DOI 10.5162/sensor2017/C2.4

Transducer misalignment - an insuperable obstacle for acoustic clamp-on liquid level measurement?

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Abstract:

The misalignment of acoustic sensors is one of the most crucial reasons for malfunction in case of level detection. Further some applications do not grant a sensor position perpendicular to the surface. By simple improvement of the transducer and applying a linear propagation model the current contribution proposes a solution to compensate the misalignment in case of non-invasive (clamp-on) fluid level detection applications. In the range of the acoustic divergence spread, the tilt angle can be identified and the sound propagation path and corresponding roundtrip time - used for level estimation – corrected. The bases are a simple linear triangulation with at least a three-element transducer and an automatic adaption of the acoustic excitation.

Key words: acoustic level detection, clamp-on, signal processing.

Motivation

The non-invasive fluid level detection and monitoring with acoustic waves is a common technique in several industrial applications. The clamp-on-approach is advantageous since it can be attached or applied to most common tanks or vessels. In practice, however, different technical reasons (e.g. structure borne sound, damping, reflection loss, bad coupling or misalignment of transducer) hinder their extensive and reliable usage [1, 2]. In fact, a transducer misalignment at the process vessel or the tilt of the vessel itself lead to a non-perpendicular incidence of acoustic waves at the liquid-gas interface and thus to a malfunction of the sensor (Fig. 1). Especially due to a misalignment (β – tilt angle hereinafter) of narrow beam ultrasonic clamp-on-sensors the liquid level determination cannot be applied adequately in process monitoring or other tasks. In about 50% of use cases the perpendicular installation of sensors relative to the liquid level is prevented and often the measurement fails. Already there exist some technical solutions for this problem by either using a phased array system or applying a time reversal approach. The first is very flexible concerning changing process condition and moving interfaces but need quite expensive phased array transducers and hardware. The second approach (time reversal) can be applied in case of very complex structures of the vessel even if the fluid surface is not in perpendicular sight to the transducer. As main drawback, a time consuming calibration of each vessel for all filling state, sensor positions and tilt angle is necessary. Hence in practice it is suitable for static systems only. The presented research work exemplifies a simplified practical solution for the mentioned problem by applying a simple triangulation technique in combination with a 3-channel sensor design.

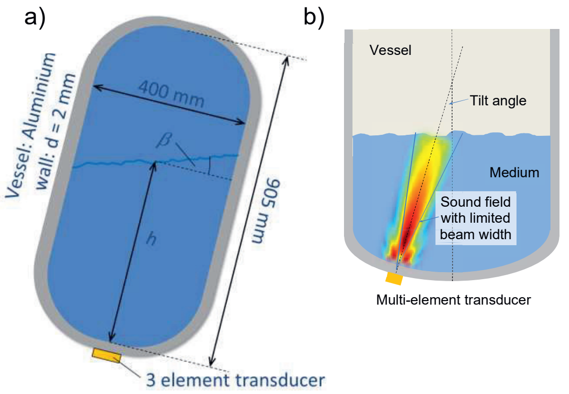

Fig. 1. Schematic representation of acoustic clamp-on liquid level detection in case of a) a tilting of a vessel (schematic of tank used for laboratory measurements referred in this work) and b) a transducer misalignment.

Experimental system

Most common industrial applications of liquid level monitoring concern cylindrical vessels – along one of the main axes of the cylinder. Hence – as proof by example – the system design and signal processing is done on a (small scale) laboratory system using a pressure tank with variable water filling level. The tank was mounted on rig which enables the variable tilting of the whole vessel (without changing the sensor configuration) (Fig. 2.).

The main components of the level detection approach are a single element transducer which can be grouped individually into arrays and the automatic compensation algorithm. The latter supports a calculation of the misalignment angle β and a correction of the acoustic time of flight (mainly used for level measurements). Similar to the full matrix acquisition in sampling phased array techniques the measurements are done sequentially in transmit-receive mode for each transducer combination. The impulse-echo signals are not recorded (diagonal elements of the matrix) (Fig. 3.). In the current realization a transducer with rectangular active areas is used (Fig. 4). The asymmetric acoustic field supports a preconditioning of the sensitive plane (tilt direction plane x-z). Further the cross sensitivity to out of plane reflections is reduced. On the basis of this transducer 3 types of 3- to 5-element arrays are grouped. The first type is similar to a linear array with an acrylic wedge to match the circular vessels wall (Fig. 5 a). The second and third types are flexible sensors, which easily could be mounted on slightly curvilinear surfaces (Fig. 5 b and c).

