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Paper 3.1

A Powerful New Diagnostic Tool for Transit Time Ultrasonic Meters

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A POWERFUL NEW DIAGNOSTIC TOOL FOR TRANSIT TIME ULTRASONIC METERS

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1 INTRODUCTION

Ultrasonic flow meters produce a wealth of information that can be used to evaluate meter performance. Users can monitor this information to determine if any maintenance is required thus eliminating the need for routine maintenance and recalibration. Unfortunately this usually means rather heavy user involvement to track and analyze the information produced by the ultrasonic meter. The trending of individual chord velocities and speeds of sound are examples of this [1]. Also some diagnostics require a good understanding of how the meter works especially those associated with signal detection and measurement. Other diagnostics require additional equipment such as a gas chromatograph which allows the speed of sound to be calculated for comparison with the measured value [2]. The comparison of the measured and calculated speeds of sound resulted from a desire for a positive indication that the meter was working correctly. This is now a requirement of the NPD [3] for ultrasonic meters.

What is truly desired is an indication from the ultrasonic meter that the measurement is being made correctly without the necessity of trending large amounts of data. It is important to remember that the only measurements made by a transit time ultrasonic meter are the transit times of the ultrasonic pulses as they traverse from one transducer to the other. If it can be shown that the time measurements are correct then it follows that the meter is working to the best of its ability.

This paper presents a new diagnostic indicator which, together with a few other indicators, confirm correct meter operation. Most of the diagnostics are null indicators or can be configured as null indicators, i.e. the indicated values are near zero when the meter is operating normally. These indicators are focused on the time measurement and therefore do not necessarily give information on bad flow conditions such as a half open valve immediately upstream of the meter.

2 A BRIEF REVIEW OF THE THEORY OF TRANSIT TIME ULTRASONIC METERS

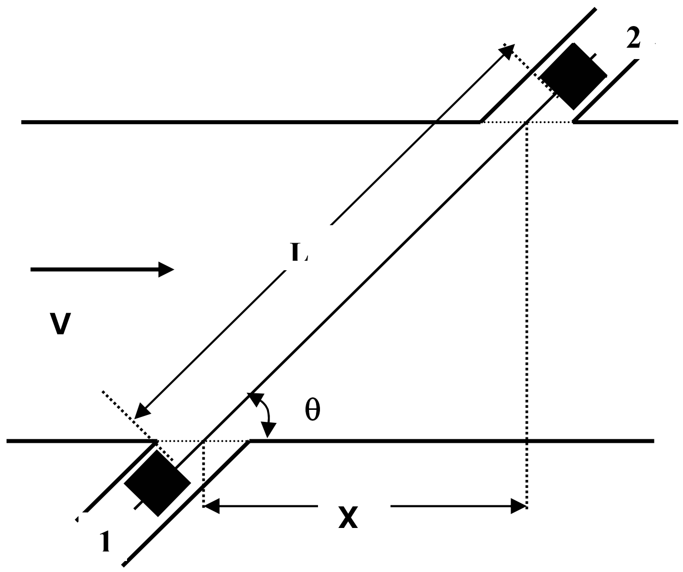
Figure 1 shows a diagram of an ultrasonic meter with one acoustic path. There are two transducers disposed along the meter at an angle Θ to the flow. These transducers alternately emit and receive ultrasonic signals for which transit times are measured for both the upstream and downstream traveling signals. Both velocity and the speed of sound are calculated from the measured transit times, the separation of the transducers, and the axial component of the transducer separation within the bore of the meter.

The velocity is given by
$$V = \frac{L^2}{2X}\frac{(t_1 - t_2)}{t_1 t_2} = \frac{L^2}{2X}\frac{\Delta t}{t_1 t_2} \tag{1}$$

The speed of sound is
$$C = \frac{L}{2}\frac{(t_1 + t_2)}{t_1 t_2}\left[1 + \frac{M^2}{2}\frac{X^2}{L^2}\tan^2\theta\right] \tag{2}$$

Equation (2) includes a second order term that is important at high velocities.

The only measurement made by a transit time ultrasonic meter is time. For a more detailed description of the theory please see [4].



Where:
L = transducer separation
X = axial component of L in the bore
θ = angle of path to the flow
C = speed of sound
V = velocity of the fluid
M = V / C
t_1 = upstream transit time
t_2 = downstream transit time
$\Delta t = t_1 - t_2$

Fig. 1 – Diagram of a Transit Time Ultrasonic Flow Meter

3 ANATOMY OF THE TIME MEASUREMENT

The time measured by an ultrasonic meter is the total time from pulse initiation to pulse reception which includes the true transit time and any time delays associated with the electronics, transducers, and signal processing. The true transit time is the time required for the pulse to travel from the face of the transmitting transducer to the face of the receiving transducer, i.e. the time spent traveling through the fluid. The difference between the measured total time and the true transit time is the delay time. The delay time for a transducer pair may be determined at the factory by subtracting a calculated transit time from the total time measured by the meter.

