THEORY OF ULTRASONIC FLOW MEASUREMENT—GASES AND LIQUIDS

Class 3190

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Introduction

Ultrasonic flow measurement systems (UFMs) are being applied with increasing frequency to hydrocarbon flow measurements. Most of these UFM s are transit time (also called time-of-flight) systems—they measure the transit time of ultrasonic energy pulses traveling with and against the direction of flow. This paper will outline the principles of three kinds of transit time UFMs:

- Externally mounted ("strap on") transit time meters measuring liquid flow. In meters of this kind, the ultrasonic pulses travel through the liquid on a path at an angle determined by the physical properties of the liquid, the pipe on which transducer assemblies are mounted, and the mounting hardware.
- "Chordal" transit time meters measuring liquid flow. In meters of this kind, the transducers are installed in wells, similar to the thermowells that are sometimes used to house RTDs or thermocouples. The angles of the acoustic paths in these meters are determined by the mechanical design of the transducer wells and the spool piece in which the wells are mounted. The term "chordal" is used here because, in Caldon's designs of meters of this type, the acoustic paths are arranged in parallel chords across the spool. Other manufacturers arrange paths differently, but unless otherwise noted, the discussion will generally apply to their meters as well.
- Chordal meters measuring gas flow. Mechanically, these meters resemble chordal meters that measure liquid flow. But different factors affect the performance of UFMs for gas, and they merit separate discussion.

It will be noted that there will be no coverage of externally mounted UFMs measuring gas flow. The technological challenges confronting the design of such meters are formidable (as will be evident from the discussion that follows). A few manufacturers provide external meters for a limited range of gas applications, but they have not found wide use.

Discussion

Transit Time Measurement Fundamentals

A transit time ultrasonic flow measurement system transmits 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. In the configuration shown, a pair of transducers are mounted to form a diametral diagonal path through flowing liquid, but the fundamental principles described in the following paragraphs apply to gas and liquid, internal or external.

If the upstream (A) transducer is excited by a burst of electrical energy, it will transmit a packet or pulse of mechanical (acoustic) energy into the adjacent medium. In Caldon's LEFMs, 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 0.5 to 3 megahertz range for liquid flows, and in the 50 to 500kilohertz range for gas flows. The transducer is usually designed to be directional, so, in the configuration illustrated in the figure, a significant fraction of the acoustic energy 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 (by the number of clock pulses accumulated).

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

1) $t_{AB} = [L_{path} / (c_{path} + v_{path})] + \tau_{non\ fluid\ delay}$

2) $t_{BA}, = [L_{path} / (c_{path} - v_{path})] + \tau_{non\ fluid\ delay},$

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

$\tau_{non\ fluid\ delay}$ 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 LEFMs, the same transmitter produces each pulse and the same electronic detector detects each pulse. Consequently, the difference in the transit times, Δt, 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) $\Delta t = 2 L_{path} v_{path} / (c_{path}{}^{2} - v_{path}{}^{2})$

In most liquids the sound velocity is two orders of magnitude larger than the fluid velocity, c ranging from 2500 ft/sec to 5500 ft/sec versus v of 2 to 30 ft/sec. Hence equation 3B can be approximated

3C) $\Delta t \cong 2\, L_{path}\, v_{path} / c_{path}^{\,2}$
Or
3D) $v_{path} \cong \Delta t\, c_{path}^{\,2} / (2\, L_{path})$

Some early UFMs had the user input sound velocity from a look-up table in equation (3D) to find path velocity. This procedure is not consistent with good accuracy. In most liquids, sound velocity varies strongly with temperature and weakly with pressure. Hence varying liquid product temperature renders the meter calibration invalid.

If sound velocity is determined from transit time by one of the methods described in a later paragraph, equation (3D) is an acceptable approximation to determine path velocity in liquids. Even with a relatively compressible hydrocarbon like liquefied natural gas (with, therefore, a relatively low sound velocity) the error due to v^2 is unlikely to exceed 0.01%. However, the approximation of equations (3C) and (3D) is usually unacceptable for gas flow. Here neglecting the v^2 term can introduce velocity-dependent errors of 1% or more.