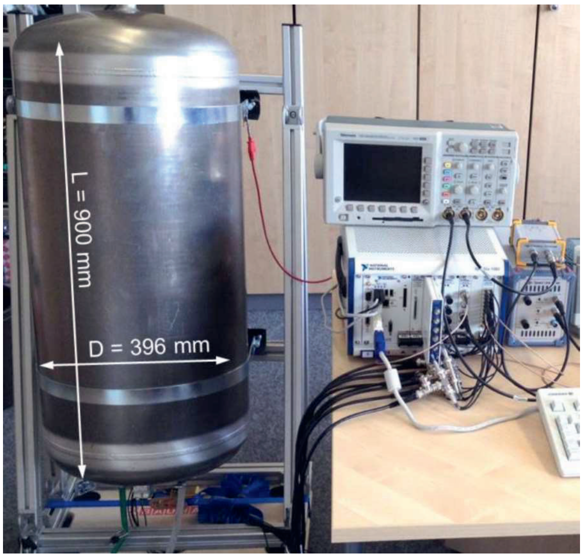

Fig. 2. Experimental rig with cylindrical water-filled vessel (aluminum, wall d = 2 mm).

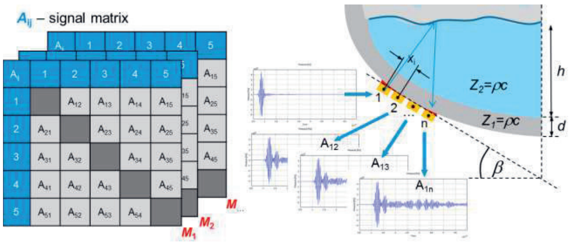

Fig. 3. Schematic of the transducer array and the acquisition procedure to measure the full information matrix A.

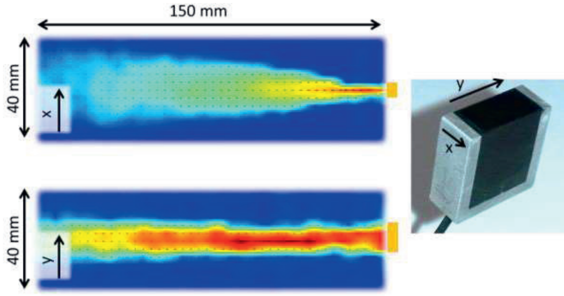

Fig. 4. Intensity plot of the acoustic field in water measured with a background schlieren system and corresponding single-element acoustic transducer [Sonotec Ultraschallsensorik Halle GmbH] (center frequency f = 1.052 MHz, active edge length x = 6 mm / y = 11 mm, divergence angle x: 20° / y: 8°).

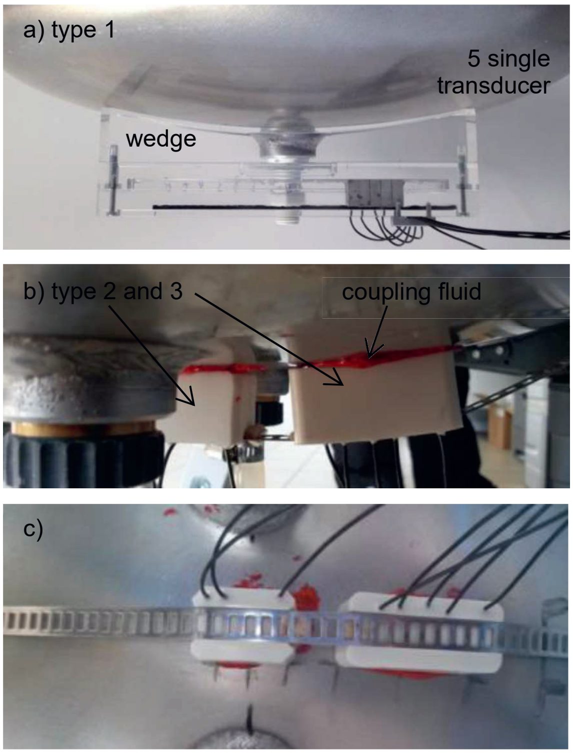

Fig. 5. Side and bottom view of 3- and 5-element transducer mounted at the bottom of the test vessel a) type 1 with acrylic delay line and b) flexible type 2 and 3 with direct contact with coupling fluid.

