Turbulence Profile Effects on the Accuracy of Ultrasonic Meters

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Keywords:

Ultrasonic meter, turbulence effects, USM, turbulence intensity profile, rotational dependence, flow conditioning plate, USM meter factor error, CPA turbulence intensity, flow jetting, sinuosity.

Abstract:

By rotating an upstream flow conditioning plate, an USM's meter factor can shift producing a measurement error. USM meter factor shifts were compared to a theoretical turbulence intensity model of the upstream flow conditioning plate suggesting a correlation. USM meter factor shifts were corrected for using a turbulence correction factor based on turbulent sinuosity.

Executive Summary

Properly installed and calibrated, multipath ultrasonic meters (USM) have exceptional uncertainty. USM measurement success is due to their underlying physics, design, technological improvements, and testing. Their unprecedented diagnostics are able to infer flow turbulence by looking at the standard deviations in their signals.

Ultrasonic Meter (USM) data where the upstream flow conditioning plate (FCP) was systematically rotated, revealed a rotational dependency in the USM's meter factor. USM errors as great as 0.3% were observed. Subsequent Pitot traverse studies and CFD modeling ruled out velocity profile jetting after the FCP as the source of the meter factor shifts.

Signal standard deviations in the individual chordal sound paths of the tested USMs were compared to a theoretical turbulence intensity model of the upstream FCP. After validation, a turbulent sinuosity model was used to correct USM measurement errors.

- The resulting analysis suggests a relationship between turbulence intensity profiles and USM measurement errors.
- Field FCP rotational orientation should match the flow laboratory orientation used during calibration to minimize USM measurement errors.
- The USM and the flow conditioning plate should not be treated as two separate devices. They should be viewed as a flow metering package working in concert with each other.
- Using USM *Apparent Turbulence*, and the turbulent sinuosity model in this report, reduced USM average *Meter Error* from 0.08% to -0.02%.
- Quantitative USM meter factor corrections for flow turbulence intensity can be made using a turbulent sinuosity model.
- Pending a more robust data set, USM manufacturers should consider adopting a turbulent sinuosity model to correct for field turbulence intensities.
- Future turbulence intensity studies are suggested to understand and improve USM flow measurement.

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- Daniel Emerson, and SICK for their technical advice, cooperation and help throughout this investigation. Their "pursuit of the truth" and willingness to improve USM technology is both respected and appreciated.

Background

In 2007, ultrasonic meters (USM) from three different manufacturers were tested at Colorado Engineering Experimental Station Inc. (CEESI) where the upstream flow conditioning plate (FCP) was systematically rotated to see if it had an effect on the USM's meter factor. Meter factor shifts of up to 0.3% were observed. Similar tests were repeated in 2008 and 2009, producing similar results where the USM meter factors shifted as the FCP was rotated. The graph in figure 1 shows a typical USM meter factor shift as the flow conditioning plate was rotated.

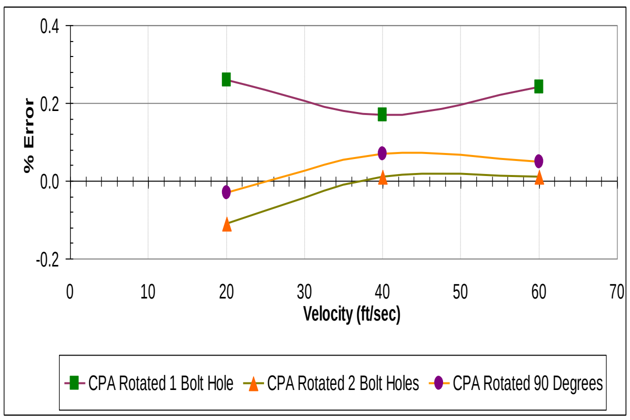

Figure 1. USM Meter Factor Shift vs. Flow Conditioning Plate Rotation

Results from the 2007-2009 FCP rotational tests prompted the measurement industry to recommend that: *flow conditioning plates in USM field installations match the flow laboratory FCP rotational orientation used during calibration.* While this recommendation reduced USM rotational errors between the flow laboratory and field installations, it did not answer why these errors occur when a FCP is rotated. The rotational dependency was particularly puzzling because the flow conditioning plates used in the testing were axially symmetric (CPA 50E plates manufactured by Canadian Pipeline Accessories).

In September 2009, the Pipeline Research Council International Inc. (PRCI) funded a study to investigate the root cause of the USM rotational dependency on upstream flow conditioning plates. One obvious theory was that the upstream FCP was producing flow jets extending 10 pipe diameters or more downstream, into the USM transducer sound paths which in turn caused an error. PRCI's technical report, *Investigation into the Jetting Behavior of Perforated Plate Flow Conditioners*, (PR-364-09606) [1], provides a detailed study of the flow jetting downstream a FCP at 0.9, 3 and 10 pipe diameters after a FCP. The PRCI study flowed 1000 psi natural gas at velocities ranging from 10 to 110 feet/second, performed multi-axis Pitot traverses, and developed detailed multi-axis velocity profiles. PRCI also funded a double-blind CFD simulation as a part of their study. The CFD results compared favorably with the experimental data. While detailed results can be found in the PRCI report cited above, flow jetting was barely detectable at three pipe diameters and could not be detected at the 10 pipe diameter location. The graphic in Figure 2 shows a CFD simulation of the velocity profile after a CPA flowing conditioning plate.