Time delays through the electronics and the transducers are physical delays in signal propagation which are essentially constant over the operating range of the meter. These delays must be known but they generally do not change appreciably over time. This leaves delays associated with the signal processing which amount to the time difference between the measurement point and the true beginning of the signal. Since the signal processing varies from one manufacturer to another, the nature of the measurement point may also vary. For example, the measurement point could be a selected zero crossing, an estimate of the beginning of the signal, or a point derived by compressing an extended signal such as a chirp. For purposes of discussion we will use a selected zero crossing as the measurement point throughout the remainder of this paper.

Errors in time measurement are generally associated with problems in the signal processing algorithms. For example, the meter may have locked onto a different zero crossing which is known as a cycle skip or peak switch. This causes a transit time error of 1 period of the signal frequency which is ± 8 μs for a signal frequency of 125 kHz. An error of half the signal period would result if a transducer was inadvertently miswired causing an inversion in the signal polarity. Also, a generally random timing error could result if the ultrasonic signals were distorted due to a very high flow rate or flow generated noise causing intermittent peak switching.

4 DETECTION OF TIMING ERRORS

It is of course important to detect and correct the timing errors described above. It is equally important to verify correct time measurement. The following indicators can be used to verify correct time measurement while also pointing out any incorrect time measurement. The examples given in Section 4 are all taken from the same 12 inch meter. Actual recorded waveforms were played back to produce the various figures. All figures were obtained using the same signal set the difference being that the signal processing algorithms were deliberately detuned to get the results for incorrect operation. The path lengths are approximately 13.69 inches for the long chords (B & C) and 9.33 inches for the short chords (A & D) The signal period is about 8 µs.

4.1 The Eta function

The new diagnostic, known as Eta, indicates correct measurement and identifies any chords where incorrect measurement is present. When the time measurement is incorrect, as in a peak switch, this indicator will show which chords are experiencing difficulty and in which direction the error has occurred. Eta is generally 0 ± 2 µs when there is no error in transit time measurement. This is true for data averaged over about 1 second or longer. Values of Eta outside the ± 2 µs window indicate an error in measurement. A value for Eta can be calculated for two chords of different length. The only requirement is that the speed of sound is the same on both chords. Since Eta values are equal to zero when the time measurement is correct there is no need to keep a trend log.

Eta can be calculated with the following equation.

$$\eta = \frac{L_{long} \times L_{short}}{L_{long} - L_{short}} \times \frac{C_{long} - C_{short}}{C_{long} \times C_{short}} \tag{3}$$

This is equivalent to the following equation involving timing error.

$$\eta = \frac{\left(L_{long} \times te_{short} - L_{short} \times te_{long}\right)}{\left(L_{long} - L_{short}\right)} \tag{4}$$

If there are no errors in transit time, te = 0, then Eta equals zero. Eta was derived for a no flow condition; however, equation (3) allows calculation with flow present. Indeed, calculation with flow is the preferred mode since the temperature of the fluid is most likely stable and constant making the speed of sound on all chords the same. Equation (4) is best used to quantify the effect on Eta for various incorrect measurement conditions. For example, a permanent cycle skip to the next later peak on both the upstream and downstream transit time measurements on short chord A results in an average transit time error of + 8 µs. If there is no error on the long chord, B, the value of Eta would be L_{long}* te_{short} / (L_{long} - L_{short}) ≈ 25 µs.

The Eta values are derived from the time measurements so there is a value for each possible combination of two chords. In the four path meter there are four Eta combinations: BA, CA, BD, and CD. These four values are compared to determine which path is in trouble. A zero value for Eta indicates that time is being measured correctly on the associated chords. If the same error exists on two chords of different length, their Eta value will equal the value of the error. This means that, if both chords A and B experienced a transit time error of + 8 µs, their Eta value would be 8 µs.

Eta can be “set” at calibration so any errors observed later reflect errors from calibrated values. This can be done by choosing one chord, say B, as the reference and modifying the delay times on the other chords to give Eta values of zero. This is best done at a flow velocity of about 25 ft/s to insure homogeneous temperature within the meter resulting in the same speed of sound at all chord locations.

Figure 2 shows examples of Eta for the cases of correct operation and incorrect operation due to a permanent peak switch towards the beginning of the signal on the B chord.

