PULSATION MITIGATION AND ITS EFFECTS ON METERING

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Abstract

Accurate flow measurement is essential in today's custody transfer, transport, and allocation applications. However pulsations, which are frequently present at field sites, adversely affect flow meters and are one of the factors that must be mitigated in order to achieve accurate flow measurement. Pulsation is any periodic variation in pressure and flow velocity either at one location in a pipe or from point to point along the pipe. This paper not only discusses the sources of pulsation and briefly shows how pulsation adversely affects flow meters, but also presents methods for mitigation of pulsation effects. Properly designed acoustic filters are the most effective means for eliminating pulsation and a design method for a simple acoustic filter is presented. Other methods to control the sources, reduce the effects, or attenuate the amplitude of pulsation are also discussed.

Introduction

Accurate flow measurement has always been important in the Natural Gas Industry and is even more essential in today's responsive and demanding operating environment. Flow meters not only determine how much energy is bought and sold but how much a company is paid for production or transportation. With flow computers, real time monitoring and and daily or even hourly nominations and accounting of gas volumes and energy, a meter user is more likely to be confronted with evidence of flow measurement inaccuracies than in the days when monthly balances were used. If a gas delivery system tends to show consistent or repetitive daily imbalances, then there is most likely an error in measurement at one or more of the meters in the system. The economic impact of such an error is greater today than in earlier times. One of the most common and difficult to identify causes of a flow metering error is pulsating flow.

There are flow meters with a long history in the gas industry such as orifice meters and turbine meters and newer flow meters such as ultrasonic and coriolis meters for which there is less history and experience. However, none of these meters are immune to pulsation effects and although the mechanisms and specific effects of pulsation are different for different types of meters, pulsations do adversely affect nearly all types of flow meters. Knowing the basic mechanisms by which pulsations affect flow meters is important not only for understanding the errors in gas measurements but also for understanding how pulsation effects can be properly mitigated.

Experience has shown that various forms and magnitudes of unsteady flow, that we generally call pulsations, are present to some degree at most gas flow metering sites including both high pressure and low pressure sites. The common sources of pulsations in Natural Gas piping systems are:

- reciprocating compressors
- rotary screw or booster compressors
- centrifugal compressors
- pressure regulating or flow control valves
- rapid load or supply transients
- vortex shedding and similar flow induced phenomena
- fluidic instabilities such as run switching and slug flow.

Some details about how these sources generate pulsation will be given later in the paper.

Due to the fact that pulsations are common at flow metering sites, it can be expected that there is a need to mitigate the effects of pulsations at major gas metering installations. If a pulsation mitigation technique is not used, then it is prudent to demonstrate by field measurement that pulsations are not present at the meter site in question. One of the best methods for mitigating pulsation effects at a flow meter is to design an acoustic filter to place between the source of the pulsations and the meter. The simple volume choke volume acoustic filter described in this paper will eliminate pulsation over a designed range of flow conditions and pulsation frequencies. There are other methods that will mitigate (eliminate or reduce) the effects of pulsation on meters but these are not as reliable and effective as properly designed acoustic filters. This paper presents some background on the various ways to mitigate pulsation effects.

Pulsation and Its Sources

Definition

Pulsation is a periodic fluctuation in local pressure and velocity that, when present, occurs at each point in a piping system. Due to the physics of flows there cannot be a variation in local pressure (pulsation) without a corresponding variation in the local velocity. Conversely, if there is a change in local velocity along the pipe there will be a dynamic change in pressure along the pipe. When pulsations are present the instantaneous pressure at any point on in the pipe varies in time while the instantaneous pressure at other points along the pipe vary in time but in general at different amplitudes and phases. Pulsations travel as pressure waves, which move at the speed of sound in both the upstream and downstream directions from the source (disturbance). Figure 1 illustrates the ideal generation of pulsation waves and shows how both pressure and velocity variations travel in a pipeline.

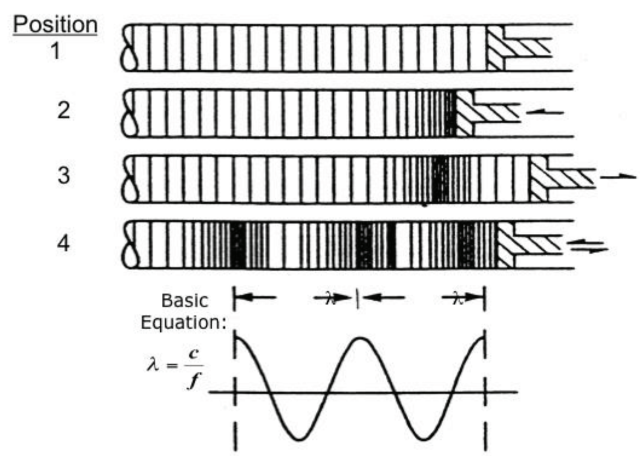

Figure 1. Illustration of Ideal Generation of a Pulsation Wave

Pulsation moves in a piping system as traveling waves and can be reflected from closed or open ends of the pipes. Closed ends are the blanked ends of headers, closed valves on branch lines, or similar terminations of pipe sections. Open ends are significantly larger diameters such as scrubbers or large diameter headers at the end of a pipe or locations where a small branch line connects to a larger diameter pipe. When traveling waves and their reflections meet or are both present in a pipe they add together to form peaks at some locations and valleys or minimums at other locations, which can appear as standing waves. Reflections from a closed end are the same as the arriving wave but travel in the opposite direction. Reflections from an open end are of the opposite sign as the arriving wave as shown in Figure 2. Standing waves occur at the natural resonant frequency of a pipe and have fixed locations of maximum amplitude (peaks) and of minimum amplitudes (nodes). Phase relationships in a standing wave are either in phase or 180 degrees out of phase.

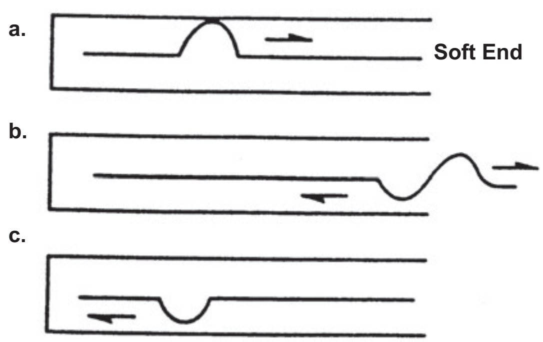

Figure 2. Traveling Acoustic Wave Reflection from an Open End.