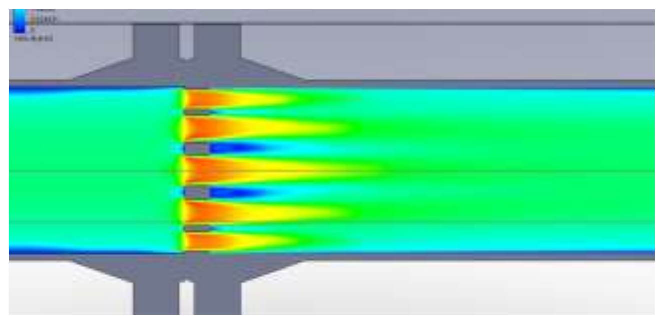

Figure 2. Flow Jetting using CFD Simulation Courtesy of CPA

Boundary-Layer-Channel-Theory Proved Wrong

With strong evidence eliminating flow jetting as the root cause of the USM rotational error, a new theory was proposed and tested in 2011. The *Boundary-Layer-Channel-Theory* suggested that near-wall (rotationally dependent) dead-zones immediately after the flow conditioning plate persisted 10 pipe diameters or more downstream prohibiting the redevelopment of the velocity profile.

Although Pitot traverses can accurately map velocity profiles in the bulk area of the pipe, near the pipe wall, it is difficult to obtain data rendering localized dead-zones undetectable. The graphic in Figure 3 shows the location of the theoretical dead-zones called *dead-zone channels*.

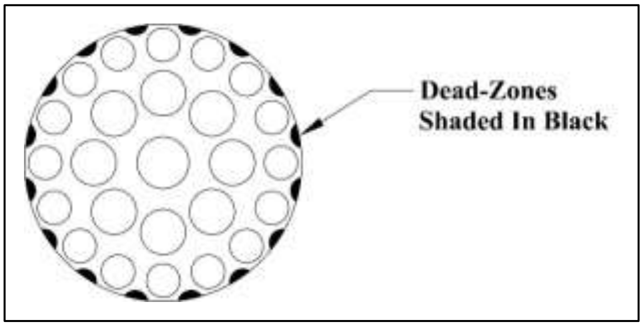

Figure 3. Near-Wall Dead-Zones

To validate the *Boundary-Layer-Channel-Theory*, CEESI tested two 12" USMs from two different manufacturers in 1000 psi natural gas. The upstream FCP was sequentially rotated from TBC (Top Dead Center) to 9°, 12°, 18°, 22.5°, 27° and 36° respectively. The same sequence of tests were repeated using an extremely rough meter tube (approximately 500 µ-inch) installed between FCP and the USM. In theory, the rough pipe wall would promote the rapid redevelopment of a turbulent boundary layer, quickly dissipating the localized dead-zone anomalies. Figures 4 & 5 show the roughened meter tube.

Figure 4. Roughened (500 µ-in) Meter Tube Inlet

Results from the 2011 FCP rotational tests are shown in Figures 6 and 7. Embarrassingly, the roughened meter tube had no effect on the rotational error and the *Boundary-Layer-Channel-Theory* was shown to be incorrect. A new theory had to be proposed.

Figure 5. Close-up of Roughened Meter Tube (mechanical pencil in foreground for scaling)

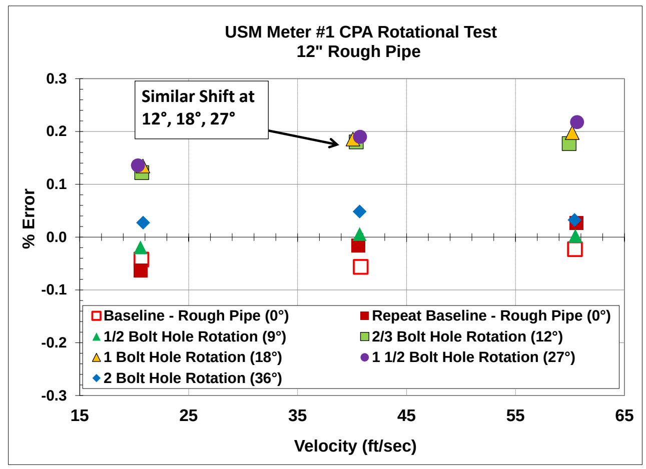

Figure 6. Roughened Meter Tube Rotational Error Results for USM Meter #1

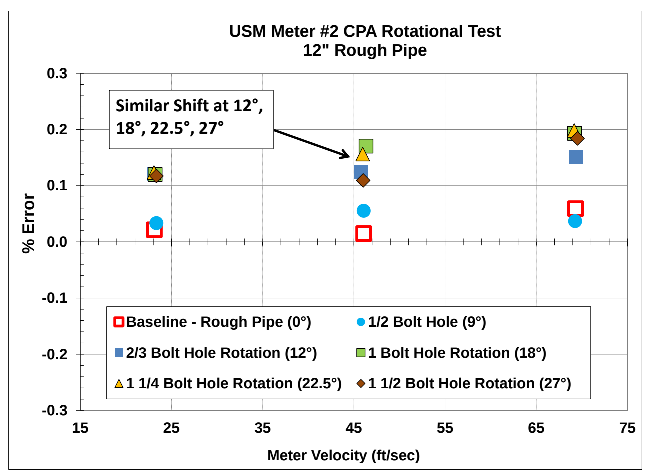

Figure 7. Roughened Meter Tube Rotational Error Results for USM Meter #2

How Does Turbulence Affect Sound Waves?

