An Ultrasonic Density Probe

Jan van Deventer and Jerker Delsing

Luleå University of Technology, S-971 87 Luleå, Sweden

Abstract: **An ultrasonic density probe for liquids using a single transducer is developed, as a first step in the design of an ultrasonic mass flowmeter. The probe is based on the reflection of sound at the probe's interface with the fluid. The amplitude of the echo from that interface indicates the characteristic acoustic impedance of the liquid. The liquid's density is the ratio of its acoustic impedance to the speed of sound through it. The latter is obtained by measuring the time necessary for the transmitted sound pulse to be echoed back from a reflector located at a known distance in the fluid. The probe consists of two buffer rods in series behind which sits a transducer. This arrangement removes any dependence on the amplitude of the initial pulse. The effects of temperature on the buffer rods' characteristics are numerically compensated for by the dependence of the measured speeds of sound on the temperature of the traveled media. Results show an accuracy of better than 1% with a 95% confidence level for water at temperatures ranging from 2 to 40°C.**

I. INTRODUCTION

In the process and energy industries, mass flowmetering is preferred over volumetric flowmetering as variations in the density of the measured liquid have a significant impact on product quality or cost assessment. Transit time ultrasonic volumetric flowmeters—which calculate the flow speed from the change in the speed of sound through a liquid flowing between two ultrasonic transducers—have been in use for several years. The ultimate goal of the research is to transform a transit time flowmeter into a mass flowmeter by examining the liquid's density information. The current work presents an accurate ultrasonic density probe, which could easily become part of an ultrasonic flowmeter.

The operating principle of the ultrasonic density probe is based on the reflection of sound at the interface between the probe and the liquid. When an acoustic wave traveling through a medium encounters a boundary to a new medium, part of its energy is transmitted while the rest is reflected. The distribution of the reflected and transmitted energies can be estimated by examining the bulk properties of the media and the boundary conditions. If the boundary is smooth and perpendicular to the assumed planar acoustic wave, the coefficients of reflection and transmission depend on the characteristics of the medium, namely the characteristic acoustic impedance of each material. The acoustic impedance z can be expressed mathematically as $z=\rho c$ with ρ representing the density and c the bulk speed of sound. For an acoustic wave traveling from the probe p to the liquid l, the coefficient of reflection is:

$$R = \frac{(z_l - z_p)}{(z_l + z_p)}.$$

R is calculated as the ratio of the amplitudes of the reflected and incident waves, and z_l can be resolved since the probe's acoustic impedance z_p is known. The speed of sound through the liquid can be calculated from the time required for the part of the pulse which was transmitted in the liquid to be echoed back from the other side of the liquid container located at a known distance. The density of the fluid can thus be resolved by dividing the characteristic acoustic impedance of the liquid by the speed of sound through it. This simple concept is quickly complicated by the realization that electronic and environmental variations affect the probe greatly. The amplitude of the initial pulse is dependent on the stability of the associated electronics, while changes in temperature will alter the probe's material characteristics such as sound attenuation thereby modifying the amplitudes of both the incident and reflected pulses. To address the problem of variations in the amplitude of the initial pulse, different schemes have been investigated. One solution has been the introduction of a receiver in the probe's buffer rod [1]. A thin PVDF plastic membrane covered by electrodes on each side is inserted in the buffer rod perpendicular to the sound propagation. It picks up planar acoustic waves to provide the initial pulse as a reference as well as the subsequent echoes. Another solution involves the addition of a second transducer in parallel [2]. Both transducers emit a pulse of similar amplitude into the measured liquid. The second transducer provides the reference as its pulse travels through less liquid and is almost totally

0-7803-4153-8/97/$10.00

reflected when it encounters air. A third scheme inserts a new buffer rod between the probe's buffer rod and the transducer [3]. The present research focuses on this design for it provides an easy transformation from a transit time ultrasonic flowmeter into a mass flowmeter. The problem of temperature is addressed by recognizing its effect on the speed of sound in the probe. Tests are conducted at various temperatures to verify the operation and accuracy of the probe.

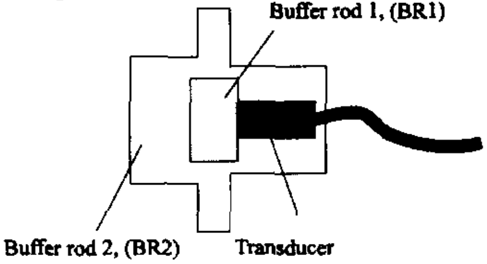

Fig. 1 The probe.

