

PULSATION EFFECTS ON ORIFICE METERING CONSIDERING PRIMARY AND SECONDARY ELEMENTS

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INTRODUCTION

The use of orifices for commercial flow measurement has a long history dating back more than 70 years. Orifices are extensively used in the United States natural gas, petroleum and petro-chemical industries and are important as one of the most practical ways to meter large volumes of gas flow. These meters are very reliable and cost effective; and if properly used, can be relied upon to give accurate results.

Proper use normally requires the steady flows for which orifices were intended and for which the orifice coefficients were developed. In actual field installations, flow is often not steady but subject to the periodic changes in pressure and velocity that are referred to as pulsation. Pulsation can be caused by compressors, pressure regulators, control valves, fluctuating loads, or by flow-induced phenomena within the piping. It is known and well recognized that pulsation causes errors in orifice meter results. In fact, A.G.A. Report No. 3 on Orifice Metering of Natural Gas, which is also API 14.3, clearly states that: "Reliable measurements of gas flow with an orifice cannot be obtained when appreciable pulsation . . . are present at the measurement point."

Although the potentially adverse effects of pulsation are well recognized, the nature of resulting error mechanisms and what should be done to correct such problems have not been well publicized. Discrepancies in orifice flow measurement are often reported by operating companies and in the open

literature, but the amplitude of the associated pulsation and the resultant errors are seldom measured or even considered. This paper will describe the types of pulsation-induced errors and measurements that should be made to identify pulsation effects on orifice metering. Pulsation affects both the orifice itself and the secondary system causing different errors in each part of the measurement system.

The first step towards eliminating pulsation-induced errors lies in identifying and understanding the error producing mechanisms. Through a continuing research effort, sponsored by the Gas Machinery Research Council (GMRC) of the Southern Gas Association (SGA), progress has been made in understanding the effects of pulsation on orifice metering. The dominant error mechanisms can now be identified and quantified. Effects on the secondary measurement equipment can also be identified and their relative importance considered. With proper pulsation measurements, conditions at an orifice can be judged to be acceptable or unacceptable for accurate flow measurement. When the meter site conditions are found to be unacceptable for accurate measurement, pulsation control techniques are available, as part of the SGA/GMRC program, to eliminate the pulsation.

PRIMARY ELEMENT ERRORS DUE TO PULSATION

Pressure and flow variations in the flow stream cause a change in the differential pressure across an orifice, which is a basic error in indicated flow.

Square Root Error

The most fundamental error at an orifice is the square root error (SRE). SRE results from averaging the differential pressure from a square law device before taking the square root. The differential pressure across an orifice is shown in the basic orifice relationship, Equation 1, which confirms that ΔP is proportional to flow rate squared. This square law relationship is also shown in Figure 1.

$$\Delta P = KQ^2 \quad [1]$$

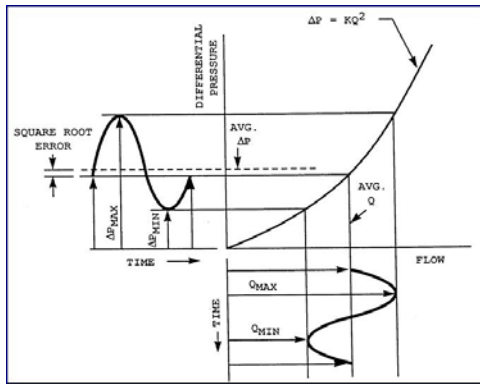


FIGURE 1. Orifice Relationship that Results in Square Root Error

Let us consider a flow that is modulating or pulsating, the differential pressure will follow the square law curve so that the average value of ΔP will not occur at the same point at which the average value of velocity occurs.

Because of the square law relationship, the average value of differential pressure is always higher than the ΔP , which

corresponds to average flow. The difference between the average differential pressure and the differential pressure that corresponds to average flow is referred to as SRE. This is a real condition or increase in ΔP that exists at the orifice plate. The SRE is independent of the secondary system used and is a direct result of averaging the differential pressure before determining the flow rate.