Signal extraction

Fig. 6 illustrates one element of the signal matrix A_{21} for a typical measurement scenario under transducer misalignment. The investigations have been carried out with type 3 sensor (Fig. 5). Consecutive each element was stimulated with a gaussian shaped sine burst with 10 periods and an amplitude of 20 Vpp. The receive signals at all other elements of the group were recorded. Exemplary the resulting intensity plot depicts the envelope of the receive signals at first transducer element (R1) when stimulating the second one (T2). The graph is scaled for the calculated roundtrip path h_{meas} depending on different liquid levels h_{real} in case of an alignment error of $\beta = 5.2°$ (Fig. 6). It is obvious that the filling-dependent information cannot be extracted automatically by simple analysis methods (e.g. threshold definition) for all filling levels. The knowledge of expected disturbing signals (e.g. for $h > 550$ mm marked as clutter Fig. 6 a) and the time frame (meas. window), containing the relevant signal component, is mandatory.

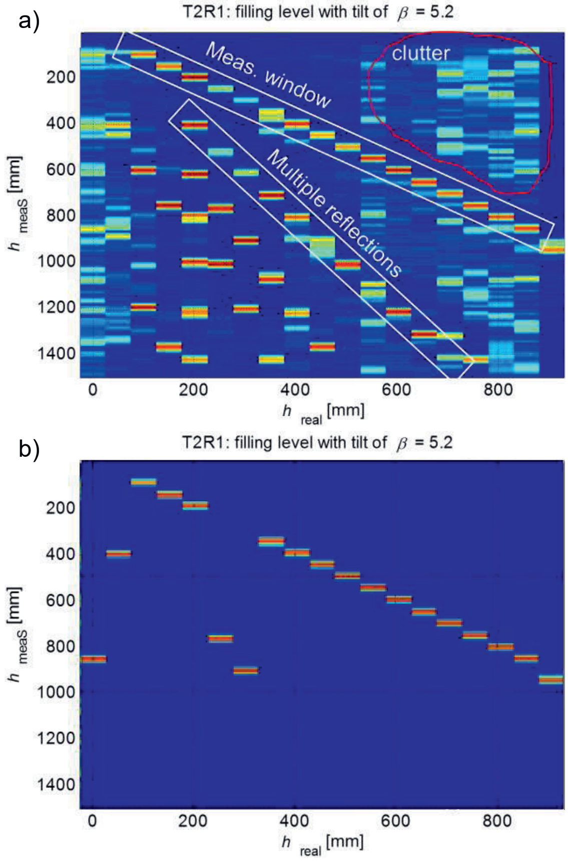

Fig. 6. Envelope of level-dependent receiver signal (10 sine-bursts, f = 1 MHz) at a test vessel (vertical cylindrical tank d = 400 mm and max. filling level h_{max} *= 905 mm) with non-perpendicular acoustic incidence (see Fig. 3.): signals between transducer element 2 (T2 - transmitter) and element 1 (R1 - receiver) with intermediate distance dx = 7 mm): a) raw data and b) after pre-processing (correlation, filtering, weighting).*

Of course, the representation additionally depends on the tilt angles and arrangements of single elements in the transducer group. Nevertheless the level dependent signals can be extracted or separated by applying a cross correlation with the ideal transmitted signal, a matched filtering and a normalization. The preprocessed data (Fig. 6 b) are the basis for the following triangulation correction since it the predicted filling height h_{meas} still contains an error of approx. 1% due to the tilted surface.

Triangulation and compensation

Taking a classical beamforming into account and calculating the corresponding angular sensitivity (Fig. 7) one can see, that for the present configuration (Fig. 5) a tilting of $\beta < 6°$ (= misalignment) in maximum would be possible. This angular range can be widened when using a triangulation within the beam spread of the single element transducers. According to the measured sound field in Fig. 4 a maximum tilt compensation of $\beta < 20°$ could be gained. Due to the different divergence angles of the rectangular transducer a preferred xz-plane can be used for compensating the misalignment angle by 2D-triangulation and analysis of time delay and amplitudes between the single transducer elements (Fig. 8). The reduction of the problem to a 2D-triangulation leads to an approximation for the roundtrip delay ΔT between the single element transducers within a transducer group (1). The analysis of this equation as well as the empirical verification (Fig. 10) confirm that the time delay ΔT between two transducer element pairs significantly depend on the tilt angle β between the plane of ultrasonic transducer and liquid-gas-interface (Fig. 9).