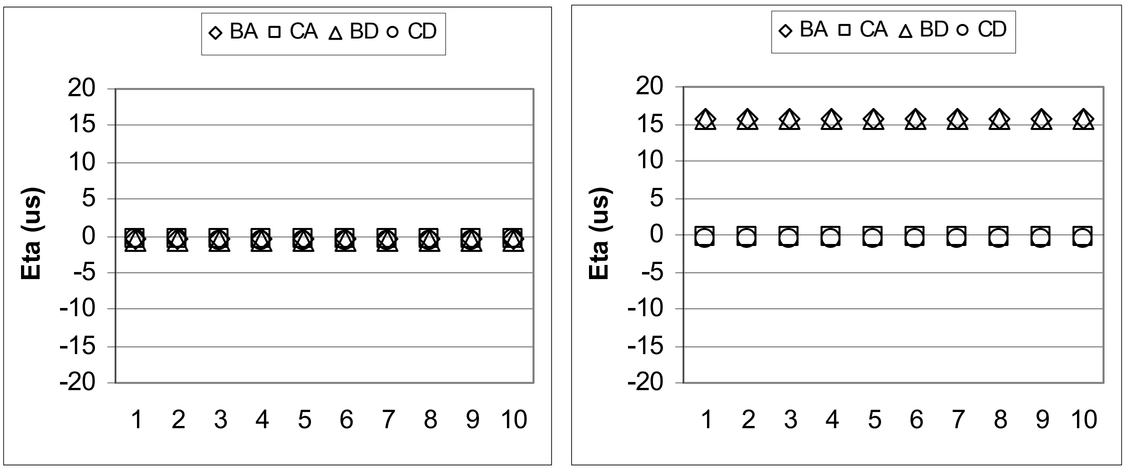


Fig. 2 – Eta Values: Left - Correct Operation, Right – Permanent Peak Switch on Chord B

Some conditions do exist, unfortunately, in which the time measurement is in error but Eta is still near zero. Low occurrences of an intermittent peak switch will not show up in data averaged over a one second interval or longer. As the rate of occurrence increases, one will see a shift in the Eta values. There are also some permanent peak switch conditions for which Eta will be near zero but fortunately these are unusual and should rarely occur. Other indicators will easily spot these conditions. One such example is the case where the up and down stream signals on a chord are peak switched but in opposite directions which creates a very large delta t error, and thus a large velocity error for that chord.

4.2 Turbulence

The ultrasonic meter is very sensitive and is affected by the turbulence in the flow. The Turbulence indicator is an estimate of the turbulence in the flow. The percent Turbulence is calculated as $100\sigma_{\Delta t}/\Delta t$ [5]. Since Turbulence is derived from the transit time difference on a chord, there is one value for each chord. Normal meter operation exhibits turbulence levels in the 2 to 5 % region at flow rates above about 3 m/s for all meter sizes, which is consistent with normal flow turbulence. The percent Turbulence levels increase as the flow rate decreases from 3 m/s due to the presence of non-flow related noise and a decreasing delta t value in the denominator.

Turbulence levels above 5 to 6 % indicate either changing flow rate or intermittent measurement problems such as intermittent peak switches. See [5] for a further description of the Turbulence indicator. Figure 3 shows examples of turbulence for correct operation and operation with an intermittent peak switch on a 12 inch meter at 100 ft/s.

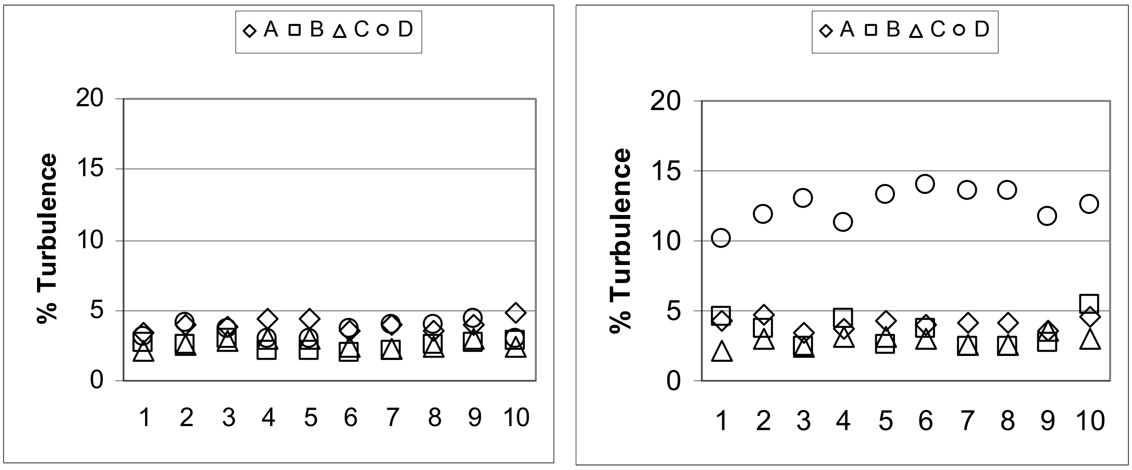


Fig. 3 – Turbulence: Left – Correct Operation, Right – Intermittent Peak Switch on Chord D

4.3 SPF

SPF indicates which zero crossing is being measured. It represents the time difference between the zero crossing selected for measurement and the beginning of the signal [6]. See Figure 4. Since there are two signals per chord, upstream and downstream, there are two SPF indicators per chord giving a total of eight indicators for a four path meter.