Before we can discuss turbulence intensity profiles and their influence on ultrasonic meters, we need understand how *sound waves* travel through gas and understand the concepts of *turbulence* and *sinuosity*.

Sound Waves

Waves can be generally categorized into two types, transverse and longitudinal waves:

> *A transverse wave displaces the medium perpendicular to the direction of propagation of the wave, similar to the ripple in a pond. Traverse waves cannot propagate in a gas or in a liquid because there is no mechanism for driving motion perpendicular to the propagation of the wave.* [2]

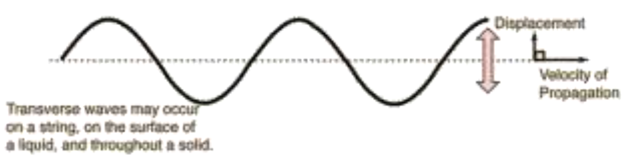

Figure 8. Traverse Wave [2]

> *A longitudinal wave displaces the medium parallel to the propagation of the wave, like a slinky.* [2]

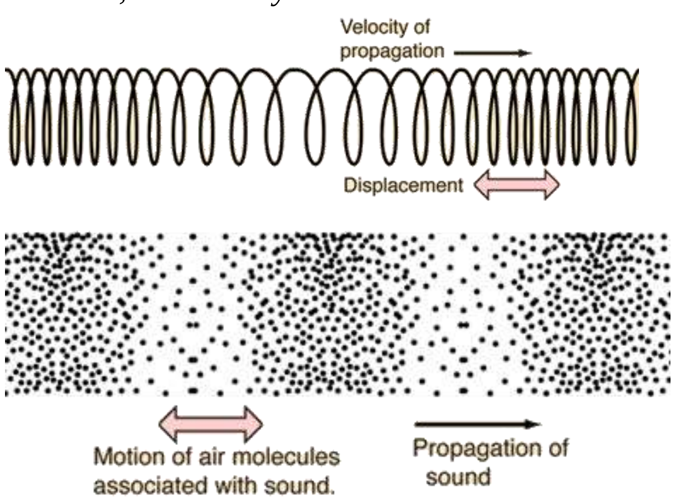

Figure 9. Longitudinal Wave [2]

[2]Taken from: http://hyperphysics.phy-str.gsu.edu/hbase/Sound/

Turbulence

Figure 10 shows flow turbulence at different Reynolds Numbers. Flow turbulence is created when faster fluid layers collide and interact with slower layers creating fluid shearing and separation. Shearing and separation create *vortices, eddies, and swirls that can persist for dozens and even hundreds of pipe diameters after they are generated.* Flow turbulence can have large and small structures, fast and slow frequencies.

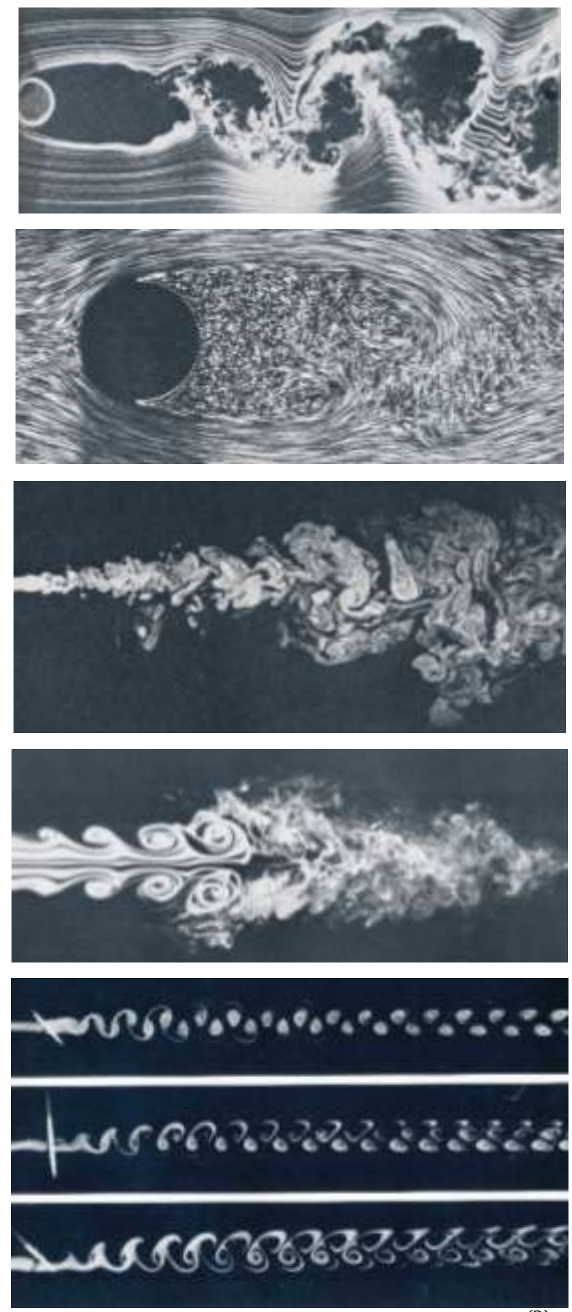

Figure 10. Flow Turbulence Examples [3]

Sinuosity

Sinuosity is an adjective defining how much something curves or bends. A winding river is said to be a sinuous river.

