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Introduction

A time-of-flight ultrasonic flow measurement system projects acoustic energy along one or more diagonal paths through the pipe in which flow is to be measured. Such an acoustic path is illustrated in Figure 1. If the upstream or A transducer is excited by a burst of electrical energy, it will transmit a packet or pulse of acoustic energy into the adjacent medium. In the LEFM, the electrical excitation of the transducer also initiates a time measurement by causing counts from a precision electronic clock to be accumulated in a counter. The pulse of ultrasound will consist of several cycles having a frequency typically in the 1 to 3 megahertz range. The transducer is designed to be directional, so, in the configuration illustrated in the figure, the acoustic pulse will travel in a straight line from transducer A to transducer B, where it will produce a small burst of electrical energy. If the arrival of the energy at transducer B is detected with suitable electronics and this detection causes the accumulation of clock pulses in the time counter to stop, the elapsed time t_{AB}, from the time of transmission to the time of detection has been measured.

If, now, the downstream or B transducer is excited and the arrival of acoustic energy at transducer A is detected, the time of flight @A can be measured in like manner. The measured times are related to the dimensions properties and velocity of the fluid system as follows:

1. t_{AB}= [L_{path} / (C_{path} + V_{path}) I + $t_{\text{non fluid delays}}$

2. t_{BA}, = [L_{path} / (C_{path} - V_{path}) I + $t_{\text{non fluid delays}}$,

Where L_{path} is the length of the acoustic path

C_{path} is the mean ultrasound propagation velocity along the acoustic path with the fluid at rest

V_{path} is the mean fluid velocity projected onto the acoustic path, and

$t_{\text{non fluid delays}}$ is the total of the electronic and acoustic delays exterior to the fluid.

Each energy pulse traverses exactly the same path in the non fluid media and, in Caldon's LEFM, the same transmitter produces each pulse and the same electronic detector detects each pulse. Consequently, the difference in the times of flight, Δ t, is given by:

3A) $\Delta t = t_{BA} - t_{AB} = [L_{path} / (c_{path} - v_{path})] - [L_{path} / (c_{path} + v_{path})]$

Putting both terms over a common denominator and performing the algebra:

3B) $\Delta t = 2 L_{path} v_{path} / (c_{path}^2 - v_{path}^2)$

Since v_{path} is in the order of 5 to 15 feet/second and c_{path} is in the order 4000 to 5000 feet/second, v_{path}^2 is insignificant relative to C_{path}^2. Thus,

3C) $\Delta t = 2 L_{path} V_{path}/C_{path}^2$

Or.

4) $v_{path} = \Delta t \, c_{path}^2 /(2 L_{path})$

In compressed water, sound velocity varies strongly with temperature and weakly with pressure. Consequently, to find v_{path} using equation 4, not only must the time differential, Δ t, and the length, L_{path}, be measured, but also the sound velocity itself must be determined. Conceptually, if the non-fluid delays can be calculated or measured, the sound velocity can be determined from the times of flight, using equations 1 and 2. In fact, Caldon internal (chordal) systems use this method for the sound velocity determination. But the non fluid delays in externally mounted LEFM systems are significantly less certain, so these systems employ a separate acoustic path, normal to the pipe axis for the determination of sound velocity. The normal path is used because it lends itself to the precise measurement of non fluid delays, as well as times of flight.

Summarizing the principles thus far elaborated:

- The fluid velocity projected along an acoustic path can be measured using the times of flight of pulses of ultrasonic energy directed between a pair of transducers. The distance in the medium separating the transducers must also be measured or otherwise determined, as well as the ultrasound velocity in the fluid medium at rest.

- The ultrasound velocity in the fluid medium at rest can also be measured using the times of flight and transducer separation distance, subject also to a knowledge, by measurement or calculation, of the total time delay in the non fluid media of the energy transmission path.

Using these principles, how accurately can the fluid velocity projected along the acoustic path be measured? Essentially, with an accuracy determined entirely by the accuracy of the measurements of the times of flight and the separation distance and the accuracy of the measurement or calculation of the non fluid delays.