For precision, therefore, a gas UFM must use its transit time measurements to determine $(c^2 - v^2)$ as well as Δt. The transit times in the fluid, t_{fAB} and t_{fBA} are found by subtracting the non fluid delay from the measured transit times. For a given application, the non fluid delay $\tau_{non\ fluid\ delay}$ may be calculated or measured (or both).

4A) $t_{fAB} = t_{AB} - \tau_{non\ fluid\ delay}$
4B) $t_{fBA} = t_{BA} - \tau_{non\ fluid\ delay}$

The product of these fluid transit times yields the following:

5) $t_{fAB}\, t_{fBA} = [L_{path} / (c_{path} + v_{path})] \times [L_{path} / (c_{path} - v_{path})]$

$$= L_{path}^{\,2} / (c_{path}^{\,2} - v_{path}^{\,2})$$

Combining equations 3B and 5, the following expression is obtained for the product of the acoustic path length and the fluid velocity projected onto the path.

6) $L_{path}\, v_{path} = (½) L_{path}^{\,2}\, \Delta t / (t_{fAB}\, t_{fBA})$

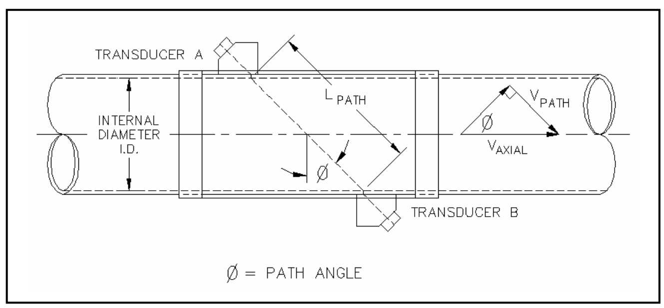
This relationship is fundamental to the operation of all transit time flowmeters. Essentially it says that the product of the path length and the mean velocity along that path can be determined by transit time measurements with an absolute accuracy limited only by

- The accuracy of the transit time measurements
- The accuracy of the measurement (or calculation) of the non fluid time delay
- The accuracy of the path length measurement

This is of course only a statement about the accuracy of a path velocity measurement—not volumetric flow. The accuracy with which one or more of these path velocity measurements gets translated into volumetric flow is affected by other factors, both acoustic and hydraulic. These factors will be covered in later discussion.

Note that the sound velocity can also be determined from the measurements of the transit times by substituting the fluid transit times in equation 5. [The v^2 term can be calculated using equation 6 or, if it is small compared to c^2, neglected.] The sound velocity of a product is a state variable like temperature and pressure and in a pipeline carrying a single product can be used with pressure to determine temperature. Alternatively, in multiproduct pipelines, sound velocity can be used alone, or with a temperature measurement, to detect product interfaces.

Figure I
Geometry of a Transit Time Acoustic Path



How accurately can the fluid velocity projected along the acoustic path be measured using equation (6)? Essentially, with an accuracy determined entirely by the accuracy of the measurements of the transit times and the separation distance, and the accuracy of the measurement or calculation of the non fluid delays.

Some Numbers

How big are the times and time differences that UFMs measure? Suppose a 2-path chordal UFM with a path angle ϕ of 45° is measuring crude oil flow in a 12 inch pipeline. Petroleum product sound velocities usually lie in the range of 2700 ft/sec to 5000 ft/sec. If a sound velocity of 4500 ft/sec is assumed (typical of a medium crude), the transit times will be about 280 µsec. The time difference, Δt, at rated flow will equal 430 nanoseconds (1 nanosecond = 10^{-9} seconds), for a pipeline velocity of 5 ft/sec. If a 10:1 turndown is specified for this meter, the Δt at the low end of the flow range will be 43 nanoseconds.