Figure 11. Example of a Sinuous River

One can define the *Sinuosity Index* (SI) or the *Sinuosity Coefficient* as the "actual path length" divided by the "shortest path length" of a curve.

$$SI = \frac{Actual\ Path\ Length}{Shortest\ Path\ Length}$$

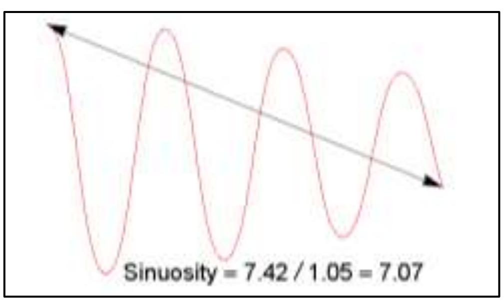

Figure 12. Sinuosity

Sound waves can be pushed around by cross winds. Higher frequency sound waves have a greater tendency to be "blown around" by crosswinds.

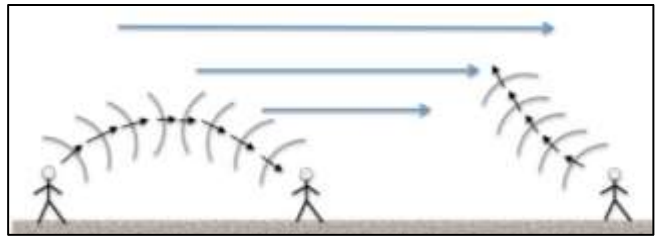

Figure 13. Sound Waves Being Pushed Around by Crosswinds

Turbulent Sinuosity

As turbulent vortices are generated in a flow stream, a sound wave traveling across them will be randomly pushed around, (sometimes right, left, up, down, upstream, downstream). The sound wave path length will increase as the turbulence increases. The increased path length will be a function of the *Sinuosity Index.*

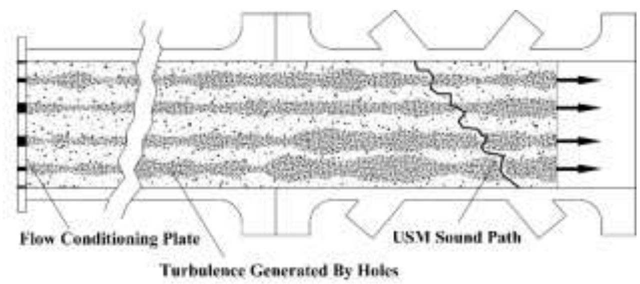

Figure 14. Turbulence Propagation from the Flow Conditioning Plate to the USM

Velocity Profiles vs. Turbulence Intensity Profiles

A *velocity profile* is a map of how velocities are distributed across the pipe. A *turbulence intensity profile* is a map of how turbulence levels are distributed across pipe. Figures 15 & 16 shows how *velocity profiles* and *turbulence intensity profiles* are often a mirror image of each other. Figure 17 shows a CFD model of a *velocity profile* downstream of a CPA flow conditioning plate.