II. PROBE

A. Probe design

The introduction of a new buffer rod (buffer rod 1, BR1) between the transducer and the buffer rod in contact with the fluid (buffer rod 2, BR2) presents a new interface. This interface will reflect part of the initial pulse's energy which the transducer receives as the first echo. The amplitudes of the incident pulse and its transmitted pulses can be quantified since the acoustic impedances of the two buffer rods and, accordingly, the coefficients of reflection and transmission at that interface are known.

Sound attenuation, which has been omitted thus far, plays a major role in the calculations of the liquid density. There are many causes for this attenuation such as diffraction (beam spreading) [4] and thermal conductivity [5], but a detailed understanding of these is not necessary as they can be lumped together. The issues remaining are the dependency of the acoustic attenuation on frequency and temperature. The frequency dependent attenuation is addressed by analyzing amplitudes at a single frequency while the speed of sound in each buffer rod discloses a corresponding temperature and attenuation

B. Probe model

Referring to fig. 2, at t_0, the transducer emits a broadband pulse with an amplitude A_0. The pulse propagates through the first buffer rod with speed c_1 but is exponentially attenuated with respect to the traveled distance d_1. It is echoed back at the interface with buffer rod 2 and again it is exponentially attenuated. At time t_1, the received echo has an amplitude

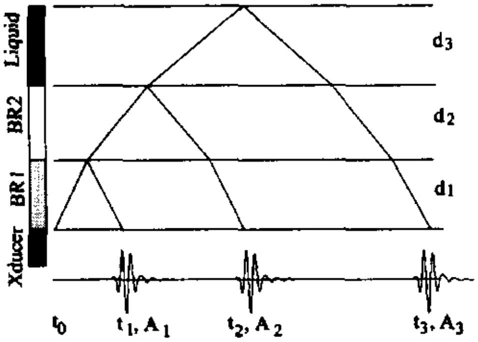

Fig. 2 Lattice diagram with received signal.

$$A_1 = A_0 R_{1,2} e^{-2d_1 a_1} \tag{1}$$

where a is the attenuation per meter in the medium referred to by its index, namely buffer rod 1, over the thickness of the buffer rod's thickness d. The factor of 2 accounts for the back and forth propagation of the pulse. The indices of the reflection coefficient refer to the media on either side of the interface so that in general, an acoustic wave propagating from medium i to medium j will have the following coefficients of reflection and transmission

$$R_{i,j} = \frac{z_j - z_i}{z_i + z_j}; T_{i,j} = \frac{2z_j}{z_i + z_j} \tag{2}$$

At time t_2, the echo from the interface between buffer rod 2 and the liquid is received by the transducer. Its amplitude can be modeled as

$$A_2 = A_0 T_{1,2} R_{2,3} T_{2,1} e^{-2d_1 a_1} e^{-2d_2 a_2} \tag{3}$$

The unmeasured A_0 is eliminated with the use of equation 1 and solving for the characteristic acoustic impedance of the liquid z_3 generates the following equation:

$$\rho_3 c_3 = z_2 \frac{4A_1 z_1 z_2 e^{2d_2 a_2} - A_2 (z_1{}^2 - z_2{}^2)}{4A_1 z_1 z_2 e^{2d_2 a_2} + A_2 (z_1{}^2 - z_2{}^2)} \tag{4}$$

The attenuation of sound $d_1 a_1$ disappears because both echoes undergo the same decay through buffer rod 1. The speed of sound through the liquid is

$$c_3 = \frac{2d_3}{(t_3 - t_2)} \tag{5}$$

A variation in temperature changes the dimensions (thus density), speed of sound and attenuation in both buffer rods. Determining the time of flight in the two buffer rods allows for recognition of the changes in the speed of sound. From calibration, the relation of the speed of sound to the dimensions and attenuation changes can be established (fig. 3). This calibration data is used to correct the characteristic acoustic impedances z_1 and z_2 and the attenuation factor a_2 (eqn. 4). It should be noted here that the distance to the reflector d_3 is assumed to be constant regardless of the temperature, creating a density error of the liquid in the order of $3x10^{-16} kg/m^3 {}^\circ C$.

C. Design constraints

Some dimensional and material constraints have been placed on the design of the probe. In order to maximize the resolution of the echoes' amplitude, they must be of similar magnitude when received by the transducer. The characteristic acoustic impedances of the buffer rods should be chosen carefully without overlooking the attenuation effect in buffer rod 2 such that

$$R_{1,2} \approx T_{1,2} R_{2,3} T_{2,1} e^{-2d_2 a_2} \qquad (6)$$

The reflection from the first interface is smaller than the one from the probe-liquid interface, as the latter is attenuated in buffer rod 2. The length of buffer rod 2 is adjusted to properly reduce the second echo. Buffer rod 1 must be long enough to allow the initial ringing of the transducer to settle down before the first echo comes back. Additionally, to prevent any interference between the echoes, the time necessary for the acoustic pulse to travel in one medium must different than the one in the other medium. This is achieved by having one buffer rod longer than the other. Finally, to avoid any reflection by the spreading sound beam from the side walls, the diameter of the buffer rods are much larger than the diameter of the transducer.