A mathematical definition of SRE can be developed from the fact that the average flow is proportional to the average of the instantaneous square root of ΔP as opposed to the square root of the average ΔP . That is to say, if the square root of the differential pressure is taken at every instant in time, and these square root values are averaged, the result will represent the correct flow in the absence of other errors. The incorrectly indicated flow is represented by the square root of the average differential pressure. Comparing the incorrect to the correct averaging can be expressed in Equation 2, where the percentage error in flow is related to the difference between the square of average ΔP and the average of square roots of ΔP :

$$E_f \% = \frac{\sqrt{\Delta P} - \sqrt{\overline{\Delta P}}}{\sqrt{\overline{\Delta P}}} * 100 \quad [2]$$

There are many approximate equations for SRE in the literature, but most of those that predate 1983 are incomplete. Because of the details that were omitted from earlier analysis, little progress was made in quantifying SRE until more recent developments under the GMRC's program at SwRI, which developed Equation 2. As a result of these advancements, a device called the square root error indicator (SREI), which uses Equation 2 with a microprocessor to measure SRE, has been developed and

patented. The SREI digitizes the differential pressure signal and determines the amount of SRE at an orifice. Using a fast response differential pressure transducer and an SREI, any company can determine if they have pulsation problems at their orifices.

To illustrate how SRE functions to measure or represent the error at an orifice, a sequence of pulsating flow tests have been performed. In these tests, two orifices in series measured the same flow stream. One orifice was isolated from pulsation by upstream and downstream pulsation isolation filters; so that it experienced steady flow at the same time the second orifice was exposed to pulsation of various frequencies. The difference between the flow inferred at the orifice subjected to pulsation and at the steady flow orifice is the total pulsation induced error. The heavy line in Figure 2 shows the amplitude of this total error over a range of frequencies used in the testing. The SRE was also measured during these tests and is plotted as the light line in Figure 2. The results of these tests clearly indicated that SRE accounts for most of the total error at an orifice in pulsating flow. Thus, SRE can be measured and used to indicate the presence of pulsation-induced error at an orifice. It is evident in the graph of Figure 2 that there are some other smaller errors at an orifice in pulsating flow.

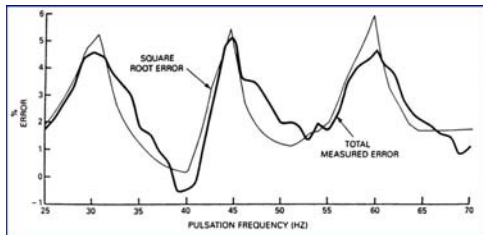


FIGURE 2. Total Pulsation-Induced Error and SRE at Various Frequencies

Inertial Error

Inertial error is one of the other primary element errors that can be clearly identified. Equation 1 does not describe the complete pulsation response of an orifice because it was developed with the assumption of steady flow. Developing an orifice equation from time dependent unsteady flow considerations, including the unsteady continuity and momentum equations, results in Equation 3:

$$\Delta P(t) = KV(t)^2 + L \frac{dV(t)}{dt} \quad [3]$$

In this equation, L is a coefficient of the rate of velocity change, which is dependent on certain dynamic properties of the orifice. Just as with a solid object, when gas is in motion through an orifice and the differential pressure changes (decreases), the gas tends to remain in motion due to its inertia. As a result of this inertia, flow velocity changes lag behind differential pressure changes and the simple relationship between ΔP and flow is distorted. On the orifice relationship plot as flow changes, the differential pressure is not always on the square law curve, which can be seen in Figure 3.