The transit time of an external UFM, like that in Figure 2, may be slightly smaller than the chordal example because physical properties of the pipe and fluid dictate a shallower path angle. With typical petroleum product properties and steel pipe, the angle will be about 20°. [How the path angle of an externally mounted UFM is determined will be described later.] The transit times for an external meter mounted on the same 12 inch pipe will lie in the 250 µsec range. The Δt at rated flow of 180 nanoseconds. [To increase the magnitude of the Δt many externally mounted UFMs are configured in a "bounce" or V mode, wherein the two transducers are mounted on the same side of the pipe and the acoustic path length is doubled. This arrangement doubles both the t and Δt.]

Clearly, one of the challenges of a UFM measuring liquid flow is the accurate measurement of very small times and particularly time differences (Δt). For a 10:1 turndown and a linearity of 0.2%, the chordal UFM described above must measure time differences with an accuracy of ± 90 picoseconds (1 picosecond = 1×10^{-12} seconds). The externally mounted UFM must do even better—it must measure time differences with an accuracy of ± 35 picoseconds if it is configured in the direct mode (as in Figure 2 below) and ± 70 picoseconds if it is configured in the bounce mode.

Some UFMs achieve these accuracies and better. To do so, their designers must pay particular attention to what is called the reciprocity of the signal processing that they use—the non fluid delays must be *exactly* the same in the upstream and downstream direction. Signal quality is also essential—here, elimination of noise is the key.

There are different challenges for the designers of UFMs that measure gas flow. Here the transit times and Δt's are several orders larger than for meters measuring liquid flow. For example, the transit times for a two path chordal meter measuring the flow of natural gas in a 24 inch pipeline would be around 1.75 milliseconds. At rated flow, the time difference (Δt) would lie in the 100 to 200 µsecond range, depending on pipeline velocity. A major challenge in gas flow measurement lies in reliably detecting a relatively small ultrasonic pulse, possibly in the presence of noise. Dealing with wide variations in transit times due to turbulence and other factors is also more difficult in gas versus liquid meters.

The small size of received pulses in ultrasonic gas flow measurements is the inherent result of what is called the acoustic impedance mismatch between the transducers and the flowing medium. Because the pulse-producing transducer is relatively dense and stiff and the flowing medium is relatively light and compressible, most of the acoustic energy reaching an interface between the two stays where it started. That is, a large fraction of the energy is reflected rather than transmitted. There are at least two such interfaces in every acoustic path. Pulses traveling liquid paths also are attenuated at interfaces, but the degree of attenuation is several orders less challenging in the liquid case.

Translating Path Velocities into Axial Velocities and Volumetric Flow

All of the preceding describes a methodology for measuring 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 pipe cross section.

The first of these conditions requires a knowledge of the angle ϕ between the acoustic path and the pipe axis, illustrated in Figure 1. It also requires a knowledge of the fluid velocity component *normal* to the pipe axis, if there is any (i.e., the transverse fluid 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; its impact will be discussed later. From the trigonometry:

5) $$v_{path} = v_{axial} \sin \phi$$

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.

Equation 4 can be rewritten in terms of the axial fluid velocity in the way of the acoustic path:

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

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

The specifics of how the path angle is determined and how one or more axial velocity measurements along the path(s) are translated into volumetric flow depends on whether the meter is external or chordal, and if chordal, the arrangement of the chords. The external meter will be covered first.

Principles of Externally Mounted Transit time Systems

In an externally mounted UFM, Snell's Law of Refraction constrains the geometry of the path traveled by acoustic pulses through the flowing fluid. Essentially these pulses must travel in a diametral plane. Such a configuration is shown in Figure 2. Here the path length is related to the internal diameter of the pipe, ID, by

7) $L_{path} = ID/ \cos \phi$.

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

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

This is the governing equation for externally mounted transit time ultrasonic flowmeters, in the absence of transverse flow. As has been noted, 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.