When traveling waves add together to form a standing wave it is the same type of acoustic resonance as when an organ pipe tunes up to produce a musical tone. A specific pulsation frequency and its harmonics are associated with the acoustic resonance of any simple piping configuration. A pipe's resonant frequency is the speed of sound in the gas divided by length of the pipe element (between ends) times the fraction of acoustic wavelength involved in the resonance, such as a half or a quarter wavelength. Typical resonance conditions occur for half waves between two open ends or two closed ends while quarter waves occur between one open and one closed end, as shown in Figure 3. Multiples of the fundamental half or quarter wave resonant modes occur at higher frequencies for the same length of pipe. From the relationship between speed of sound, pipe length, and end conditions, the resonant frequency of meter runs, headers, or branch lines can be calculated.

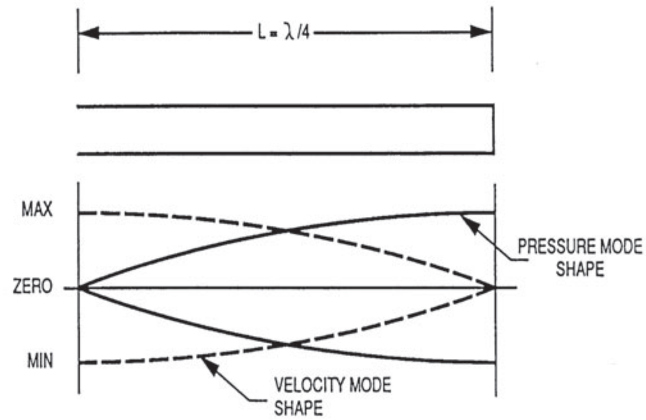

Figure 3. Quarter Wave Pulsation Resonance Between Open and Close Ends

The amplitude of pulsation in a piping system reaches its largest potential value at a resonant condition when the traveling waves and their reflections add together to form standing waves with pressure maximums in fixed locations and velocity maximums in other locations. Pulsation problems at metering sites almost always involve resonant conditions because that is when the amplitudes are the highest and the pulsation modes are stable and repeatable. Pulsation induced meter problems can exist at non-resonant conditions but any measurement error will be smaller and less regular. It is important to comprehend the resonant behavior of pulsations in piping in order to understand how a pulsation spreads from its sources, how it affects meters, and what actions will mitigate the effects of a particular pulsation.

Sources

Reciprocating compressors are a common and well-known source of pulsations. The action of pistons in cylinders, as idealized in Figure 1, combined with the sudden opening and closing of suction and discharge valves produces large amplitudes somewhat square pulses that include the fundamental and higher order pulsation frequencies. The frequencies produced by reciprocating compressors and the frequencies that are typical of acoustic resonances at flow meter installations are typically in the range from approximately 5 to 75 Hertz. Thus, although practical pulsations can occur from 0.5 to over 500 Hz, most of the significant problems at gas metering sites occur at frequencies that can be excited by reciprocating compressors. Rotary screw and other types of booster compressors also produce pulsations in this or a slightly higher frequency range. Therefore, all reciprocating compressors, screw compressors, and most booster compressors operating in the vicinity of gas meters should have pulsation control filters (volume-chock-volume) bottles designed for and installed on or at the compressor, as this is the best way to mitigate pulsations.

Centrifugal compressors generally produce high frequency low amplitude blade passing pulsation or moderate amplitude pulsations at lower frequencies due to flow phenomena within the compressor. Centrifugal compressors also provide flow energy that can contribute to vortex shedding, flow induced excitation, and fluid instabilities. There are also off-design operating conditions at which centrifugal compressors produce significant low to moderate-frequency pulsations that are related to stall, surge, or internal instabilities. Thus, pulsations that produce errors at flow meters, can be caused by centrifugal compressors. Pulsations that result from abnormal operations of centrifugal compressors or compressor system behaviors can often be mitigated by correcting the compressor operating conditions or modifying the system characteristics with respect to flow excitation.

Pressure regulating valves and flow control valves introduce broadband (wide frequency range) pulsations in flows under certain conditions. This type of pulsation energy is usually low to moderate in amplitude, however it can excite acoustic resonances in piping and meter runs with the result that large amplitudes appear at the system natural frequency. In practice, pressure regulating and flow control valves introduce dynamic changes in pressures and flows and piping systems sometimes amplify these pulsations. Rapid changes in flow demand or supply can also cause transient excitations to which the piping responds. Mitigating regulator or control valve pulsation involves changing excitation from the valves, changing piping responses, or providing acoustic isolation between the disturbance and the responsive pipe. More details on mitigating these pulsation behaviors will be provided later in this paper.

One type of pulsation source that does not require compressors, valves, or machinery of any type is the flow induced or self-excited pulsation phenomena. One common flow induced pulsation source is vortex shedding at a pipe branch or around an obstruction in the flow. Vortex shedding, which is normally low in amplitude can excite a piping resonance and thereby cause a large amplitude pulsation. One example of this is when flow passes over a closed off branch line or unused meter run at just the right velocity to produce vortex shedding at the frequency that excites the branch line quarter wave resonance. Figure 4 is an illustration of vortex shedding at a Tee junction with excitation of the branch line. This is exactly what happens when you blow across the top of a coke bottle to produce a tone. Vortex shedding can also occur at thermowells, within valves, in gauge or sample lines, at shutoff meter runs, in headers, or at other obstacles such as support struts or divider vanes. Vortex shedding takes place whenever flows pass over structures or across no flow branch lines and the amplitude of the resulting pulsation is usually very low but is dependent on the piping response. The size of an obstacle or diameter of a branch line and the velocity of the flow affects the frequency of the vortex shedding. Thus pulsation from flow-induced sources can be a problem at one flow rate and not at higher or lower flows. Other similar types of flow induced pulsation mechanisms such as flutter and galloping, involve flow passing over vibrating structures such as valve components, sample probes, or other elements in the flow. This behavior is similar to aircraft wing flutter or galloping of telephone lines in the wind. All of these flow induced pulsation sources are affected by size and position of the obstacle or branch line, by flow velocity, and by configuration of the excited piping. Mitigation of flow-induced pulsation involves changing the size of the obstacle or diameter of the branch line, velocity of flow, or acoustic length of the resonant pipe.