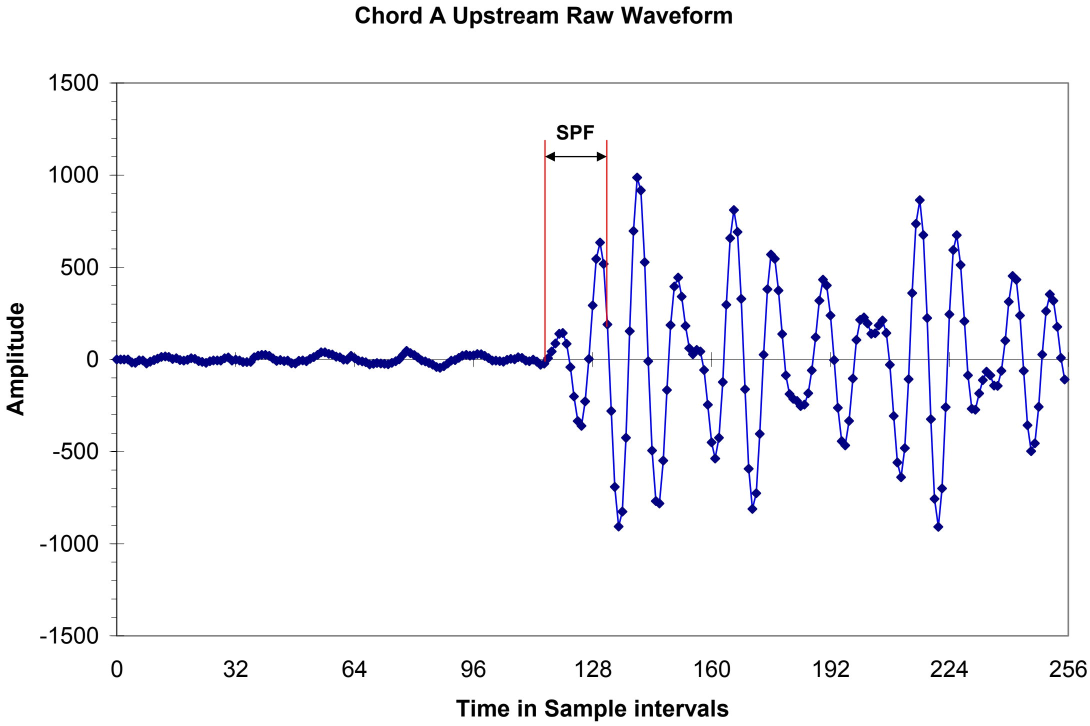


Fig. 4 – Waveform Showing SPF

SPF is one of the parameters used by the signal processing algorithms to select a zero crossing for measurement. The SPF indicator represents an average over about 1 second. It is measured in sample intervals and its value is typically 15 ± 3. A cycle skip will change SPF by about ± 10 depending on the direction of the cycle skip. SPF is converted to a null indicator by subtracting 15 from the value. Thus, correct measurement is indicated by zero +/- 3, a late cycle skip is indicated by 10 +/- 3, and an early cycle skip is indicated by -10 +/- 3. Figure 5 shows examples of SPF for correct operation and operation with a permanent peak switch on chord B.

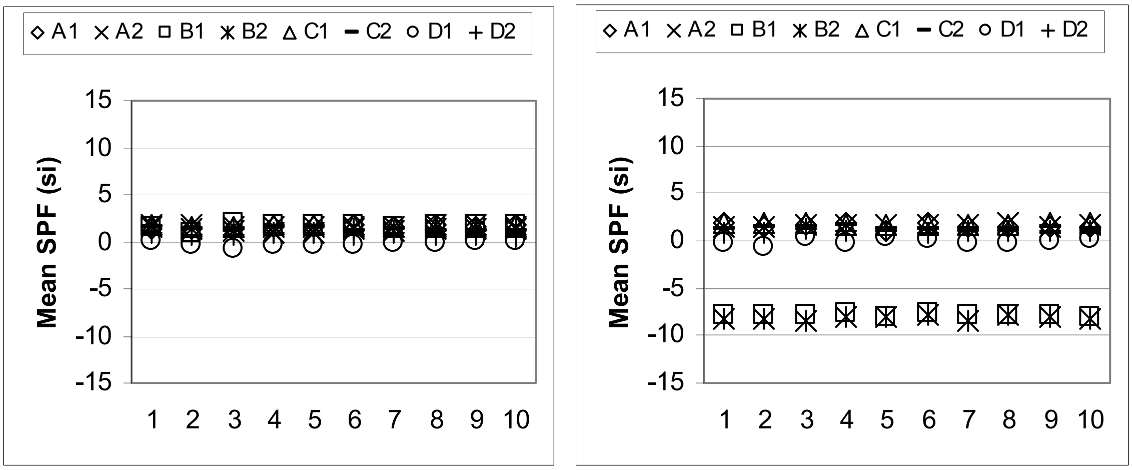


Fig. 5 – SPF: Left - Correct Operation, Right – Permanent Peak Switch on Chord B

4.4 SPF Spread

SPF Spread is simply the maximum value of SPF minus the minimum value of SPF for a given path and direction for the data used to calculate the Mean SPF in Section 4.3. There are two indicators per chord. SPF Spread should be small for normal operation and correct time measurement. If it approaches 10, an intermittent cycle skip is indicated. Figure 6 shows examples of SPF Spread for correct operation and operation with intermittent peak switches on all chords.