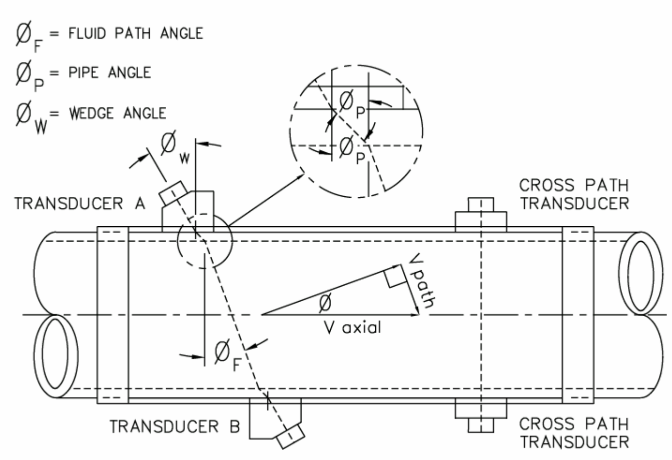
It should be pointed out that for externally mounted transit times ultrasonic systems, the path angle ϕ is not simply determined by transducer placement. Figure 2 provides a picture of external system acoustics. Piezoceramic transducer elements are mounted on wedges which, in turn, are mounted on the exterior of the pipe. The wedge optimizes the acoustic interfaces between the transducer-wedge assembly and the pipe wall and between the pipewall and the fluid. The three angles of the ray path in Figure 2, ϕ_F, ϕ_P and ϕ_W are the path angles followed by the pulses in the fluid, pipe, and wedge respectively. The angle ϕ_F is equivalent to ϕ, the angle through the fluid, that has been used in the discussion of Figure 1. The wedge, the pipe, and the fluid angles are all governed by Snell's law of refraction. They are also affected by the size, placement, and configuration of the wedges. Snell's law stipulates that

9) $\sin \phi_F / c_F = \sin \phi_P / c_P = \sin \phi_w / c_w$

Where c_F, c_P and c_w are the respective sound velocities of fluid, pipe, and wedge.

If the three sound velocities are measured or otherwise determined, it remains only to establish one of the three angles. The angle ϕ_W would seem to be the obvious choice-to determine the others, and thus the acoustic path through the fluid, since the wedge can be manufactured with a precise geometry.

Figure 2
Acoustics of an Externally Mounted Transit time UFM



But determining the exact angle of the path in the fluid from the wedge angle is not always straightforward. If the transducers are acoustically distant from one another, ϕ_w can be determined by assuming the path connects the centers of the piezoceramic elements (refer again to Figure 2). Note that in this case, the ray path is not necessarily perpendicular to the transducer face; hence the wedge angle is not necessarily equal to the mechanical angle of the sloping face.

On the other hand, if the transducers are acoustically close to one another, ϕ_w *is* 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. Often, the acoustics are such that neither assumption is exactly valid, and both wedge configuration and transducer placement affect the path angle through the fluid.

Returning to equation 8, it can be seen that the accuracy of the velocity measurement of an externally mounted transit time system is a function not only of the accuracy of the time, distance and non fluid delay measurements, but also of the accuracy with which their acoustics can be characterized. The answer one obtains from equation 8 is very sensitive to the tangent of the angle ϕ_f.

An accurate fluid sound velocity measurement is crucial to establishing the path angle ϕ. To enhance the accuracy with which fluid sound velocity is determined in its external meters, Caldon employs a second pair of transducers, mounted so as to form an acoustic path normal to the pipe axis (the “cross path” in Figure 2). This arrangement is inherently less susceptible to variations in the physical properties and dimensions of the pipe than is the diagonal path. Data from this path can also be used to compensate for transverse flow, as noted below.

The variable of interest is volumetric flow—not velocity. Volumetric flow Q is given by

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

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

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

For the determination of volumetric flow from an acoustic system with transducers on a diametral diagonal as they are in an externally mounted UFM, 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 at Reynolds numbers in the 10^6 range, the velocity measured along a diametral diagonal will typically be greater than the true mean velocity by 5 or 6%. The exact number depends not only on kinematic viscosity, diameter and velocity (that is, the Reynolds Number) but also on relative roughness of the pipe wall. At a Reynolds number of 10^4, the measured velocity may be 10% or 12% greater than the true mean. In the laminar flow regime it is 33% greater. On the other hand, a short distance downstream of a header the measured velocity and mean velocity may be within 1 or 2% of each other. Summing up, in a specific application, meter calibration may vary with:

- product (because viscosity and hence Reynolds Number varies),
- velocity (which is also an element of Reynolds Number),
- pipe condition (because velocity profiles vary with relative roughness as well as with Reynolds Number), and
- with hydraulic configuration (because this too affects velocity profile).