All of this describes a methodology for determining a fluid velocity projected onto an acoustic path. To determine volumetric flow rate from one or more sets of path measurements requires that

(1) the path velocity (or velocities if more than one measurement is made) be related to the axial fluid velocity which produced it, and

(2) the axial fluid velocity for the acoustic path (or paths, if there is more than one) be related to the mean axial velocity for the entire pipe cross section.

The first of these conditions requires a knowledge of the angle between the acoustic path and the pipe axis, as illustrated in Figure 1, and also a knowledge of the fluid velocity component normal to the pipe axis in the way of the acoustic path, if there is any (i. e., transverse velocity). The projection of the axial fluid velocity onto the acoustic path is shown in Figure I (no transverse velocity component is shown in the figure; this will be discussed later). From the trigonometry:

5) v_{path}

Where v_{axial} is the mean axial fluid velocity projected along the acoustic path, and

φ is the angle of the acoustic path through the fluid, measured from the normal to the pipe axis.

Thus, equation 4 can be rewritten in terms of the axial fluid velocity in the way of the acoustic path:

6A) $v_{path} = V_{axial} \sin(\varphi) = \Delta t \, c_{path}^2 / (2 L_{path})$

Or

6B) $V_{axial} = \Delta t \, c_{path}^2 / (2 L_{path} \sin(\varphi))$

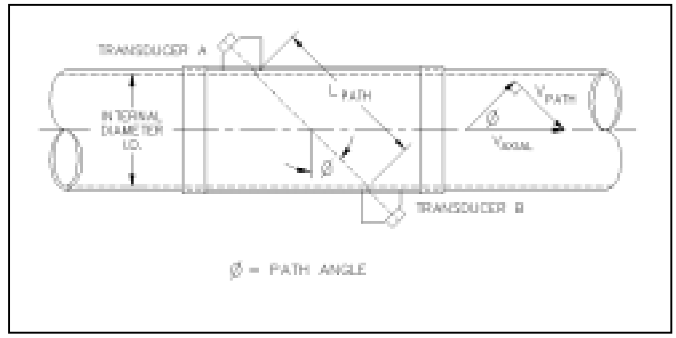
If the transducers are placed such that the acoustic path lies along a diametral diagonal, then

7) $L_{path} = ID / (\cos(\varphi))$

Where ID is the internal diameter of the pipe.

Figure I

Geometry of a Time-of-Flight Acoustic Path



Principles of Externally Mounted Time-of-Flight Systems

For the diametral configuration, from equations 6B) and 7 the axial velocity averaged over the pipe diameter defined by the acoustic path is given by

8) $V_{axial} = \Delta t \, C_{path}^2 / (2 \, ID \tan(\varphi))$

This is the governing equation for externally mounted time-of-flight ultrasonic flowmeters, in the absence of transverse flow. The acoustics of the pipe wall and fluid require placement of the transducers for such meters on diametral diagonals; hence, externally mounted ultrasonic flowmeters are essentially velocimeters. From the velocity measured in accordance with equation 8, the flow must be determined.

It should be pointed out that for externally mounted time-of- flight ultrasonic systems, the path angle (p is not simply determined by transducer placement (as might be inferred from figure 1). Figure 2 provides a clearer picture of external system acoustics. The three angles of the ray path in this figure, $\varphi)_{fluid}$, φ_{pipe}, and φ_{wedge} are governed by Snell's law of refraction, as well as the size and placement of the transducer piezoceramic elements and the configuration of the wedge.
Snell's law stipulates that

9) $\sin(\varphi_{fluid}) = \sin(\varphi_{pipe}) / C_{pipe} = \sin \varphi_{wedge}) / c_{wedge}$

If the three sound velocities are measured or otherwise determined, it remains only to establish one of the three angles φ_{wedge}, is the obvious choice-to determine the others, and thus the acoustic path.

This is not always straightforward. If the transducers are acoustically distant from one another, phi_{wedge} can be determined by assuming the path connects the centers of the piezoceramic elements (refer again to Figure 2).

If the transducers are acoustically close to one another, φ_{wedge} can be determined by the mechanical configuration of the wedge; it is the angle between a normal to the transducer transmitting surface and a normal to the axis of the pipe. The acoustics of a typical feedwater installation are such that neither assumption is exactly valid, and both wedge configuration and transducer placement affect the acoustic path.

