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INSTALLATION EFFECTS ON SINGLE- AND MULTI-PATH ULTRASONIC METERS

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Abstract: This paper takes an analytical approach to examine the effects of swirl, asymmetry, pipe roughness, and Reynolds Number on the performance of a meter that utilizes a single bounce path through the center line (e.g., Daniel JuniorSonic) and a meter that employs four chordal paths (e.g., Daniel SeniorSonic).

A simple "power law" velocity profile is used to study the effects of pipe roughness and Reynolds Number. Mathematically generated axial velocity profiles, similar to those from bends and Tees, are used to study the effects of asymmetry. A solid body rotation is used to study the effects of swirl on the performance of both meters.

The single path meter requires typical corrections from 4 to 8% for changes in velocity profile due to variations in pipe roughness and Reynolds Number. The single path meter output varies about 6%, depending on the path orientation relative to the asymmetry and creates a bias error of about +/-3%.

The 4-path meter does an excellent job of integrating the velocity profile to give the correct flow rate over a wide range of both Reynolds Number and roughness values. The 4-path meter integrates the asymmetric profiles to give an answer within 0.1 to 0.3% of the flow, irrespective of orientation. Furthermore, it has sufficient diagnostics to recognize changes in operating conditions.

Simple bulk swirl, centered on the pipe axis, has no effect on the performance of either meter. This paper examines the effects of deviations from this simple ideal swirl.

EFFECTS OF REYNOLDS NUMBER AND WALL ROUGHNESS ON SINGLE PATH CENTER LINE ULTRASONIC METERS

Power Law Velocity Profile

The velocity profile in pipe flow is quite complex. A simple power law is a good approximation of velocity near the pipe wall, although not exact at the pipe center, because the velocity gradient (dv/dy_R) is not zero, resulting in a discontinuity. This discontinuity is not too serious because there is no flow through the center of the pipe; although the velocity is at a maximum, the area is zero. The Power Law is given by:

$$\frac{v}{V_{max}} = \left[\frac{y}{R}\right]^{\frac{1}{n}} \qquad (1)$$

where: V_{max} = the velocity at the meter axis
y = the distance from the meter wall
n = the 'power'
v = the velocity at y
R = the meter radius

By integrating over the pipe area, one obtains the average flow velocity V_{avg}:

$$V_{avg} = V_{max} \frac{2n^2}{(n+1)(2n+1)} \tag{2}$$

By integrating along the pipe diameter, one obtains the average chord velocity V_{chd}:

$$V_{chd} = V_{max} \frac{n}{n+1} \tag{3}$$

Then the correction factor (CF) shown in Figure 1 is given by

$$CF = \frac{V_{avg}}{V_{chd}} = \frac{2n}{2n+1} \tag{4}$$

Correction Factor from Power Law n

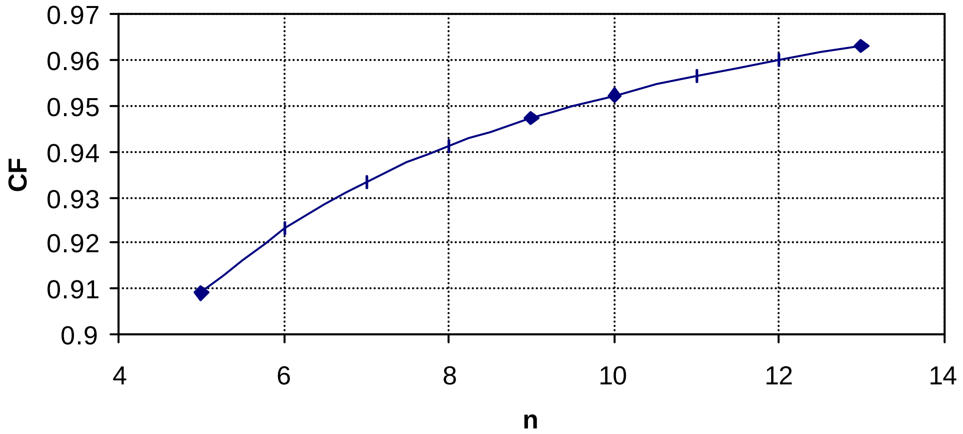

Figure 1

Relationship between: n - Re - k/D - f
To be able to use this correction factor one needs to express *n* in terms of the Reynolds Number (*Re*) and wall roughness (*k*). Fortunately, Prandtl and Nikuradse [Ref.1] sorted this out in the 1930's when considering friction loss in pipe flow. The friction factor (*f*) depends upon *Re* and the relative wall roughness (*k/D*), but it can also be related to the velocity profile through the shear stress at the pipe wall. The Moody friction factor chart can be used to show *n* from $f=1/n^2$ (see Figure 2).