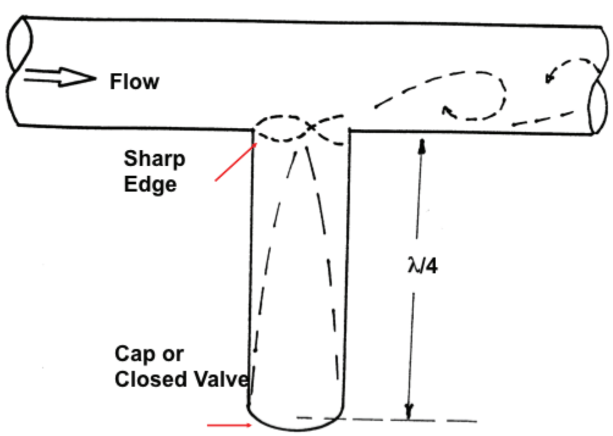

Figure 4. An Illustration of Flow Induced Vortex Shedding Exciting a Branch Pipe

Since the sources, including compressors, control valves, flow and load changes, and flow induced phenomena are common in meter piping and can cause pulsations, particularly when the piping is resonant at the excitation frequencies, significant amplitudes of pulsation and the resulting measurement problems often occur at meter installations.

Methods for Mitigation of Pulsation

There are several approaches to mitigating pulsation effects on gas flow meters and the most practical method for a particular situation depends on the source and frequency content of the pulsation, the piping configuration, and the type of meter. The best overall method for mitigating pulsation effects is the application of an acoustic filter. Acoustic filters are less dependent on the source of pulsation, the type of meter, or the piping responses than other mitigation methods, because acoustic filters isolate a meter from pulsation sources for all frequencies above the filter's cutoff frequency. There are many specific requirements and different configurations to consider when designing acoustic filters including the cutoff frequency required, the local flow velocity, the space available, and the pressure drop allowed. For other than the simplest, most basic application of acoustic filters, an experienced acoustic design engineer should be consulted to apply acoustic filter technology. The acoustic filter described in this paper is a simple symmetric in-line low pass filter that performs extremely well to eliminate pulsations from any source if the minimum frequencies to be filtered are known. The symmetric in-line acoustic filter can be used in many metering situations. This simple filter design is basic and can be applied by meter station design engineers to isolate meters. A step-by-step acoustic filter design method for simple symmetric in-line acoustic filters is presented later in this paper.

There are a number of other techniques for mitigating pulsation effects that can be considered for particular sources, piping configurations, or situations. Among the alternate pulsation mitigation methods are changing pipe length or diameter, changing meter location in the piping, taking a pressure drop at a selected location, adjusting control valve or control system responses, or using piping volume elements. Distance of the meter from the pulsation source is however, NOT an approach for mitigating pulsation because pulsations can travel extremely long distances. Low frequencies such as a 2 Hz pulsation have been measured at distances of over 20 miles from the pulsation source. Typical pulsation frequencies of 5 to 45 Hz can be present several miles from their source and high frequencies over 100 Hz have been observed hundreds of yards to a mile or more from the source. Thus, moving a meter to a location away from the pulsation source is not generally an effective or practical mitigation method. Separating a meter a considerable distance from a pressure regulator or flow control valves that produce high frequency noise can, in some cases, be effective.

A detailed consideration of meter location that places a meter, in a low response part of a piping run can be used to reduce pulsation effects in some cases. For example, a turbine meter, if moved to a location of minimum velocity modulation, will have greatly reduced pulsation-induced errors. The center of a meter run between two large diameter headers (open ends) is a location with negligible velocity modulations for the first order half-wave resonance as shown in Figure 5. For a specific meter run length and a natural gas with a certain speed of sound (depends on temperature and pressure) this half wave resonance only occurs at one frequency so this must be the pulsation frequency that is the problem or this mitigation method will not work. Pressure mode shapes are shown by solid lines and velocity modulation mode shapes are shown by the dotted lines in Figure 5. It is essential to understand the pulsation mode shapes to use this type of selected meter locating to mitigate certain pulsation problems.

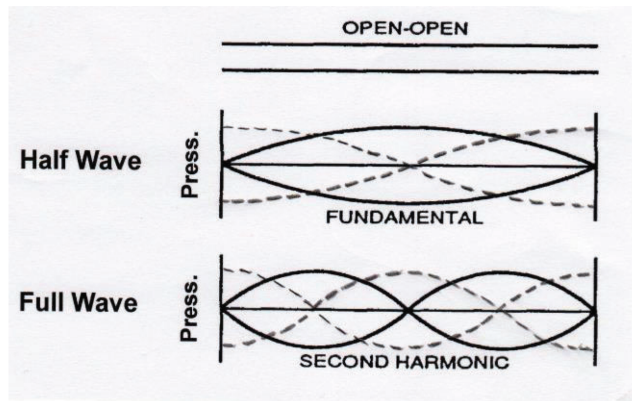

Figure 5. Half Wave and Full Wave Resonance Modes Possible in a Meter Run

A similar relocation of an ultrasonic meter to a location away from large velocity modulation will also reduce the pulsation effects. However, ultrasonic meters also need to be located away from high frequency sources to reduce the effect of noise as well as help reduce pulsation effects. Moving a flow induced pulsation source such as thermowells, branch connections, or other vortex producing disturbances away from high velocities or resonant piping can mitigate the occurrence of flow-induced pulsation. Relocation can, in selective cases, be a mitigation technique when the pulsation frequency is known and the pulsation mode shape (location of peaks and nodes) is determined. However, random relocation of a meter or addition of distance between the meter and source will almost never assure a reduction of pulsation effects.

Selecting pipe lengths to avoid resonant frequencies or placing a meter in a different pulsating condition by changing pipe length can be an effective mitigation technique when a specific pulsation frequency is known to be the problem. If a nearby compressor is to operate at a certain speed, the meter run and header lengths should not be designed as half wave or quarter wave lengths for that frequency or its harmonics. That is to say that meter runs, headers, and connecting pipe segments should NOT be simple fractions (1/4, 1/2) of the speed of sound divided by the compressor speed in Hertz. If the distance between fixed meter station headers is the wrong length, a possible resonant length, then changing the diameter of part of the meter run will change its effective length and avoid a pulsation problem. Changing the diameter of say the downstream third or part of a meter run following the meter can be a mitigation technique because a change in diameter changes the acoustic length of a pipe. However, in the case when a compressor speed varies significantly, there may not be an acceptable pipe length that can avoid all potential pulsation problems in which case an acoustic filter should be considered.

A change of length can be very effective in the case of a branch line that is excited by vortex shedding. Changing the branch line length can prevent the resonance and significantly reduce the pulsation amplitude. For orifices, the gauge line length should generally be short but should also be selected to avoid resonance at compressor or other excitation frequencies. A change in pipe length can be considered for any resonance pipe if the change will eliminate pulsation rather than just change the pulsation frequency.

