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Pulsation Effects on Orifice Meters

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Pulsation Effects on Orifice Meters

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Abstract

The effects of unsteady differential pressure on orifice meter accuracy have been discussed in many technical articles. However, there is still some confusion in the industry concerning the different causes of this phenomenon. More importantly, the different techniques which are used to minimize the resulting flow measurement errors are not universally understood.

Acoustic resonances that are associated with the internals of the orifice meter and gage lines can affect measured differential pressures. Such internal resonances are present in all orifice meters where the differential pressure transducers are installed on orifice taps some distance away from the orifice plate.

Errors can also result from improper averaging of differential pressures. These problems are usually categorized as “square root errors”.

Digital flow meters can minimize the classical square root error problems by calculating flows based on instantaneous differential pressure, instead of the average pressure. However, if the differential pressures are modulated by “false pulsation” due to gage line resonances, the computed flow rates will be incorrect when square root corrections are applied.

In the following text, these phenomena are discussed in detail. Techniques for reducing errors attributable to square root errors and/or the effects of gage line pulsation are presented. Case histories illustrating pulsation effects on orifice meters are also included.

1. Introduction

Orifice meters have been used to measure the flow rate of natural gas for almost 100 years. Despite the invention of many other types of flow meters during this period, today there are tens of thousands of orifice meters in use in gas transmission stations alone. It is estimated that approximately 80 percent of all flow meters are orifice meters [6].

Orifice meters rely on the principle that pressure drop across an obstruction is proportional to the square of the flow rate. A typical orifice meter is shown in Figure 1.

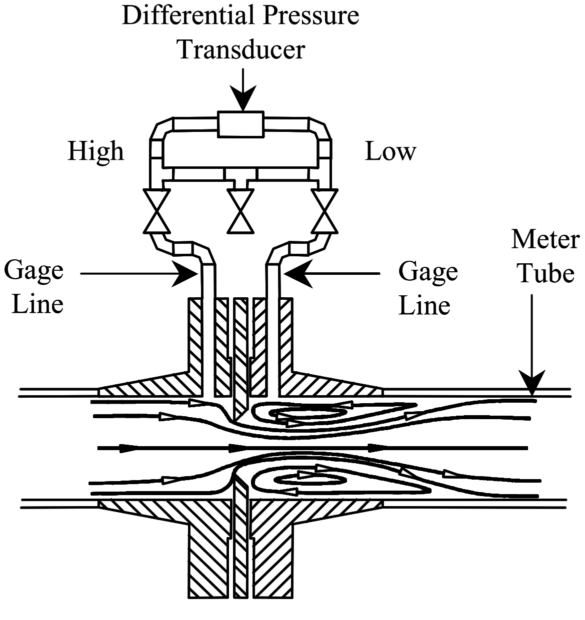

Figure 1 – Typical Orifice Meter

In principle, any device capable of inducing pressure drop can be used. However, sharp-edge orifice plates are relatively simple to produce and have well-known characteristics over a wide range of flow conditions.

The pressure drop across an orifice plate is typically measured using a differential pressure transducer. Within the transducer, pressure from either side of the orifice plate is applied across a diaphragm. The resultant measurement is the difference in pressure at any instant in time, which can be converted to flow if the characteristics of the orifice plate are known.

This arrangement works well for steady flow. However, if there is modulation of the instantaneous differential pressure across the orifice (known as Dynamic Differential Pressure, or DDP), the measurement may be corrupted (termed a Meter Error). Even though most meter errors are small, the resultant costs can be large, especially on pipelines where the flow rates are measured in hundreds of MMSCFD.

Due to the widespread use of the orifice meters, much research has been conducted on the effects of DDP on the accuracy of the meters. The results of these research projects have been described in many technical papers and in manuals published by the American Gas Association (AGA) [1-4].

