Receiver Signal Quality of Ultrasonic Clamp-on Sensors in Dependency on the Transducer Positions

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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. 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 the 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.**

Keywords—ultrasonic clamp-on sensor; receiver signal quality; propagation of sound; transducer positioning

I. Introduction

Today, a well-known application area for ultrasonic clamp-on sensors is in the flowmeters which are used in many industrial processes [1-6] .

Ultrasonic clamp-on sensors offer the opportunity to measure other parameters, for example density and the concentration of ingredients in fluids [7-10] .

Other kinds of ultrasonic clamp-on sensors allow detection of the composition of homogenous alloys or can distinguish synthetic materials without any chemical analysis [11]. Such systems are used where non-destructive material control is required.

A. State of the Art

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 [12].

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 [13]. 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.

B. 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.

C. 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 section ‘Measurements’ contains a description of the experimental setup, the measurement results and an interpretation of the represented series of receiver signals. In section ‘Development of an 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.

II. Theory

One of these optimal relative positions results from the v-, and w-model arrangements of the transducers. The basis of these model arrangements is the SNELLIUS-law of reflection. It describes the change of the direction of propagation at boundaries between media with different sound velocities [14].

The sound propagation between an ultrasonic transmitter and an ultrasonic receiver (see Figures 1 and 2) takes place by Rayleigh waves (surface acoustic waves) and by transversal and longitudinal waves.

Furthermore, as is generally known, ultrasonic sound velocity depends on material properties [15]. 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 [16]. Furthermore, the sound velocity of Rayleigh waves is less than the sound velocity of transversal waves [17].

$$c_{RAYLEIGH} < c_{transversal} < c_{longitudinal} \,. \qquad (1)$$

Figure 1 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.

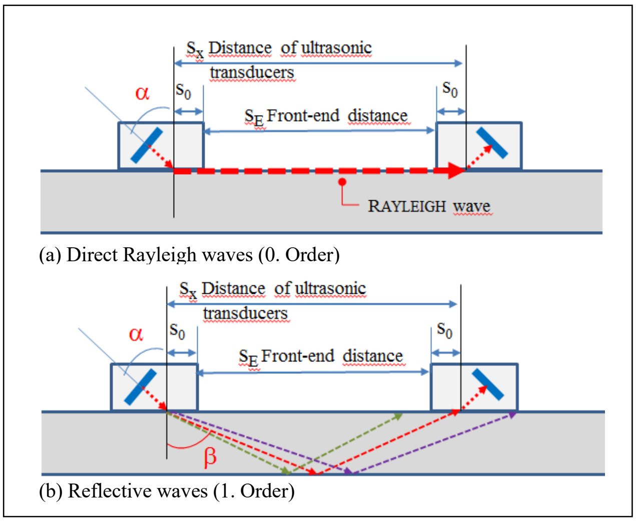

Figure 1. Paths of ultrasonic waves at the wall of the pipe

Another aspect of sound propagation is the superposition of different orders in the pipe through the fluid (Figure 2).

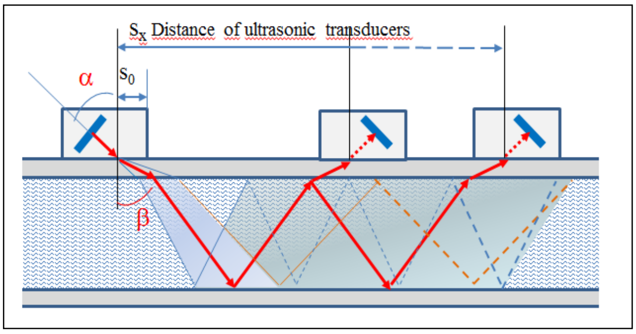

Figure 2. Sound propagation with beam spread instead of supersonic jets

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 (Figure 2).

III. Measurements

A. *General Description of the Experimental Setup*

The experimental setup is shown in Figures 3 to 6. Each horizontal pipe (Figure 3) 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 (Figure 3a). Figure 3 shows the main parts of the experimental setup.