One method by which the amplitude of pulsation in a line can be reduced, with few other effects or changes, is to take a pressure drop. Pressure drop through a restricting valve or orifice will not, in general, eliminate a pulsation or change its frequency but it will reduce the amplitude. If a very large pressure drop, near 50 percent of the line pressure can be taken, then the pulsation can be completely eliminated. However, taking a major pressure drop is not practical in most cases. Under normal conditions, a restricting orifice, placed near a velocity modulation maximum, will reduce the amplitude of pulsation and mitigate its effect but it will not eliminate the pulsation entirely.

One pulsation effect reduction method that applies specifically to orifice meters is to reduce the beta ratio of the orifice so that DP is increased while the pulsation amplitude remains constant, as this will reduce the pulsation error. In most cases, changing the orifice size will not affect the amplitude of pulsation coming from a source. The best general solution for orifices, turbines, ultrasonic, and other meters remains to use an acoustic filter and thereby filter out the pulsations.

A final comment on pulsation mitigation methods other than acoustic filters is that large vessels or volumes are not acoustic filters and will not eliminate or completely remove pulsation but they will in many cases attenuate or absorb some pulsation amplitude. Therefore, although they will not be effective in all cases, scrubber vessels and large header where they are to be installed should be used to help reduce pulsation amplitude.

Pulsation Effects on Meters Without Mitigation

It is important to know how pulsations affect flow meters of various types in order to determine if pulsation is adversely affecting a meter and to understand what to change to mitigate the pulsation effects. Several common natural gas custody transfer meters and how they are affected by pulsations are discussed in the following paragraphs. More is known about the pulsation responses of traditional flow meters such as orifice and turbine meters than about the newer meters, such as ultrasonic or coriolis meters because there has been less research and experience with the newer meters, however some behaviors of these meters in pulsation flow are known and useful for planning mitigation steps.

Orifice Meters
In the case of orifice meters, pulsation affects both the primary measurement device (orifice tube) and the secondary system (gauge lines and transducers). The most basic pulsation induced error at an orifice meter is called square root error (SRE) because it is the result of averaging the differential pressure across a square root controlled device. Flow through an orifice is proportional to the square root of DP and what should be averaged to determine flow rate is the square roots of the instantaneous DPs. However, accurate and repeatable transducers, even of the modern smart type, cannot follow pulsating changes in DP sufficiently rapidly for the instantaneous DP to be measured. Therefore, the average DP is determined and pulsation must be controlled to avoid significant SRE. Figure 6 shows the relationship between DP and flow rate for an orifice and indicates what happens when the flow is fluctuating.

As seen in Figure 6, there is a DP that corresponds to the average flow rate and an average DP that is higher. As pulsating flow velocity increases to a maximum, DP follows the square law curve to a maximum DP and then as velocity decreases to a minimum, DP follows the curve to a minimum DP. Because of the square law curve, the maximum DP is farther above the DP that corresponds to the average flow rate than the minimum DP is below the DP that corresponds to the average flow rate. Therefore, when the DP signal is averaged, which is what transducers attached to orifices do, the average DP is higher than the DP that corresponds to the average flow rate. This real difference across the orifice plate between what the average DP is and what it should be for the same flow rate as a steady flow is a pulsation effect and is known as the square root error (SRE).

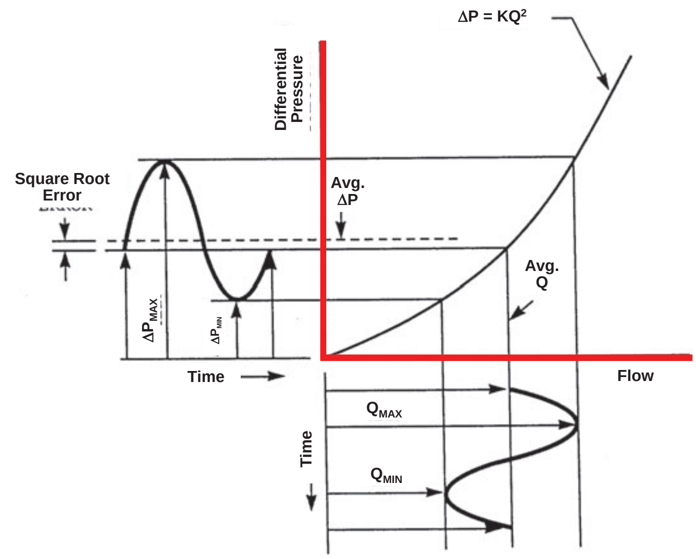

Figure 6. Square Root Error Results from Pulsation Effect on Orifice Square Law Curve

SRE is always positive and increases with increasing pulsation amplitude. SRE is a data processing error that results from averaging the DP signal before taking the square root but this cannot be avoided because of the low frequency response and basic capability of stable and accurate DP transducers. However, using fast response DP transducers, that are less accurate, a mathematical relationship can be used to determine the magnitude of SRE, as shown in Equation 1. This method for determining SRE is a patented process developed at SwRI during research sponsored by the Gas Machinery Research Council and is the basis for the commercially available Square Root Error Indicator that measures the magnitude of SRE.

$$SRE\% = \frac{\sqrt{\overline{\Delta P}} - \overline{\sqrt{\Delta P}}}{\sqrt{\overline{\Delta P}}} * 100 \qquad \text{Equation 1.}$$

SRE is not the total pulsation induced error at an orifice meter. When tests that measure the difference between actual flow and flow indicated by an orifice subjected to pulsation are conducted and SRE is measured, it can found that SRE accounts for most but not all of the pulsation induced error. Most of the difference between total error and SRE is the inertial error. It can be shown mathematically that inertia in a changing gas flow through an orifice causes a differential pressure across an orifice that is needed to accelerate or de-accelerate the gas stream. A good feature of the inertia effect is that when averaged over time it averages to zero. However, a negative feature of the inertia effect is that if the instantaneous DPs are square rooted to eliminate SRE, then the inertia effect is not zero.

It has been found through years of research and hundreds of tests that SRE is a good indicator of the amount of pulsation effect at an orifice but that it is not an exact or total measure of pulsation effects. SRE cannot be used to correct an orifice measurement for the effects of pulsation but it can be used to indicate if pulsation is causing a problem at the orifice. Allowable pulsation levels according to the latest API 14.3/AGA Report No. 3 standard are given as a 10 percent RMS variation in the DP, which corresponds to a SRE of approximately 0.125 percent. In summary, pulsation does adversely affect orifice meters, SRE will not accurately correct the measurements, and the best way to reduce orifice errors due to pulsation is to mitigate the pulsation levels at the meter. Successful mitigation can be confirmed by tests, which show a low SRE.