The adverse effects of pulsation have been known for many years. In fact, the AGA has stated that erroneous differential pressure averaging is the most dominant and frequently encountered flow measurement error. In addition, the AGA has stated "reliable measurements of flow cannot be obtained with an orifice meter when appreciable pulsations are present at the point of measurement. Currently, no satisfactory theoretical or empirical adjustment for orifice measurement in pulsating flow applications exists that, when applied to custody transfer measurements, will maintain the measurement accuracy predicted by this standard" [3].

Although new electronic flow meters (smart meters) have minimized many of the classical flow root error problems due to real pulsation, gage line pulsation can still result in measurement errors in some installations.

Following are case histories illustrating this point. Various pulsation problems with electronic orifice meters, and methods to reduce the pulsation amplitudes and the effects of the pulsation on the meters are presented.

2. Causes of Dynamic Differential Pressure (DDP)

There are two basic causes of unsteady differential pressure that can cause meter error – (1) unsteady flow through the orifice and (2) pulsation due to gage line resonances. DDP errors due to flow modulation through the orifice can be reduced by square-root error correction methods. However, gage line resonances can be corrected only if that component of the pulsation can be isolated and removed.

2.1 Unsteady Flow in Meter Tubes

Unsteady flow in orifice meter tubes at gas transmission stations are generally the result of oscillatory flow induced by reciprocating compressors. The flow modulations are a result of intermittent flow through the compressor suction and discharge valves. In double-acting compressors, pulsations occur primarily at 1× and 2× running speed. The pulsation levels are generally lower at higher harmonics of running speed (unless acoustical resonances in the system amplify the higher frequency pulsation).

The pulsation amplitudes at each harmonic can vary significantly depending on the head-end and crank-end cylinder loading. These uneven loading conditions occur when compressors are operated at various load steps with different combinations of cylinder unloaders and variable pocket settings.

Acoustic filters are sometimes installed at gas transmission stations to attenuate the pulsation levels in the suction and discharge piping systems. Generally, these filters consist of two volumes connected by a relatively small diameter pipe (choke tube). The combination of these acoustic elements produces a "low-pass" filter, which attenuates pulsation at frequencies above its "cutoff" frequency (Helmholtz frequency), Figure 2. Normal practice is to design the Helmholtz frequency below the lowest pulsation frequency to be attenuated. Effective pulsation reduction can usually be achieved for pulsation frequencies above approximately twice the Helmholtz frequency.

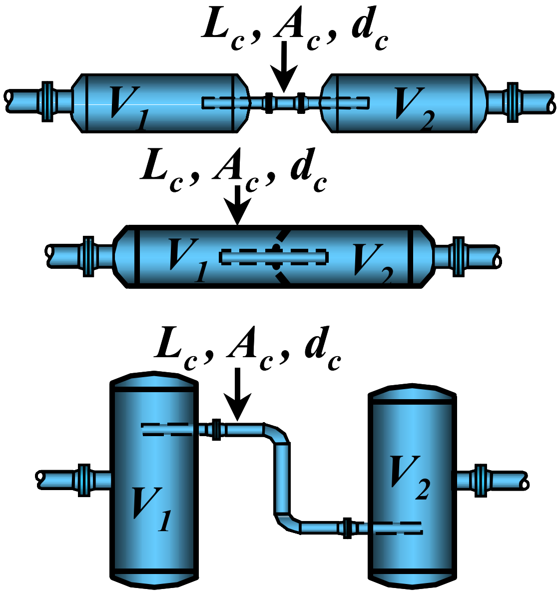

Figure 2 – Typical Helmholtz Acoustic Filter

$$f = \frac{c}{2\pi}\sqrt{\frac{A_c}{L_c^{'}}\left(\frac{1}{V_1}+\frac{1}{V_2}\right)} \tag{1}$$

Where,

f = Helmholtz frequency (Hz)

c = speed of sound (ft/s)

A_c = Area of choke tube (ft^2)