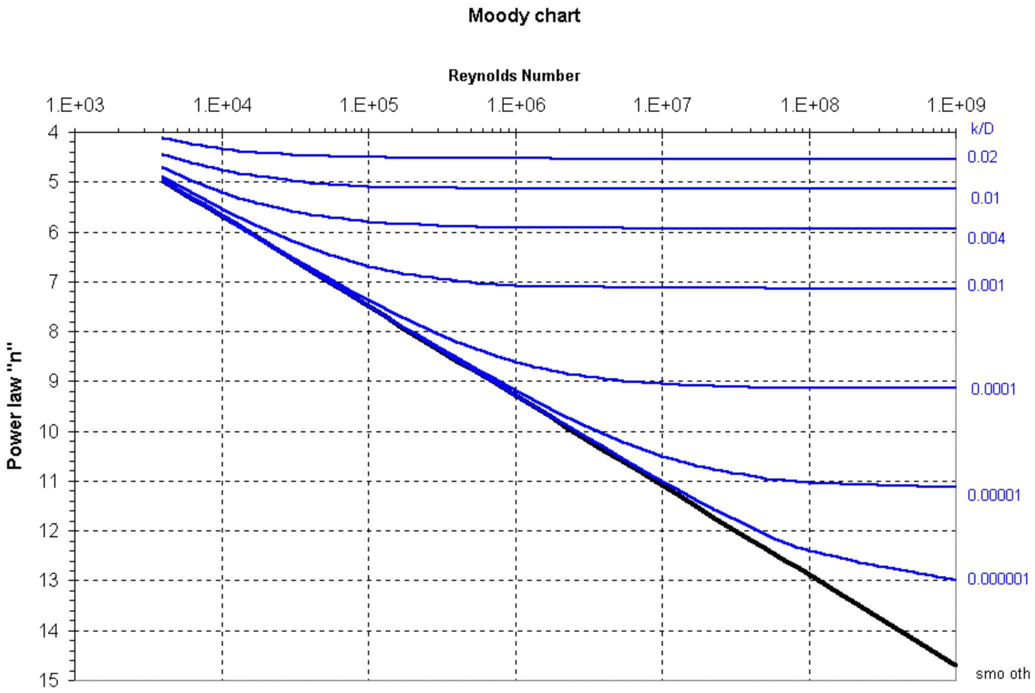

Figure 2

This work shows that a meter using a single path through the center of the pipe will overestimate the flow by 4 to 9% if no correction factor is applied. This overestimate results from high velocity in the center of the pipe, which affects the line integral disproportionate to the small area represented.

Reynolds Number

It is quite straightforward to calculate the Reynolds Number from *Re* = *vdr/m*
Measuring the pressure and temperature allows reasonable estimates of the density (*r*) and viscosity (*m*). Then the CF can be calculated from this live value of *Re*.

Wall Roughness

If *k/D* is known, it is easy to calculate a correction factor. Although *k/D* might be known for a new pipe, there is no measure of how it changes with time. Hence, it is not possible to make a live correction for *k/D*. Thus, it is quite easy to produce 0.5 to 1% error with time as the pipe roughness changes, without any means of correction, because *k* is not measured.

EFFECTS OF REYNOLDS NUMBER AND PIPE ROUGHNESS ON THE 4-PATH ULTRASONIC METER

The arrangement of four chordal paths proposed by British Gas is shown in Figure 3

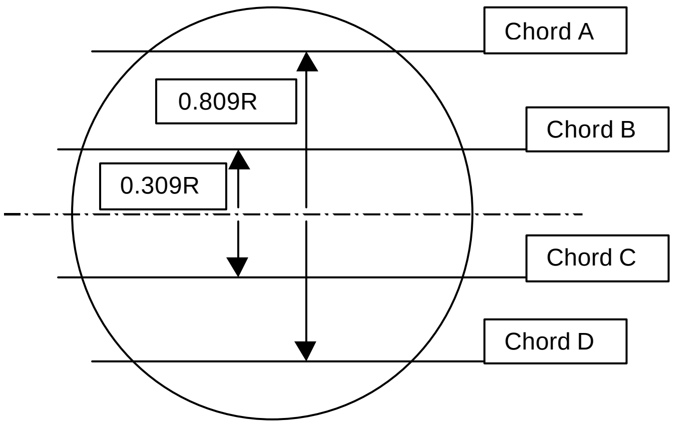

Figure 3

A Gauss-Jacobi numerical integration gives the average flow velocity (V_{avg}) over the area of the pipe from the weighted sum of the line averages along the chords V_i

