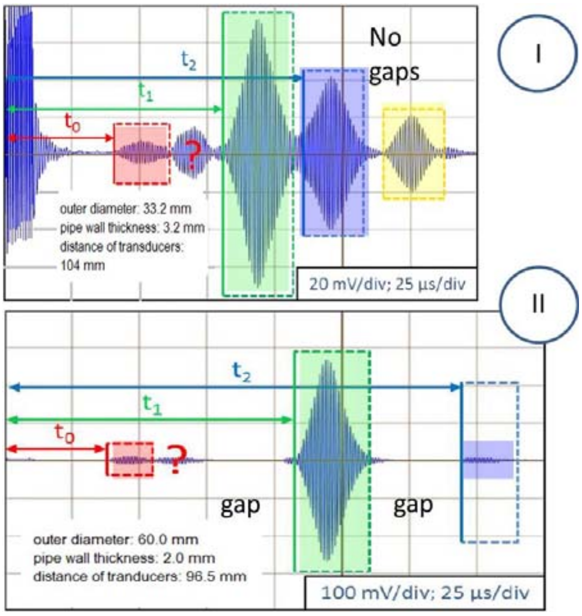


Fig. 14. Signals of two different pipes [20].

The forms of the receiver signals (Fig. 14) are very different.

While the scope-screenshot of Case I represents the transmitter and receiver signals of the situation with a smaller outer diameter but a thicker wall of the pipe, in the screenshot of Case II only the receiver signal is shown.

The transducers were mounted in both cases with fixed but different distances [$s_{x(I)} > s_{x(II)}$, Table 1].

One of the observations is, that there is no gap between the signal parts of different orders in case, while significant gaps are found in Case II.

According to the fact, that we have not a supersonic jet, but rather a widely spread beam, the sound propagation of all cases is characterized by overlies of different orders. The mapping of orders to signal parts is done by colors in Fig. 14 in the same way like in Fig. 9 (Green correspondents to the first order, blue to the second and yellow to the third; Red represents the result of the surface acoustic wave at the pipe – the so called Rayleigh-wave).

The superposition of reflections makes it difficult to interpret every signal part. The signal part, which is labeled by a question mark, may be the result of transversal waves or of signal parts higher orders in the solid material of the pipe. This was not consequently analyzed yet.

Because of the larger pipe diameter, in Case II the transit times both of the first (t_1) and of the second order (t_2) are longer than Case I.

However, the transit time (t_0) of the Rayleigh-wave is shorter in Case II than in Case I, because of the shorter distance of the ultrasonic transducers there.

As result of a second study, a representative measurement series of signals of the receiver channel in dependency on the distance of the ultrasonic transducers is printed in Fig. 15.

The pipe with the geometric parameters of Case II (Table 1) was used for this measurement series.

The observed parasitic crosstalk is helpful to detect absolute transmitting times of the ultrasonic signal passing the distance between the transmitter and the receiver by analyzing the data of only one channel.

A significant correlation between the transit time and the transducer distance is shown. The relevant time slot of the receiver signal can be easily observed.

Furthermore, the experiment indicates that the amplitude of the receiver signal does not decrease with the distance of the transducers. Constructive and destructive interferences seem to have the effect of periodical increasing and decreasing of the envelope curve of the receiver signal. In this case, the best signal noise ratios are found to be:

- $s_{X1} = s_{E(50)} + 24$ mm = (50+24) mm = 74 mm,
- $s_{X2} = s_{E(65)} + 24$ mm = (65+24) mm = 89 mm.

Such studies will be continued by using a novel automatic transducer positioning system.

4. Automatic Transducer Positioning

Following evaluation of experiments and some theoretical studies an automatic transducer positioning system for clamp-on sensors was developed and implemented [21]. This positioning system (Fig. 16 and Fig. 17) consists of a motorized linear track.

Only one of the pair of transducers is moved by the system. A stepper motor is used for this functionality.

