Measurements at the Speed of Ultrasound

by Lawrence C. Lynnworth, *New York Epsilon '58*

Introduction

The word *bent* has a special meaning to readers of this magazine: a structural element used, for example, in post and beam construction. Its more common meaning brings to mind a shape like a rod or a line that seems headed one way but then takes a sudden turn. A common example is a stick held in water at an angle, partly immersed, partly in air. It appears bent. The explanation is familiar. The speed of light is about 33% faster in air than in water. Therefore, the light rays bend (refract) when they strike the interface obliquely. This article explores how this simple concept underlies *ultrasonic* devices used in two different fields: NDT and PCI (nondestructive testing and process control instrumentation). Conversely, we'll also try to show that devices that look pretty simple can lead one to fundamental design principles or at least illustrate such principles in action. The device we'll look at is an acoustic wedge, and its purpose is to bend ultrasonic rays. But first, let's return to our stick in water.

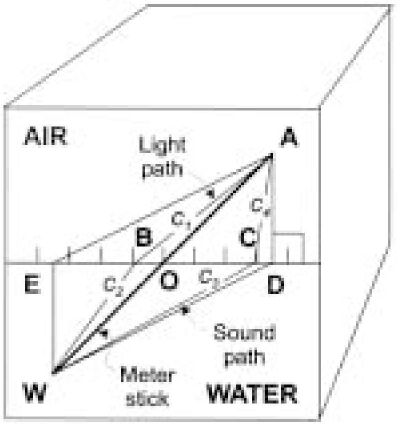

Figure 1. Meter stick AOW, midpoint O, is half-immersed in water and is inclined at 45º. Paths between A and W for light rays and for ultrasound rays are drawn according to Fermat's Principle of shortest time. The lengths $P_{\pm}$ of the longer and shorter path segments may be calculated using the law of cosines. If one denotes the distance from O to the bend at B or C as $|x|$, then $P_{\pm} = (x^2 \pm 0.7071\,|x| + .25)^{1/2}$. Trying different values for x, one finds a near-minimal time for light of 3.85 ns at $|x| = 9.5$ cm and 1,543 µs for sound at $|x| = 28$ cm. The time of travel along each segment P_+ or P_- is obtained by dividing $P_{\pm}$ by the appropriate speed c_i, where $i = 1, 2, 3$ or 4.

The refracted angle is easily calculated by Snell's Law of refraction, relating the index of refraction n and the sines of the angles of incidence and refraction. Suppose we designate the stick in Figure 1 as having end points A and W. Let it be straight, one meter long, its midpoint O at the water's surface, and angled at 45º. The AOW path taken by the stick is straight, "the shortest distance between two points." The path that *light* takes from point A in air to point W in water, however, is not straight, but rather the one that takes the shortest *time.* This is *Fermat's Principle of least time.* Finding the fastest route — the one that yields the shortest time between two points — applies to sound waves as well as to electromagnetic (light) waves. Sound waves include *ultrasonic* waves (waves having frequencies above 20 kHz). The fact that sound or ultrasound waves bend as a function of the sound speed ratio encountered obliquely at an interface, is the basis for several devices used in industry. The particular devices may or may not be interesting to the reader at the moment. Fermat's Principle, however, is of considerable importance, and exploring its range of validity and limitations, accordingly, is a worthwhile pursuit. This short article does not conduct such pursuits. Instead, it merely points out that even a simple device like an acoustic wedge (the analog of an optical prism, with respect to bending the incident rays) touches on important principles.

Some readers may want to explore characteristics, similarities, and differences between ultrasonic and light waves. For example: why do ultrasonic waves, encountering an interface obliquely, sometimes launch vibration modes different from the one comprising the initial wave? Perhaps the best-known difference between rays of light and ultrasound is that light travels fastest in vacuum, while ultrasound doesn't travel at all in vacuum, and in air, where it does travel, it does so much slower than in water or most solids. In glass, light exhibits dispersion, meaning light travels at different speeds for different wavelengths. *Visible* light includes wavelengths from 0.4 to 0.7 µm. The fact that a glass prism sepaates white light into its colorful spectrum demonstrates that even over wavelengths spanning a range <2, dispersion exists. In heavy flint glass at an IR (infrared) wavelength of 2 µm (beyond the red end of the visible spectrum) the index $n = 1.6$, while at a UV (ultraviolet) wavelength of 0.36 µm, just beyond visible violet, $n = 1.7$. This 6% increase in n on going from IR to UV occurs at wavelengths differing by a factor of nearly six. Ultrasound, however, would travel in the same glass at essentially constant velocity for the same ratio of wavelengths or even over a wider range. This can be verified at commonly used ultrasonic frequencies like 1 to 10 MHz.