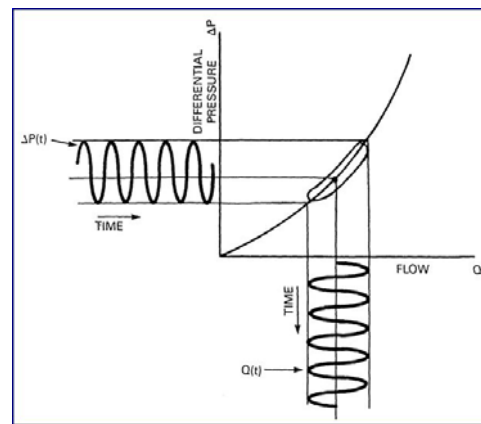


FIGURE 3. Inertial Effect on Orifice Coefficient for Rapidly Varying Flow

Inertial effects do distort the differential pressure but are unlike SRE in that inertia does not increase the average ΔP . Therefore, if we correctly average ΔP , the inertial error is eliminated but SRE is present. If the instantaneous ΔP 's are square rooted to eliminate SRE, the inertial error appears because it involves a change in the time-varying differential pressure. Fortunately, the inertial error is not as large as the SRE. In fact, inertial effects are insignificant unless the pulsations are fairly large in amplitude and at a relatively high frequency. It is, however, partially because of inertial errors that SRE measurements should not be used to correct measured flows, but primarily to determine if pulsations are adversely affecting an orifice installation.

Results from a large number of tests are plotted in Figure 4. The plot shows the residual error versus the differential pressure modulation. Residual error is defined as actual measured error in flow minus the SRE. If SRE were the only error in orifice measurement, then the residual error would be zero.

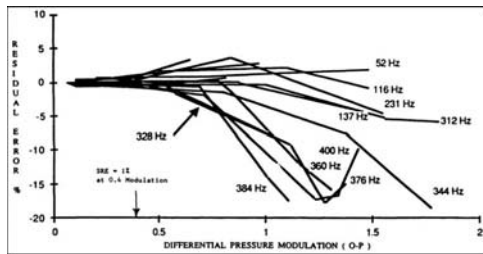


FIGURE 4. Orifice Response to Pulsations

In Figure 4, the residual error is near zero in the region where the differential pressure modulation is below 40 percent. Differential pressure modulation is the zero to peak variation in differential pressure divided by the average differential pressure. At larger modulations, above 40 percent,

Figure 4 clearly demonstrates that residual error becomes negative as a result of the inertial effect. Figure 4 also shows that for pulsation frequencies below 100 Hz, the inertial effect is generally small. Inertial effects are important if the pulsations are above 40 percent ΔP modulation and the frequency is above approximately 100 Hz. When inertia of the flow through an orifice does become significant, the differential pressure for a given flow is reduced. Thus, a negative error with respect to the SRE is produced. The most important feature demonstrated in Figure 4 is that up to a level of 40 percent differential pressure modulation, which corresponds to approximately 1 percent SRE for simple pulsation patterns, the response of an orifice to pulsation is predictable. At most metering installations, inertial effects will not cause significant errors.

Coefficient Shifts

The final error that affects the primary element, as a result of pulsation, is coefficient shift. In all of the discussions to this point, it has been assumed that the orifice flow coefficient, K , is constant. However, it is known that under some conditions, a change in the orifice coefficient is possible. Figure 5 shows the results of a coefficient shift.

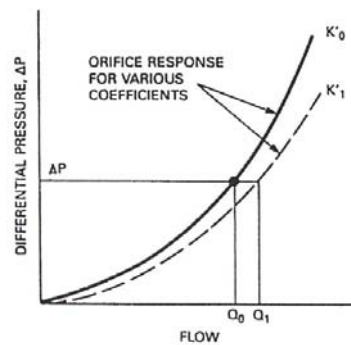


FIGURE 5. Effect of a Shift in Orifice Coefficient

Swirl and flow profile distortions are known to cause coefficient variations up to several percent. Furthermore, pulsations are known to cause distortion of average velocity profiles so there is reason to believe that pulsation was the cause of coefficient shifts. Because of other errors, it is difficult to specifically isolate pulsation-induced shifts in orifice flow coefficients. Throughout most of the orifice flow testing sponsored by SGA/GMRC and conducted at SwRI, with pulsation sources both upstream and downstream of the orifice, there has been no verifiable or consistent indication of coefficient shifts. However, many of these tests were performed at relatively low pressures and without the highest accuracy obtainable. This area of identifying possible coefficient shifts is the subject of continuing research efforts.