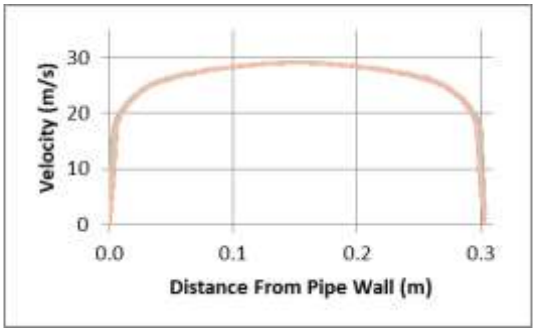

Figure 15. CFD Generated Velocity Profile

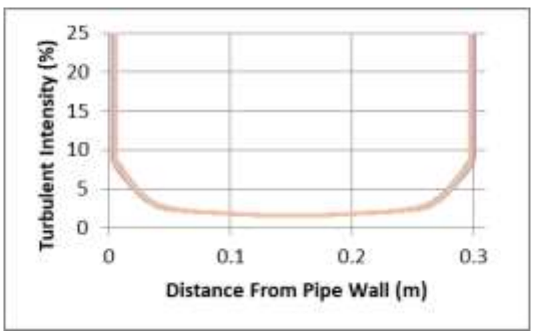

Figure 16. CFD Generated Turbulence Intensity Profile

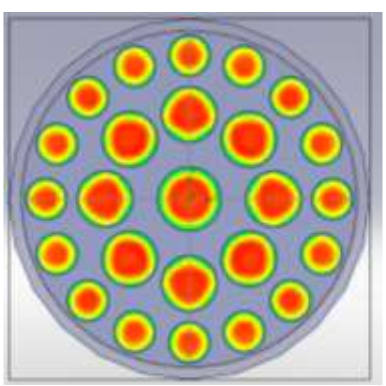

Figure 17. Velocity Profile Downstream of Flow Conditioning Plate

FCP Turbulence Intensity Model

Combining the concept of *turbulent sinuosity* and overlaying the USM chordal path locations relative to the upstream flow conditioning plate (FCP) as it is rotated, we can see how different rotations expose the USM paths to different holes in the FCP. Exposure to different percentages of holes produces different turbulence levels in each chord on the USM. Different FCP rotations are shown in Figure 18 for USM Meter #1. FCP holes that cross the USM chordal path are shaded making it easier to see the hole-chordal path interaction.

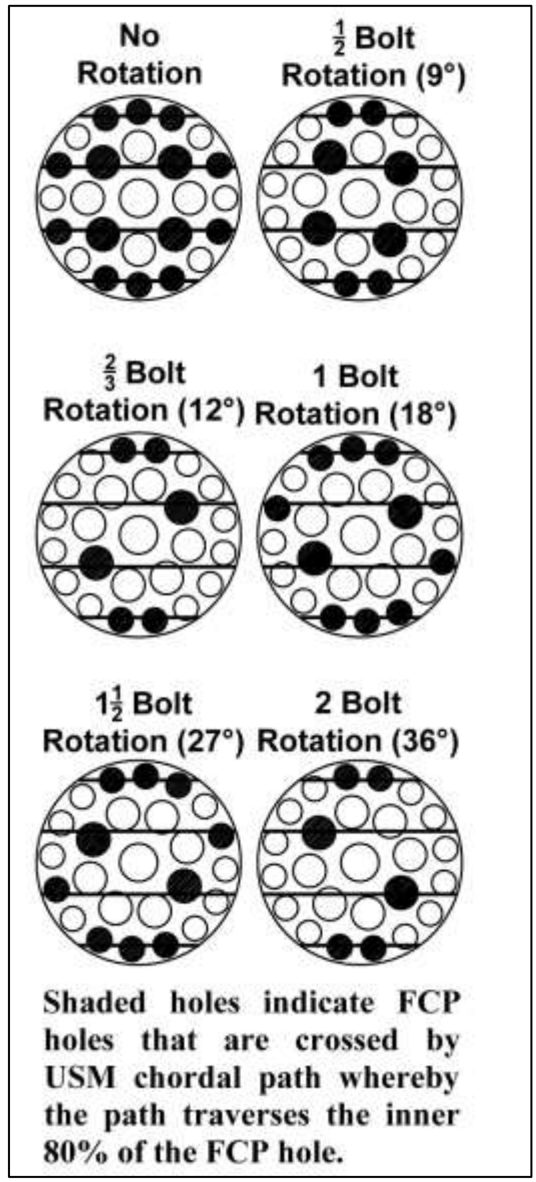

Figure 18. USM Meter #1 Chordal Path Locations Relative to Upstream FCP

Analyzing USM Apparent Flow Turbulence

USMs do not measure flow turbulence, but they can infer flow turbulence by calculating the standard deviation of a group of signals traversing its meter body. The greater the signal standard deviation, the greater the sound wavelets get "pushed around" by turbulent vortices. In this paper we define *Apparent Turbulence* as the standard deviation of the USM signals traversing its meter body.

The 2011 FCP rotational data was re-examined. USM signals were individually analyzed on a chord-by-chord basis, and signal standard deviations were calculated. USM Meter #1 Apparent Turbulence Summary Table is shown in Figure 19.

			Average Apparent Turbulence							
Velocity (FPS)	Rotation Angle (°)	Bolt Rotation	Chord A	Chord B	Chord C	Chord D	Ave of A&D	Ave of B&C	Wgt. Ave All Chords	Average of All chords
20 FPS	0	0.00	4.051	2.781	2.836	3.993	4.022	2.808	3.144	2.84
20 FPS	9	0.50	4.315	2.675	2.630	3.787	4.051	2.652	3.039	2.76
20 FPS	12	0.67	3.899	2.453	2.439	3.551	3.725	2.446	2.800	2.62
20 FPS	18	1.00	4.108	2.756	2.669	3.976	4.042	2.712	3.080	2.74
20 FPS	27	1.50	4.086	2.756	2.705	3.776	3.931	2.731	3.063	2.74
20 FPS	36	2.00	3.863	2.479	2.554	3.517	3.690	2.517	2.841	2.62
40 FPS	0	0.00	3.667	2.448	2.325	3.470	3.568	2.387	2.713	
40 FPS	9	0.50	3.607	2.407	2.220	3.436	3.522	2.314	2.647	
40 FPS	12	0.67	3.345	2.324	2.227	3.291	3.318	2.276	2.564	
40 FPS	18	1.00	3.618	2.344	2.253	3.343	3.481	2.298	2.625	
40 FPS	27	1.50	3.407	2.314	2.236	3.264	3.335	2.275	2.568	
40 FPS	36	2.00	3.380	2.278	2.248	3.210	3.295	2.263	2.548	
60 FPS	0	0.00	3.576	2.396	2.363	3.340	3.458	2.380	2.678	
60 FPS	9	0.50	3.381	2.334	2.261	3.302	3.341	2.297	2.586	
60 FPS	12	0.67	3.268	2.207	2.217	3.156	3.212	2.212	2.489	
60 FPS	18	1.00	3.374	2.229	2.201	3.177	3.276	2.215	2.508	
60 FPS	27	1.50	3.450	2.347	2.264	3.208	3.329	2.306	2.588	
60 FPS	36	2.00	3.252	2.234	2.197	3.016	3.134	2.216	2.469	