What about *ether drift*? Ultrasonic anemometers use the fact that sound travels faster in the direction of the wind and slower against the wind. This *contrapropagation* time-difference effect is analogous to timing identical twins swimming upstream vs downstream. The twin traveling *with* the current swims faster, relative to the shore. There is no corresponding “optical anemometer,” as is well known to anyone familiar with either the Michelson-Morley experiment or relativity (c = constant). [1]

Before discussing the angle beam bent-ray concept and its use in NDT and PCI flow measurement, let’s take a moment to consider Figure 1 in more detail. [Applications of Fermat’s Principle of least time or Snell’s Law of refraction to medical diagnosis apparatus, to explaining earthquake wave arrival times in seismology, meteorology (thunder propagation), and other fields is left to the reader’s imagination and interest.]

Figure 1 illustrates some of the consequences of speed in air being faster than in water (for light), but the opposite for ultrasound. The speeds for electromagnetic (light) waves are taken as $c1 = 3 \times 10^8$ m/s in air and $c2 = (3/1.33) \times 10^8$ m/s in water (index $n = 1.33$). For acoustic or ultrasonic waves, the speeds are taken for 20ºC as $c3$ = 1,482 m/s in water and $c4$ = 343 m/s in air. To an observer in air, the W end of the stick looks like it is closer to the surface than it really is. Intersection point B is about 9.5 cm to the left of point O, while intersection C is about 28 cm to the right of O. The paths are bounded by parallelogram ADWE. The acoustic path lies to the right of O and is bent more than the light path because (a) $c3 > c4$ and (b) the ratio $c3 / c4$ (1482/343 = 4.32) is over three times greater than the optical index n.

A peculiar coincidence was noticed in preparing this figure. The 1972 source of $c3$ for pure water lists the value at 20ºC as 1,482.343 m/s, which I rounded off to 1,482 m/s for the present calculations. Water’s disregarded digits after the decimal point, 343, happen to be equal numerically to the sound speed $c4$ in air at the same temperature. *Another* peculiarity is that, if one constructs a 1 m^3 box and fills it with air or other gas at standard conditions (0ºC, 760 mm Hg), the *weight* of the gas in pounds very nearly equals the molecular weight MW divided by ten. Example for air: MW = 29, density = 2.9 lb/m^3. Why? Hints: Avogadro’s Number; gram molecular volume; 1 kg = 2.2 lb. In these hybrid units the density of water is about 2,200 lb/m^3.

What do (a) MW or (b) standard conditions have to do with minimizing transit time? Answer: (a) Soundspeed squared in a gas is inversely proportional to average MW. This means, if our (dry) air at 20ºC were to pick up some moisture, its (dry) MW of 29 would be diluted with some H_2O of MW = 18, and the speed of sound would *increase*. The increase is small, ≤0.2% for RH (relative humidity) = 50% and ≤0.4% for RH = 100%. This dilution or averaging of MW also means the *density* of moist air is less than that of dry air at the same temperature and pressure. (b) At 0ºC the speed of sound in dry air is 331 m/s, slower than at 20ºC by about 3%. Now back to our story.

NDT Using Angle-Beam Transducers

About 50 years ago Moriarty [2] reported that a plastic wedge, Figure 2a, in which *longitudinal* waves were introduced obliquely against a steel pipe, provided a useful way to generate *shear waves in the pipe* for purposes of inspection. The shear waves, zigzagging down the pipe wall at angles of incidence in the pipe that did *not* mode convert, were able to travel substantial distances along

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Larry has authored some 200 papers and reports, published several chapters and one book, and has over 40 U.S. patents, some of which deal with angle-beam transducers and buffered waveguides.

After graduating, Larry worked primarily in non-destructive testing, first at Avco in 1959-62 and then at his current employer. By 1970 his focus had shifted to ultrasonic measurements of process measurands, and his work since has been related to ultrasonic flowmetering.

He is a reviewer for several journals, became an IEEE fellow in 1993 for contributions to ultrasonic measurement of flow, temperature, and liquid level, and has served as an expert witness.

the pipe. If the pipe geometry is uniform, then reflections occur only when a defect or other discontinuity is encountered. The angle-beam wedge is used routinely nowadays to inspect welds and to find cracks or disbonds. Depending on the wedge angle, one can launch shear or Rayleigh (surface) or Lamb (plate) waves in the metal object. The refracted angle for Rayleigh or Lamb waves can be 90˚, because the speed of these waves can be roughly 50% greater than the speed of the compressional (longitudinal) wave in the wedge. The ultrasonic inspection frequencies are typically 1 to 10 MHz. However, if tiny flaws are to be detected, a shorter wavelength is required (similar to going from an optical microscope to an electron beam microscope for higher resolution). If the required short wavelength is not 1 mm but rather 1 µm, then the ultrasonic frequency must be raised by a factor of 1,000. Ultrasonic microscopes exist today, operating in the gigahertz range in which the wavelength is shorter than the wavelength of visible light (~ 1/2 µm for green light in air). This means that ultrasonic resolution can be finer than with visible light and that ultrasonic inspection can be carried out beneath the surface of *opaque* objects.

