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Torsional Sensor Applications in Two-Phase Fluids

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Abstract

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Torsional Sensor Applications in Two-Phase Fluids

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Abstract—A solid corrosion-resistant torsional waveguide of diamond cross section has been developed to sense on-line and in real-time the characteristics of the liquid in which it is submerged. The sensor can measure, among other things, the liquid content of a bubbly medium; the density of adjacent pure liquids; the equivalent density of liquid-vapor mixtures or particulate suspensions; a suspension's concentration; and the liquid level. The sensor exploits the phenomenon that the speed of propagation of a torsional stress wave in a submerged waveguide with a noncircular cross section is inversely proportional to the equivalent density of the liquid in which the waveguide is submerged. The sensor may be used to conduct measurements along distances ranging from 20 mm to 20 m and over a wide range of temperatures and pressures, e.g., from the cryogenic temperature of liquid nitrogen, -196°C , up to hot pressurized water at 300°C and 7 MPa. A self-calibrating three-zone sensor and associated electronics have also been developed to compensate for any sensor inaccuracies due to operation over a wide range of temperature. In some of the water experiments at room temperature, unexpected attenuation of the guided torsional waves was observed. This excess attenuation depends in part on the waveguide's surface finish. It appears to be caused by air microbubbles adhering to the waveguide, imposing one of the practical limits on the maximum sensor length in nondegassed or aerated water.

I. INTRODUCTION

THE idea that an ultrasonic wave propagating in a solid structure can sense the presence and nature of the adjacent medium is not new. Looking back twenty or more years, one finds that many of the early "sensor" aspects of guided ultrasound were amplitude- or attenuation-related. By 1945, for example, it had already been demonstrated by Firestone and Ling [7] that a Rayleigh wave could be damped by touching the path with one's finger. Transmission of longitudinal and shear waves from solids into liquids was also familiar to Firestone and Ling, who observed and analyzed the transmission coefficients for these waves as a function of angle [7]. Early amplitude- or attenuation-related sensor examples include the viscosity or viscosity*density extensional-wave sensor of Roth and Rich (1953) [31] and the Rayleigh, shear and longitudinal liquid level sensor concepts of Van

Valkenburg (1957, 1962) [33], [34], and his co-worker Mongan (1961) [27]. In the past ten years or so, amplitude-based Lamb wave sensor developments include the work of Gillespie *et al.* [8], Dieulesaint *et al.* [6], and White and co-workers, some of which is contained in [29].

Time or time-related sensor responses include the reduction in resonant frequency of a torsionally vibrating crystal due to the loading by the adjacent liquid, e.g., Mason (1947) [23]. The phase-shifting effect of a complex impedance load is utilized in an oblique incidence reflection coefficient viscosity sensor described by Mason *et al.* (1949) [24] and McSkimin (1960) [25]. An alternate form, at normal incidence, is shown in Moore and McSkimin (1970) [28]. In 1960, Ageeva [1] demonstrated the slowing down of flexural waves in an Al strip upon immersion in water, an effect explained by Landau and Lifshitz [15]. Solie and Tønning (1972, unpubl.; in [18, p.435]) showed by their calculations that the sound speed of a Rayleigh wave, c_R , depends on the presence of water and its direction of flow. In 1990, Varadan *et al.* [35] demonstrated the use of SAW devices to measure skin friction associated with turbulent flows, a c_R effect.

The slowing down of extensional waves was demonstrated by one of the authors by immersing a solid waveguide that had been threaded [16]. He later demonstrated the slowing down of torsional waves in a submerged waveguide with noncircular (rectangular) cross section [17]. For a rectangular stainless steel (SS) cross section of aspect ratio = 3, immersion in water decreases the torsional sound speed c by some 5% compared to its value in air or vacuum: sensitivity $S_{\blacksquare} \equiv |\Delta c/c| \approx 5\%$.

Although a number of torsional slow wave sensors were built between 1977 and 1985 to sense density [16], liquid level [17], and void fraction [2], a quantitative explanation of their response to the adjacent liquid's density was not reported until 1986 [3]. The diamond-shaped optimization of the sensor cross section was not reported until 1989 [10], [11], allowing a three-fold improvement in sensitivity S over the rectangular 1977 design for the same aspect ratio, i.e., $S_{\blacklozenge} \approx 15\%$ for $b/d = 3$, for a SS sensor.

The initial 1977 experiments were motivated by a requirement to sense water density during flow at high temperature and high pressure, including conditions where single phase would not prevail. Tests on the early sensors immediately disclosed that they also responded to liquid level, not just density, and to viscosity if the liquid were sufficiently viscous (e.g., cold glycerine). Density and viscosity effects can now be separated and measured simultaneously by using waveguides with different cross-sectional geometries (Kim *et al.*, [12]).

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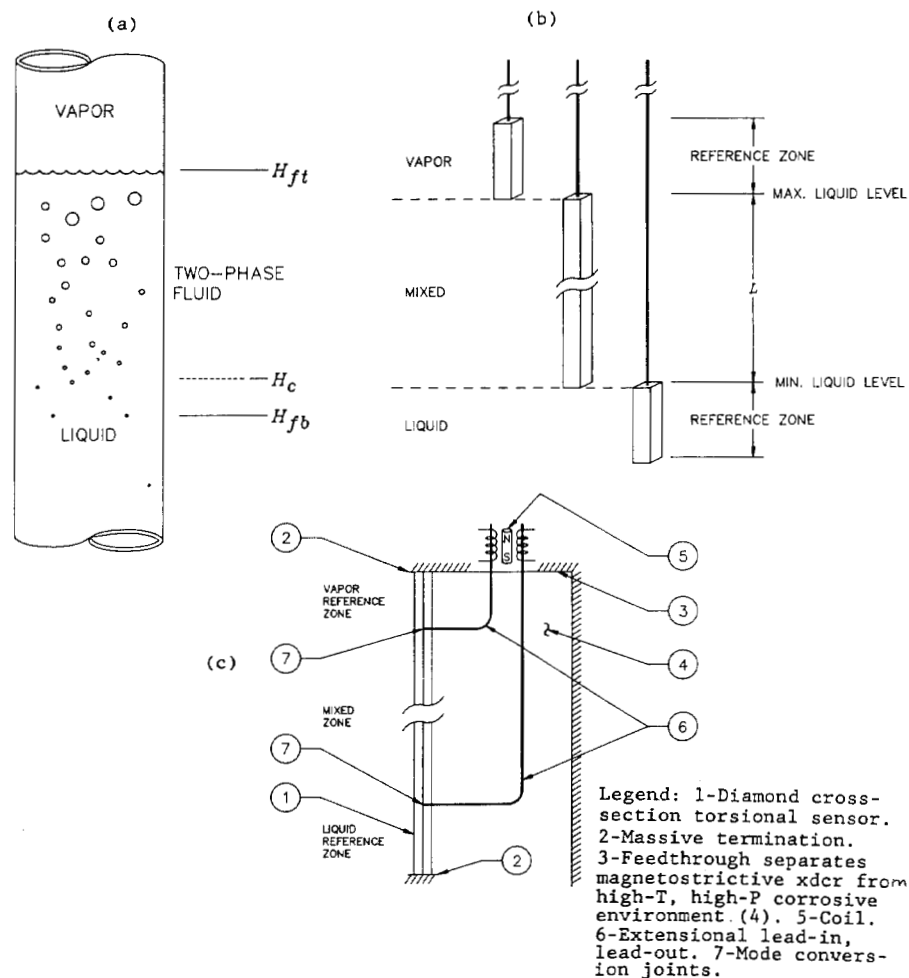


Fig. 1. Two-phase fluid whose "collapsed" or equivalent level H_c is to be determined. Three-zone torsional sensor is the primary approach discussed in this paper for this application. (a) Schematic in which H_{ft} = level at top of foam, H_{fb} = level at foam bottom, and H_c = collapsed level. (b) Concept of three (separate) torsionally interrogated zones, two of which are reference zones. (c) Three zones contained along one waveguide, as in the present paper.