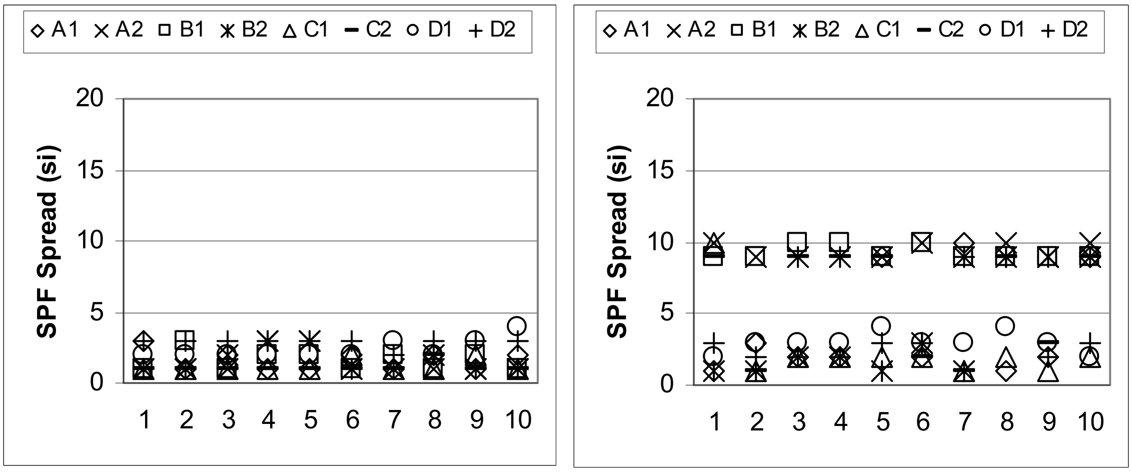


Fig. 6 – SPF Spread: Left – Correct Operation, Right – Intermittent Peak Switch on all Chords

5 EXAMPLES

Following are three examples showing all four indicators. These examples demonstrate how the indicators verify correct operation or identify a problem. The examples are from either an eight or twelve inch meter. Again, the signal processing algorithms were deliberately set incorrectly to force the incorrect operation observed.

5.1 Permanent Peak Switch

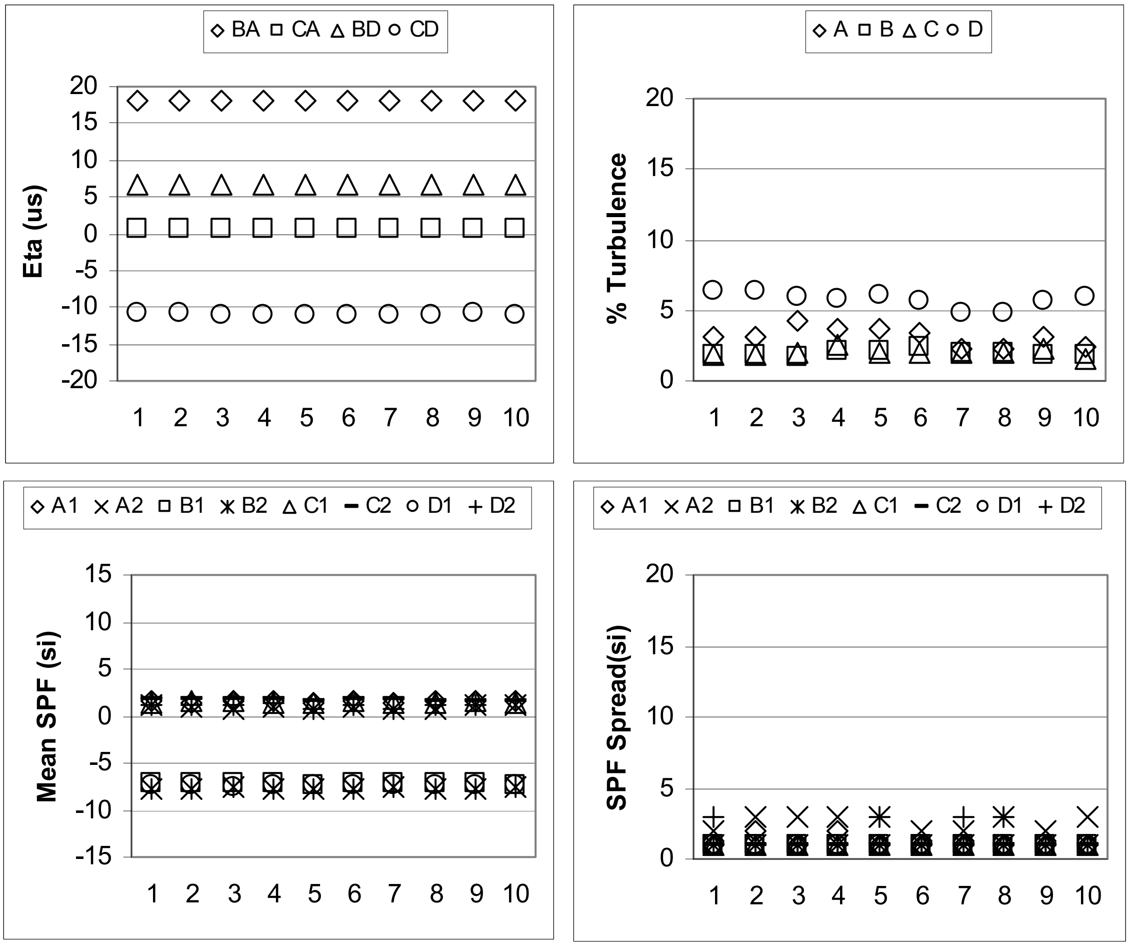


Fig. 7 – 8 inch Meter: Permanent Peak Switch on Chords B and D, 75 ft/s

Examination of the four indicators in Figure 7 reveals the following:

- The η values indicate a timing problem. The value for chords C and A is near zero indicating that the time measurement is correct on these chords.
- For this 8 inch meter L/ΔL is about 2.4 for chords A and D and 3.4 for chords B and C. Therefore $\eta = 3.4te_{Short} - 2.4te_{Long}$.
- For chords B and A, Eta is about 18. Since the measurement on A is correct, chord B must be in error. Therefore $18 = -2.4te_B$ and $te_B = -7.5$ which looks like a peak switch to an early peak on both the upstream and downstream transit time measurements.
- For chords C and D, Eta is about -10. Since the measurement on C, is correct chord D must be in error. Therefore $-10 = 3.4te_D$ and $te_D = -3$ which looks like an early peak switch on only one of the transit time measurements on chord D.
- The indicators for mean SPF confirm early peak switches on the transit time measurements for B1, B2, and D1.
- All turbulence indicators are about 6% or less which is normal.
- All indicators for SPF Spread are 4 or less indicating consistent measurement at the selected zero crossing.
- The conclusion is a permanent peak switch to an early peak exists on the time measurements for B1, B2, and D1.

5.2 Intermittent Peak Switch

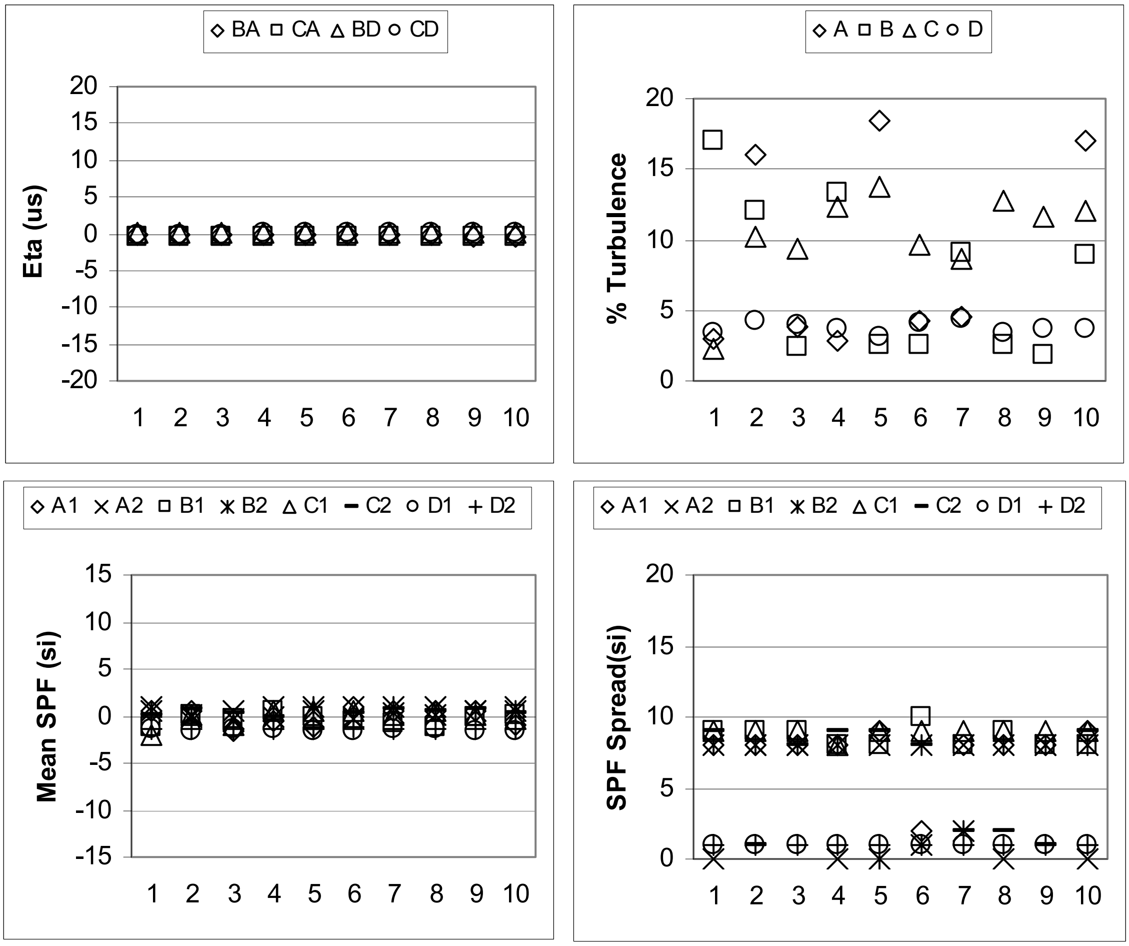


Fig. 8 – 12 inch Meter: Intermittent Peak Switch on Chords A, B, and C, 25 ft/s

Examination of the indicators in Figure 8 reveals:

- All Eta values are near zero indicating correct time measurement.
- All average SPF values are near zero indicating correct zero crossing selection.
- The turbulence indicators for chords A, B, and C are well above 6% indicating either changing flow or a timing problem.
- The normal turbulence level on chord D tends to rule out changing flow.
- The SPF Spread indicates intermittent peak selection errors on chords A, B, and C.
- The conclusion is that low levels of intermittent peak switching exists on chords A, B, and C.