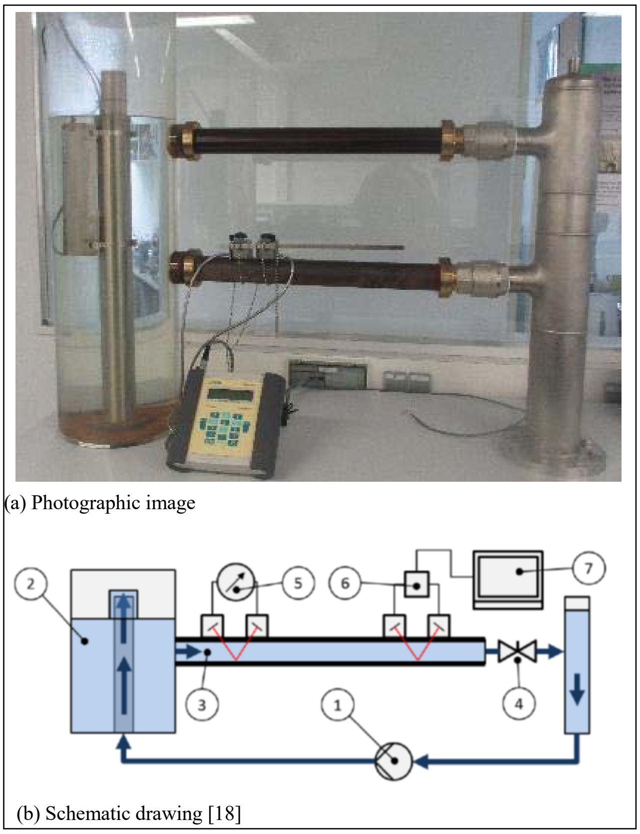

Figure 3. Setup with water filled pipes for testing ultrasonic clamp-on sensors

The experimental setup (Figure 3b) 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) PM 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 steel (Figure 4). This made it very simple to change the distance between the transducers in the test scenario.

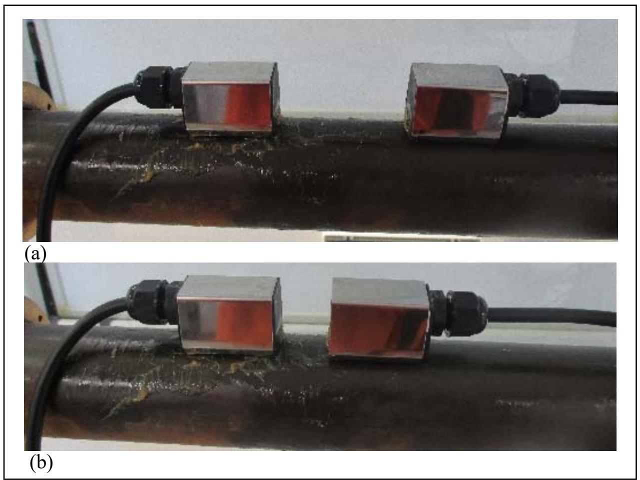

Figure 4. A pair of magnetic ultrasonic clamp-on sensors on a pipe of rusty steel mounted at different distances

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 Figures 1 and 5. Ultrasonic transducers of a TUF2000-Clamp-on flowmeter were used for the experiments (Figures 4 and 5). In Figure 5 the pipe-sided design of the transducers used is photographed.

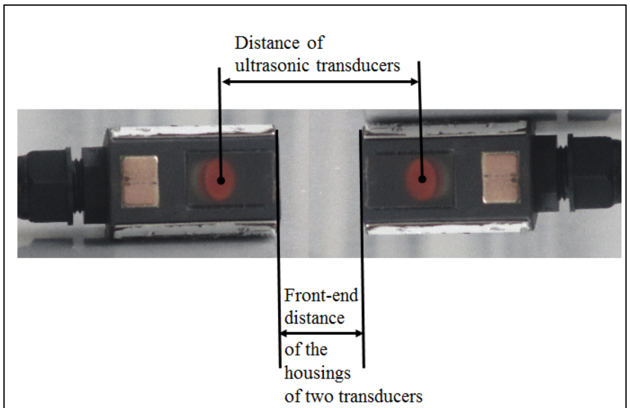

Figure 5. Distance between the ultrasonic transducers

B. 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 main parameters of the experimental setup are:

- The outer diameter of the used steel pipe: 60 mm.
- The thickness of wall of the pipe: 2±0,1mm.
- The distance of ultrasonic transducers:

$$s_{TR} = s_E + 2*s_0 \; ; \quad (2)$$

(s_E = Front-end distance s_0 = 12 mm [18]).

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). In the detected signals of the receiver the transmitting burst is also observed (Figure 6). This is a helpful effect of electromagnetic crosstalk (see below).

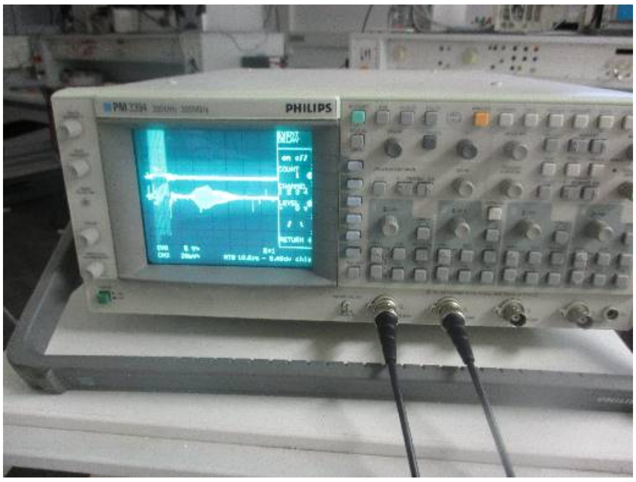

Figure 6. Typical visualization of the transmitter and the receiver signal with electromagnetic crosstalk