Figure 19. USM Meter#1 Apparent Turbulence Summary Table

Turbulence Intensity Correction Factor (TIF)

Turbulence intensities are greatest in locations where velocity gradients are the steepest, i.e. near the pipe wall, and near hole edges. Figure 20 shows the different parameters used to develop a theoretical turbulence intensity model for USM sound paths being downstream of a flow conditioning plate.

$$TIF = f(HE) + g(FACL, BACL, TCL, CWF)$$

Where:

TIF=	*Turbulence Intensity Factor*
HE=	*Number of hole edges*
FCL=	*Free Chord Length*
BCL=	*Blockage Chord Length*
TCL=	*Total Chord Length*
CWF=	*Chord Weighting Function*

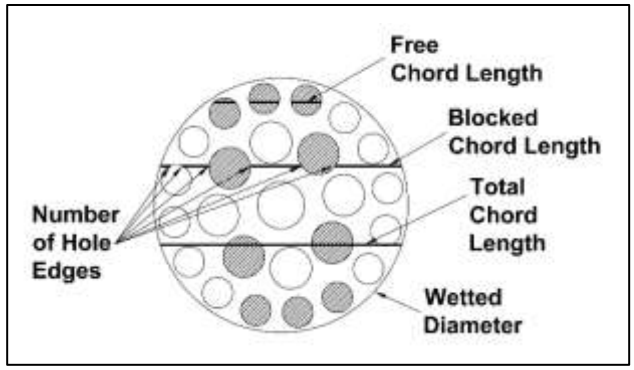

Figure 20. Parameters Used To Develop the Theoretical Turbulence Intensity Model

Curve fitting techniques were applied to the turbulence intensity parameters shown in Figure 20 and resulting *Turbulence Intensity Factors (TIF)* were plotted against USM *Apparent Turbulence* values. *Apparent Turbulence* values from the USM outer two chords (A&D) were grouped together and the inner two chords (B&C) were grouped together for analysis.

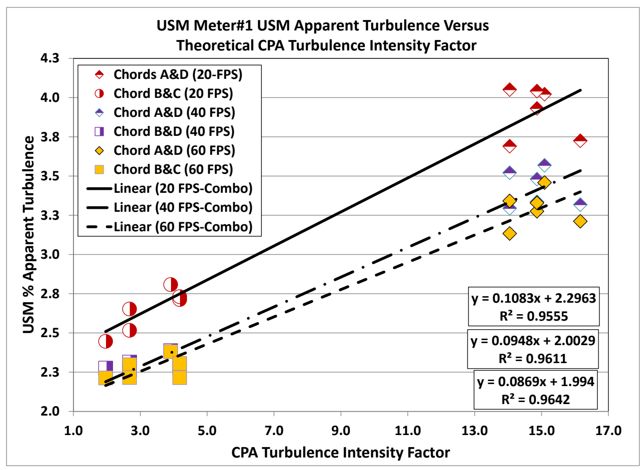

Figure 20. USM Meter#1 Apparent Turbulence Versus Turbulence Intensity Factor (TIF) Results

A strong correlation can be seen between the USM chordal *Apparent Turbulence* and the *TIF*. Regression errors (coefficients of determination) ranging from 0.95 to 0.96 are shown in the graph in Figure 20.

With a strong correlation between the USM chordal *Apparent Turbulence* (signal standard deviation) and the turbulence intensity model, a new set of equations were developed to correlate USM *Apparent Turbulence* to measurement error using turbulent sinuosity.

USM Turbulent Sinuosity Model & Results

The shortest path between two points is a straight line. Sinuosity is the measure of how meandering a path is compared to a straight line. When a sound wave travels across a moving fluid, its path length is increased by the fluid's turbulence. Due to flow turbulence, an USM's actual sound wave path length is always greater than the straight line distance between the transducers when fluid is flowing. The greater the flow turbulence, the greater the sinuosity of the sound wave path length.

The governing USM equations can be rewritten to account for the increased sound path length due to turbulent sinuosity. An abbreviated derivation of these equations can be found in Appendix A of this report.

Using *Apparent Turbulence* values from the FCP rotational data from 2011, USM meter factors were corrected for turbulent sinuosity on a chord-by-chord basis. Reduced meter factor error results are plotted against *Apparent Turbulence* are shown in Figures 22, 23, and 24.

Correcting for turbulent intensity reduced the measurement error:

- Uncorrected Average Meter Error: 0.08%
- Corrected Average Meter Error: -0.02%
- Std Dev. of uncorrected Meter Factor: 0.093%
- Std Dev. of corrected Meter Factor: 0.088%

Figure 21 summarizes reduced meter factor error results using the turbulent sinuosity model.