The system is augmented with sensors to detect the temperature, the pipe outer diameter and the pipe wall thickness. Measurement results can be logged via interface functions. LabVIEW has been used to control the hole positioning system and to log the senor data. This makes a complete, generic measurement system for pipes.

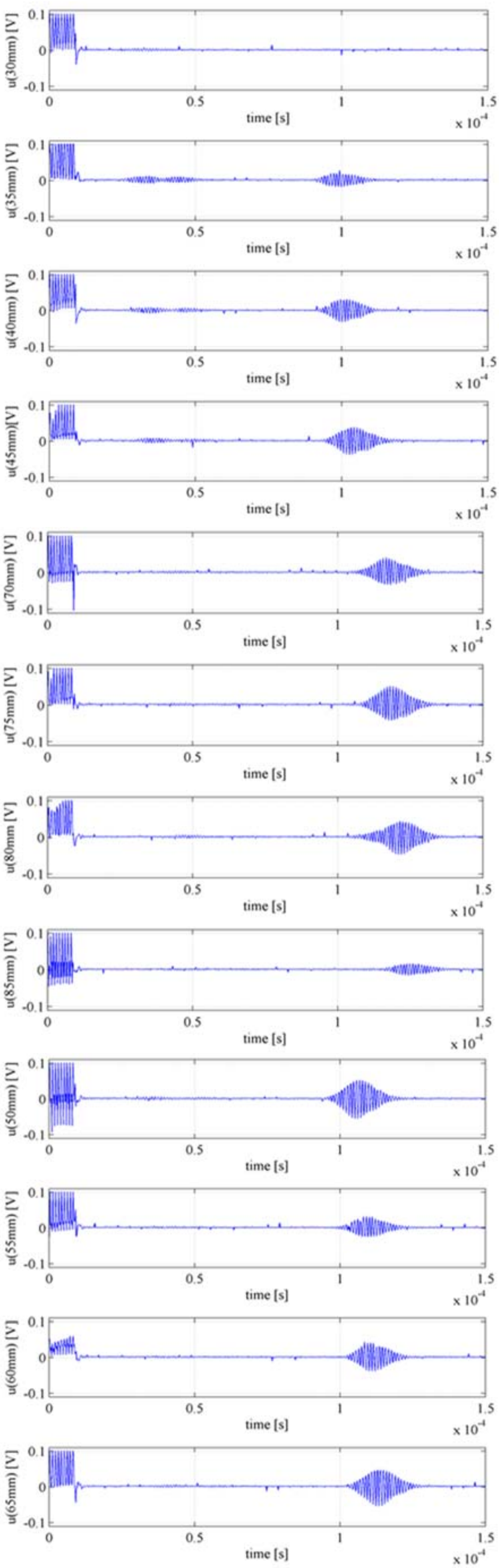


Fig. 15. Measurement series of receiver signals in dependency of the front-end distance of transducers.

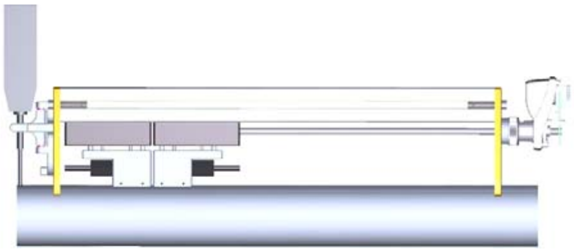


Fig. 16. Construction of the positioning system [21].

Fig. 17. Photographic image of the automatic positioning system [21].

5. Summary and Outlook

A study was made of signal quality and the resulting signal noise ratio dependent on the distance between the transducers. During the study, a system was created which automatically detects all relevant parameters to set the optimal distance between the ultrasonic clamp-on transducers in a particular application [21].

Including further variables would require additional sensors in this solution, for example sound velocities, temperature or geometric parameters of the pipe. But it seems possible to measure the effect of all relevant parameters with the required accuracy by varying the position of the pair of ultrasonic transducers [15]. By motorized motion of one transducer the ultrasound path between the transmitter and the receiver can be varied optimally for different measurement tasks.

Acknowledgements

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