Returning to equation 8, it can be seen that the accuracy of the velocity measurement of an externally mounted time of flight system is a function not only of the accuracy of the time, distance and non fluid delay measurements, as developed previously, but also of the accuracy with which their acoustics can be characterized.

For a thermal power determination, the mass rate of feedwater flow and its specific enthalpy are the variables of interest. With a time of flight ultrasonic flow measurement, a determination of volumetric flow is a necessary first step to the mass flow determination. The volumetric flow Q is given by

10A) $Q = (\text{internal pipe cross sectional area})\ v_{mean,\ axial}$

where $v_{mean\ axial}$ is the mean or average fluid axial velocity over the internal pipe cross sectional area.

10B) $Q = [\pi\ ID^2/4]\ v_{mean\ axial}$

For the determination of volumetric flow from an acoustic system with transducers on a diametral diagonal (for example, an externally mounted LEFM), it thus remains to relate the diametral axial velocity to the axial velocity averaged over the pipe cross section. The two velocities are rarely the same. In a long straight section of feedwater pipe, the velocity measured along a diametral diagonal will typically be greater than the true mean velocity by 5 or 6%. On the other hand, a short distance downstream of a header the two may be within 1 or 2% of each other. The differences between diametral axial velocity and mean axial velocity arise because of the differences in the shapes of the velocity profiles. The diametral diagonals of externally mounted ultrasonic meters do not sample the region near the pipewall proportionate to its area, and oversample the region near the middle of the pipe.

Caldon ultrasonic systems use a profile factor, PF, to relate the axial fluid velocity measured along one or more acoustic paths to mean axial fluid velocity. Specifically

11A) $V_{mean,\ axial} = (PF)\ V_{axial,\ path}$

Thus,

11B) $Q = [\pi\ ID^2/4]\ (PF)\ v_{axial,\ path}$

11C) $Q = [\pi\ ID^2/4]\ (PF)\ \Delta t\ c_{path}^2/[2\ ID \tan(\varphi fluid)]$

Equation 11C is used by Caldon for externally mounted systems operated in the direct mode, that is, where one or more diagonal paths are formed by transducers mounted on opposite sides of a pipe. As has been noted however, the inference of axial velocity from diagonal path delta t is only valid in the absence of significant transverse velocity.
Unfortunately, transverse velocity is often present in locations where it is practical to install an externally mounted ultrasonic system. Caldon LEFMs deal with transverse velocity in one of two ways:

(1) The time differential from the path normal to the pipe axis (which, it will be remembered, is used to determine fluid sound velocity) is used to calculate transverse velocity and the result is subtracted from or added to the path velocity as appropriate, or

(2) The diagonal path is configured in the 'bounce' mode-i.e., both diagonal path transducers are mounted on the same side of the pipe so as to form a V-shaped acoustic path through the fluid. In this configuration, the transverse velocity projection on one leg of the V (relative to the axial component) is offset by the equal and opposite projection on the other leg. For this mode, the divisor of equation 11C is doubled (because the acoustic path in the fluid is twice as long).

To determine the profile factor PF of equation 11, the hydraulics at the location of the measurement must be characterized. It is Caldon's practice to accomplish this by a full or part scale test at a certified hydraulic test facility. In the facility, the flow indication of an externally mounted LEFM, modeling the LEFM to be installed in the plant, is recorded as well as the flow as measured by a weigh tank. If the test accurately models the plant installation, and if the weigh tank and test LEFM are accurate, the test results yield the profile factor. The profile factor input to the LEFM for the test is 1.000.

Hence, the profile factor for the plant is given by

12) $PF = V_{mean, axial} / v_{axial, path} = [Q_{weightank}/Area_{pipe}]/[Q_{LEFM}/Area_{pipe}]$

$P F = Q_{weigh tank} / Q_{LEFM}$

The accuracy of a profile factor determination by this procedure rests on the answers to three questions:

(1) How accurate is the weigh tank?

(2) How accurate is the test LEFM?

(3) How accurately does the model of the test facility represent the LEFM installation in the plant?