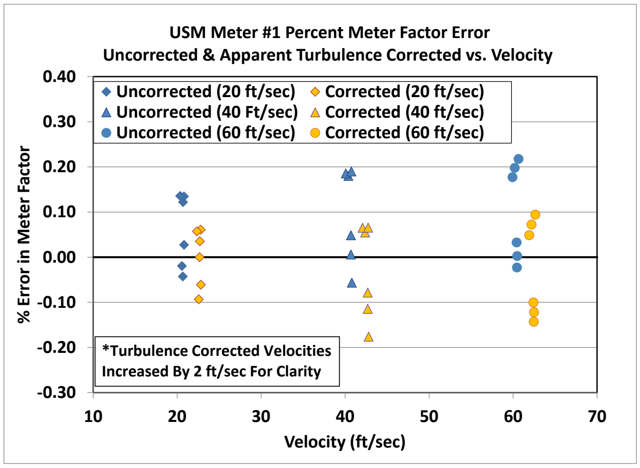

Figure 21. Meter Factor Error vs. Velocity

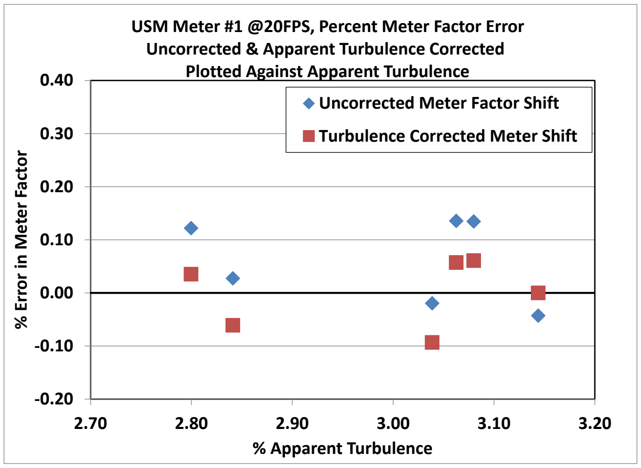

Figure 22. Meter Factor Error vs. Apparent Turbulence at 20 Feet/Second

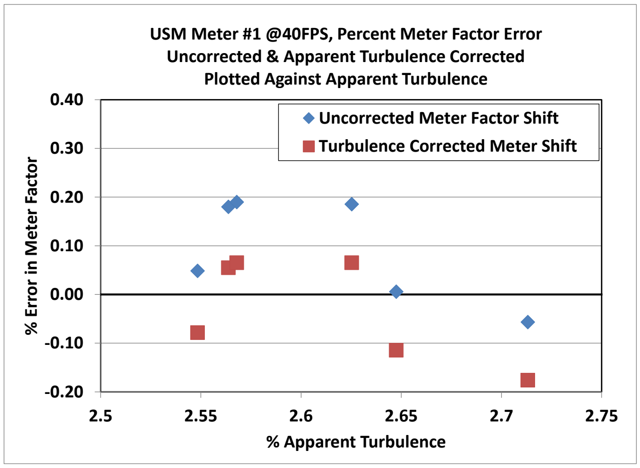

Figure 23. Meter Factor Error vs. Apparent Turbulence at 40 Feet/Second

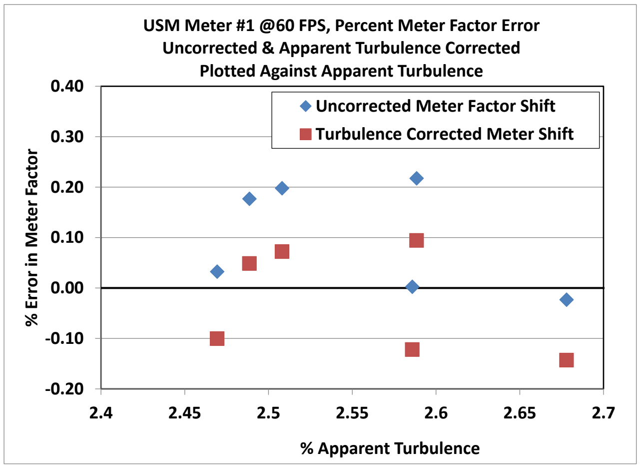

Figure 24. Meter Factor Error vs. Apparent Turbulence at 60 Feet/Second

Conclusions:

Ultrasonic Meter (USM) data where the upstream flow conditioning plate (FCP) was systematically rotated, revealed a rotational dependency in the USM's meter factor. USM errors as great as 0.3% were observed. Subsequent Pitot traverse studies and CFD modeling ruled out velocity profile jetting after the FCP as the source of the shifting meter factors.

A theoretical turbulence intensity model of the upstream FCP was developed and compared to USM signal standard deviations on a chord-by-chord basis. A strong correlation was observed between USM chordal *Apparent Turbulence* and the turbulence intensity model. Regression errors (coefficients of determination) ranging from 0.95 to 0.96 suggest USM chordal *Apparent Turbulence* is strongly related to upstream fluid turbulence intensity.