Pulsation also affects the secondary system of an orifice including gauge lines and transducers. Gauge lines that connect an orifice fitting to the transducers can amplify a pulsation signal or attenuate the pulsations and in the process, change the apparent DP. When gauge line amplification occurs, as shown in Figure 7, the actual pulsation amplitude and SRE at an orifice can be small such that the effect of pulsation on the orifice is negligible. However, pulsation at a transducer can appear large and if SRE is determined at the end of the gauge lines there is an apparent pulsation error. Gauge line amplification is usually a result of a gauge lines being resonant at the pulsation frequency or a higher order. It should be noted that measurements to determine SRE should always be made close coupled to the orifice and not at the ends of gauge lines.

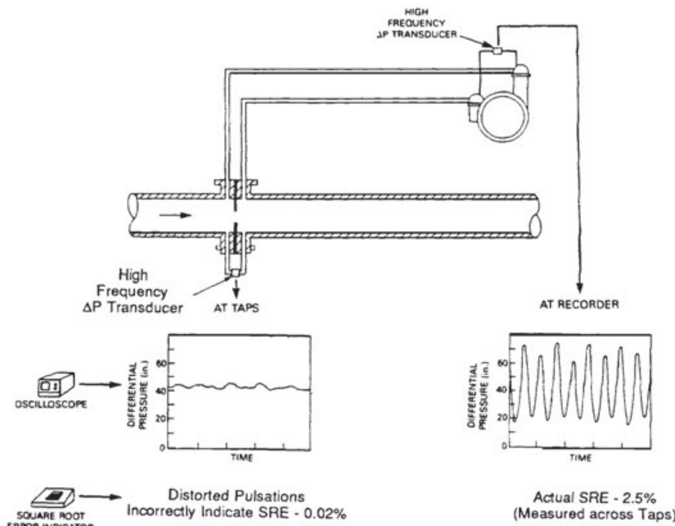

Figure 7. Amplification or Orifice DP in the Gauge Lines

The opposite of gauge line amplification is attenuation, which can occur when gauge lines are not responsive to the pulsation that is present. When attenuation occurs, there can be large pulsation amplitudes and a significant SRE at the orifice while there is no indication of pulsation or an error at the ends of the gauge lines. If attenuation is present (not common) and SRE is not measured at the correct location (directly connected to the orifice), then a pulsation error can be missed.

Gauge line shift is a change in DP along the length of a gauge line that is known to occur and results from several phenomena when gas is alternately flowing into and out of a gauge line. Results of laboratory measurements of pressure along a gauge line with pulsation are shown in Figure 8. There is a change in the pressure at the entrance to the gauge line and a pressure gradient along the gauge line. One of several reasons for these changes in gauge line pressure under dynamic conditions is that the resistance to flow into the gauge line is less than the resistance to flow out of the gauge line. There are other mechanisms involved in gauge line shifts, which are frequency dependent. Research has shown that the amplitude of gauge line shift is related to the velocity head and is usually only a few to 10s of inches of water. However, a few inches of water out of perhaps 30 to 50 inches of DP can produce a large measurement error.

Pulsation effects or interactions with transducers that measure orifice flows are an issue of sampling the data correctly. To sample pulsation information from a fast response transducer, data must be taken at more than twice the pulsation frequency. However, if the transducer is a slow response device like the smart transmitters used in the gas industry, then sampling at a high frequency will not provide more information. A transducer should be sampled at approximately two times its update rate or one to a few times a second. Sampling a transducer slower than its response rate will cause data about flow changes to be lost and possible errors to develop. In order to diagnose pulsation

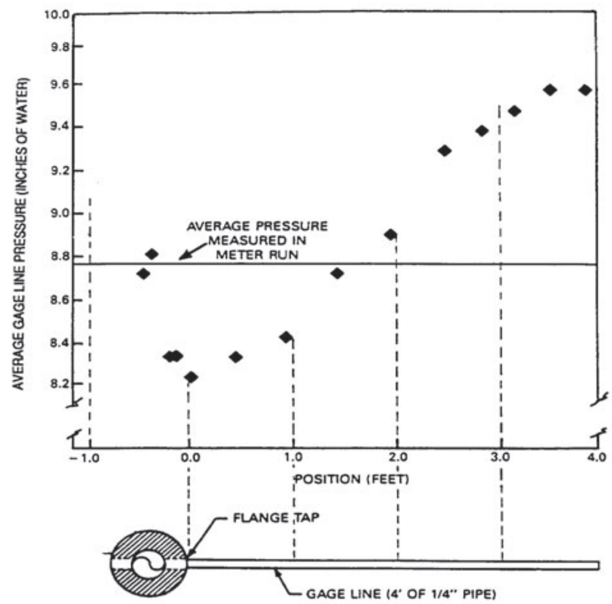

Figure 8. Measured Pressure Along a Gauge Line Indicating a Shift in DP

errors at an orifice, a trained person using a proper SRE Indicator should measure SRE. To eliminate or reduce secondary system errors due to gauge line and transducer response at an orifice, the first step is to shorten and change the responses of the gauge line while the second step is to reduce pulsation amplitude at the meter. Thus mitigating pulsation amplitude at a meter and in the gauge lines will eliminate errors at an orifice meter.

Turbine Meters

Turbine meters are repeatable, wide range, direct indicating flow meters that have advantages in selected metering application. Turbine meters are adversely effected by pulsation, which can cause errors from low levels to over 50 percent depending on many factors including pulsation frequency, modulation amplitude at the meter location, flow rate, gas density, and both meter and pulsation properties. The effects of pulsation on turbine meters are somewhat complex but when an error is caused, it is almost always a positive or over registration error. Given this complexity, the industry standard, AGA Report No. 7, indicates that pulsation causes a positive error in turbine meter measurements that is dependent on all the factors mentioned above. The standard also indicates that to avoid errors, pulsation should be eliminate by filtering or reduced by increased pressure drop between the source and the meter.

A number of tests have been conducted with turbine meters in pulsating flow and some results are shown in Figure 9 where the zero percent baseline is the steady flow calibration for the meter. The pulsation-induced errors in this test vary from 0 to over 20 percent at different flow rates and different frequencies. The reasons that the results in this case depend on the pulsation frequency is that in the test piping as frequency changes the pulsation mode shape and resulting velocity modulation at the meter changes. Turbine meters are velocity measuring devices and are susceptible to velocity variations in pulsating flow rather than pressure variations.