With respect to question (1), at the test facility used by Caldon (Alden Research Laboratories), the weigh tank measurement is traceable to NIST standards and is accurate to +/-1/4%. The answer to question (2) will be discussed in Appendix B; it should be noted at this point, however, that through the use of multiple acoustic paths, and a dimensionally controlled pipe section time measurement and dimensional uncertainties for the test LEFM tend to be significantly smaller than the uncertainties in these categories for the plant measurement.

With respect to question (3), it is appropriate to discuss the elements of hydraulic modeling, before endeavoring to provide an answer. In a pipe flowing full, inertial and viscous forces on the fluid usually determine the velocity profile. Occasionally, in the presence of significant density gradients, gravitational forces can also play a role, but in the flow measurements described in this paper, they are usually insignificant. For a theoretical development of the forces affecting particle velocity, the reader is referred to any good text on fluid mechanics, for example Binder.[1]

Reynolds number is used by fluid system engineers to characterize the relative importance of inertial and viscous forces in establishing fluid behavior; it is the ratio of a characterizing inertial force on a fluid particle to a characterizing viscous force on the same particle. In feedwater systems operating at significant power levels, the dominant force is usually inertial, as manifested in a Reynolds number in the order of 10 to 30 million.

For the velocity pattern in a model to duplicate the velocity pattern in the plant, the ratios of the forces along each major axis of the model to each other must equal the comparable ratios for the plant.

If the inertial forces are solely responsible for the velocity pattern, it may readily be shown that the force ratios are duplicated if the model dimensions along each major axis bear the same relation to each other as do the comparable dimensions in the plant-that is, the model must be geometrically scaled.

Although viscous forces are very small in nuclear feedwater systems, they can affect, marginally, the shapes of velocity profiles. This is particularly the case in long straight runs of pipe where the viscous forces, which are generated at the pipewalls, can make their presence felt over the full pipe cross section.

Feedwater flow is highly turbulent; fluid velocity is not constant, but is characterized by quasi-random variations about a mean. These variations occur along all three major system axes and the transverse components of turbulent velocity are the means whereby momentum is exchanged between fluid streams whose nominal direction is parallel to the pipe axis. By this momentum exchange mechanism, the viscous forces near the wall eventually affect the flow velocity near the middle of the pipe, though it may require more than 60 pipe diameters for the momentum exchange to equilibrate.

Accordingly, viscous forces must be given some consideration profiles with widely differing profile factors possess angular in the modeling of feedwater piping for purposes of establishing profile factor. Ideally this would be accomplished by running the hydraulic test in a scale model of the plant piping at a Reynolds number equal to that which obtains in the plant. Unfortunately, this is not possible. Reynolds number is given by (V D / v), where V is a characteristic fluid velocity (in this case, the mean fluid velocity), D is a characteristic system dimension (in this case, the pipe internal diameter), and v is the kinematic viscosity of the fluid. In a few hydraulic test facilities it is possible to equal or exceed in the facility the V D product for the feedwater system. For example at the Alden Research Labs employed by Caldon, flow velocities of up to 1.75 times feedwater velocities can be achieved in pipes with internal diameters ranging from 0.67 to 1.0 times the plant pipe ID. But it is not possible to duplicate the viscosity of hot feedwater in the hydraulic test facility.

At 440°F-representative of a final feedwater temperature in a US nuclear plant-the viscosity of pure water is about 20% of the viscosity at 100 'F-typical of the temperature at which the test facility is operated. Consequently, it is necessary to extrapolate profile factor results obtained at facility Reynolds numbers over the I to 3.5 million range, to the plant Reynolds number in the IO to 25 million range.

[1] *Fluid Mechanics*, R.C. Binder, Ph.D.. Prentiss-Hall 1949

This extrapolation is accomplished using a procedure similar to that used for flow nozzles and similar momentum-flux-based flow measurement devices. At the test facility, profile factor is measured for 4 or 5 Reynolds numbers, ranging from about l million to 3.5 million. The profile factor data are plotted against Reynolds number and a logarithmic best fit determined. The use of the logarithmic fit is appropriate since the interaction of inertial and viscous forces is by the turbulent diffusion mechanism, which is likely to be characterized exponentially.