$$V_{avg} = \sum W_i V_i = 0.1382\,V_A + 0.3618\,V_B + 0.3618\,V_C + 0.1382\,V_D \qquad (5)$$

where the weighting factors, W_i, are determined for the specific chord locations.
Note that

$$\sum W_i = 0.1382 + 0.3618 + 0.3618 + 0.1382 = 1 \qquad (6)$$

The significance is that a uniform velocity, $V_A = V_B = V_C = V_D = V_{avg}$, would give the correct answer. Another interpretation of W is the proportion of pipe area associated with the chord velocity to obtain the flow, which must add up to 1, (i.e., the complete pipe area).

The average chord velocity (V_i) is calculated as shown in Figure 4.

$$V_i = \int_0^{\sqrt{R^2 - z^2}} v\,ds$$

with

$$\frac{v}{V_{max}} = \left[\frac{y}{R}\right]^{\frac{1}{n}}$$

$$y = R - r \text{ and } s^2 = r^2 - z^2$$

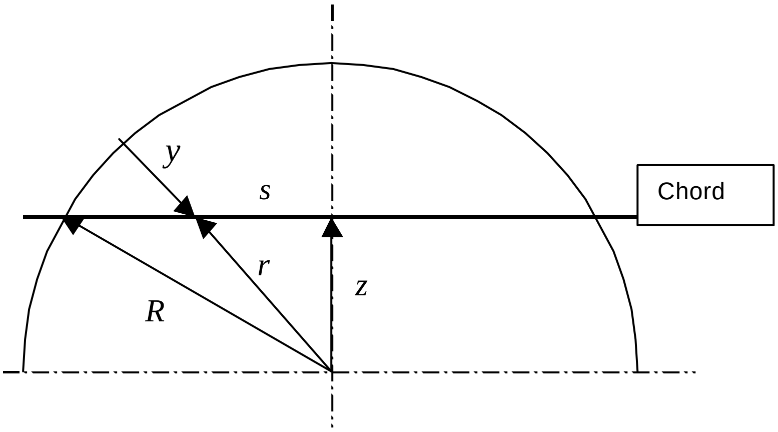

Figure 4

These equations are integrated numerically by dividing *s* into 10 or more parts (note that care is required with the segment next to the wall, because of the very steep velocity gradient linear interpolation is insufficient). The result shown in Figure 5.