A USM *Turbulent Sinuosity* model was created using the governing USM equations. Using the *Turbulent Sinuosity* model and FCP rotational data collected from 2011, USM meter factors were corrected using USM *Apparent Turbulence* values. A reduction in the average *Meter Error* from 0.08% to -0.02% was realized.

Quantitative USM meter factor corrections for flow turbulence intensity can be made using a turbulent sinuosity model.

Recommendations:

- Field FCP rotational orientation should match the flow laboratory orientation used during calibration to minimize USM measurement errors.
- The USM and the flow conditioning plate should not be treated as two separate devices. They should be viewed as a flow metering package working in concert with each other.
- Manufacturers should collect, record, and fingerprint *Apparent Turbulence* for all laboratory testing. Field installation *Apparent Turbulence* levels should be compared to laboratory values.
- Pending a more robust data set, USM manufacturers should consider adopting a turbulent sinuosity model to correct for field turbulence intensities. The author envisions the following sequence:
    - Manufactures collect field data to assess the range and scope of *Apparent Turbulence.*
    - Conduct flow laboratory testing where varying turbulence intensity levels are generated upstream while recording USM *Apparent Turbulence* readings.
    - Apply a *Turbulent Sinuosity* model to recorded data to further define USM meter factor dependency on upstream turbulence intensity.
    - Apply turbulence intensity meter corrections to field installations.

The author acknowledges that turbulence intensity takes many forms including low and high frequency structures, but I believe first order turbulence intensity corrections are possible and the next evolutionary step towards lower USM uncertainty. Flow laboratory background turbulence intensity monitoring, acoustic sampling equipment and spectrum analyzers will likely be required to better understand this phenomenon.

USM turbulence intensity modeling gives rise to new opportunities for USM technology. The next generation of USMs will likely fingerprint laboratory turbulence levels and compare it to field turbulence levels, and not only flag a diagnostic warning, but apply a turbulent intensity correction factor. Such a correction could be user selectable. This potentially will give USM technology an even bigger lead over other technologies marking a new era of even lower uncertainty.

The next generation USMs will likely correct for turbulence intensity. USM manufacturers who understand how to correct for turbulence intensity will enjoy a marketing edge over their competition.

Appendix A

Abbreviated USM Turbulent Sinuosity Derivation:

The general equation for fluid velocity in a USM can be written as:

$$V = \left(\frac{L}{2\cos\theta}\right)\frac{(t_{up} - t_{down})}{(t_{up})(\ t_{down})} \tag{1}$$

Equation (1) can be modified to account the added time delay (t_d) due to turbulent sinuosity:

$$\Delta V = \left(\frac{L}{2\cos\theta}\right)\frac{(t_{up}+t_d)-(t_{down}+t_d)}{(t_{up}+t_d)(\ t_{down}+t_d)} \tag{2}$$

The time delay (t_d) can be defined as the time difference between (t_{up}) and $(\ t_{down})$, 3 times the turbulence intensity (I), and an intensity coefficient (*k*):

$$t_d = 3\Delta tkI \tag{3}$$

The "3" in equation (3) is related to the added time it takes a sound wavelet to travel with the flow and the added time to travel against the flow relative to the time difference Δt. Equation (1) and (2) can be combined:

$$\frac{\Delta V}{V} = \frac{\left(\frac{L}{2\cos\theta}\right)\frac{(t_{up}+t_d)-(t_{down}+t_d)}{(t_{up}+t_d)(\ t_{down}+t_d)}}{\left(\frac{L}{2\cos\theta}\right)\frac{(t_{up}-t_{down})}{(t_{up})(\ t_{down})}} \tag{4}$$

Equation (3) can be substituted into equation (4), rearranging:

$$\frac{\Delta V}{V} = \frac{(1+2kI)(t_{up})(t_{down})}{(t_{up}+3\Delta tkI)(t_{down}+\Delta tkI)} \tag{5}$$

The bulk velocity $(\bar{V})$ is defined by the weighted chords as:

$$\bar{V} = 0.1382\ V_A + 0.3618V_B + \ 0.3618V_C + 0.1382V_D \tag{6}$$

Chords (A & D) and (B & C) can be combined:

$$\bar{V} = (2)0.1382\ V_{A\&D} + (2)0.3618V_{B\&C} \tag{7}$$

Combining equations (5) and (7) produces the total error in the velocity $(\Delta E_{sinuousity})$:

$$\Delta E_{sinuousity} = \frac{\Delta V}{V} = (2)(0.1382)\left[\frac{(1+2kI_{A\&D})\left(t_{up_{A\&D}}\right)\left(t_{down_{A\&D}}\right)}{\left(t_{up_{A\&D}}+3\Delta t_{A\&D}kI_{A\&D}\right)\left(t_{down_{A\&D}}+\Delta t_{A\&D}kI_{A\&D}\right)}\right] + \cdots$$

$$\ldots(2)(0.3618)\left[\frac{(1+2kI_{B\&C})\left(t_{up_{B\&C}}\right)\left(t_{down_{B\&C}}\right)}{\left(t_{up_{B\&C}}+3\Delta t_{B\&C}kI_{B\&C}\right)\left(t_{down_{B\&C}}+\Delta t_{B\&C}kI_{B\&C}\right)}\right] \tag{8}$$

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