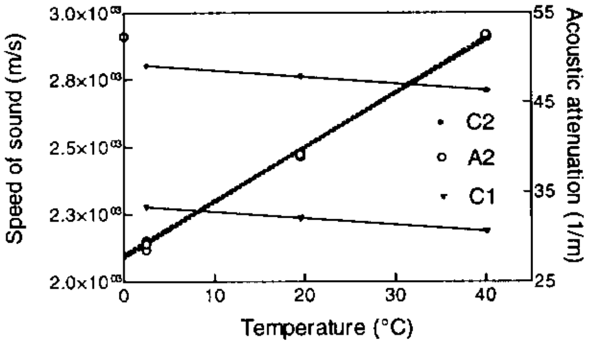

Fig.3. The probe's acoustic characteristics versus temperature

D. Probe construction

The exoskeleton of the probe is made of polymethylmethylacrylate plastic (fig. 1). Its front is buffer rod 2 with a diameter of 40 mm and a length of 20 mm. Inserted in it, first comes buffer rod 1 composed of polyether sulfones plastic. Its diameter is 26 mm with a length of 15 mm. On the other side of buffer rod 1 is a 10 mm unfocused narrowband piezoelectric transducer with a center frequency of 3.7 MHz. Panametrics coupling fluid B, which is glycerin based, acoustically connects the probe's components. The acoustic impedance of buffer rod 1 and buffer rod 2 are $3.07x10^6$ and $3.23x10^6$ *Pa s/m* respectively.

III. SIGNAL PROCESSING

A. Frequency dependent amplitudes

The three echoes are located with a trigger level, extracted and centered into 512 data point long windows. A Fast Fourier Transform algorithm [4] provides a discrete frequency spectrum of each echo. The amplitude of the echoes A_1 and A_2 are calculated at the peak frequency of the discrete spectrum of second echo.

B. Times of flight

The time of flight through each medium is first approximated by the difference between the start of two successive windows. The cross correlation method fine tunes this estimate by correcting it with the lead or lag time of the first echo versus the second within the 512 point windows.

The correlation scheme shifts the first echo g in time by τ samples, multiply each of its element with the next echo h's corresponding element and summing the elements of the product vector.

$$Corr(g,h)_\tau \equiv \sum_{k=0}^{N-1} g_{\tau+k} h_k \qquad (7)$$

This sum will reach an absolute maximum when the first signal has been shifted by the correct time. The absolute values of the sums are taken to cover the case when the following echo undergoes a 180° phase change by bouncing off a material with a higher acoustic impedance (eqn.. 2). To improve processing speed, the cross correlation is executed in the frequency domain by convoluting the first echo by the complex conjugate of the second echo

$$Corr(g,h)_\tau \Leftrightarrow G_k H_k^* \qquad (8)$$

The discrete Fourier transformed echoes were calculated earlier for the amplitude determination and the inverse FFT will lead back to the time domain. The absolute value of the maximum will point to the correct time shift.

The time of flight through buffer rod 1 can not be measured by the above method because the excitation spike and the first echo are too dissimilar.

The solution to this is, in a calibration situation, to introduce an additional buffer rod BR0 between buffer rod 1 and the transducer. By then applying the above given technique, the time of flight in buffer rod 1, Δt_{ref}, can be measured at a reference temperature. Returning to the original configuration, a reference signal is recorded at the reference temperature. Remembering that the acquisition started at t_0, the start of the reference's first echo is not correct and needs a correction factor δ added to it such that

$$\Delta t_{ref} = t_{ref.echo1.start} + \delta \qquad (9)$$

Subsequent acquisitions are compared to this reference echo

$$t_{flight1} = t_{echo1.start} + \delta - Corr(echo1, ref.echo1) \qquad (10)$$

The cross correlation (eqn. 7) between the two echoes corrects for any time variation in the start of the echoes.

IV. EXPERIMENTS AND RESULTS

A. Experimental setup

The probe is fastened horizontally to the measurement cell. The measurement cell consists of two stainless steel plates separated by two 30 mm brass bars, all of which sits on a plexiglas bottom. The rear stainless steel plate faces the probe with its polished surface while the back side is rough and angled to dissipate any transmitted energy.