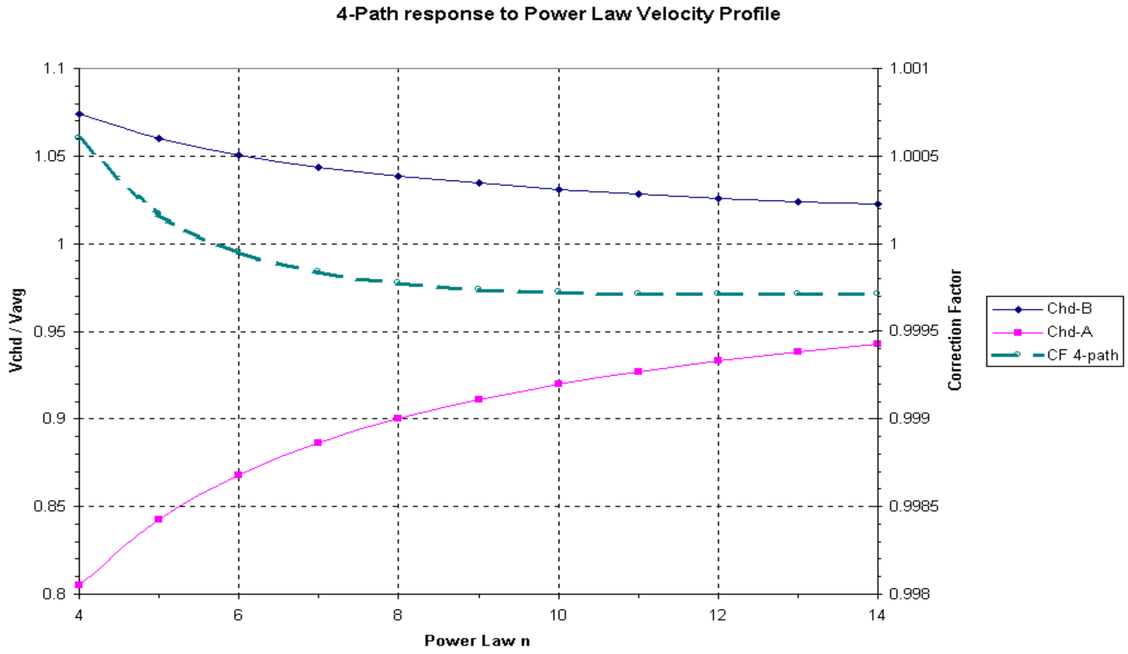

Figure 5

The 4-path meter does an excellent job of integrating a power law profile, with a maximum error of 0.06% at n = 4, and from n = 5 to 14 the error is reduced to 0.03%. Thus, the meter should be immune to normal changes in Re and k. The chords still see the changing profile, offering considerable diagnostic information [Ref 3]. The meter that depends on a single path through the center shows a 7% variation over the n = 4 to 14 range.

THE EFFECT OF FLOW PROFILE ASYMMETRY ON SINGLE AND MULTI-PATH ULTRASONIC METERS

For this study two mathematically generated profiles were used [Ref. 2] with equations:

$$V(r,q)=\frac{2}{p^5} * r(1-r)^{1/4} * q^2 (2p-q)^2 + (1-r)^{1/9} \tag{7}$$

$$V(r,q)=0.6846 * r(1-r)^{1/9} * e^{-0.2q} \sin q + (1-r)^{1/7} \tag{8}$$

Where V(r, q) is measured in cylindrical coordinates, with r = the radial position from 0 (at center) to 1 (at the meter wall) and q = the angle in radians from 0 to 2π (0 to 360 degrees) a full circle.

These profiles are plotted as velocity contours in Figures 6 & 7 with the V_{avg} =1. Profile A05 (Equation 8) is a very asymmetrical flow produced by the jet from a half closed gate valve and Profile A07 (Equation 7) is similar to that produced by a single bend.

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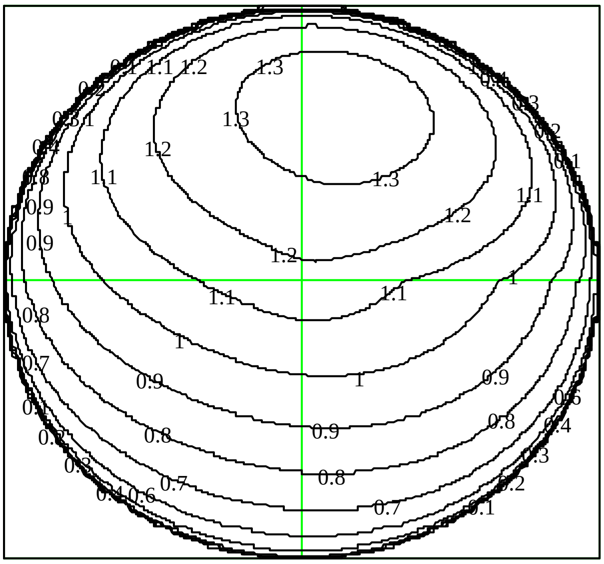