In 1967 I became interested in acoustic wedges in which the *incident* ultrasonic wave was shear, not longitudinal. I found a few laboratory applications, like launching Rayleigh waves in graphite or producing a large refracted angle in water inside the pipe, but I didn't find any high-quantity industrial application for this until 1996 and, only then, after making the wedge *thin* in the direction perpendicular to the page.

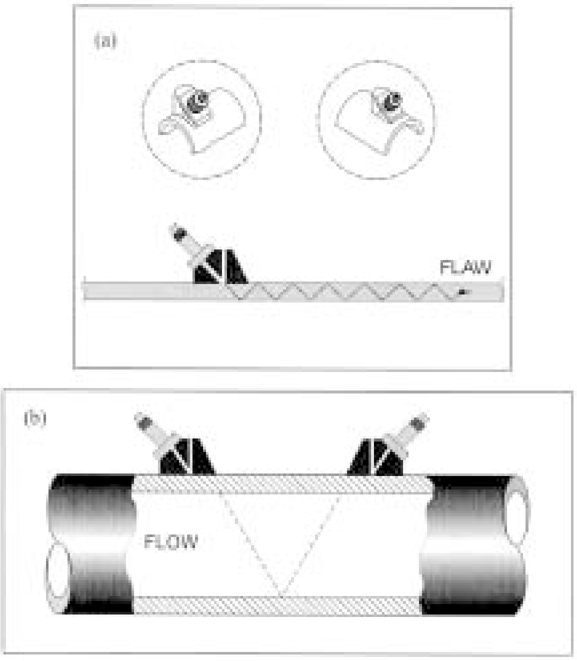

Figure 2. Acoustic wedges bend beams of ultrasound. The propagation of the bent or refracted beam is influenced by the scattering and transmission characteristics along its path. Ultrasonic instruments use the refracted rays to nondestructively sense flaws or noninvasively sense flow. In (a) one angle beam transducer typically is used alone in monostatic pulse-echo mode. Interrogation can be in the axial or circumferential direction. In (b) a pair of clamp-on transducers measures flow of liquid by the contrapropagation (upstream - downstream) bistatic method. If the liquid is so cold or so hot that "ordinary" plastic wedges and "ordinary" piezoceramics no longer work, one remedy is to substitute buffer waveguides having the shape of a hockey stick (Figure 3).

Clamp-on Ultrasonic Flowmeter Transducer

In the industrial field of process control, flow is one of the four most important measurands. (The others are temperature, pressure, and level.) The first clamp-on ultrasonic flowmeters appear to have originated in Japan. By 1964 it had been recognized by the Japanese clamp-on flowmeter pioneers that a plastic wedge, much like the axially-oriented one in Figure 2a, could be used to launch waves through a steel pipe wall, into and across the water inside, and to receive the waves at a diagonally opposite point or after one bounce (Figure 2b). By timing the ultrasonic waves in each direction, the small difference in transit times Δt can be interpreted in terms of the average flow velocity across the tilted-diameter path. This method has since been developed by several manufacturers and used in tens of thousands of applications.

At temperature extremes, either at the cold cryogenic domain of liquid nitrogen or at the hot end as exemplified by superheated water or superheated steam, the plastic wedge design of Figure 2b no longer suffices for two reasons. First, the piezoceramic probably would disbond from the plastic wedge because of differential thermal expansion/contraction. Second, at high temperature, the piezoceramic would no longer generate and detect ultrasonic waves, analogous to a magnet becoming demagnetized. While these problems can be overcome through judicious choice of materials, that route is expensive and does not necessarily cover all temperatures of interest.