A Heraeus HT4010 temperature test chamber houses the measurement cell and probe. The transducer is connected to a Panametrics Pulser-receiver Model 5072PR located outside the chamber. The received analog signal is sampled at 200MHz by a Sony-Tektronix RTD 710 digitizer with a resolution of 10 bits. Averaged 32 times, the digitized waveform is transferred to a workstation via a GPIB interface. There, a program reduces the signal to a density measurement. A Systemteknik S2541 thermolyzer, accurate to 0.01°C, monitors the temperatures of the liquid sample and the measurement cell's environment using two PT100 probes. Every two seconds, an RS232 connection updates the workstation with the temperature information.

B. Calibrations

Before any ultrasonic measurements are made, the dimensional variations of the probe are measured as a function of temperature. Next, the time of flight through each buffer rod as a function of temperature is measured as well as the coefficient of attenuation in buffer rod 2. These relationships are linear in the range of operation. Figure 3 shows the speed of sound corrected for thermal expansion in both buffer rod and the attenuation in buffer rod 2.

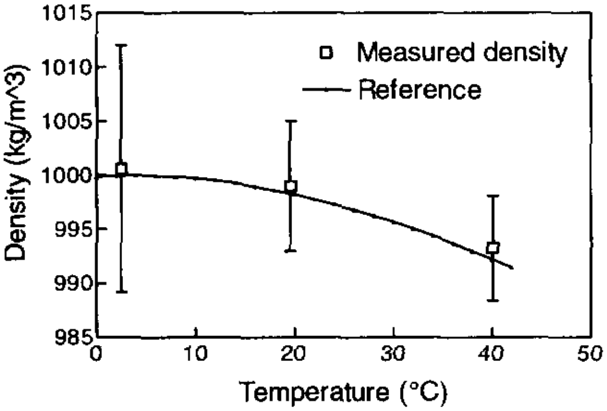

Fig. 4 Density measurements versus temperature

C. Density measurements

Density measurements are made at three different temperatures. The means show a bias error of $1\ kg/m^3$ or *0.1%* with respect to tabulated data [7]. The precision index is $4.8\ kg/m^3$ or *0.48%*. Any increase in the latter is due to thermal variations in the temperature test chamber.

The error analysis of the probe, based on equation 4, showed that the critical measurements belonged to the speed of sound calculations. The time of flight being the most sensitive followed by the length measurements. Cross correlation offers a good way to obtain the time of flight down to the sampling resolution of the digitizer.

Two types of error were not considered in the error analysis were the flatness of the buffer rods and the couplants between the buffer rods. If the buffer rods are not flat, the beam is either focused or dispersed. This type of error is absorbed in the overall attenuation since no specific cause is addressed. The acoustic coupling between the probe's components is ensured by a liquid couplant. Permanent bonding has been avoided to enable the easy evaluation of different materials. However, the drawback of temporary bonding or coupling is the alterations of the characteristics of the couplant with time modifies the attenuation in the probe.

V. CONCLUSION

Transforming a transit-time volumetric flowmeter into an accurate ultrasonic mass flowmeter without additional transducers is feasible. This paper presents a single transducer liquid density probe. It shows its capability for high accuracy measurements with a true bias error of *0.1%*. The design of the probe overcomes instability in the associated electronics and transducer long term characteristics with the introduction of a new buffer rod. The change of the speed of sound through each buffer rod provides a good estimation of their temperature, which is used to compensate for changes in acoustic attenuation and volumetric variables. Future works will investigate the side wall effects as the buffer rods' diameters are reduced.

REFERENCES

[1] J. C. Adamowski, F. Buiochi, C. Simon and E. C. N. Silva, *"Ultrasonic measurement of density of liquids"*, J. Acoust. Soc. Am., Vol.97, No. 1, pp. 354-361, January 1995.

[2] A. R. Guilbert and M. L. Sanderson, *"A high accuracy ultrasonic mass flowmeter for liquids"*, FLOMEKO 96 proceedings, pp. 244-249.

[3] J. Delsing, *"A new type of ultrasonic densitometer"*, Ph.D thesis on ultrasonic flowmeters, Lutedx/(TEEM-1036)/1-48/(1988)

[4] E. P. Papadakis, "Absolute measurements of ultrasonic attenuation using damped nondestructive testing transducers", Journal of Testing and Evaluation, JTEVA, Vol. 12, No. 5, Sept 1984, pp. 273-279.

[5] A. B. Bhatia, *"Ultrasonic absorption"*, Oxford at the Clarendon Press, 1967

[6] W. H. Press, S. A. Teukolsky, W. T. Vetterling and B. P. Flannery, *"Numerical receipies in C"*, Second edition, Canbridge University Press, 1992.

[7] G. W. C. Kaye and T. H. Laby, *"Tables of physical and chemical constants"*, 14th edition, Longmann Group Limited, 1973.