Figure 6. Profile A05 Equation 8

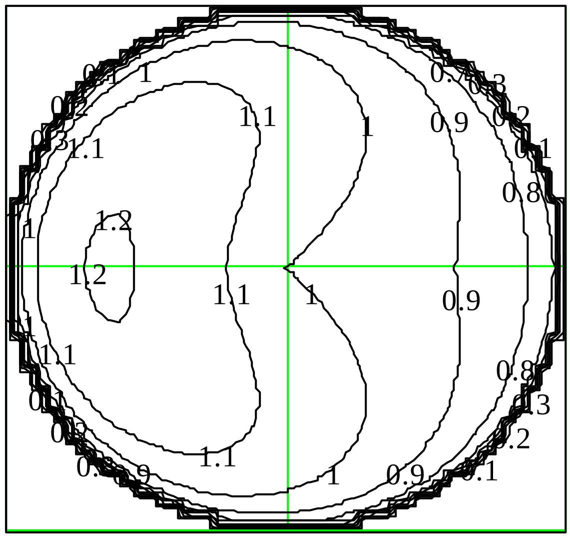


Figure 7. Profile A07 Equation 7

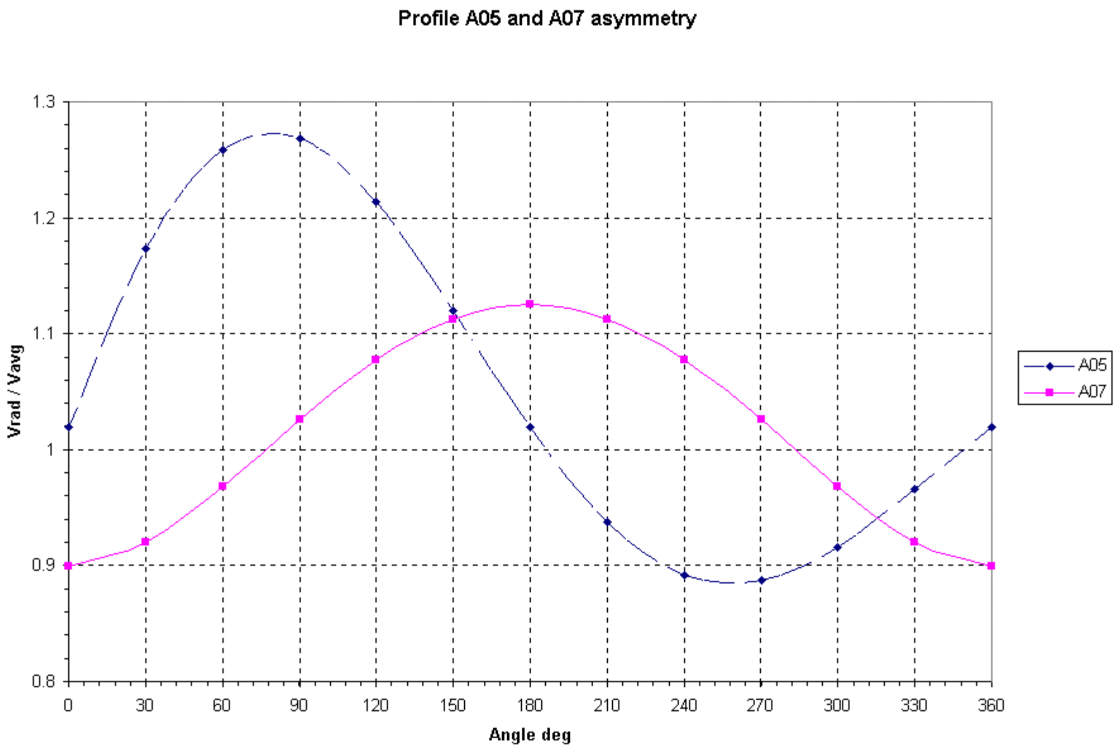


Figure 8

The asymmetry is shown in Figure 8 by the variation in the velocity on a radius with angle.

The results for a single path through the centerline are shown in Figure 9.