In this regard the extrapolation procedure is very nearly identical to that used to extrapolate the discharge coefficient for a flow nozzle operating in the same Reynolds regime (except only that the logarithmic fit for the nozzle is constrained by a procedure that the writer considers invalid).

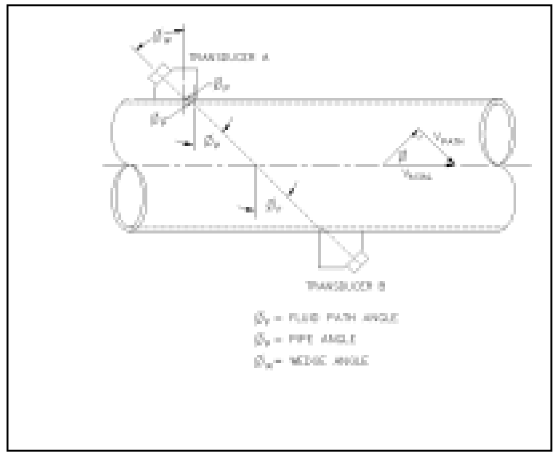
Based on measured profile factor data, most locations selected for LEFM flow measurements show very little or no sensitivity to Reynolds number. This is by design; LEFM locations are selected where inertial forces dominate the shaping of the profile to an even greater extent than is captured by the numerical value of the number (e. g., IO or 15 diameters downstream of a header). Mazzola and Augenstein[2] is suggested for readers interested in more detail on Caldon's experience in profile factor measurements. All externally mounted LEFMs used for the measurement of feedwater employ at least two acoustic planes. Each plane consists of

(a) a cross path for the measurement of sound velocity and, possibly, for the measurement of cross (transverse) flow and

(b) a diagonal path configured either in the direct or bounce mode, for the measurement of axial velocity. The two acoustic planes are usually perpendicular. The axial velocity and sound velocity determinations of each plane are averaged for the flow calculation. This arrangement enhances the accuracy of the flow measurement, primarily because of the multiple time, geometry, and acoustic measurements. The arrangement provides limited insight into hydraulics, however, since many profiles with widely differing profile factors possess angular symmetry.

Figure 2

Acoustics of an Externally Mounted Time-of-Flight LEFM



Principles of Chordal (internal) Time-of-Flight Systems

The discussion from equation 8 onward has focused on externally mounted LEFMS, where the acoustic paths are diametral and the acoustics themselves are determined by the properties and placement of transducers and the dimensions and properties of pipe and fluid. It is appropriate at this point to consider the operative equations for a chordal or internal system. In these systems, transducers are inserted in wells, somewhat similar to thermowells. The ultrasound generated by a transducer passes through the 'face' of the well in a direction normal to the face. Opposing transducer wells are located so that the centerlines normal to their faces coincide and form the nominal acoustic path. This is the first of two important distinctions between external and chordal systems: the angle of the acoustic path in a chordal system is established mechanically by the angle formed by the centerline connecting the two transducer wells and the axis of the spool piece (i. e., pipe). As a consequence, the path angle for a chordal system (or angles for systems with multiple chords) can be established with an accuracy determined by dimensional control of the spoolpiece as opposed to the acoustics of wedges, pipe and fluid. Path angle is crucial to determining the axial velocity subtended by the acoustic path (refer again to equation 6B). Since dimensions are typically controllable with much greater precision than acoustics, chordal systems possess an inherent accuracy advantage on this score.

[2] D.E. Mazzola and D.R. Augenstein, *Hydraulic Testing of External Mount Ultrasonic Flow Meters*, July 1995

In order directly to measure volumetric flow, one must integrate the axial fluid velocity over a cross section normal to the pipe axis, as illustrated in Figure 3. That is,

13) $Q = \iint_{\text{cross section}} v_{\text{axial}} (x, y)\, dx\, dy$

A four path chordal system approximates this double integration. To understand how, recall equation 6B.