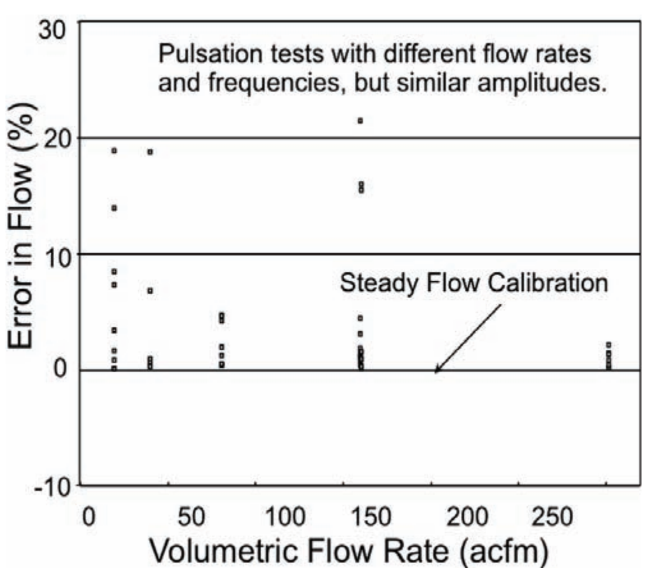

Figure 9. Pulsation Test Results for a Turbine Meter

Thus, at some frequencies, the velocity modulation at the meter is large and the error is large while at other frequencies, with the same overall pulsation level, the velocity modulation at the meter is small and the error is small. Pulsation effects at a turbine meter can be mitigated by reducing the pulsation amplitude or by changing the meter location with respect to the pulsation mode shape such that the velocity modulation at the meter location is reduced.

There is a theory of how pulsation effects turbine meters, which can be used to predict the magnitude of meter error if a number of key parameters about the pulsation frequency, amplitude, and mode shape and about the flow rate, gas density, and meter design are known. The most difficult parameter to know at a turbine meter is the magnitude of the velocity modulation through the meter. In a laboratory where the velocity variations at the meter were measured with a hot film anemometer, the theory was used to predict the meter error, as shown in Figure 10. It is clear from the result that if the velocity modulation at the meter's location can be measured, then the approximate errors at turbine meters can be predicted and if the local velocity modulation can be reduced, then the pulsation effect on the turbine meter can be reduced.

What Figure 10 indicates about mitigating pulsation effects on turbine meters is that if velocity modulation at the meter can be reduced by filtering, reducing the amplitude of velocity modulation with pressure drop or other changes, or placing the meter at a location of low velocity modulation then the pulsation error can be greatly reduced.

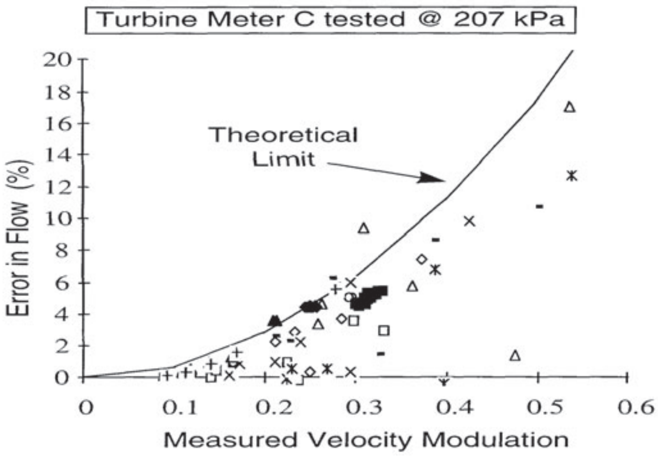

Figure 10. Pulsation Error at a Turbine Meter as a Function of Velocity Modulation

Ultrasonic Meters

Ultrasonic meters are one of the newest and most popular meters for measuring large volumes of gas flow but they are adversely affected by pulsation. Ultrasonic meters measure the transit time of high frequency acoustic pulses that travel in both the upstream and downstream direction across one or more paths that traverse the pipe. The difference in these transit times is a direct indication of the gas velocity in the pipe. The measured times are affected by velocity profiles, acoustic signal characteristics, and steadiness of the flow and must be corrected for these effects.

Most ultrasonic meters interrogate the flow velocity many times a second, but average and report the results approximately once per second or every few seconds and therefore do not track or report changes that take place during pulsating flow. Many newer ultrasonic meters do measure and report the variation of velocity for each path over a averaging time. Most meter manufacturers call this value turbulence, however it is NOT a measure of turbulence but rather a measurement of the unsteadiness or pulsation in the flow. Although this diagnostic output from advanced ultrasonic meters is mislabeled as turbulence, it can be a useful indication of pulsation or large scale changes in velocity being present in the flow. If the reported "turbulence" value is below a few percent, there is not a significant pulsation level or flow disturbance at that meter. However, if the reported "turbulence" (not actually turbulence) level approaches or is higher than 10 percent, then it is extremely likely that a troublesome pulsation is present at the meter.

Careful testing has confirmed that pulsation does adversely affect ultrasonic meters in some conditions. Although there is a lot to learn about ultrasonic meters in pulsating flow some tests have been conducted that indicated pulsation errors can vary from of tenths to 4 to 7 percent or more. Figure 11 is a typical test result for an ultrasonic meter in pulsating flow.

Depending on the meter sampling rate and pulsation frequency a large amplitude pulsation at an ultrasonic meter can show up as an indicated "turbulence" signal. These "turbulence" levels cannot be used to determine pulsation error but can indicate that pulsation are present and indicate the effectiveness of any mitigation steps.