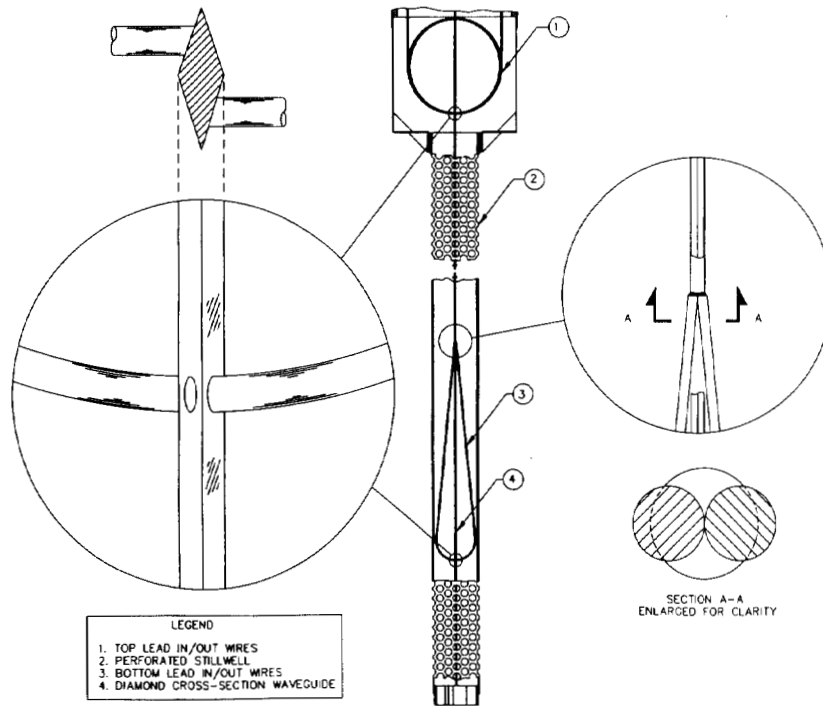
Kim's work [10] led to the diamond cross section being preferred for density and/or liquid level applications, while a different sensor cross section (e.g., a threaded tube) is needed if one wants to separate density from viscosity effects.

In the Applications section, one particular problem, that of measuring the equivalent height of a fluid column ("collapsed" liquid level) is discussed in some detail. This measurement is needed in order to operate steam generator power plants efficiently and safely, especially during depressurization transients when two-phase conditions occur. At all times, during transient as well as during steady-state conditions, it is important to be able to calculate the water mass available for heat transfer. Until now, this determination has generally been derived from liquid level, which in turn is obtained from differential pressure (ΔP) sensors comprised of a pressure transmitting diaphragm/bellows and displacement detectors (Weldon and Lyman, 1981 [36]). The ΔP systems currently in use in pressurized and boiling water reactors ((PWR's) and (BWR's)), respectively sense pressure in a "variable" leg and in a "reference" leg. Over time, gas may diffuse, convect or by other means migrate into the reference leg's water column and dissolve. When there is rapid pressure release, the gas

suddenly comes out of solution, forcing some of the reference water up and out of the reservoir atop the reference column (see Fig. 1, especially Fig. 1(e), top). This translates to an erroneously high computation of water level available for heat transfer in the variable leg. (One remedy already in use is to continuously resupply gas-free water to the reference leg.)

A different approach to solving this problem would be to avoid the reference leg entirely, i.e., sense the actual level nearer to where heat transfer is most important, without relying on a remote reference. The torsional sensor discussed here after further development and qualification for nuclear service *might* be appropriate for that measurement. The torsional sensor might also complement the existing pressure sensor in the reference leg, to provide a more accurate *collapsed* reference level during transients and/or after an overflow, or whenever an unexpected or potentially unsafe condition is indicated by a ΔP sensor.

Certain features of the present sensor design for sensing the equivalent level, such as rugged mode conversion joints, reflectionless splitting of a waveguide, self-calibration zones, and the nearly reflectionless transducer feedthrough which isolates the magnetostrictive element from the high-pressure



(d)

Fig. 1. (Continued) (d) General arrangement and some details of an actual torsional wave sensor utilizing the three-zone elements of (b) and (c). For comparison with noninvasive (flexural or bending wave) alternative, refer to (e).

corrosive environment, might be usable elsewhere, not just for steam generator collapsed liquid level applications. The torsional sensor of the noncircular cross section being developed for that application is fundamentally similar to one that has been used in the laboratory for several density applications such as the measurement of the density of pure liquids, liquid + vapor bubbles, or liquid + undissolved solids. The one-dimensional analysis of a straight waveguide [10] allows one to predict the $\Delta c/c$ response of toroidal sensors too, when the toroid radius is greater than or comparable to the torsional wavelength. The toroid has been studied with respect to potential applications in aircraft fuel mass gaging in wing tanks.

One of the unexpected results of this work was the discovery during what should have been a mundane experiment at room temperature, of an attenuation term for torsionally guided waves that appears to correspond to air microbubbles adhering to the noncircular portion of the waveguide. This time-dependent effect is less apparent at 50 kHz than at 100 kHz, less in polished than in unpolished waveguides, and enhanced if air is bubbled through the water and absent if the water is deaerated. This effect imposes one of the practical limits on the maximum immersed length of the noncircular

cross section torsional sensor length, for a waveguide of a particular surface condition.

II. THEORY

The speed of propagation of a torsional stress wave traveling in a waveguide of uniform cross section is affected by the characteristics of the medium in which the waveguide is submerged. As the torsional wave travels through the waveguide, the solid/fluid interface is alternately accelerated and decelerated. If the waveguide's cross section is not circular, the fluid's motion is induced via the generation of both a pressure field and a drag force. The pressure field is generated when the motion of the solid's surface induces a velocity component normal to the surface. The drag force results from the viscous effect. Consequently, the torsional wave needs to overcome the combined inertia of the solid waveguide (I_s) and the adjacent fluid (I_f). To the first-order approximation (see Bau [3], Kim, [10], and Kim and Bau [11] for details), the torsional wave speed (c) in a straight waveguide is:

$$\frac{c}{c_0} = \left(1 + \frac{\rho_f I_f}{\rho_s I_s} \right)^{-1/2} \quad (1)$$