A different solution is represented in Figure 3. This solution adds a buffer waveguide to the wedge. To avoid unwanted mode conversions along the waveguide and to introduce the incident wave at as low a sound speed as is currently practical, the piezoceramic element is selected to be in the shear mode. This means particle motion is transverse to the direction of propagation. This device has now been used in about a hundred different flow applications at high temperature and also one at cryogenic temperature in Korea. The ultrasonic wave is "bent" in the fluid and travels just a few degrees off normal, but this path is angled enough to produce a time difference between upstream and downstream interrogation directions. (In the fluid, the ultrasonic wave is not only refracted, but also mode converted to the longitudinal mode. Inviscid fluids do not support shear waves.) We leave as "exercises for the reader" analysis of how the energy is partitioned among the various modes; how the average velocity along the tilted diameter relates to the true average over the pipe's cross-section; and how the individual

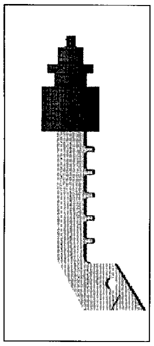

Figure 3. A thin solid waveguide, about 250 mm long in this example, allows ordinary shear-mode piezoceramics to be applied to clamp-on measurement of the flow velocity of water in pipes at 300°C. Details appear in the author's U.S. patent 6,047,602 (April 11, 2000).

waves or pulses are timed to subnanosecond precision. The author trusts that such aspects will not leave the reader frustrated and "bent out of shape." Some hints are found in [3-5] and in the references therein.

At the moment, one of the exercises for the author is to improve the measurement of sound speed within the wedge so that the electronic instrument with which it is used can more accurately compute refracted angle and flow velocity.

Conclusion

Nondestructive testing of metal plates and pipes and noninvasively measuring the flow of fluids through pipes are of concern to engineers in two apparently diverse fields. The acoustic wedge, however, forms part of the solution for each of these two problems and so forms a bridge between two fields and between the engineers in those fields. Fermat's Principle of least time, well known in optics, also forms a bridge, as it applies to light and to ultrasonic waves. If one has the time and inclination to analyze a simple-looking technical device, the acoustic wedge in our present examples, some insight is obtained into the broader field of wave propagation. Wave propagation, in turn, can yield information of value to NDT and process control engineers, to the extent that the waves interact with the measurand of interest without too much distracting influence by interfering variables.

References

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[2] Moriarty, C. D., *Trans ASME,* 73, 225-235 (April 1951). Other early contributors to angle beam transducers for NDT include: Firestone, F.A., "Surface and Shear Wave Method and Apparatus," U.S. patent 2,439,139 (1943); Firestone, F.A. and Ling, D.S., "Method and Means for Generating and Utilizing Vibrational Waves in Plates," U.S. patent 2,536,128 (1951).

[3] Lynnworth, L. C., "Ultrasonic Flowmeters," Chapter 5, pp.407-525 in: Mason, W. P. and Thurston, R. N. (editors), *Physical Acoustics,* 14, Academic Press (1979).

[4] Lynnworth, L. C., *Ultrasonic Measurements for Process Control,* Academic Press, Inc. (1989).

[5] Lynnworth, L. C. and Mágori, V., "Industrial Process Control Sensors and Systems," Chapter 4, pp. 275-470 in: E.P. Papadakis (guest editor), *Ultrasonic Instruments and Devices: Reference for Modern Instrumentation, Techniques, and Technology,* 23 in the series *Physical Acoustics,* Academic Press (1999). [This book also includes a chapter on NDT by E.P. Papadakis.]

Director of Communications & Development

Patricia B. McDaniel has joined Tau Beta Pi's Knoxville, TN, staff in the newly created position of Director of Communications and Development.

Pat earned her B.A. at Bucknell University and her M.B.A. at California Lutheran University. She began her career in development as director of annual giving at the St. Mary's Foundation in Knoxville before advancing to director of development for Knoxville College.

Pat has extensive experience coordinating volunteers for non-profit organizations, as well as conducting fund-raising campaigns, writing grants, and organizing special events. She will be working on the Scholarship Development Campaign, new insignia items, an updated planned-giving booklet, a national engineering student convocation in 2002, and much more. Tau Beta Pi welcomes her and her efforts and assistance in building this dynamic Association, and we hope that you will have an opportunity to meet her.

Design Competition Links Industry with Future Tau Bates

The District 1 Design Contest was hosted this year by Massachusetts Eta on April 8, 2000. This popular competiton, now a District 1 tradition, was established to allow teams of first- and second-year engineering students to practice their problem-solving and presentation skills. Within a time limit of five hours, the teams must study a problem and prepare a 15-minute presentation to a panel of judges representing both the academic and industrial communities. The teams compete for a $500 prize provided by a corporate sponsor.

This year the teams were asked to design a radio beacon that could be deployed in remote locations in the continental US. The teams were presented with solar maps of the nation, information on solar cells, and battery charging characteristics in order to design a cost-effective power supply for the radio beacon.

From a field of five teams, the University of Hartford's team members, Adam Bibb, Ghaith Hammouri, and Trisha Marks, were awarded the winning prize, which was sponsored in part this year by General Electric. Many of the previous design contest participants have gone on to become active members and officers of Tau Beta Pi and founders of successful companies.