L_c = Length of choke tube (ft)

$L_c^{'} = L_c + .6d_c$ (ft)

d_c = Choke diameter (ft)

V_1 = Volume of primary bottle (ft^3)

V_2 = Volume of secondary bottle (ft^3)

Acoustic filters are sometimes designed assuming that the head-ends and crank-ends of the cylinders are evenly loaded, such that the pulsation occurs primarily at 2× running speed. Problems can occur when pulsations are generated below the Helmholtz frequency because these pulsations will not be attenuated. This can occur when the compressors are operated at speeds below the design speed, or more commonly when the head-ends and crank-ends of the cylinders are not evenly loaded. Depending on the location of the cut-off frequency, the pulsation levels at 1× running speed may not be attenuated and can even be amplified. As discussed in Case History No. 1, problems of this type can generally be corrected by designing acoustic filters with the cutoff frequency below 1× running speed.

2.2 Acoustic Resonances of Meter Tubes

Pulsation levels in meter tubes can also be amplified in installations with multiple meter tubes when only 1 or 2 tubes are in service and several tubes are blocked on one end and open on the other ends. The dynamic flow into and out of the tubes, which are closed on only one end can sometimes increase the flow modulation (pulsation) in the flowing tube(s).

Field data obtained during the tests discussed in Case History 2 indicated that blocking both ends of the non-flowing meter tubes could significantly reduce the dynamic differential pressures in the flowing tube(s).

2.3 Gage Line Acoustic Resonances

As defined by the AGA, gage lines (impulse lines) are tubing or piping which connect the pressure taps on the primary element (meter tube) to the secondary element (recording device or transmitter). In cases where the flow transmitter is connected directly to the orifice taps, gage lines refer to all of the fittings and the internal passages between the taps and the differential pressure transducer.

In some instances, acoustic resonances of the gage lines can result in erroneous indicated flow rates. A gage line can be approximated acoustically by a tube with one end open (orifice tap end) and the other end closed (differential pressure transducer end). The fundamental acoustic mode of this system is typically referred to as the quarter-wave acoustical resonance.

The quarter-wave acoustic natural frequency can be approximated using the following equation.

$$f = C/4L \qquad (2)$$

Where,

f = quarter-wave acoustical natural frequency, Hz

C = speed of sound in the gas, ft/sec

L = effective length of the gage line between the orifice tap and the transducer, ft

If the acoustic natural frequency of the gage lines is near or coincident with the frequency of pulsation in the meter tube, the pulsation levels at the pressure transducer at the end of the gage line can be amplified by a factor of 20 or more. In this case, it may be impossible to distinguish between dynamic differential pressures caused by this acoustical resonance from those caused by actual flow through the meter.

Keeping the gage lines very short to ensure that the quarter-wave stub frequency is well above the pulsation frequencies generated by the compressors can usually minimize this problem. Many manufacturers recommend mounting the flow transmitter directly on the orifice taps to minimize the lengths of the gage lines. This problem is also illustrated in Case History No. 1.

Mounting the flow computer or transmitter directly on the orifice taps will usually raise the gage line acoustic natural frequency out of the range of significant excitation from the reciprocating compressor; however, this acoustic natural frequency can also be excited by flow turbulence. In some cases, the errors due to this pulsation at the gage line acoustic natural frequency can be very high as discussed in Case History No. 2.

3. Flow Calculations for Unsteady Flow

The instantaneous flow rate through an orifice can be represented by the ideal orifice equation below:

$$Q(t) = C \times \operatorname{sign}\left(\Delta P(t)\right)\sqrt{\left|\Delta P(t)\right|} \qquad (3)$$

Where,

$Q(t) =$ Instantaneous flow rate

$C =$ Orifice flow number (including density, flow coefficient, etc.)