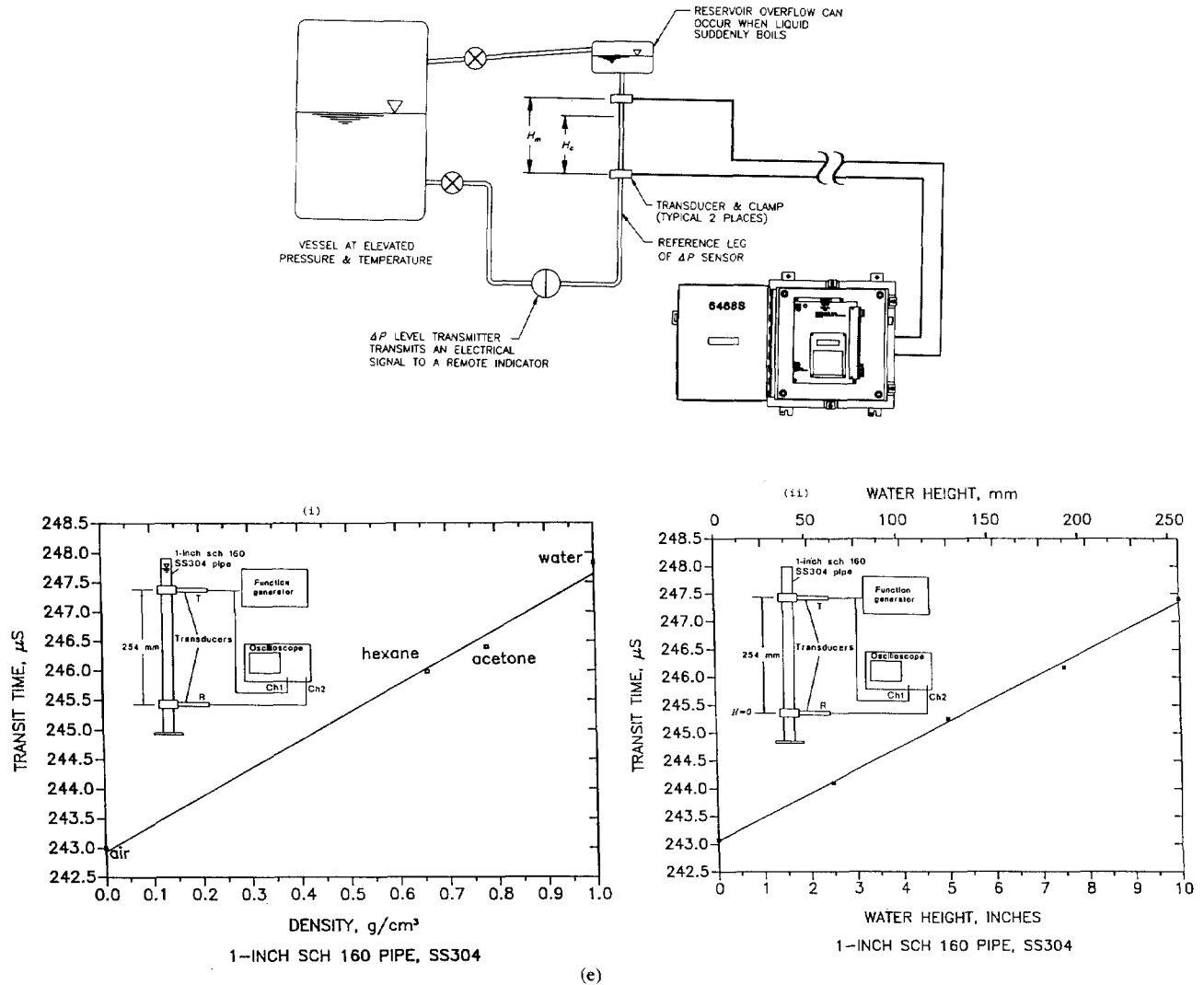


Fig. 1. (Continued) (e) Proposed application of flexural or bending waves, generated and detected with clamp-on transducers. This clamp-on alternative to the torsional sensor of *d* also can use magnetostrictive transducers external to the pressure boundary. However, in this clamp-on schematic, the normally incident extensional waves are mode converted not to torsion but to flexure (or a bending wave) in the pipe. In a thick-wall pipe such as 1-in schedule 160 (6-mm wall thickness), the sensitivity $S_{\text{flex}} = (\Delta t / \Delta H)_{\text{flex}}$ is only about 25% of that for the torsional sensor of (d). However, this may still suffice for some applications in a ΔP reference leg. Graph (i) demonstrates flexural wave transit time calibration in liquids of different density. Graph (ii) shows increase in t_{flex} as water height increases.

where $c_0 = K(G/\rho_s)^{1/2}$ is the torsional wave speed for a waveguide in vacuum, G is the solid's shear modulus, $K = (D/I_s)$ is a "shape" factor, D is the cross section's torsional rigidity, and ρ_s and ρ_f are, respectively, the solid's and adjacent medium's densities.

To the first-order approximation, the fluid's apparent inertia (I_f) can be taken as a sum of the inviscid ($I_{f,i}$) and viscous ($I_{f,v}$) contributions. $I_{f,i} = 2A_1 I_s$, where A_1 is a constant of order one. A_1 depends only on the cross section's geometry. For example, for a diamond-shaped cross section of aspect ratio 3, $A_1 \sim 1.4$ [11]. For a circular cross section, $A_1 = 0$.

The viscous apparent inertia $I_{f,v} \approx A_2 I_s (\nu/\omega a^2)^{1/2}$, where (a) is a characteristic dimension of the cross section, $\nu = \mu/\rho_f$ is the kinematic viscosity, f is the wave's frequency, $\omega = 2\pi f$, and A_2 is a geometry-dependent constant. For example, for a waveguide with characteristic cross-sectional dimension $a = 5$ mm, operating in water at room temperature and at a frequency

of 50 kHz, $(\nu/\omega a^2)^{1/2} \sim 2 \times 10^{-3}$, and $I_{f,v} < 0.01 I_f$. For a similar waveguide operating in glycerin under the same conditions, $(\nu/\omega a^2)^{1/2} \sim 2 \times 10^{-2}$ and $I_{f,v} \sim 0.1 I_f$. For more detailed discussion of viscous effects, consult Kim [10] and Kim *et al.* [12]. Since most of the results presented in this paper pertain to low viscosity fluids such as water, hereafter we shall neglect the viscous contribution to the apparent inertia.

Since typically $(\rho_f I_f)/(\rho_s I_s) \ll 1$, (1) suggests, to a good approximation, the linear relationship

$$\frac{c}{c_0} \approx 1 - \frac{\rho_f I_f}{2\rho_s I_s} \sim 1 - A_1 \frac{\rho_f}{\rho_s} \quad (2)$$

in which the torsional wave speed depends explicitly on the adjacent medium's density and implicitly on the temperature (through c_0 's dependence on temperature). Note that the adjacent medium's density need not be constant along the waveguide. If the density varies slowly as a function of axial

length, the wave speed will also vary as a function of axial location.

Equation (2) suggests that through the measurement of the torsional wave speed in a submerged waveguide, one can obtain information on the characteristics of the adjacent medium. This dependence creates the opportunity for a variety of rugged, on-line, real-time sensors. Since typically the torsional wavelength is purposely made long compared to the cross-sectional dimensions of the sensor (to avoid dispersion), and since most applications so far involve temperatures well below the recrystallization temperature of the waveguide metal, at least in vacuum the attenuation coefficient of the torsional wave is small (e.g., at 100 kHz, $\alpha < 1$ dB/m). Accordingly, the sensing can be done along or near the remote end of paths ranging up to some 20 m in length. The *shortest* practical sensor for use with pulse echo or through transmission electronic intervalometry equipment depends on sensor sensitivity to a particular measurand (e.g., ρ_f) and the electronics' resolution of transit time. In a waveguide sensor length L of 10 cm, for a SS316 density sensor of aspect ratio $b/d = 3$, ρ_s resolution of 1 mg/cm^3 is achievable if transit time can be resolved to 10 ns, i.e., density resolution of 0.1% for fluid densities near that of water.

In the following, we describe a few possible applications. Then, in the next section, we give the details of relevant experimental results.

A. Density Measurement of a Homogeneous Fluid

The most obvious application of the torsional wave sensor is the measurement of the adjacent liquid's density. The liquid need not be simple. As we report later, we have measured the equivalent density of suspensions and liquid vapor mixtures. If a known length of the waveguide is submerged in its entirety in a liquid medium, then the effect of the liquid on the transmission time of the torsional stress wave is:

$$\frac{\Delta t}{t_0} = \left(1 + \frac{\rho_f I_f}{\rho_s I_s}\right)^{1/2} - 1 \sim A_1 \frac{\rho_f}{\rho_s} \quad (3)$$

where t_0 and Δt are, respectively, the transmission time when the waveguide is submerged in vacuum and the difference between the transmission time in the medium of interest and in vacuum.

B. Measurement of Equivalent Density of a Variable Density Liquid

When the adjacent medium's density varies as a function of location along the length of the waveguide, one can measure the average density along the waveguide's length:

$$\bar{\rho}_f = \frac{1}{L} \int_0^L \rho(x) dx. \quad (4)$$

Since

$$\frac{c(x)}{c_0} = \left(1 + \frac{\rho_f(x) I_f}{\rho_s I_s}\right)^{-1/2} \sim 1 - A_1 \frac{\rho_f(x)}{\rho_s} \quad (5)$$

we have

$$\frac{\Delta t}{t_0} = \frac{1}{L} \int_0^L \left[\left(1 + \frac{\rho_f(x) I_f}{\rho_s I_s}\right)^{1/2} - 1 \right] dx \sim A_1 \frac{\bar{\rho}_f}{\rho_s}. \quad (6)$$

Such a measurement may be of interest, for example, when one wishes to measure the liquid content of a liquid-vapor mixture in which the vapor content varies along the length of the waveguide.

C. Measurement of Liquid Level

Another application of the torsional wave sensor is the measurement of liquid level. Consider a waveguide of total length L with a part of its length, L_m , submerged in a liquid of known density. If we assume that the transmission time in the exposed part is approximately the same as in vacuum, then

$$\frac{L_m}{L} = \frac{1}{A_1} \frac{\rho_s}{\rho_f} \frac{\Delta t}{t_0}. \quad (7)$$

1) *Reflection Coefficient*: At a liquid/vapor interface, the torsional wave in a noncircular cross section experiences an impedance discontinuity. Let Z_2 and Z_1 denote, respectively, the torsional impedance of a waveguide submerged in vacuum (or gas) and liquid. Then

$$r = \frac{Z_2}{Z_1} = \left(1 + \frac{\rho_f I_f}{\rho_s I_s}\right) \frac{c_2}{c_0} \sim 1 + A_1 \frac{\rho_f}{\rho_s} \quad (8)$$

and so

$$R_p \sim \frac{A_1}{2} \frac{\rho_f}{\rho_s}. \quad (9)$$

III. APPLICATIONS

A. "Collapsed" or "Equivalent" Liquid Level

The equivalent level application requires measurement in a multiphase fluid column of the *collapsed* or *equivalent* water level H_c at high temperature and high pressure (Fig. 1 (a)–(e)). This application arose because a need exists, motivated in part by heat transfer considerations, to measure H_c , but not H_{fb} , nor H_{ft} . (H_{fb} is the bottom foam interface between foam and "solid" water. H_{ft} is the top foam interface between foam and vapor.) A further need exists to measure H_c more reliably than has been experienced with conventional diaphragm-based hydrostatic pressure sensors. By "collapsed" water level we mean the level of an equivalent column of liquid water whose mass per unit area equals that of the actual multiphase fluid.