5.3 All Delay Times Set to Zero

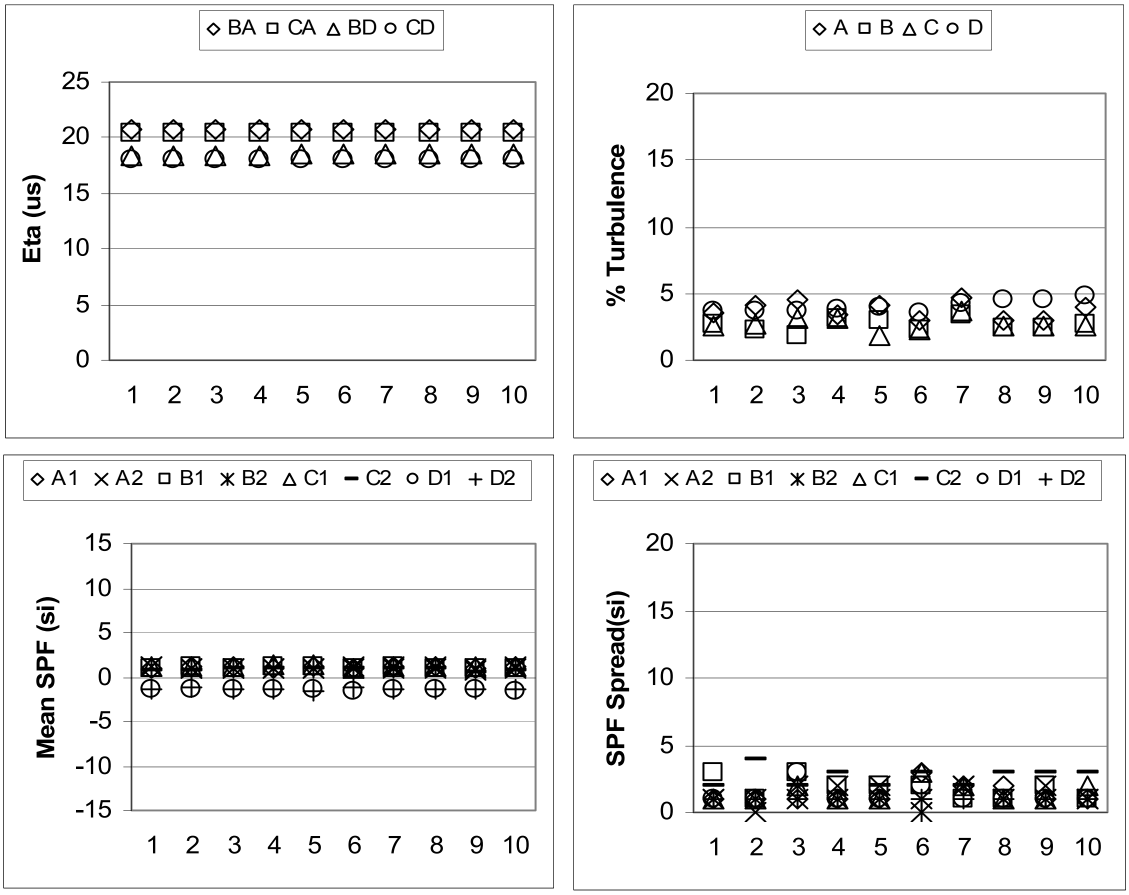


Fig. 9 – 12 inch Meter: All Delay Times Set to Zero

Examination of the indicators reveals:

- The turbulence levels on all chords are less than 6% indicating normal measurement.
- The average SPF values are near zero indication correct zero crossing selection.
- The SPF Spread values are all less than 6 indicating consistent zero crossing selection.
- All Eta values are high at about 20 μs indicating a significant timing error.
- Since the correct zero crossing is being selected, the error must be elsewhere. The only thing left is incorrect delay times.
- Since delay times for the transducers are about 20 μs, the transit time error should be about 20 μs on each chord thus making all Eta values equal to about 20 μs.

6 LIMITATIONS OF ETA

There are a few limitations of Eta.

- The meter geometry must be correct or the results will be unpredictable.
- If temperature stratification exists, causing real variance in the speed of sound, the Eta values will drift apart as the speed of sound variance increases. This is a small effect and generally observable only at very low flow rates.
- Some peak switch combinations do result in a zero value for Eta. As mentioned previously, an early and a late switch on the two transit times of the same chord is a good example. In this case the Mean SPF would indicate the peak switches.
- The system of equations that define Eta are dependent, i.e. there are an infinite number of possible solutions. It is therefore possible to enter a set of delay times which are incorrect but still have a zero value for Eta. If at least one delay time is correct the problem is avoided.