There is one exception that is significant for a few applications. The testing described above has been conducted on orifices with flange taps. SRE and inertial effects are applicable to other pressure tap locations such as vena contracta or pipe taps. The orifice coefficient for these other tap locations, and particularly for pipe taps, is not constant and is adversely affected by pulsation. For pipe tap orifices, pulsation definitely causes coefficient shifts. The dynamic response of a pipe tap orifice installation, with respect to changing coefficients, is such that it is not recommended for use where pulsation might be present.

SECONDARY ELEMENT ERRORS DUE TO PULSATION

Secondary recording systems always include pressure sensing lead lines, which will be referred to as gauge lines and chart recorders or electronic transmitters. Pulsation causes

several types of secondary system errors or incorrect responses, which can be as important or even more-significant than the primary element errors.

With flow, especially pulsating flow, through an orifice run, acoustic resonances can be excited in the attached gauge lines. Typically, a quarter-wave pressure pulsation will develop in a gauge line with the main piping or orifice end as a node and the closed end or pressure transmitter end as a pulsation maximum. Such acoustic resonances in gauge lines can have two very significant effects on the recorded differential pressure.

Gauge Line Amplification

The first effect is an amplification of the pulsation. An example of this is shown in Figure 6, which illustrates an actual case history and exemplifies the potentially adverse effects of high gauge line pulsation. In this installation, both a chart recorder and an electronic transmitter are connected to the orifice. If pulsation readings at the transmitter had been used to determine SRE instead of pulsation at the flange taps, greater errors would have been predicted than actually existed at the orifice. SRE measured at the orifice was 0.17 percent, while SRE measured in the gauge line at the electronic transducer was 11.8 percent. The SRE indicated at the chart end of the gauge line was low at approximately 0.3 percent. If the flow rate indicated by the chart had been corrected for SRE measured at the transmitter, then the inferred flow would have been more than 11 percent low.

In these tests, an SREI was used to measure the SRE at the orifice and also at other points along the gauge lines. The SREI has been licensed for commercialization and these devices make monitoring the pulsation

and determining the SRE simple and direct. When using an SREI, it is essential to recognize that SRE is a fundamental error that occurs at the orifice and can be correctly measured only at the orifice taps. SRE for orifice flow condition acceptability should not be measured at the recorder or at the distant ends of pressure sensing lines.

Gauge Line Attenuation

Gauge lines can also attenuate, distort, or hide the presence of pulsation, as shown in Figure 7. In this situation, which has been observed at a number of field installations, there are pulsations in the orifice run. The average ΔP , as seen across the orifice taps and on the chart, is high and incorrect.