One way to increase power plant reliability is to improve the existing methods of determining water level in a steam generator. Existing measurement methods rely on differential pressure between a fixed height reference column and a tap on the secondary side to determine steam generator water level. The requirements for a potentially improved system included the ability to operate in a high temperature, high pressure environment, self-compensation for temperature variations,

and most importantly, the ability to determine water mass available for heat transfer. During intentional or unintentional depressurization situations, the measurement environment in the variable leg and in the reference leg is a dynamic turbulent two-phase mixture where no distinct and precise "level" exists. Pressure equilibrium may not exist. Following a literature search and conceptual design review by the sponsor of this work, the torsional wave sensor concept was selected for further development at Panametrics. The initial application was for standpipe or reference leg use, with a possibility of eventually using it in the variable leg, if justified by its performance in reference leg tests.

The three-zone sensing concept with separate vapor and liquid reference zones is shown in Fig. 1 (b), which is a torsional adaptation of the zig-zag shear wave liquid level sensor of Lynnworth, Seger and Bradshaw [19]. A more practical arrangement combines the three torsionally interrogated zones into one waveguide, Fig. 1 (c). Here the sensor consists of a diamond cross section torsional waveguide with an overall length of 1.75 m (69 in). The waveguide is divided into three zones. The bottom 152 mm (6 in) is always immersed in water and is called the *liquid reference zone*. The top 152 mm (6 in.) is always in the vapor phase and is called the *vapor reference zone*. The middle 1.45 m (57 in) may be partially immersed in the liquid and/or a liquid/vapor two-phase medium and is called the *mixed zone*. Extensional mode magnetostrictive transducers are connected to the lead-in and lead-out waveguides. The extensional waveguides drive two mode conversion points — one at the junction of the liquid and mixed zones and one at the junction of the vapor and mixed zones. The mode conversion points convert the extensional wave to a torsional wave and vice versa, in a manner similar to the Scarrott–Naylor mode converter used in wire delay lines [5]. In the actual device, Fig. 1 (d), the vapor/mixed mode conversion point is driven by a couple consisting of two extensional waveguides driven by a pair of magnetostrictive transducers connected electrically in parallel. The liquid/mixed mode conversion point is also driven by a couple, here consisting of a "split" extensional waveguide driven by a single magnetostrictive transducer. For simplicity in this explanation, the schematic in Fig. 1 (c) shows only a single magnetostrictive transducer driving a single extensional waveguide for each mode conversion point. Some further details are given in Fig. 1 (d). We would have preferred to use torsional (Wiedemann effect) transducers at the top, rather than extensional. However, we were unable to find a practical way to retain the Wiedemann effect at or near the maximum temperature of this application. A second problem, much more difficult for torsional than for extensional waves, is that of achieving nearly reflectionless transmission through the pressure boundary. The extensional "solution" presented here is not totally satisfactory. One drawback, for example, is the large stillwell diameter required to accommodate the lead-in and lead-out mode conversion loops, especially at the top.

As shown in the Theory section, the increase in transit time of the torsional wave is proportional to the amount (height) and density of the medium surrounding the torsional waveguide. The transducers used in different configurations (pulse echo,

through transmission) allow the instrument to measure the transit times in all three of the zones. The transit times measured in the liquid and vapor zones compensate for the effects of temperature and fluid density provided that the fluid surrounding the torsional waveguide is isothermal. The transit time measured in the mixed zone is then used to calculate the collapsed level of the water. In some respects this is analogous to determining the liquid/solid interface in a solidifying steel ingot from the through transmission transit time [9], except in that case the sound speeds in the two phases were taken as constants, not measured dynamically during an experiment.

An earlier version of the device described herein was tested by Miller *et al.* [26]. The present device enjoys threefold improvement in sensitivity. It utilizes a > 0.5-mm thick diaphragm, more than ten times the thickness of the 50- μ m diaphragm of the 1980 design, to isolate the transducers from the steam generator's hostile environment while transmitting over 95% of the energy in the incident extensional wave. The transducer housing employs a conventional feedthrough as a secondary seal. Furthermore, the present device utilizes transducers which can operate at 300°C (higher than the maximum temperature to be encountered in this application) and incorporates automatic temperature compensation (as long as the sensor is isothermal). Another improvement includes housing the entire sensor to make it easier to install from the top of a vertical standpipe. In the present paper, temperature compensation utilized the fact that the standpipe is sufficiently well insulated so that the temperature is uniform, top to bottom, at any given time. This allowed temperature compensation to be achieved differently from the way it was done in 1980. Wetted parts of the sensor can be made of a 600-series Inconel alloy to better withstand the corrosive environment. A prototype anti-vibration restraint system consisting of support elements secured to the stillwell has been designed, that introduces no significant echoes at support points along the diamond sensor, lead-in or lead-out elements. Finally, a new two-port instrument (denoted Model C582R) was developed to interrogate three zones rapidly, to measure the transit times of 100-kHz pulses to 10 ns, and to compute the collapsed level H_c based on torsional transit times in these three zones. The pulsing, timing, and computing functions of that instrument were recently incorporated into a special version of a portable commercial instrument (Model PT868S).

1) Suspensions and Coatings (Oil Residue; Microbubbles): In future long-term tests (>6 months), where the sensor will be continuously exposed to high-temperature, high-pressure water, it is our intent to provide equipment to determine whether any significant deposits build up on the sensor. If they do, "blowdown" is a possible remedy. "Blowdown" is one remedy used in boiler systems, to essentially steam clean the hardware as a periodic maintenance procedure.

Independent of the equivalent level application as outlined previously, during 1991 we also investigated the potential application of the torsional sensor to measuring the level of sump water containing small amounts of oil mixed in or as a film floating on top of the water. In some cases, this application involves a change in water level of several meters, in a region some 10 to 20 m below the point where it is most convenient

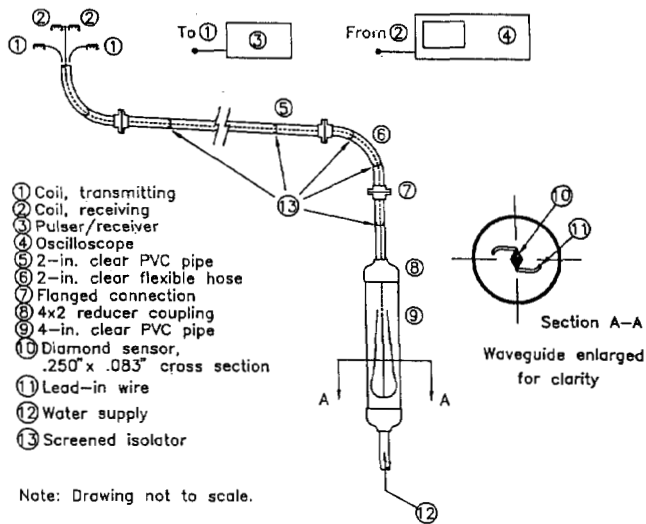
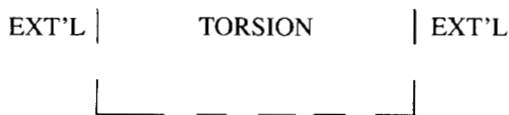


Fig. 2. Schematic of 17-m long (57-ft) diamond waveguide test, including acoustic isolation from walls of simulated stillwell.

to place the transducer. To simulate what may be a "worst case" of oil buildup, we coated a vertical sensor with SAE 30 motor oil and then determined in an experiment with the oiled sensor fully immersed in water, the error in H when H was calculated as if the liquid were only water. In this test, the sensor read low by 5%. The oil (whose density is some 15% less than water's) in effect reduces the average density in the vicinity of the sensor. To eliminate this error, one needs to minimize the oil buildup, or measure the oil contribution. Fig. 2 illustrates 40-kHz one-way torsional transmission along a clean dry SS diamond cross section waveguide of 18 m (57 ft) long, with the extensional lead-out long enough so both transducers can be located at one end. If lead-in and lead-out are both short, and if frequency is lowered, still longer torsional sensors may be used:



If a long sensor were immersed, some increase in attenuation is to be expected if viscosity is nonzero. Upon immersion in freshly drawn tap water, however, an attenuation effect is observed, which is not due to viscosity but apparently is due to air in the water that attaches as bubbles to the waveguide. The effect is preventable by removing the air. The oscillogram traces in Fig. 3 shows how the bubble attenuation can be introduced and removed. Polishing the waveguide and/or reducing the frequency from 100 kHz down to 50 kHz reduces the effect. One possible (but as yet unproven) explanation for the increase in α in aerated water is that attached bubbles are compressed by the rotating waveguide and lose heat to the water.