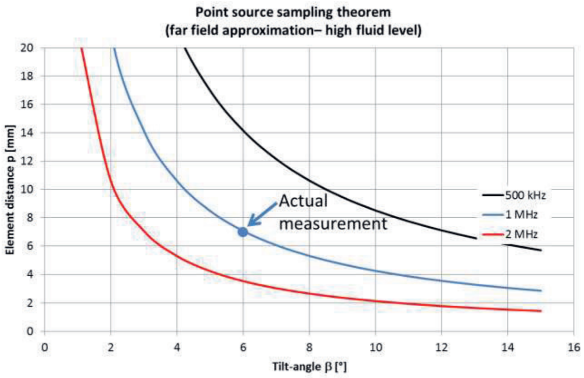

Fig. 7. Angular resolution due to the sampling theorem of a classical phased array

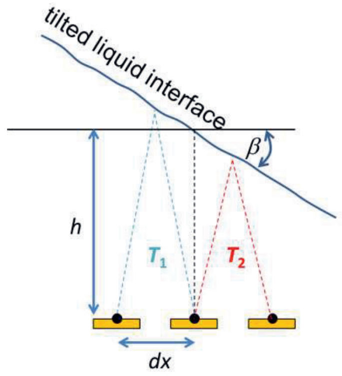

Fig. 8. Triangulation for the round trip times difference ΔT = T1-T2 (1) between three single transducers; Tx – transmitter, Rx - receiver.

$$ {}^{R1}_{R2}\Delta T = \frac{2}{c_0}\left[\sqrt{\left(h + {}^{dx}/_{2} \cdot tan\beta\right)^2 + \left({}^{dx}/_{2}\right)^2} - \sqrt{\left(h - {}^{dx}/_{2} \cdot tan\beta\right)^2 + \left({}^{dx}/_{2}\right)^2}\right] \qquad (1) $$

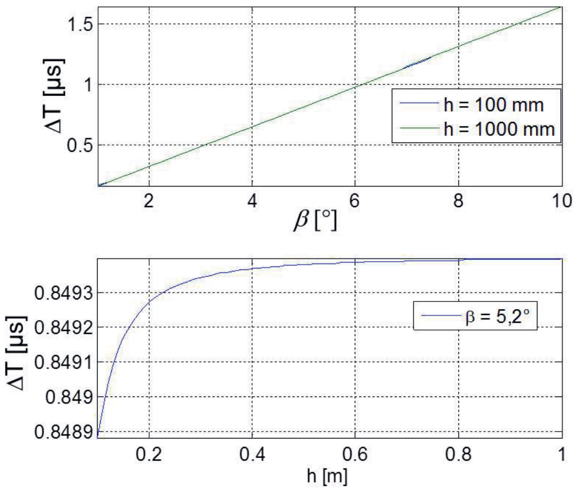

Fig. 9. Phase shift ΔT depending on tilt angle β and filling height h.

The calculation of the phase difference ΔT for variable tilt angle β and filling height h with equ. 1 shows that the variance in height delivers a negligible influence on the phase difference. Hence this phase information can be used to predict the absolute value of misalignment of the transducers axis to the liquid surface (nearly independent from filling height). A dependency on the liquid level itself is not very pronounced within a multi-element transducer configuration and can be neglected. Additionally the gradient of the amplitudes ΔU within the multi-element-transducer clearly provide information about the sign of the tilt angle, i.e. the direction of misalignment (Fig. 10 a). With both parameters, amplitude gradient ΔU und time delay ΔT the misalignment can be quantified and the exact liquid level can be deduced (with known sound velocity of the liquid).