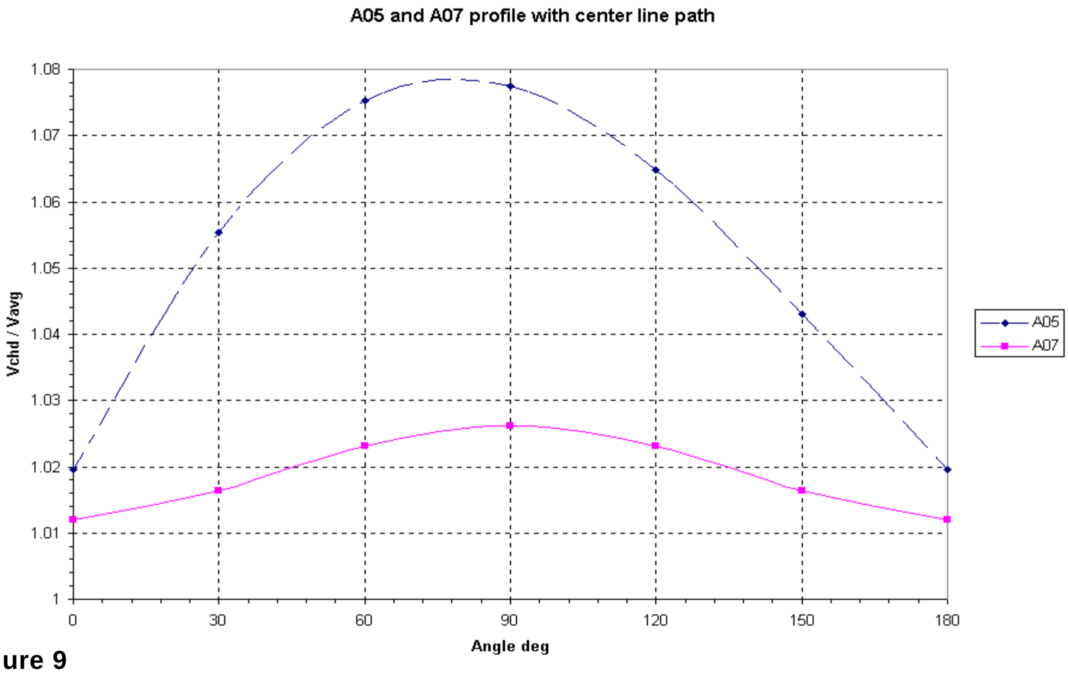


Figure 9

The errors are quite large, from +1 to +8%, depending upon the orientation of the path. Even after applying CF = 0.95, the errors would still be +/– 3%.

Figure 10 shows the profile results from a 4-path meter.

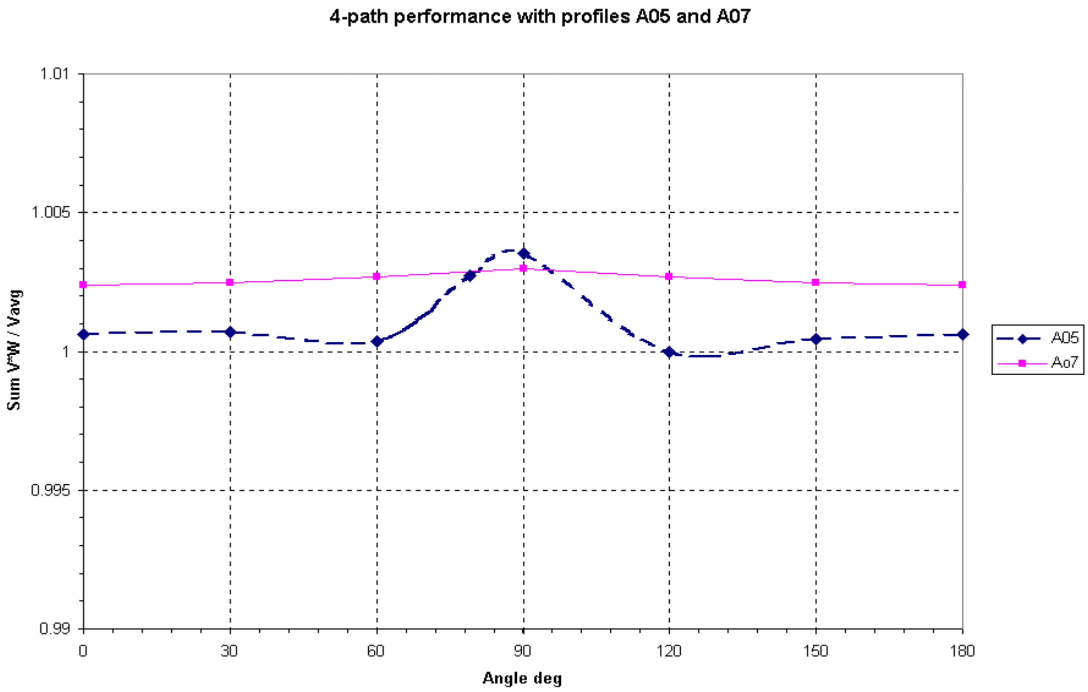


Figure 10

Errors range from +0.1 to +0.3%, which is an order of magnitude better than the single path through the centerline.

THE EFFECT OF SWIRLING FLOW ON SINGLE AND MULTI-PATH ULTRASONIC METERS

Case 1. If we consider bulk swirl, solid body rotation with angular velocity (ω) about the pipe axis, then the swirl velocity (*w*) has magnitude (ω*r*) and direction normal to *r*. Thus, with a centerline path the swirl velocity is normal to the path and has no component along the path. Hence, the centerline path is immune to such swirl.