It remains to be seen, whether these observations, perhaps combined with suggestions due to Kirkpatrick and Kuzniak [14] will be adaptable to sensors as long as 30 m, as may be required for some of the potential collapsed level applications

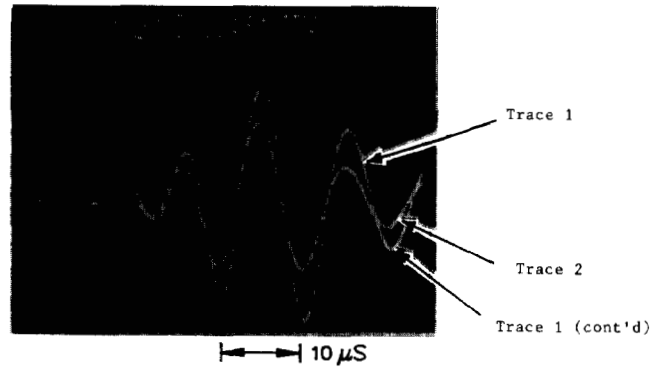


Fig. 3. Oscillographic traces depicting attenuation in a diamond cross section sensor apparently caused by air microbubbles adhering to its surface.

in PWR's/BWR's. On the other hand, a short torsional sensor installed inside the top meter or so of the reference leg may suffice, to indicate whether or not the reference leg is full, and to indicate the average density of the fluid near the top of that leg. (A clamp-on alternative to this proposal is suggested in Fig. 1 (e).)

Although microbubbles or oil buildup attenuate the signal in applications where the sensor is wetted, it will be appreciated that if the sensor were stretched or otherwise centralized inside a dry sealed sheath, these sources of attenuation are avoided. The sensor then could be used to measure average temperature and the temperature profile. The torsional velocity at room temperature in a SS diamond cross section of aspect ratio 3 is about 1500 m/s, which is low compared to the extensional velocity of 5000 m/s. The torsional diamond cross section sensor of aspect ratio 3 is some 3.3 times as sensitive to T as the extensional sensor that previously might have been proposed. Hot zones as long as 100 m occur in bakery ovens [21]. Such temperature profiling applications have recently been identified, in which some of the collapsed level sensor technology might be adapted. In particular, in applications where cleanliness and/or safety is important, the present feedthrough, which separates the transducer and its coil from the process, may offer advantages over competing thermometric technologies. To be successful in the long baking oven temperature sensing application, the ultrasonic temperature sensor would have to prove itself as being more reliable, and hence, more economical in the long run than the presently used thermocouples or resistance temperature detectors (RTD's), without sacrificing accuracy.

2) Design: The water level H is given by

$$H = H_k \frac{L_L L_V t_M - L_M L_L t_V}{L_V t_L - L_L t_V} + H_0 \quad (10)$$

where

- L_L liquid reference zone length,
- L_V vapor reference zone length,
- L_M mixed zone length,
- t_L transit time in liquid zone,
- t_V transit time in vapor zone
- t_M transit time in mixed zone.
- H_0 liquid level offset,
- H_k slope calibration factor.

L_L , L_V , and L_M are programmed into the electronic console memory.

The other parameters t_L , t_V , and t_M are obtained by measuring the transit times of the three zones (see Fig. 1 (d)):

$$t_L = (1/2)(t_{FDEDF} - t_{FDF}) + T_{wL} \quad (11)$$

$$t_V = (1/2)(t_{ABCBA} - t_{ABA}) + T_{wV} \quad (12)$$

$$t_M = t_{ABDF} - (1/2)(t_{ABA} + t_{FDF}) + T_{wM}. \quad (13)$$

The parameters T_{wL} , T_{wV} , and T_{wM} are generally small and account for measurement errors due to variations in signal shape and tolerance of the zone lengths. These values are programmed into the instrument, usually during calibration. The transit times t_{FDEDF} , t_{FDF} , etc., are measured parameters. Time t_{FDEDF} is the time for an ultrasonic pulse to travel from point F at the transmitting transducer (Fig. 1 d), through the lead-in/out waveguide to the mode conversion point at D , then through the reference zone waveguide from D to E , where it is reflected and travels back to D and then to F . At F the ultrasonic pulse is received by the same transducer. Time t_{FDF} is the time for the ultrasonic pulse to travel from point F to the mode conversion point D , where part of the energy is reflected and returns to point F . Similar paths can be traced for t_{ABCBA} and t_{ABA} . The loops at the top act as delay lines so that the vapor reference zone can be torsionally interrogated without interference from extensional echoes.

In each of the above cases, the same transducer is used to transmit and receive the ultrasonic pulse, in "pulse echo" mode. An exception is the "through transmission" measurement of t_{ABDF} . In this case the ultrasonic pulse is transmitted from the transducer at point A , travels to the mode conversion point at B , through the mixed zone to the second mode conversion at D , and then to point F , where it is received by the other transducer. The 100-kHz pulse center frequency is a compromise. Higher frequency would allow a smaller loop and better resolution of time, but would increase attenuation and dispersion for the present sensor's cross-sectional dimensions. For long-path transmission, e.g., 20 m (Fig. 2) the period of the received pulse is 25 μ s, the reciprocal of which is 40 kHz. In a test of the same elements but in short lengths, the period of the received pulse was 20 μ s. In other words, long sensors act like low-pass filters.

a) Signal capture: The way we presently interrogate the sensor, at least three transmissions are required to determine all the transit times. One transmission is required to capture the signals needed to determine both t_{ABA} and t_{ABCBA} . Another transmission captures the signals needed to determine t_{FDF} and t_{FDEDF} . A third transmission is required to capture the signal needed to determine t_{ABDF} .

In each case the Model C582R instrument sets a "window" straddling the expected arrival times of the signal. The maximum and minimum arrival times are determined from the mechanical sensor geometry and the extremes of sound speed due to temperature, fluid density, and level variations. The instrument then searches only these windows for the received signal.

b) Signal averaging: Two levels of averaging are used—zone averaging and global averaging. The two reference zones, liquid and vapor, are always immersed or "dry," respectively. The transit times in these zones are, therefore, fairly constant over time. There will be some variation with temperature, but this occurs relatively slowly compared to the response time of the C582R. The mixed zone transit times are level dependent and may change rapidly. The transit times in the reference zones may, therefore, be averaged over time to obtain accurate and stable measurements, without affecting response time. Absolute accuracy in the transit time measurements for the reference zones is more critical to overall accuracy due to their relatively short lengths.

The transit time measurements are divided into the "measurement cycles" during which all three zones are interrogated and a level calculation completed and displayed. Each measurement cycle takes typically 0.3 s.

The number of interrogations of each zone is set by the zone averaging factor, n , which is programmed independently for each zone. (The number of interrogations = 2^n .) Typically, in each measurement cycle, the C582R dwells most of the time on the through transmission measurement of the mixed zone and only a relatively short time on each of the two pulse-echo measurements of the reference zones. The number of interrogations is usually programmed to 32 ($n = 5$) for the mixed zone versus 8 ($n = 3$) for each of the reference zones. The *zone averages* are calculated by averaging the transit times from these interrogations to obtain the averages for t_{ABA} , t_{ABCBA} , t_{FDF} , etc. The zone transit times are calculated using (11)-(13) to obtain t_L , t_V , and t_M .

Before these zone transit times are used for the level calculation, however, the *global average* is calculated. This is determined by a "boxcar" average in which the last N values from the last N measurement cycles are averaged. The global averaging factor N may be independently programmed for liquid, vapor, and mixed zones. In the boxcar average, each of the N measurements are given equal weight and at each measurement cycle the newest measurement is added and the oldest measurement is erased. The global averaging N is usually set to 1 for the mixed zone and 30 for each of the two reference zones. After each measurement cycle, the level is calculated using the global averages of t_L , t_V and t_M using the equation

$$H = H_k \frac{L_L L_V \overline{t_M} - L_M L_L \overline{t_V}}{L_V \overline{t_L} - L_L \overline{t_V}} + H_o \quad (14)$$

where

$$\begin{aligned} \overline{t_V} & \text{ global average transit time in vapor zone,} \\ \overline{t_L} & \text{ global average transit time in liquid zone,} \\ \overline{t_M} & \text{ global average transit time in mixed zone.} \end{aligned}$$

By dwelling for most of each cycle on the mixed zone, and averaging the reference zones over a large number of cycles, the instrument can obtain stable, accurate readings, but nevertheless, maintain a rapid response.