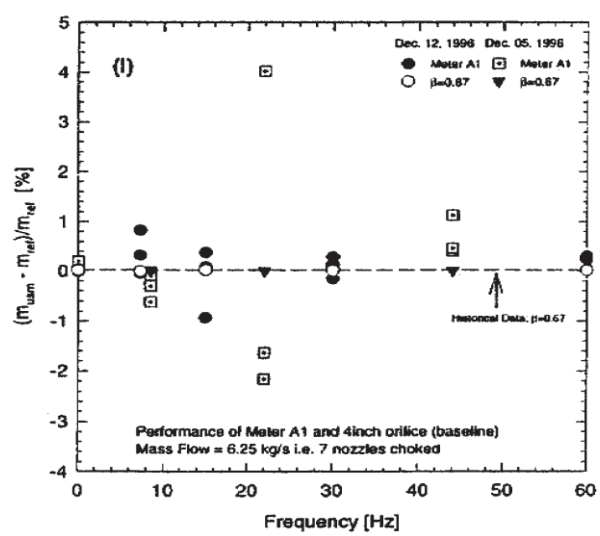

Figure 11. Typical Pulsation Effects on an Ultrasonic Meter

One of the reasons that pulsation effects ultrasonic meters is that pulsation is known to change the average velocity profile as shown in Figure 12 and ultrasonic meters are known to be sensitive to velocity profile shape. Some types of ultrasonic meters can be adjusted for velocity profile shapes and these meters could be adjustable for improved results in pulsating flow. However, the meters that can be adjusted for velocity profile effects could only be properly adjusted if calibrated in the same pulsating conductions as found in the field. Any meter adjusted for a given pulsating flow would not be accurate in steady flow or other pulsating flow conditions. Thus, adjustments for pulsating flow are impractical, not generally reproducible, and should NOT be done. Another reasons ultrasonic meters are effected by pulsation is that noise or broadband energy from sources such as pressure regulating valves can interfere with the characteristics of the acoustic pulses and with detection of the arrival time of transmitted pulses. In these cases, a practical solution is to reduce or eliminate pulsation and acoustic noise at the meter location or to change the frequency range and content of the transmitted timing pulses.

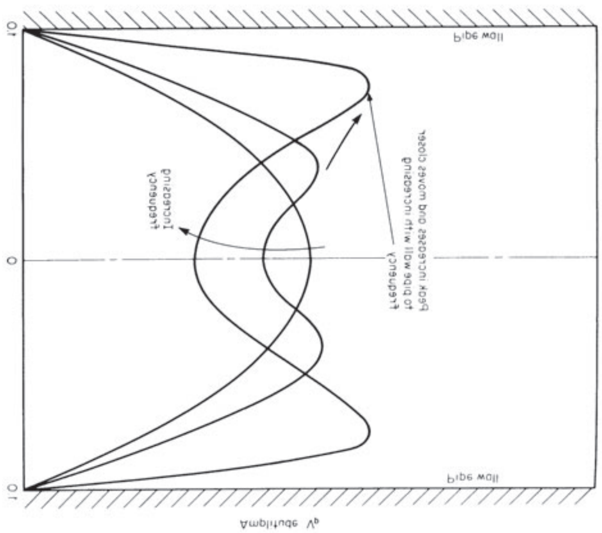

Figure 12. Average velocity profiles without and with Pulsations of moderate and high amplitudes.

Other Meters

Most other meters that are used for fuel flow measurements, unit flow measurements, and check measurements including Coriolis meters, pitot probes or annubars, V-cone meters, venture meters, and vortex shedding meters that are all adversely affected by pulsation. The differential producing meters are affected by pulsation in the same basic way that orifice meters are affected. Coriolis meters are generally affected by the vibrations caused by pulsation and by flow limits and can be severely affected at some frequencies and less affected at other frequencies. Pitot probes and the multi-port pitots, such as annubars and similar devices, have the same type of responses as gauge lines and therefore are adversely affected by pulsation. Some frequency specific adjustments can be made to some meters such as vortex shedding meters to correct for certain pulsating flow but this is not a correction for all pulsation conditions. Rotary type positive displacement meters are an exception and are not significantly affected by pulsation but do produce pulsation as a result of their operations and can adversely effect parallel or nearby meters. In general, the best approach for eliminating errors in pulsating flow is to filter or otherwise mitigate the pulsation levels.

The Solution - Acoustic Filter Design

The best method for controlling pulsation is to place an acoustic filter between the pulsation source and the flow meter to be protected. There are many approaches for designing acoustic filters and most should be applied to specific situations by experienced acoustic design engineers. The filter design described in this paper is a symmetric, in-line low pass, acoustic filter that performs extremely well and can be used in metering situations to eliminate pulsation in selected frequency ranges. This filter design is basic and can be applied by meter station design engineers. As the name implies, the subject filters are low pass filters that let pulsation below their natural frequency pass through and filter out (reduce the amplitude of) pulsation at frequencies above their natural frequency. One property of this type of filter that must be considered is that it amplifies pulsation at and near its natural frequency and therefore, pulsation energy that is to be controlled should never be coincident with the filter's natural frequency. These filters are placed directly in the mainline and are symmetric, meaning that the acoustic length of each element, a volume, a choke, and another volume are the same. Other types of filters can take up less space, can be non-symmetric, can be used on side branches and can be extremely effective when properly designed by acoustic filter experts. Symmetric in-line acoustic filters are effective and easy to apply in metering applications.

The things that need to be known in order to design a symmetric in-line acoustic filter are the operating conditions including pressure, flow rate, and most importantly, the frequency of pulsation to be eliminated. The following steps and simple equations can be used to size an appropriate volume – choke – volume filter. The first step is to calculate the frequency to use as the natural frequency of the filter, which must be at least 20 percent and preferably 30 percent below the lowest frequency to be eliminated. The lower this frequency the larger and more costly the acoustic filter so that if a higher frequency is found to be adequate, it will be more economical. In the simplest design approach, the selected natural frequency for the filter (fo) should be at least 20 percent below the lowest pulsation frequency to be eliminated. Additionally, the selected natural frequency should not correspond to any known pulsation energy in the system.

The second step is to determine the choke tube size. The choke tube internal velocity is selected to be approximately 100 feet per second at the highest expected flow rate. Slightly higher choke tube velocities can be used to reduce the filter size if a higher pressure drop is acceptable. A lower choke tube design velocity can be used to reduce pressure drop. However, to be effective, the choke tube must take some pressure drop and have a minimum velocity at the lowest flow rate of approximately 10 to 15 feet per second as a typical secondary guideline. If your design calls for a wider flow range than from approximately 120 to 10 feet per second, then an acoustic filtering experts should be consulted. A design method that achieves a maximum choke tube velocity of approximately 100 feet per second is adequate. With a known volumetric flow rate (q) in cubic feet per second, the following equation gives the first estimate of choke tube inside diameter in inches. The actual inside diameter of the choke tube selected should be the next standard pipe size of heavy wall pipe, that is larger than the calculated inside diameter.

$$IDc = 1.354*(q)^{0.5}$$

Heavy wall pipes should be used within acoustic filters because the dynamic forces from pulsation, which are eliminated past the filter, act on the filter elements.

After the choke tube size is determined, the third step is to calculate the inside diameter of the filter bottles, which must be at least four times larger than the coke tube diameters in order to be acoustically effective. However, it is practical to choose a filter bottle diameter that is 8 to 12 times larger than the choke tube diameter so that the filter length will not be excessive. Select a practical first guess for the filter bottle inside diameter (IDb) in inches that has a heavy wall thickness. After selecting an available bottle inside diameter, the acoustic length for filter elements can be calculated from the next equation,

$$Lf = 0.225*c*IDc / (fo*IDb)$$

where c is the speed of sound in ft/sec and fo in Hz is the planned natural frequency of the filter. If this length is unreasonable or uneconomical, then a different inside diameter for the bottle can be selected as long as it is at least four times the inside diameter of the choke tube.