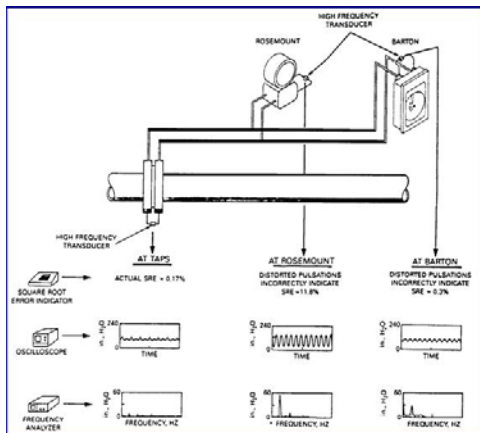


FIGURE 6. Results of Gauge Line Amplification of Pulsations

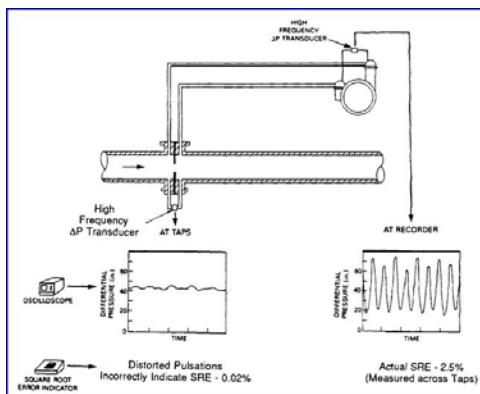


FIGURE 7. Attenuation of Pulsation in a Gauge Line

Because of gauge line attenuation, if an attempt were made (using proper high frequency response instrumentation) to determine the differential pressure modulation or the SRE at the chart location, no indication of the error would be present. The chart recording is in error, but there is no way for the measurement engineer, technician, or operator to be aware of the pulsation. Proper instrumentation needs to be placed across the orifice taps without the normal lengthy gauge lines attached.

Gauge Line Shifts

The second type of problem that pulsation in a gauge line can cause is a shift in the indicated pressure. While pressure shifts due to gauge lines have long been suspected, they have only recently been measured and verified. Figure 8 is an indication of what has been observed when careful measurements are made at points "a" and "b" on a gauge line. Not only is the pulsation amplitude different between points "a" and "b," but the average static pressure is different. This distortion of the differential pressure is totally a result of the gauge line, and not the orifice, but it can substantially effect the flow measurement.

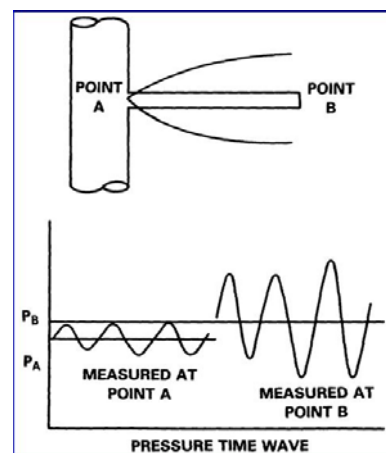


FIGURE 8. Typical Pressure Signals in a Gauge Line with Pulsations

As a practical matter, gauge line shift can sometimes be observed when metering valves are pinched. If the manifold valves leading to the recorder are pinched until the chart paint reduced, a change in average indicated differential pressure could often be observed. This process merely indicates that gauge line errors are probable, but neither reading is necessarily correct. Instead of pinching valves, excessive pulsation at the orifice should be eliminated.

Research into gauge line shifts is relatively new and the precise causes have not yet been completely quantified. Gauge line pressure shifts have been measured under laboratory and field conditions. Figure 9 shows the results of some careful laboratory measurements where a gradient in static pressure along the gauge line was verified.

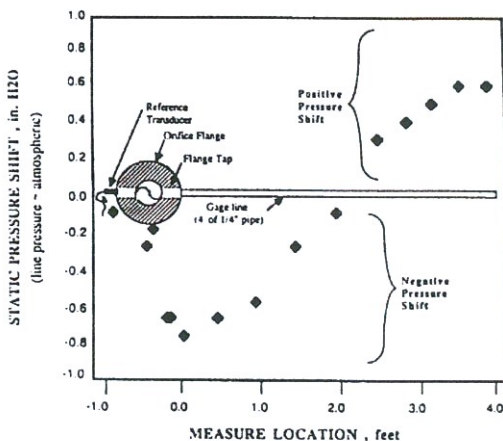


FIGURE 9. Static Pressure

Measurements along a Gauge Line

The causes of pressure distortions in gauge lines include rectification and kinetic energy effects. These occur most predominantly in gauge lines that do not have a uniform inside diameter. Rectification results from the fact that losses for flow into the gauge line are not the same as losses for flow out of the

gauge line. Research is still in progress to define these pressure distortions, while methods for predicting the amount of gauge line shift are being developed. Typically, gauge line shifts are one to a few inches of water. In measuring a single static pressure, gauge line shift makes little difference; however, in determining a differential pressure, the error can be significant. It has been found that if the pulsation in the main pipe and the gauge lines are small, gauge line shifts are less likely. If pulsations are kept to a minimum, the chances of avoiding any significant error due to gauge line shift are greatly improved.