3) Bubbly Liquid Experiments and Tests: In the absence of air bubbles introduced intentionally, the observed increase in

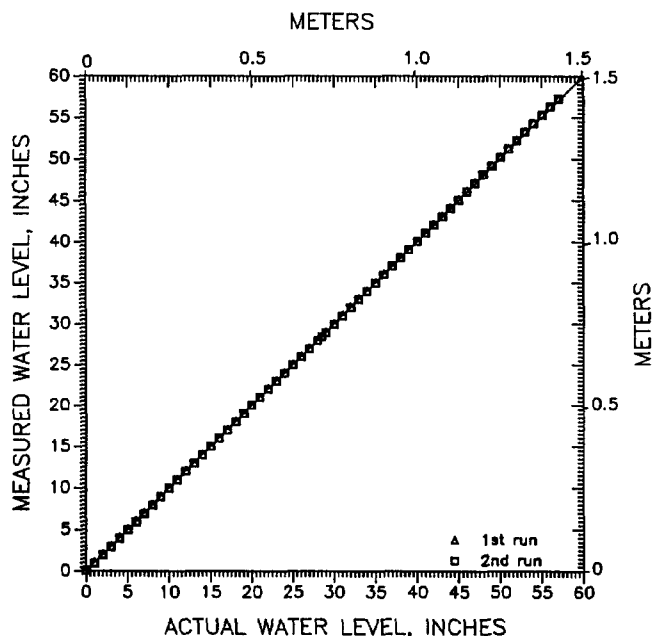


Fig. 4. Actual water level versus measured water level, covering a range of 1.45 m, at room temperature.

transit time for the sensor of Fig. 1 (c) is directly proportional to the water level, Fig. 4.

To simulate at room temperature, the case of a boiling liquid, air was introduced through an air stone at the bottom of the water column, raising the observed top of the foam by 5 cm. This resulted in a 23-mm apparent increase in level, based on the increase in transit time. The fact that there was any change at all in the transit time is attributed to the inhomogeneous state of the bubbly fluid. It is acknowledged that the air/water simulation may be a poor simulation of the uncollapsed condition of interest. Some earlier work on the use of torsional sensors of different cross sections in bubbly flow is due to Arave [2], reproduced in [20, p. 440].

Another bubbly liquid experiment consists of immersing a ring sensor in the vapor above boiling liquid nitrogen, then in the boiling region, and finally submerging it completely into the liquid. This leads to the set of three oscillogram traces in Fig. 5. In all three cases, the temperature $T \approx -196^\circ\text{C}$. It is seen that the transit time and its jitter indicate the nature of the cryofluid: vapor; boiling two-phase region; liquid. More attenuation is observed upon immersion of the ring than for a straight length of the same cross section, suggesting that it may be associated with the toroidal shape.

B. Fuel Mass Measurement Aboard an Aircraft

To determine the mass of fuel on board an airplane, in each tank, it is customary to sense both the liquid level, and separately, the density at one "representative" point, e.g., near the bottom of the wing tank. In many (but not all) cases, there is sufficient mixing so that one-point ρ -sensing suffices in each tank or tank section. From the tank geometry, ρ , and other information on roll, pitch and yaw, the quantity of fuel remaining can be calculated. Acoustic resonators are now widely used as avionic ρ sensors, similar in principle

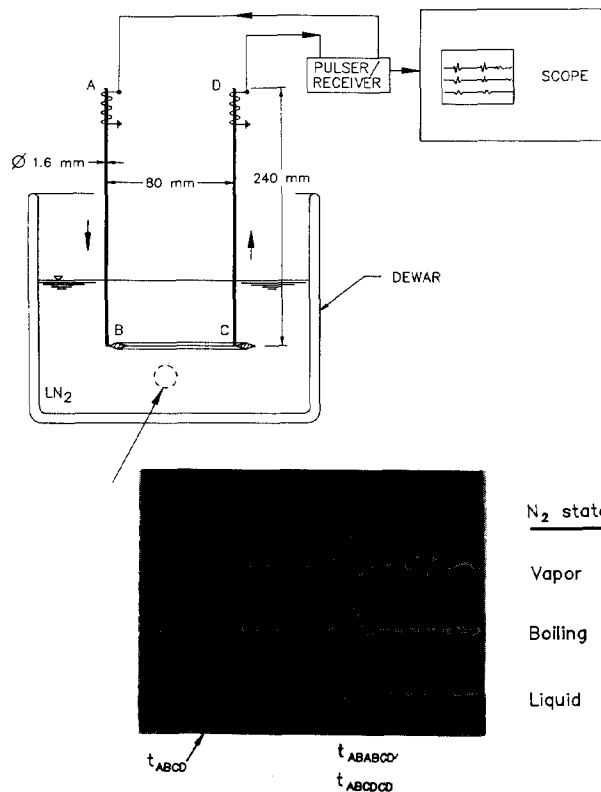
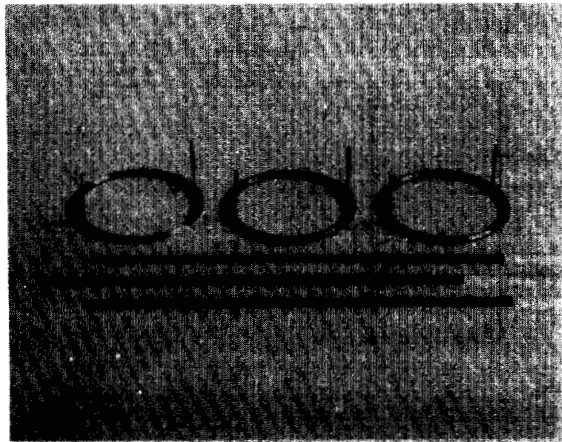


Fig. 5. Torsional diamond ring sensor tests at -196°C in nitrogen vapor, just above the liquid's surface (top trace), in boiling liquid (middle trace) and fully immersed in liquid nitrogen (bottom trace). Sweep: $20 \mu\text{s}/\text{div}$. In the schematic, the dotted circle (arrow) represents a warm steel wrench introduced to boil the nitrogen (middle trace).

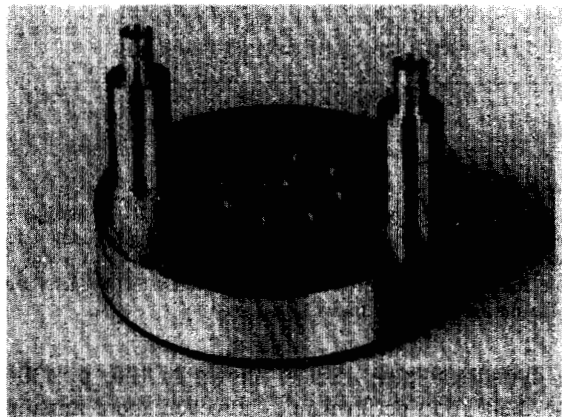
to the cylindrical tube sensors shown in [20, p. 430-432]. Despite their good performance, however, there remains, for some avionic applications, a desire to improve the ρ sensor with respect to factors such as reliability, ease of maintenance, size, weight, drift, number of conductors in the wiring harness, accuracy, and price.

In an attempt to achieve such improvements, some laboratory experiments were conducted with diamond cross section toroidal sensors, i.e., diamond rings excited in the torsional mode. One such sensor is illustrated in Fig. 6. Similar to the collapsed or equivalent liquid level sensor, mode conversion is used to launch and detect the torsional wave. Broadband 100-kHz pulses propagate symmetrically cw and ccw, adding up opposite their launch point. After traveling along the semicircular paths, the signal is still broadband and shows little or no evidence of dispersion (see again, Fig. 5). By immersing the diamond-ring sensor in liquids of different ρ , one obtains, at room temperature, the calibration function shown in Fig. 7. The plotted transit times are functions of T also, and this effect must be eliminated if the sensor is to be useful over the T range of interest, $\pm 60^\circ\text{C}$, approximately. (Note that $S(= |\Delta c/c|)$ for water immersion is $\sim 15\%$, essentially the same as in a straight SS sensor of the same shape and aspect ratio, $b/d = 3$.)