Adjustments to the length of the acoustic filter elements are that the bottles are built to a length that accounts for the dished heads. The seam-to-seam length of the bottle is such that the internal volume with the heads is the same as the acoustic length times the cross sectional area of the volume based on the selected IDb diameter. The second adjustment, because of acoustic end effects, is that the physical length of the choke tube is reduced by 1.2 times its inside diameter. Then the filter elements can be assembled in order as a volume – choke – volume filter, as shown in Figure 13.

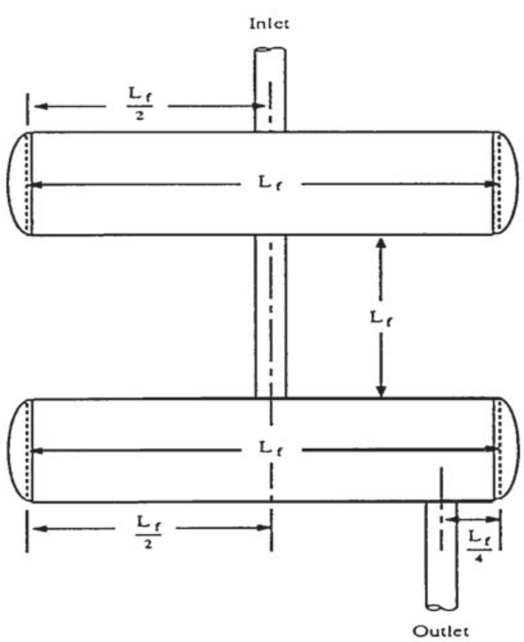

Figure 13. Symmetric Inline Acoustic Filter

Details of the acoustic filter design include considerations such as the inlet pipe should enter the acoustic center of the first filter volume while the outlet pipe comes off at the 1/4 acoustic length point from the second bottle. If this arrangement is not used, then selected frequencies called pass band frequencies will propagate through the filter and not be eliminated. The choke tube connects the centers of the two acoustic filter bottles. The main lines where they enter the bottles can be of whatever size the main piping is, which is usually larger than the choke tube and smaller than the bottles. The pipe connections to the bottles should be reinforced with saddles or pads and should not use weld-o-lets because of the high local stresses caused by weld-o-lets.

As an example calculation, consider a case where a reciprocating compressor is operated between 300 and 360 RPM, is always double acting, and is affecting a meter run located approximately 200 feet from the suction of the compressor. Double acting compressors tend to cancel or significantly reduce the amplitude of their fundamental pulsation and show higher pulsation amplitudes at the second and fourth orders. For the example compressor, the fundamental pulsation ranges for 5 to 6 Hz and the second order ranges from 10 to 12 Hz. The second order needs to be filtered out and the natural frequency of the filter should not coincide with the fundamental pulsation. In this case, the natural frequency of the filter can be placed at 8 Hz, which is between the highest frequency for the fundamental and the lowest frequency for the second order and is over 20 percent below the main pulsation frequency to be eliminated (10 to 12 Hz).

The flow rate in our example is 10.5 MMSCFD at a pressure of 925 psia and a temperature of 75 °F with a 0.61 specific gravity gas. The volumetric flow rate is found to be 2.038 cubic feet per second and the speed of sound is calculated as 1416 feet per second. The equation for the choke tube diameter is used with the result of 1.933 inches. A practical choke tube ID of 1.939 inches, which is heavy wall two-inch pipe, is selected. The filter bottle inside diameter would have to be at least 7.75 inches but to avoid an awkward layout, an inside diameter of 13.124 inches is selected. This is a 14-inch heavy wall pipe. With this diameter, the acoustic element length can be calculated from the length equation to be 5.888 feet. Because of the end effects, the physical length of the choke tube should then be 5.694 feet. The resulting acoustic filters can be constructed as a one bottle design with a baffle separating the two equal acoustic size filter volumes. The choke tube is then entirely internal to the bottle, the ends of the choke tube should be supported, and the baffle plate should be as thick as the bottle walls. The single bottle arrangement of the acoustic filter is shown in Figure 14.

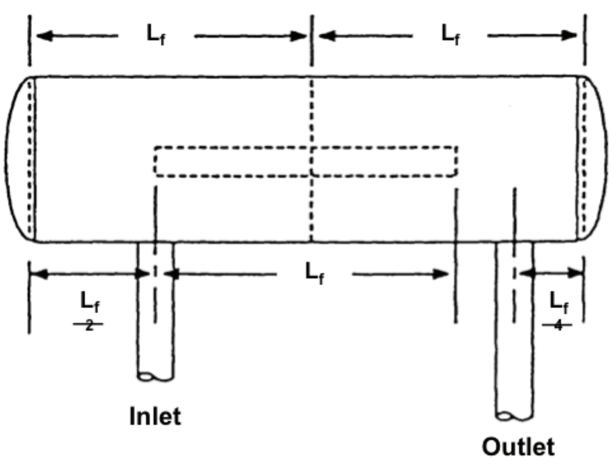

Figure 14. Single Bottle Arrangement for Volume-Coke-Volume Acoustic Filter

As with all pressure vessels, both chambers of the filter bottle should have drain connections. The inlet pipe connects to the center of the first chamber but the outlet pipe connects from the 1/4 acoustic length of the second volume. The choke tube length is shortened by 1.2 times its ID as before and a bell month can be added to the inlet side of the choke tube to reduce pressure drop with no effect on the acoustics.

Conclusions and Recommendations

There are many known sources of pulsation in gas flow lines and pulsations from these sources are frequently found at field meter sites. These pulsations do adversely affect nearly all gas flow meters with different mechanisms such as Square Root Error and velocity modulation effects. By evaluating pulsation sources and pulsation effects on meters, a number of mitigation methods can be understood and applied. The most effective and applicable pulsation mitigation method is the use of acoustic filters. The other pulsation mitigation methods include changing pipe lengths and diameters to change resonant frequencies, relocating meters to low velocity modulation locations, using pressure losses to reduce pulsation amplitudes, and adjusting control responses and operating conditions. Only the acoustic filter is both highly effective and widely applicable. Simple in-line symmetric acoustic filters, designed in accordance with steps presented in this paper, are one of the most effective methods for mitigating pulsation effects in gas flow metering. For many mitigation methods, including for acoustic filters, knowing what pulsation frequencies must be controlled is essential.