With the 4-path meter the situation looks more complex as shown in Figure 11

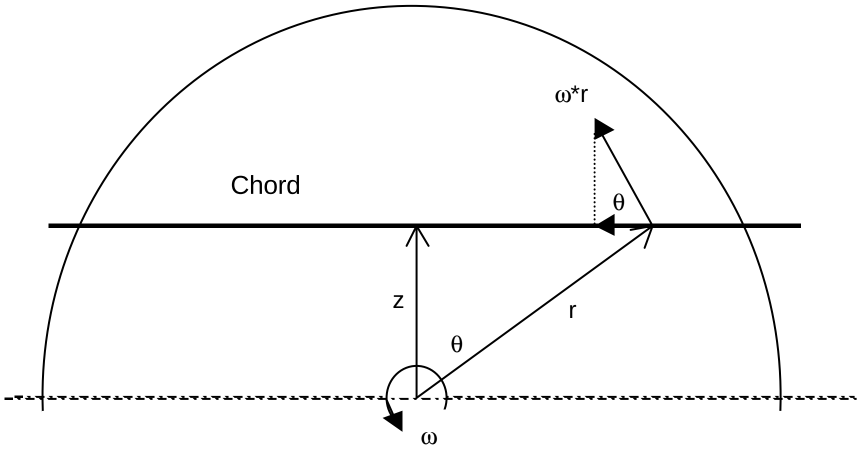


Figure 11

The swirl component along the chord is $w*r \cos q = w*r*z / r = w*z$, a constant. Hence, the line integral of the swirl component along the chord is ω*z. The swirl component for chord A is $w*0.809R$ and for chord B is $w*0.309R$

If we integrate to find the swirl contribution to the flow,

Chord A gives $w*0.809*0.1382R = w*0.1118R$

Chord B gives $w*0.309*0.3618R = w*0.1118R$

The swirl contributions are the same value but are in opposite directions (because the chords are crossed; see Figure 12). Hence they cancel, making the 4-path meter immune to such swirl. This is unique to this British Gas 4-path design, because *W* (the weighting factors) is inversly proportional to *z* (the chord locations).

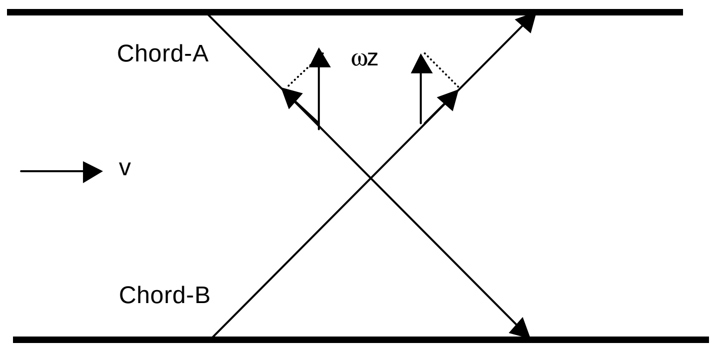
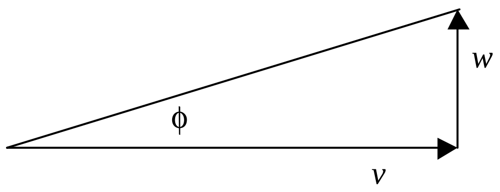


Figure 12

Case 2 If we consider bulk swirl which is NOT centered on the pipe axis but offset by a perpendicular distance or eccentricity (*e*), then a centerline path looks very similar to Figure 11 and gives the swirl component along the path ($V_\omega = \omega * e$). To estimate the error caused by this we need to consider the swirl angle ϕ defined below as:



$\tan\phi = w/v$
v = the average axial velocity
w = maximum swirl velocity = ω*R
thus $\omega = v \tan\phi / R$ and $V_\omega = e\, v \tan\phi / R$

If we consider swirl from two bends out of plane with $\phi = 14^o$ giving $\tan\phi = 0.25$, and say that the eccentricity of the swirl $e = 0.1R$ then $V_\omega = 0.025v$ which is a 2.5% error. For more severe swirl from a header with $\phi = 26^o$ giving $\tan\phi = 0.5$ or a greater eccentricity of the swirl $e = 0.2R$, the error would be 5%

With a bounce path it is similar to the cross in Fig 12 and the swirl components cancel.