The differences between diametral axial velocity and mean axial velocity arise because of the differences in the shapes of the velocity profiles. The diametral diagonal paths of externally mounted ultrasonic meters undersample the region near the pipewall relative to its area, and oversample the region near the middle of the pipe relative to its area.

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

Hence,

11B) $Q = [\pi\ ID^2/4]\ (PF)\ \Delta t\ c_F^2 / (2\ ID \tan \phi_F)$

Equation 11B is used by Caldon for externally mounted systems operated in the direct mode, as in Figure 2. These meters can produce excellent linearity and repeatability, providing the range of Reynolds number coverage is not too broad.

As has been noted, the inference of axial velocity from diagonal path Δt (implicit in equation (11B)) is only valid in the absence of significant transverse velocity.

Unfortunately, transverse velocity is sometimes 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 a path normal to the pipe axis (which path is also 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. That is, 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 approximately equal and opposite projection on the other leg. For this mode, the divisor of equation 11B 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. Caldon draws on an extensive library of hydraulic model testing for external systems for this purpose. For readers interested in more detail on Caldon's experience in profile factor measurements for external systems, Mazzola and Augenstein[1] is suggested.

Principles of Chordal (internal) Transit time Systems

The discussion in the preceding section has focused on externally mounted LEFMs, where the acoustic paths are diametral and the acoustics themselves are determined by the properties and placement of transducer wedges and the dimensions and properties of pipe and fluid. It is now appropriate to consider the operative equations for a chordal or internal system. In these systems, transducers are inserted in wells that are, as noted before, somewhat similar to thermowells. The ultrasound generated by a transducer passes through the “face” or “window” 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. As a consequence, the path angle for a chordal system (or the angles for systems with multiple chords) can be established with an accuracy determined by dimensional control of the spool piece as opposed to the acoustics of wedges, pipe and fluid. Path angle is crucial to determining the axial velocity subtended by the acoustic path (as was shown in equation 6B). Since dimensions are typically controllable with much greater precision than acoustics, chordal systems possess an inherent accuracy advantage on this score.

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 6:

6) $L_{path} v_{path} = (½) L_{path}^2 \Delta t / (t_{fAB}\, t_{fBA})$

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

Also recall, from equation (5)

5) $v_{path} = v_{axial} \sin \phi$

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

14) $L_{path1} = L_{chord1} / \cos \phi_1$

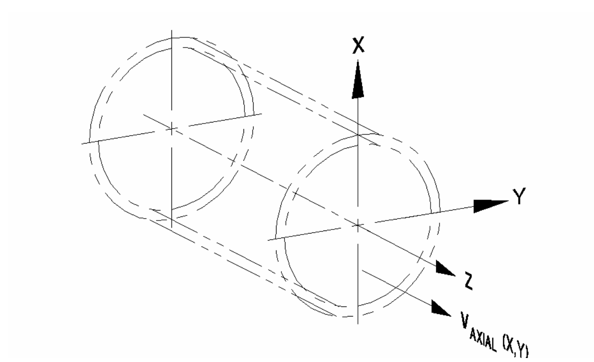
Substituting for v_{path} and L_{path} in equation (6), the following expression is obtained for chord 1:

15A) $(v_{axial\,1} L_{chord\,1})(\sin \phi / \cos \phi) = (½) L_{path}^2 \Delta t / (t_{fAB}\, t_{fBA})$

15B) $v_{axial\,1} L_{chord\,1} = (½)(L_{path1}^2 / \tan \phi_1)(\Delta t / (t_{fAB}\, t_{fBA}))$

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 along the y axis.