C. Signal Interpretation

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. For instance, a representative measurement series of signals of the receiver channel dependend on the distance of the ultrasonic transducers is printed in Figure 7 (Ultrasonic transducer distance s_{TR} =: front-end distance value s_E + 24 mm):

$$s_{TR} = s_E + 2*12 \text{ mm.} \quad (3)$$

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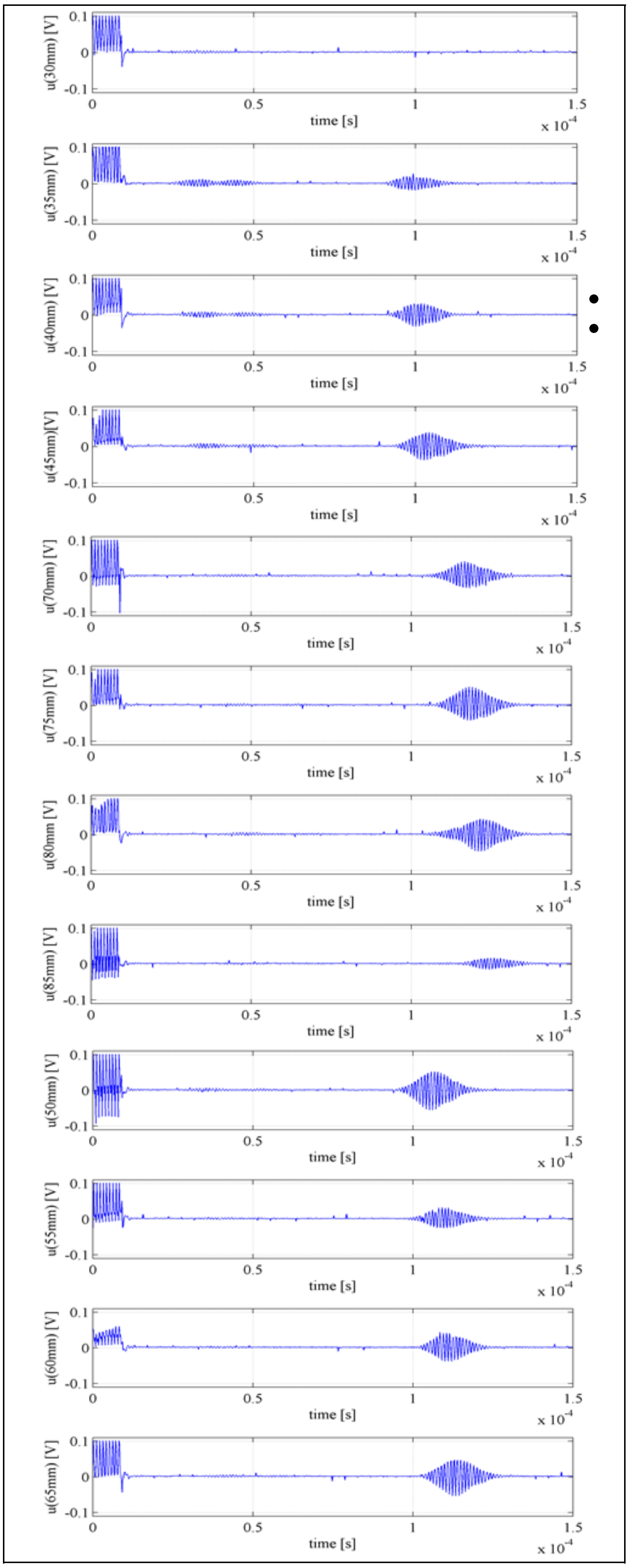

Figure 7. Measurement series of receiver signals in dependency of the front-end distance of transducers (from 30 mm up to 85 mm / step: 5 mm)

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:

- $s_{TR\_1} = s_{E\_50} + 24$ mm = (50+24) mm = 74 mm,
- $s_{TR\_2} = s_{E\_65} + 24$ mm = (65+24) mm = 89 mm.

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

IV. Development of an Automatic Transducer Positioning System

Following evaluation of experiments and some theoretical studies an automatic transducer positioning system for clamp-on sensors was developed and implemented [19]. This positioning system (Figures 8 and 9) consists of a motorized linear track. The system is augmented with sensors to detect the temperature, the pipe outer diameter and the pipe wall thickness. This makes a complete, generic measurement system for pipes.

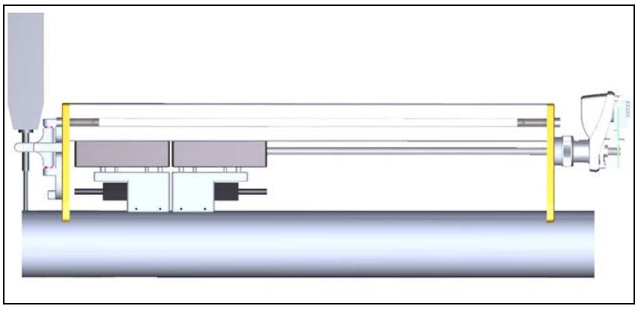

Figure 8. Construction of the positioning system [19]

The system is augmented with sensors to detect the temperature, the pipe outer diameter and the pipe wall thickness. This makes a complete, generic measurement system for pipes.

Figure 9. Photographic image of the positioning system [19]

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

V. 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 [19].

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. By motorized motion of one transducer the ultrasound path between the transmitter and the receiver can be varied optimally for different measurement tasks.

ACKNOWLEDGMENTS

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