With the 4-path meter, *e* will increase the swirl component to *z+e* on the A and B chords but reduce it to *z-e* on the C and D chords. The net effect of this swirl on the meter is *0.3618(B+C) – 0.1382(A+D)*, which cancels to zero. Thus the 4-path meter is insensitive to the eccentricity of the swirl.

Case 3. Solid body rotation is unrealistic as the maximum swirl velocity ($w = \omega * R$) occurs at the pipe wall (*R*). In a viscous fluid, the velocity at the wall must be zero and there will be a boundary layer building up to the maximum velocity. Work with swirl suggests that the maximum velocity occurs at about 0.95R.

With a centerline path, the swirl velocity is always normal to the path and has no component along the path. Hence, the centerline path is immune to any variations in the swirl distribution.

With the 4-path meter there is a geometric effect because the 5% change in R changes the length of Chord A by 15% but that of Chord B by only 6%. If we assume that the maximum swirl velocity decreases linearly from 0.95ωR to zero at the wall, then the wz swirl contribution on Chord A is reduced by 7.5% and on Chord B by 3% Thus, they no longer cancel as in Case 1. The net effect is $2*0.1118\omega R(7.5-3)/100 = 0.01\omega*R = 0.01\, v \tan\phi$.

If we consider swirl from two bends out of plane with $\phi = 14^o$ giving $\tan\phi = 0.25$, then the error will be 0.25%. For more severe swirl from a header with $\phi = 26^o$ giving $\tan\phi = 0.5$ or the maximum swirl velocity occurring at 0.9R, the error would be 0.5%.

CONCLUSIONS

Single path meter

In fully developed flow corrections of 4 to 8% are necessary for *Re* and *k* variations. *Re* can be corrected dynamically from knowledge of *r* and *m*, but variations in *k* can cause uncompensated errors of as much as 1%. In asymmetric flow, variations of 6% can occur due to the location of the chord relative to the asymmetry. A typical error of 2 to 8% will become +/– 3% when the normal *Re* correction is applied. The *Re* correction is inappropriate with disturbed flow since it is based on fully developed flow.

With any distribution of swirl centered on the pipe axis, the single centerline path is error free. If the swirl is eccentric then errors of 2 to 5% can occur on a direct path, but a bounce path is error free.

A flow conditioner could help improve the disturbed profile, but at the expense of additional pressure loss, cost, blockage and potential fouling. Furthermore, bi-directional flow would require two flow conditioners with separate forward and reverse calibrations. A better approach is to use a multi-path meter, with suitable path locations and integration techniques, which can compensate for disturbed velocity profiles.

Multi-Path meter

In fully developed flow, errors of only 0.06% account for all *Re* and *k* effects. In asymmetric flow, the integration error was only 0.1 to 0.3%, irrespective of orientation. This is at least 20 times better than the errors with a single path meter. With bulk swirl centered on the pipe axis, or eccentric, the 4-path meter is error free. If the swirl is not a solid body rotation to the wall, then errors of 0.2 to 0.5% can occur. This is unique to the British Gas 4-path design, because the weighting factors are inversly proportional to the chord locations.

Fixed upstream pipe-work would normally be associated with a fixed velocity profile; however, with "T" pieces or headers, the velocity profile can change with the proportion of flow in the respective branches. The 4-path meter would detect such changes through the velocity profile, while the integration technique would still give the correct flow rate. In fact, the velocity profile is a very useful diagnostic tool provided by the 4-path meter.

The better accuracy and superior diagnostic ability of the 4-path meter justify the claim that the 4-path meter is suitable for fiscal measurement while the single path meter is not suitable for fiscal measurement.

Another interesting observation from this flow asymmetry work is that the velocity profile seen by the four chords is not unique for different orientations in the same flow. Hence, it would be extremely difficult to devise a better integration technique (e.g., variable W_i) that makes use of this velocity profile information. In fact, it is shown to be unnecessary as the Gauss-Jacobi integration method works remarkably well and has been optimized for the 4-path configuration.

REFERENCES

[1] "Boundary Layer Theory" by H. Schlichting, McGraw-Hill Book Co. 1960
[2] Franc S, Heilmann C and Siekmann H. E. "Point velocity method for flow rate measurement in asymmetric pipe flow" Flow Meas. Instrum. Vol. 7 No. 314 1996
[3] K. J. Zanker "The effects of Reynolds number, wall roughness, and profile asymmetry on single- and multi- path ultrasonic meters" NSFMW Oct 1999