Figure 3
Integration of Axial Velocity over a Pipe Cross Section



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

16) $Q = ID\,[w_1 L_{chord1} v_{axial\,1} + w_2 L_{chord2} v_{axial\,2} + w_3 L_{chord3} v_{axial3} + w_4 L_{chord4} v_{axial4}]$

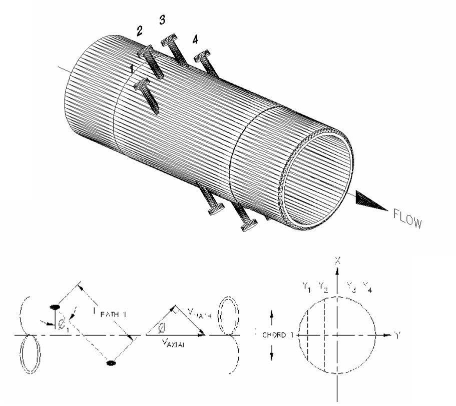
Or, substituting the lengths and times measured by the UFM in a more general expression:

17) $Q = (ID/2)\,\{\sum_{I=1}^{N} (w_i L_{pathi}^2 / \tan \phi_i)(\Delta t_i / (t_{fABi}\, t_{fBAi})\}$

where, in the four path system, the subscript can take on values from I through 4. Note that the times t_{fABi} and t_{fBAi} in the above are transit times in the fluid;

non fluid delays must be determined and subtracted from the measured transit times to obtain the times used in this expression.

Figure 4
A 4 Path Chordal LEFM



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[2].

This integration technique will integrate polynomials up to the seventh order without error. Caldon has collected extensive calibration data for four path systems operating in a wide variety of hydraulic configurations. These data were obtained at a certified facility, for the most part at high Reynolds Numbers. The data show that a meter factor in the 0.994 to 1.004 range is necessary, primarily to account for the difference between the circular geometry and the rectilinear geometry for which the Gauss procedure was developed. The data also demonstrate that the meter factor for four path Gaussian integration will handle a broad range of hydraulic geometries, with departures from nominal 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.

Incorporating a profile factor PF, in equation 17, the algorithm used by Caldon for chordal systems is obtained:

18) $Q = (PF)(ID/2) \{\sum_{I=1}^{N} (wi\, L_{pathi}^{2} / \tan \phi_i)(\Delta t_i / (t_{fABi}\, t_{fBAi})\}$

Where $\Delta t_I = t_{BAi} - t_{ABi}$
$t_{fABi} = t_{ABi} - \tau_{non\ fluid\ delay}$ and
$t_{fBAi} = t_{BAi} - \tau_{non\ fluid\ delay}$.

Transverse velocity components can affect chordal systems as they do external systems, but usually to a lesser degree. The vortices produced by a single bend 5 diameters upstream of a chordal UFM may affect the calibration by 0.1 or 0.2% (versus several percent for an external system without transverse velocity compensation). The swirl produced by nonplanar bends can significantly alter the calibration of both chordal and external systems unless the distance between the UFM and the second bend is enough to center the swirl. Generally speaking, UFMs are more forgiving of upstream and downstream hydraulics than turbine meters. By following a few rules, the use of flow conditioners can be avoided.

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. If the transducer aperture is large with respect to the pipe internal diameter, the hydraulics and acoustics of the pockets can influence the velocities measured. The profile factor for such installations, in addition to its other functions, must account for the influence of the pockets.

Summary of LEFM Principles

The velocity measurements of Caldon's transit time ultrasonic systems rest on first principles. The accuracy with which one can measure velocity does not rest on an empirical relationship, but on the accuracy with which one can measure the transit time, the dimensions, and, in the case of external systems, the acoustics of the installation.

Translating the velocity measured by an external UFM into a volumetric flow is essentially an empirical process. The calibration of external meters is sensitive to pipe condition and Reynolds Number, limiting their flow range in some applications.

The velocity measurements of Caldon's chordal UFMs lie along four mathematically specified, parallel chords. Because these four measurements are combined in accordance with the rules of a predictable numerical integration method the volumetric flow determination of a Caldon chordal system rests on first principles.

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