In principle, one could use a Pt or Ni RTD (resistance temperature detector) to sense T . However, this adds conductors to the wiring harness. One partial remedy is to use Ni Span C (for which dc/dT can be made small through proper heat treatment). This material is used in some of the existing avionic



(a)



(b)

Fig. 6. (a) Diamond cross section rings made of SS, Ti, and Al. (b) Photograph of a housed sensor.

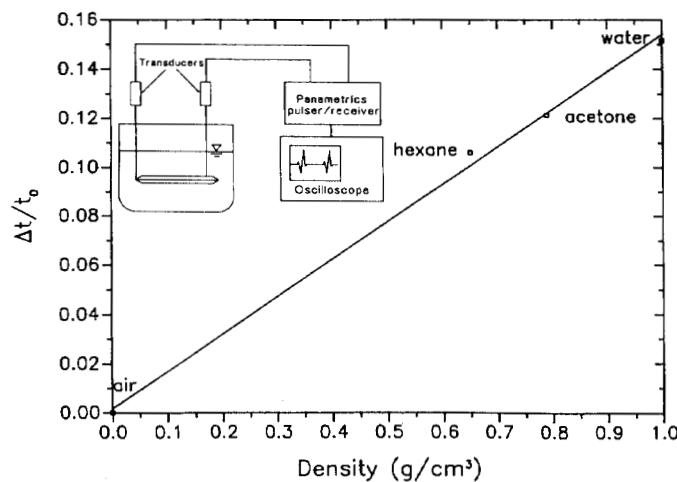


Fig. 7. Calibration data showing the response at room temperature of the SS ring of Fig. 6 (a) to liquids of different densities. Note that $S \approx 15\%$, close to the value for a straight SS sensor of the same cross section.

resonator ρ sensors. As one of our objectives is to develop a ρ sensor that can be made of any one of a number of different

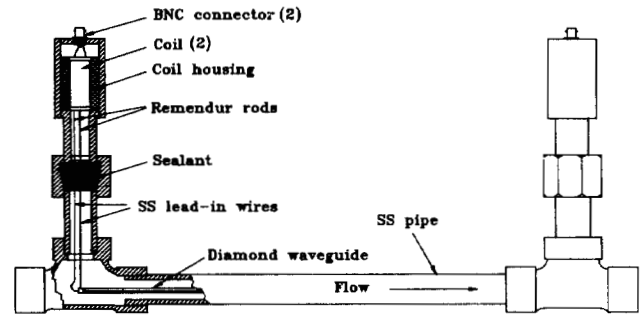


Fig. 8. Use of diamond cross section sensor interrogated in the torsional mode to sense fluid density ρ_f and, as in [26], interrogated also in the extensional mode to measure temperature T .

metals (Ti, SS316, etc.), we are investigating ways of using the extensional sound speed c_{ext} in the lead-in, lead-out, or in the ring, to provide T compensation, perhaps along the lines of Miller *et al.* [26].

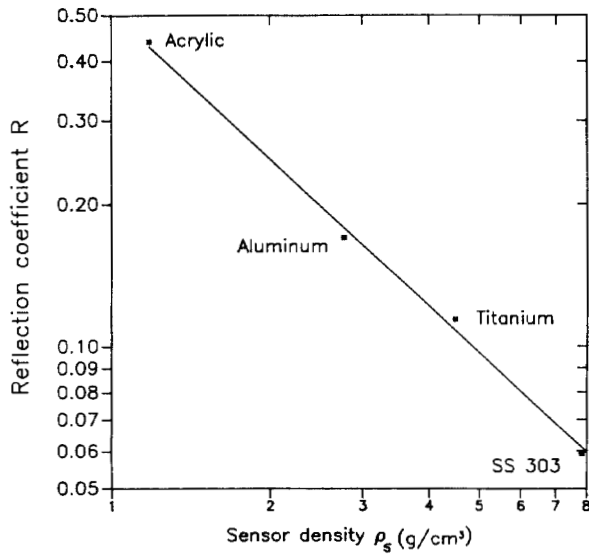
Referring again to Fig. 6, it is seen that for a SS ring diameter of 100 mm, the semi-circumference path of 159 mm has a torsional transit time that increases from $\sim 100 \mu s$ in air to $115 \mu s$ in water. If this $15\text{-}\mu s$ increase can be resolved to 15 ns, and if T effects can be eliminated, resolution of $\pm 1 \text{ mg/cm}^3$ ought to be achievable.

If the torsional sensor is positioned along the axis of a pipe, Fig. 8, it can be used to measure ρ at essentially the same time and same place that flow velocity V is being measured ultrasonically. This combination may provide a less expensive way to measure mass flowrate M_f , than with coriolis alternatives currently available. The density sensor can also be located outside the region of high flow velocity, to measure ρ while avoiding flow-induced stresses. In some avionic applications where mass flowrate M_f must be measured at a response time of 10–30 ms, the fuel density ρ_f does not change rapidly. This relaxes the requirements on the density part of such a mass flowrate sensing system.

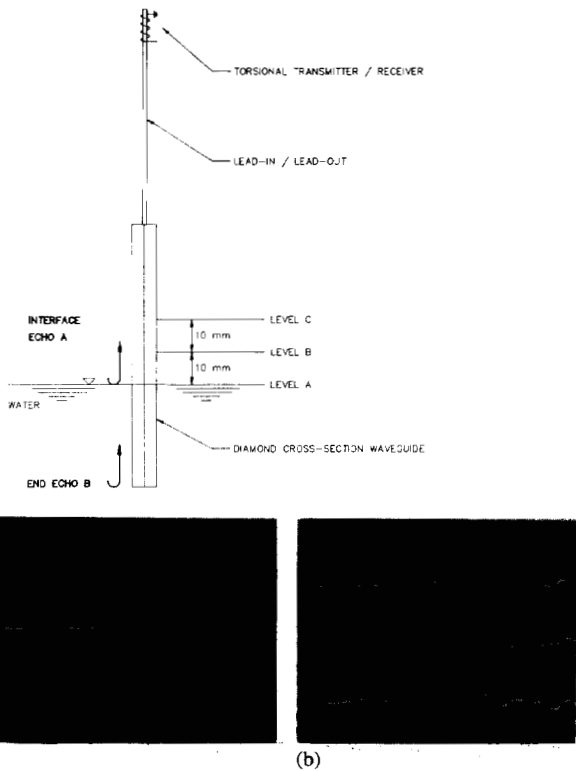
C. Reflection at an Interface

If the noncircular cross section waveguide intersects the interface between two fluids of dissimilar density, torsional reflection will occur. Measurements of the interface echo were conducted with different liquids (liquid/air interface), with sensors of different density ρ_s (SS, Ti, Al, acrylic) and with the sensor not just normal, but also inclined at angles up to 45° to the horizontal interface. Confirming the theory, the observed sound pressure reflection coefficient R_p increases as ρ_s decreases, see Fig. 9 (a). R_p is taken as the ratio of the echo amplitude at the interface to that at the free end when the waveguide was in air, prior to immersion. Note the sign of R_p . Although c_{tors} is reduced in the immersed section, the inertial term more than makes up for the reduced c_{tors} , such that $Z_2 > Z_1$ and R_p is positive. It is observed that $|R_p| \approx |S/2|$.