7 CONCLUSIONS

Four diagnostic indicators have been shown which, in combination, give verification that the time measurement is being made correctly. The indicators are:

- Eta — An indicator of transit time error.
- Turbulence — An indicator of flow turbulence.
- SPF — An indicator of the measurement point within the signal.
- SPF spread — An indicator of the consistency of measurement point selection.

Both Eta and Turbulence are derived from the transit time measurement. Mean SPF and SPF Spread are derived from a signal characteristic. An incorrect time measurement indication includes information pointing to the problem. These indicators have the following characteristics.

- They are self contained, i.e. they require no additional equipment.
- They do not require historical trends to interpret.
- They do not require extensive user knowledge of the ultrasonic meter.
- They give a clear indication that the meter is operating correctly.
- They are essentially the same for all meter sizes.
- They are essentially the same for all flow rates.

8 NOTATION

Variables

C	True speed of sound
Cm	Measured speed of sound
L	Path length
T	Gross measured time
t	True transit time
tm	Measured transit time
te	Transit time error
τ	Delay time
V	Velocity
X	Axial component of L in the bore
σ	Standard Deviation

Subscripts

1	Upstream direction
2	Downstream direction
A	Chord A
B	Chord B
C	Chord C
D	Chord D
Short	Short chord (A or D)
Long	Long chord (B or C)

9 REFERENCES

[1] R. SAKARIASSEN. On-Line Quality Control Of Ultrasonic Gas Flow Meters, NSFMW, Oct 1997.

[2] CHIP LETTON, et al. An Ultrasonic Gas Flow Measurement System With Integral Self Checking, NSFMW, Oct 1998.

[3] REGULATIONS RELATING TO FISCAL MEASUREMENT OF OIL AND GAS, Norwegian Petroleum Directorate, Jan 1997

[4] KARST VAN DELLEN. Developments In Ultrasonic Flow Metering, NSFMW, Oct 1991.

[5] K. J. ZANKER. Diagnostic Ability Of The Daniel Four-Path Ultrasonic Flow Meter, S E Asia HFMW, March 2003

[6] FREUND et al. METHOD AND APPARATUS FOR MEASURING THE TIME OF FLIGHT OF A SIGNAL, U S Patent No 5,983,730, Nov 1999.

10 APPENDIX - MATHEMATICAL BASIS FOR ETA

The four path ultrasonic meter has paths of two different lengths. Let the speed of sound, C, and the delay time, τ, be the same for two chords of different length. Then in terms of the gross time, T, measured by the ultrasonic meter:

$$C = \frac{L_A}{T_A - \tau} = \frac{L_B}{T_B - \tau} \tag{5}$$

This gives

$$\tau = \frac{L_B T_A - L_A T_B}{L_B - L_A} = \frac{L_B T_A}{\Delta L} - \frac{L_A T_B}{\Delta L} \tag{6}$$

This could be used to determine τ in operation but in general $\tau_A \neq \tau_B$. It is common practice to determine transducer delay times during the manufacturing process. These delay times are subtracted from the gross measured times to get the true transit time, t.

If we assume $\tau_A = \tau_B = 0$, then $T_A = t_A = L_A / C$ and $T_B = t_B = L_B / C$

$$\tau = \frac{L_B T_A}{\Delta L} - \frac{L_A T_B}{\Delta L} = \frac{L_B t_A}{\Delta L} - \frac{L_A t_B}{\Delta L} = 0 \tag{7}$$

Now define η

$$\eta = \frac{L_B tm_A}{\Delta L} - \frac{L_A tm_B}{\Delta L} \tag{8}$$

where tm = t + te is the measured transit time

If all the timing is perfect, then $\eta = 0$

If the timing is in error then

$$\eta = \frac{L_B (t_A + te_A)}{\Delta L} - \frac{L_A (t_B + te_B)}{\Delta L} \tag{9}$$

and

$$\eta = \frac{L_B t_A}{\Delta L} - \frac{L_A t_B}{\Delta L} + \frac{L_B te_A}{\Delta L} - \frac{L_A te_B}{\Delta L} = \frac{L_B te_A}{\Delta L} - \frac{L_A te_B}{\Delta L} \tag{10}$$

The value of η depends on the timing error. This gives a way to evaluate the effect of timing errors on η.

The above description has assumed a no flow condition. How is η calculated when flow is present? Simply averaging the up and down stream transit times will give an answer which is increasingly incorrect as the flow rate increases. Since the speed of sound is calculated for each chord the measured transit time, tm, for each chord can be calculated as the chord length divided by the measured speed of sound on that chord, L/Cm. Substitution into equation (8) gives.

$$\eta = \frac{L_B L_A}{\Delta L Cm_A} - \frac{L_A L_B}{\Delta L Cm_B} \tag{11}$$

and

$$\eta = \frac{L_B L_A (Cm_B - Cm_A)}{(L_B - L_A) Cm_B Cm_A} \tag{12}$$

Equation (12) allows the determination of η from existing values.