6B) $v_{axial} = \Delta t\, c_{path}{}^2 / (2\, L_{path} \,\text{Sin}\, (\varphi))$

Refer now to the illustration of the four path chordal system in Figure 4. It will be seen that, for chord 1,

14) $L_{path1} = L_{chord1} / \cos (\varphi_1)$

Thus, the axial velocity averaged along chord I is given by

15A) $V_{axial1} = \Delta t\, c_{path1}{}^2 \cos \ (\varphi 1) / (2\, L_{chord1} \sin (\varphi_1))$

Or

15B) $v_{axial\ 1}\, L_{chord\ 1} = \Delta t\, c_{path1}{}^2 / 2 \tan (\varphi_i)$

The LV product of equation 15B is exactly the line integral of V_{axial} dx at the location of chord 1. The chordal instrument illustrated in figure 4 performs four such integrations at locations y_1, y_2, y_3, and y_4, effectively dividing the pipe cross-section into four segments. The effective width of each segment is a fraction, w, of the internal diameter, ID, measured parallel to the y axis.

Treating the four chordal measurements as four elements of a numerical integration, the volumetric flow can be calculated as follows:

16) $Q=ID\, [w_1\, L_{chord1}\, v_{axial\ 1} + w_3\, L_{chord3}\, v_{axial3} + w_4\, L_{chord4}\, v_{axial4}]$

Or, more generally,

17) $Q=ID\, \{\Sigma_{N\ I=1}\, [w_i\, \Delta\, t_i\, c_{pathi}{}^2 / 2 \tan (\varphi_i)]\}$

where, in the four path system, the subscript can take on values from I through 4.

For Caldon chordal systems, the path locations, y, and weighting factors w are not chosen arbitrarily but comply with numerical integration rules specified by the mathematician Gauss[3].

[3] *Handbook of Mathematical Functions,* page 887, National Bureau of Standards, Applied Mathematics Series

This integration technique will integrate polynomials up to the seventh order without error. Experience in calibrating chordal systems in a wide variety of hydraulic configurations at a certified facility has demonstrated that the four path Gaussian integration will handle a broad range of axial profiles, with errors usually less than 0.2%.

The preceding discussion illustrates the second significant distinction between chordal and external systems: the chordal system is an actual, if approximate, volumetric flowmeter whereas the external system is a diametral velocimeter, which places a greater burden on knowledge of the hydraulics at the location in which it is installed.

The chordal system also uses the times of flight for each acoustic path to determine the sound velocity, c_i, for that path:

18) $c_i = L_{ffi} / [\, t_i + (\Delta\, t_1)/2 - t_{\text{non fluid delay } i}]$

Incorporating this relationship in equation 17, and including a profile factor to account for small but not negligible biases in the numerical integration, the algorithm used by Caldon for chordal systems is obtained:

19) $Q = (PF)\, (ID/2)\, \{\Sigma\, [w_1\, \Delta\, t,\, L_{ff1}{}^2 / [(\tan (\varphi_i))(t_1 + [\Delta\, t_i]/2 - t_{\text{non fluid delay } i})^2]]\}$

Why is a profile factor necessary with a chordal system? With a 4 path chordal system, the profile factor accounts for several effects:

(1) The four path numerical integration performed by Caldon's LEFM must, in effect, integrate a circular cross sectional area (refer again to the spool piece sketch of Figure 4). With a perfectly flat flow profile having a velocity V, the instrument should produce an answer of $(\pi/4)\, ID^2\, V$. The four path Gaussian path spacing and weighting factors do not integrate a circular area perfectly, however. In order to produce the above result with a flat profile it is necessary to multiply the sum of the integration elements by 0.9940 (i.e., a correction of 0.6%). Thus one function of the profile factor is to account for the circular geometry.

(2) Most velocity profiles in feedwater systems are not flat but rounded. Downstream of bends or other hydraulic disturbances the profile may be significantly and asymmetrically distorted. An additional correction to the result of the numerical integration may be necessary to account for the specifics of the profile. As has been noted, however, 4 path Gaussian integration is a powerful numerical technique. Hence, the correction necessary to account for profile is usually remarkably small, often as little as 0.1 or 0.2%.

For many LEFM chordal feedwater installations, a profile factor of 0.9960 accounts for both the circular geometry and the hydraulic profile.