As the sensor goes deeper and deeper into water: a) the free-end echo B (of $R_p = -1$) is increasingly delayed; b) the interface echo A arrives earlier and earlier (Fig. 9 (b)); and c) the sign of A is opposite that of B . It was found that for



(a)



(b)

Fig. 9. (a) Graph of reflection coefficient R as a function of the sensor density ρ_s . This pulse echo test used a Wiedemann transducer. (b) Example of reflection obtained when a diamond straight sensor intersects an interface between two fluids of different density (e.g., water/air). The reference echo (left) for the waveguide in air is recorded at 500 mV/div versus 50 mV/div for the interface echoes at the right (levels A, B, C).

angles up to 45° the interface echo A is rather tolerant of, or insensitive to, tilt. It was also observed that echo A is similarly insensitive to surface ripple. In principle, it might be possible to detect interfaces between two fluids like aviation fuel and water, or automotive gasolines and water, whose densities differ only by some 20%. However, R_p for such cases would be much harder to measure, than for the air/water case. On the other hand, detecting a distinct cryogenic liquid/vapor interface

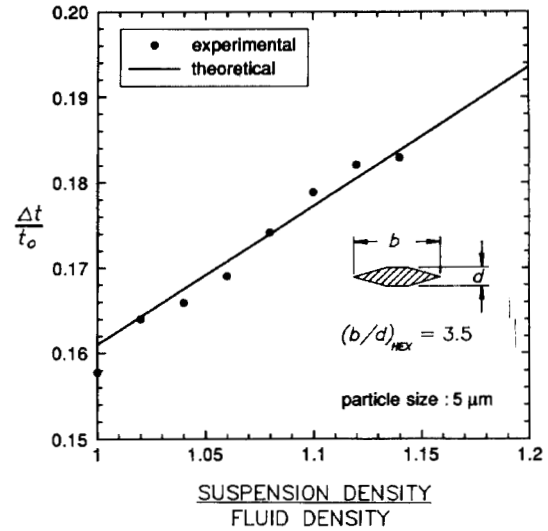


Fig. 10. The measurement of suspension concentration with 5- μ m alumina particles mixed in distilled water.

for N₂ or O₂ would be comparable to air/water, with respect to the magnitude of R_p , inasmuch as the densities of liquid nitrogen (0.815 g/cm³) and liquid oxygen (1.143 g/cm³) are comparable to that of water.

Note that the transit time of echo A down to the interface and back, yields liquid level H independent of liquid density ρ . Knowing H , one can relate the time interval between A and B to the average liquid density, top to bottom. In principle, a multizone notched sensor could yield information on the density profile, $\rho(x)$.

D. Measurement of a Suspension's Concentration

The torsional wave sensor can be used to measure the equivalent density of a suspension of particulates in a liquid. If the individual density of the two components (the solid particulates and the liquid) is known, one can obtain the mass concentration of the particles. Fig. 10 describes the effect of particle mass concentration on the transmission time of a torsional wave in a fully submerged waveguide (hexagonal cross section and aspect ratio 3.5). The symbols and solid line correspond, respectively, to experimental results and theoretical predictions ((2)). The suspension consisted of 5- μ m diameter alumina (Al₂O₃) particles in distilled water. A rotating mixer was used to maintain uniform concentration. The equivalent density of the mixture was obtained by weighing a known volume of the suspension.

For relatively low particle concentrations, the figure demonstrates good agreement between theory and experiment. We were not able to conduct measurements with higher concentration suspensions than those shown in the figure due to persistent signal drift which we attributed to a possible accumulation of particles on the waveguide's surface. This problem possibly can be solved by appropriate coating of the waveguide's surface, by occasionally operating the transducer at high enough amplitude to promote self-cleaning; by periodic purge; or perhaps by other means.

IV. CONCLUSION

The diamond cross section has been utilized in straight and toroidal sensors, fabricated of SS and other materials, and interrogated using Wiedemann-effect and/or Joule-effect magnetostrictive transducers. The choice of the transducer for this sensor is dictated largely by the temperature, feedthrough constraints, and the geometry of the application. In configurations tested to date, the diamond cross section torsional sensor appears to complement or in some cases offer potential or actual (demonstrated) advantages for measuring fluid density and collapsed (equivalent) level in harsh environments, compared to the nonacoustic sensors currently in use. On the other hand, in some applications the use of flexural or bending waves may be preferred over torsional waves. While flexural waves may not always be slowed down as much nor in as simple a manner as torsional waves, the possibility of using them with clamp-on transducers is attractive [22].

V. ACKNOWLEDGMENT

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From 1969 to 1977, he served with the Israeli Defense Force. Since 1980, he has been on the faculty of the University of Pennsylvania, Philadelphia, PA, where he is currently a Professor of Mechanical Engineering and Applied Mechanics and of Electrical Engineering.

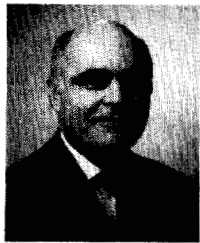
Dr. Bau is a recipient of a Presidential Young Investigator Award. He is a member of the ASME, APS, and SIAM.



Yi Liu (M'92) received the B.S. degree in electrical engineering from Xi'an Institute of Metallurgy and Construction Engineering, China, in 1981 and the M.S. degree from Beijing Institute of Technology (BIT), China, 1984.

Between 1984 and 1987, he was with BIT, where he was responsible for the development of electrodeless liquid conductivity sensors. From 1987 to 1989, he was a research investigator at Rutgers University, NJ, where he worked on in-line ultrasonic sensors for food processing. He joined Panametrics in 1990,

where he has been working on the development of acoustic sensors for measurements of liquid level, density, flow, and other process control or avionic measurands.



Lawrence C. Lynnworth (S'55-M'59-SM'70-F'93) received the B.E.E. degree from New York University in 1958 and the M.S. degree from Stanford University in 1959.

At Panametrics since 1962, he is now VP, Special Research Projects and Head, Acoustic Process Control Department and has worked on high temperature ultrasonic measurements of elastic properties of solids, high temperature NDT, and measurement of temperature and transport properties in hot gases and plasmas. More recently,

he has worked on the development of ultrasonic sensors, transducers, and test equipment for measuring process control parameters such as flow, temperature, density, and liquid level. He has authored of over 100 publications, three invited chapters, and in 1989, the book, *Ultrasonic Measurements for Process Control*. He holds 34 patents.

Dr. Lynnworth has held elected positions in the IEEE, ASNT, and ASTM, and is a member of Tau Beta Pi and Eta Kappa Nu.



Steven A. Lynnworth was born in Waltham, MA, in 1967. He joined Panametrics in 1991 as a technician working on liquid level and flow projects. His duties include design, construction, testing, and field service.



Kimberly A. Hall was born in Mineola, NY, in 1960. She received the B.A. degree in English from Rider College and the B.S. degree in electrical engineering from Northeastern University.

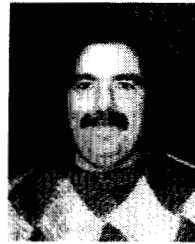
She has been working at Panametrics since 1988. Currently, she is developing and testing software for electronic instruments for acoustic applications, including level sensing and fluid flow.



Saul A. Jacobson (M'86) received the B.S. and M.S. degrees in electrical engineering from the University of Cape Town, South Africa, in 1977 and 1983, respectively.

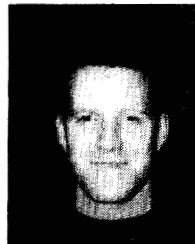
He has been involved in research and applications of ultrasonic measurement and signal processing as a graduate student at the University of Cape Town from 1981 to 1982 and at the Council for Mineral Technology, Randburg, South Africa from 1982 to 1984. In 1984, he joined Panametrics, where he has been working on the development and application of ultrasonic instrumentation for measurement of flow, density, and level.

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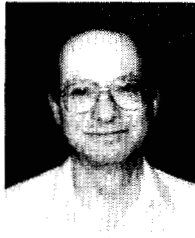
James M. Korba received the B.S. degree in mathematics from Southern Illinois University in 1973.

He has worked for Panametrics as a Software Engineer since 1979. He has developed embedded systems software which supports research and development in a variety of measurements including flow, temperature, level, and density. His previous programming work involved a variety of military and medical applications. He is a co-inventor of the differential correlation analyzer.



Robert J. Murphy was born in Waltham, MA, in 1967. He received the B.S. degree in electrical engineering from the University of Lowell, MA, in 1989.

He has worked for Panametrics since 1985, concentrating primarily in electronics as used in new flowmeter products such as liquid, gas, and two-phase flowmeters, and in special projects such as an experimental downhole flow tool.



Michael A. Strauch received the B.S. degree in electrical engineering from Northeastern University in 1990.

He has worked for Panametrics since 1991 on hardware and software development of ultrasonic flowmeters, liquid level gages, and inclusion of a thickness gage mode in a portable flowmeter.



Kyle G. King received the B.S. and M.S. degrees in electrical engineering from Union College, Schenectady, NY in 1989 and 1992, respectively.

From 1989 to 1992, he was a Project Engineer with GE Power Generation, where he was responsible for managing the design, testing, and manufacturing of power plant instrumentation and control equipment. Since 1992 he has been a Research Engineer at the High Voltage Transmission Research Center in Lenox, MA, where he is responsible for the design and development of magnetic field

management systems for transmission and distribution lines.

Mr. King was awarded the 1991 GE Young Engineer Award. He is a licensed Professional Engineer in New York. He is also a member of Eta Kappa Nu, Tau Beta Pi, and is the Secretary of IEEE Power Engineering Society, Berkshire Section.