Pressure Transmitter and Recorder Response

Secondary system errors can result from the response of the differential pressure transmitter or chart recorder to pulsation. Most of the differential pressure transducers used in gas metering, including mercury and bellows recorders, and electronic ΔP cells and transmitters, have a very poor frequency response. Typically, these devices will not track changes in the differential pressure that are more rapid than two cycles per second. Therefore, they do not follow the actual ΔP across the meter. These instruments cannot be used to determine the amplitude or even the presence of pulsation. Because such devices tend to average the differential pressure, they contain some SRE; but because of gauge line amplifications or attenuation, it is not necessarily the correct SRE. The signal from a pressure transmitter, which has a very low frequency response, does not contain the information necessary to determine the amount of SRE. It would be of no value to connect a computer that samples and calculates flow 200 times each second to a transmitter with a 2 Hz frequency response.

Flow computers have an important place in flow measurement, but they are not a panacea for pulsation-induced errors. The electronic monitoring and calculation of flow can also cause errors or inconsistency in results. An example of this, in Figure 10, illustrates a situation where a differential pressure transmitter with an adequate frequency response was being used on a process gas orifice meter. The plant's computer was used to compute the gas flow rate, but as indicated, the sample rate was every six seconds. Because of a dump valve cycle in the plant process, there was a three second transient in the flow every 12 to 13 seconds. The computer did not calculate the correct flow for several reasons including the fact that the apparent average differential pressure was not the true time average and the amplitude of modulation that might be associated with SRE was also not a correct indication. No matter what flow computer is used, if its sample rate is not adequate for the pulsation in differential pressure, it will not yield reliable results.

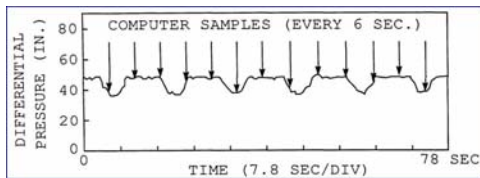


FIGURE 10. Computer Sampling in the Presence of Flow Transients

Chart recorders are commonly used to monitor the differential pressure at an orifice. It is frequently thought that chart paint is a result of pulsation at the orifice. However, chart paint is almost never a direct reproduction of pulsation by the recorder. Pulsations in gas piping systems are typically found above 5 Hz and below 100 Hz, with the 15 to 45 Hz range being very common. The frequency response of a chart recorder is usually less than 2 Hz. Chart recorders are not able to accurately respond to most pulsation.

At best, chart paint is a distorted, damped, and incomplete representation of pulsations, which are greatly suppressed in amplitude. In these cases, use of a fast clock will not produce an accurate ΔP record because the pen of the chart recorder is unable to follow the pulsation waveform. Typically, charts exposed to pulsation will not respond or paint at all and will appear smooth. If, on a 100 inch chart, the average flow corresponds to 72 inches and pulsation in the pipe is such that a 10 percent SRE is present, then the chart should show pulsation from just over 100 to below 45 inches. In other words, the upper half of the chart should be solid paint, but this is not what is actually observed.

Chart paint is often caused by phenomena other than orifice run pulsation. Sometimes chart paint is caused by actual periodic changes in the average flow rate such as engine governor hunting, regulator valve adjustments, or small adjustments in flow balance between parallel orifice runs. Even with steady flow and no pulsation in the orifice run, if there are pulsations that develop in the gauge lines, a change in ΔP on the chart can result, which will return to normal, causing paint, when the gauge line pulsation decay. Figure 11 is a chart record with paint from an installation where no pulsations were detectable in the main line piping. It should be clear that the presence of chart paint does not mean that pulsations are present.