(3) Transverse velocity components can affect chordal systems as they do external systems, but usually to a far lesser degree. Neither system is affected by the swirl produced by non planar bends, as long as the swirl is centered in the pipe. In a chordal system, the effect of the transverse component projected onto an acoustic path by a swirl is exactly offset by an equal and opposite effect on the matching acoustic path on the opposite side of the spoolpiece (with an external system, the net trans- verse velocity components are normal to the diametral path and also produce no effect). Single bends, however, create a pair of kidney-shaped vortices that cause a significant transverse velocity along the diameter parallel to the plane of the bend. A distance of roughly 30 diameters is required for these vortices completely to decay. This transverse velocity can significantly affect the indication of an externally mounted meter, if the path is parallel to the plane of the upstream bend or nearly so. The effect on a 4 path chordal meter, however, is much less pronounced because the transverse velocity projections on the inner (longer) paths tend to be offset by projections in the opposite direction on the outer (shorter) paths. Neither instrument is affected by the bend-produced transverse velocity, if its acoustic paths are perpendicular to the bend plane.

In any case, to the degree that transverse velocity is present, the profile factor for the chordal meter (and its uncertainty) must account for it. The net effect is rarely more than 0.2%.

(4) In chordal LEFMS, there is a pocket formed on the internal spool piece diameter by the aperture through which the acoustic beam passes as it makes its way from the transducer well into the flow stream. In 4 path chordal systems in small feedwater pipes- where the transducer aperture is greater than about 5% of the pipe internal diameter-the fractional length of the acoustic path within the pocket be- comes significant, particularly for the short paths. The hydraulics and acoustics of the pockets in such installations can influence the velocity measured by the short paths. Accordingly, the profile factor for such installations, in addition to its other functions, must account for the influence of the pockets. The correction is usually no greater than 0.3%.

Although the aggregate correction made by the profile factor to the result of the 4 path numerical integration is rarely more than 0.6%, it is important that this correction be made with the greatest possible accuracy, if the overall accuracy of the flow measurement is to be better than 0.5%. It is therefore necessary to determine the profile factor appropriate for each specific installation. To accomplish this, Caldon employs a procedure very similar to that employed for externally mounted system.

There is one important exception: for chordal systems, the actual spool piece to be used in the plant is normally incorporated into the hydraulic model. This means the measured profile factor has imbedded in it any biases that may be present due to the dimensional tolerances in the spool piece as constructed. It also means that the hydraulic model is of necessity to the same scale as the plant. The spool piece profile factor determination procedure is also roughly comparable to that used for the calibration of flow nozzles, except that the modeling of upstream hydraulics for the chordal spool piece is carried out with a rigor that is rarely used for flow nozzles (which are generally calibrated in straight pipe regardless of upstream hydraulic geometry).

Figure 3
Integration of Axial Velocity over a Pipe Cross Section

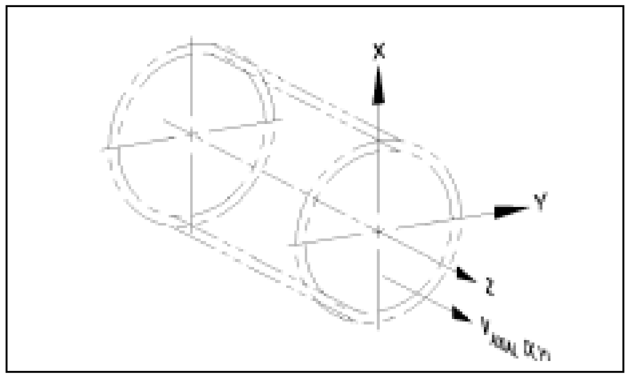
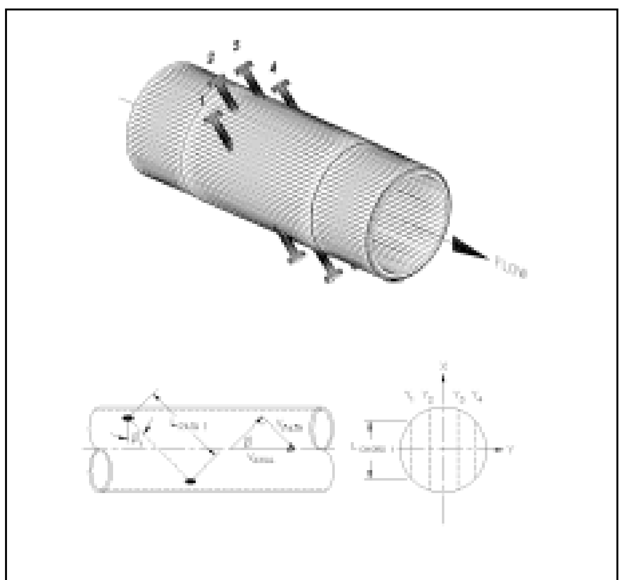