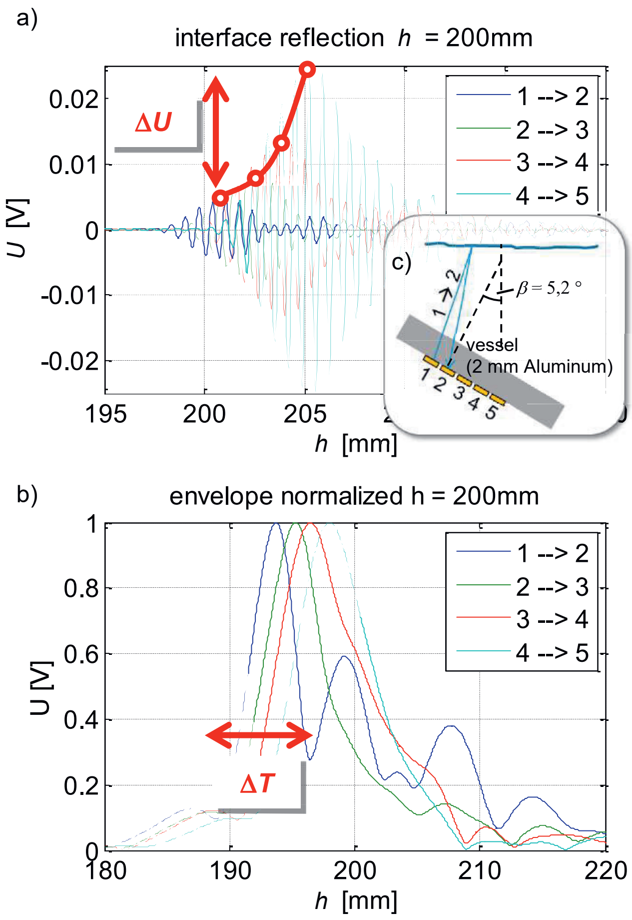

Fig. 10. Received signal (detail) of the reflection at water-air-interface (liquid level h = 200 mm), acquired with a 5-element ultrasonic clamp-on-transducer under misalignment angle β = 5.2° and displacement of 100 mm relative to vessel center. (a) Change of amplitude ΔU as a function of tilt direction.

(b) Time delay ΔT as a function of active element pairs within the 5-element transducer. (c) schematic of a group of 5-single-element ultrasonic clamp-on-transducer

Results

The aspects of linear modelling and triangulation where discussed in order to enhance the reliability of ultrasonic clamp-on systems under varying process conditions. In this context a model-based measurement has been developed and tested. Further, a multi-element ultrasonic transducer has been applied which contains a number of discrete single elements, each with an acoustic beam width in the range of the misalignment angle to be compensated. Based on specific signal processing algorithms the misalignment situation can be recognized, allowing for an automatic adaption (e.g. time delay for each element) of the acoustic excitation.

It could be shown that the triangulation with a reduced number of three to five single element transducers is suitable to compensate the misalignment of the acoustic beam (in relation to the liquid interface) due to a tilt of the vessel or the non-ideal contact of the transducer to the vessels wall. The classic approach with a phased array is not necessary. To increase the information content all acoustic path combination of the transducer group are acquired and processed. Here a signal can be identified under varying condition (tilt, filling, clutter) with low effort. Cumulative the ringing inside the vessels wall is calculated and compensated by a separate signal graph model [2]. For the validation of the triangulation algorithm an experimental rig was established, which enables the verification of selected conditions on a closed cylindrical vessel in size of d = 400 mm and filling height h = 900 mm. Thereby it could be proven by the empirical studies, that an adapted transducer group is applicable to compensate a misalignment up to 20°. Even within the raw data the reflection at an interface with a tilt angle of 15° can be separated. Hence the processing of the phase difference for algorithmic tilt compensation is possible. Beside the influence of the misalignment of the liquid interface to the acoustic propagation axis of the transducer other influences like temperature changes, moving liquid-interfaces and mismatches of the mechanical coupling of the transducers to the tank wall were investigated during the project [3] (not explained in this contribution). A special trained pattern recognition algorithm was used to distinguish those cases.

In perspective the approach is also suitable to identify the quality of the non-invasive coupling at the outer vessels surface and to reduce the interference with changing filling media and structure borne sound. Of course, the applicability of the mentioned approaches always depends on the application and may not be generalized. But in conclusion it should be sufficient to characterize an ultrasonic non-invasive system and is suitable to support the measurement and accelerate and ensure the engineering process.

Acknowledgment

The project was supported by the German Federal Ministry of Education and Research (BMBF) under contract numbers 02PK2342, 02PK2343 and 02PK2344.

The marked author is responsible for the content.

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