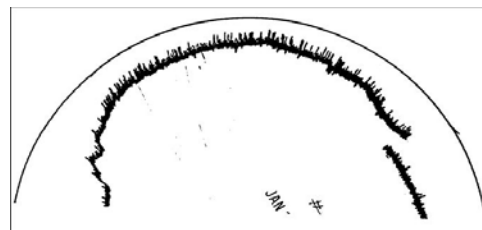


Figure 11. Chart Record from an Orifice without Pulsations

The last example in Figure 12 was taken from an installation at which a pulsation filter vessel could be valved in or out of service. When flow was passing through the filter and no pulsation was present, the chart shows some paint due to flow variation from the variable speed compressor. With no change in average flow or local conditions, the filter bottle was bypassed such that pulsation developed at the orifice. Although the nature of the paint change was little, the important change was the increase in ΔP and the corresponding error in flow that resulted from the pulsation.

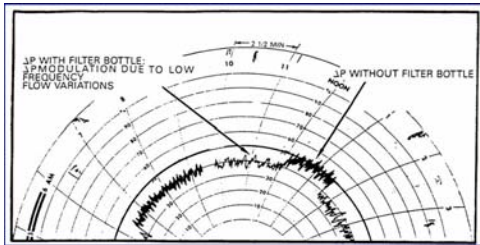


Figure 12. Orifice Chart Record without and with Pulsations

SUMMARY AND CONCLUSIONS

In view of the different types of pulsation-induced errors that can occur at the primary element and in secondary systems, it is useful to review what should be done to minimize pulsation effects on orifice measurement. Because the less definable influences of pulsation on orifice measurements, such as the inertial effect, average to zero overtime, and because most of the available ΔP transmitter or chart recorders have a slow response, the first step is to obtain the average differential pressure. This average should be taken often enough to account for normal variation in the flow rate. The second important step is to then place a fast response pressure transducer across the orifice taps and using an SREI, or at least an oscilloscope, measure the SRE or determine if there is any significant differential pressure modulation at the

orifice. If the measured SRE is small, such as less than 0.2 percent or if there are no noticeable pulsation, the orifice installation will have a high probability of yielding acceptable readings. If the measured SRE is at or over 1.0 percent or a very significant modulation in differential pressure exists, then the pulsation are large enough to cause other errors and will probably cause gauge line problems. Such pulsation should be corrected or eliminated through the use of acoustic filtering and pulsation control technology. If the measured SRE is in the middle range between 0.25 and 1.0 percent, then there are some additional checks that should be made and decisions that must be addressed by the operating company. For example, at a measured SRE of 0.5 percent, there will be approximately 1/2 percent positive bias in the flow and the possibility of other errors which, depending on the service, may or may not be acceptable. The third step, in any event, should be to use the fast response pressure transducer at the chart recorder or transmitter locations. This will not indicate the correct SRE value, but it will indicate if the pulsations have been amplified or significantly distorted along the gauge lines. If not all of these dynamic checks of the orifice installation indicate an error, the installation will most likely be acceptable. If, however, there are pulsation errors present, they should be corrected.

In conclusion, the following statements are derived from the work accomplished to date and can hopefully guide the application of this information and future investigations.

- Pulsations cause errors at the orifice primary elements, including the most significant square root error and other errors, such as inertial effects and coefficient shift.

- The amount of SRE can be measured with an instrument or the proper techniques and transducers, and can be used as an indicator of the severity of pulsation at an orifice.
- Pressure sensing gauge lines can amplify, attenuate, and distort pulsation such that recorders or transmitters are not exposed to the actual pulsation environment, resulting in incorrect indications of flow.
- When pulsations are present in the gauge line, shifts in average pressure can cause direct errors in measured flow.
- Chart recorders and the normal metering transmitters cannot follow the frequency of pulsation and cannot be used to detect, measure, identify, or compensate for pulsation.
- Where pulsations are eliminated or properly controlled, orifices can provide highly reliable and accurate gas flow measurements.