Figure 4

A 4 Path Chordal LEFM



Measurement of Properties: Temperature and Density

The preceding discussion has described the principles underlying the determination of volumetric flow using externally mounted and chordal LEFMS. What is needed for a nuclear power plant heat balance is the mass rate of feedwater flow, as well as the feedwater enthalpy. Caldon systems make use of the fact that the temperature of pure water can be determined from its sound velocity and pressure. The relationship is inherent and lends itself to a precise temperature determination. More specifically, the sound velocity c is related to other fluid properties by the following equation:

20) $C^2 = g\ \partial p / \partial \rho\ |_s$

Where p is pressure

g is the gravitational acceleration,
ρ is weight density, and
s is entropy

Numerical values of pressure, entropy, and density can be related to the temperature of compressed water, using the ASME steam tables[4]. From these relationships a correlation of temperature with sound velocity and pressure can be calculated. The correlation has been confirmed using the published technical literature[5] and by comparing LEFM measurements against calibrated secondary standards in the field.

LEFM software includes the temperature-sound velocity-pressure correlation. Pressure is usually a fixed input; it does not vary much at the typical LEFM location and the temperature determination is not sensitive to it (except near the critical point, a condition not encountered in nuclear feedwater systems). From the temperature thus determined, the LEFM also determines density, using a curve fit of the ASME tables for compressed liquid water. Mass flow is then computed as the product of volumetric flow and density. The LEFM software does not currently compute enthalpy, but the accuracy of the temperature determination is such that an enthalpy determination from the LEFM temperature output will support overall plant heat balance accuracy requirements.

The dimensions of the pipe section for an external system and the spool piece of a chordal system are, of course, affected by the operating temperature of the feedwater system.

Pressure also has a small effect on dimensions. The algorithms for both external and chordal LEFMs include corrections to as-measured dimensions for these effects. The pipe temperature is inferred from fluid temperature, which is, in turn, determined from sound velocity and pressure, as described above.

Summary of LEFM Principles

From the preceding analysis, it will be seen that the velocity measurements of LEFM time-of-flight ultrasonic systems rest on first principles. The accuracy with which one can measure velocity does not rest on an empirical relationship between the times of flight measured, but only on the accuracy with which one can measure the time, dimensions, and, in the case of external systems, the acoustics of the installation.

Translating the velocity measured by an external system into a volumetric flow requires the use of experimental results from hydraulic testing; at the present time no body of theory can provide a sufficiently accurate relationship between the diametral average fluid velocity and the bulk average fluid velocity for the full spectrum of possible fluid system configurations.

Because the velocity measurements of LEFM chordal systems lie along four mathematically specified, parallel chords, and because these four measurements are combined in accordance with the rules of a predictable numerical integration method, it may be asserted that the volumetric flow determination of a chordal system rests on first principles. The accuracy of a chordal system can be bounded within useful limits without hydraulic testing; hydraulic testing can, however, be used to enhance the accuracy of chordal systems, in much the same way it is used with flow nozzles.

The LEFM's use of sound velocity to measure feedwater temperature and density also rests on first principles, and on the use of an accepted reference for fluid properties.

4 *ASME Steam Tables, 1967, Thermodynamics and Transport Properties of Steam comprising of Tables and Charts for Steam and Water,* American Society of Mechanical Engineering, N.Y.C., NY

5 Russian sound velocity reference TBD