$\Delta P(t) =$ Instantaneous differential pressure

$$\operatorname{sign}\left(\Delta P(t)\right) = \begin{cases} -1 \text{ if } \Delta P(t) < 0 \\ +1 \text{ otherwise} \end{cases}$$

The flow number C is actually a function of flow rate, density, etc. However, for the purpose of this paper, it will be considered constant. In practice, digital flow meters can account for this variation.

Note the use of the absolute value in conjunction with the sign of the differential pressure in the orifice equation. This is used to account for flow reversal through the orifice when the dynamic differential pressures are very large and cause the instantaneous differential pressure to be less than zero.

The ideal orifice equation was developed for steady flow conditions. In the presence of dynamic flow modulation, the accuracy of the equation is unknown. At very low flow modulation frequencies, the equation should be accurate. At intermediate frequencies, the equation should at least provide a reasonable approximation. At very high frequencies, the equation may be invalid.

In practice, digital flow meters measure differential pressures at discrete times and average them over some interval of N points. The discrete form of the ideal orifice equation is:

$$\overline{Q} = \frac{C}{N}\sum_{i}^{N}\operatorname{sign}(\Delta P_i)\sqrt{|\Delta P_i|} \qquad (4)$$

Where,

$\overline{Q} =$ Average flow rate

$\Delta P_i =$ Discrete differential pressure

$N =$ Number of discrete pressure measurements in the interval

The so-called square-root-error (SRE) is caused by the way the average is performed. The error occurs when the flow is determined from the square root of the average differential pressure, instead of the average of the square root of the instantaneous differential pressure, as shown below:

$$\overline{Q}_{\text{error}} = C \times \operatorname{sign}\left(\sum_{i}^{N}\Delta P_{\text{i}}\right)\sqrt{\frac{1}{N}\left|\sum_{i}^{N}\Delta P_i\right|} \qquad (5)$$

By dividing $\overline{Q}_{\text{error}}$ by $\overline{Q}$, the flow number C is eliminated:

$$\frac{\overline{Q}_{\text{error}}}{\overline{Q}} = N \times \frac{\operatorname{sign}\left(\sum_{i}^{N}\Delta P_i\right)\sqrt{\frac{1}{N}\left|\sum_{i}^{N}\Delta P_i\right|}}{\sum_{i}^{N}\operatorname{sign}\,(\Delta P_i)\sqrt{|\Delta P_i|}} \qquad (6)$$

The SRE can be calculated as shown below:

$$\text{SRE\%} = \left(\frac{\overline{Q}_{\text{error}}}{\overline{Q}} - 1\right) \times 100\% \qquad (7)$$

The above equations are only valid if the measured differential pressures are due to actual dynamic flow modulation through the orifice.

4. Using Filtering to Minimize Gage Line Pulsation Errors

To account for unsteady flow modulation through an orifice meter, proper calculation techniques as discussed in the previous section can be used to minimize the flow error. However, if gage line pulsation is present, it cannot be properly accounted for in this way. Gage line pulsation must be removed from the differential pressure signal before the flow calculations are performed. This can often be achieved by using an electronic filter.

5. Effect of Differential Pressure Wave Shape

The shape of the differential pressure wave has an effect on the flow error. In the simplest case, the dynamic pressure is approximately sinusoidal. The differential pressure will have a sinusoidal shape if the pulsation at the meter occurs primarily at a single frequency.

However, in many situations, the dynamic differential pressure may not be sinusoidal. This can occur if the flow modulation through the orifice is composed of multiple frequencies, or if significant orifice flow modulation is combined with pulsation from gage line acoustical resonances at different frequencies.

Therefore, to obtain the correct SRE, the differential pressure signal has to be sampled using a high sampling rate, relative to the expected pulsation frequencies. Sampling rates of approximately 10-50× the expected highest pulsation frequency are usually sufficient.

Figure 3 is a plot of differential pressure vs. time for an orifice. This wave shape was generated for purposes of illustration, and represents an extremely non-sinusoidal shape.

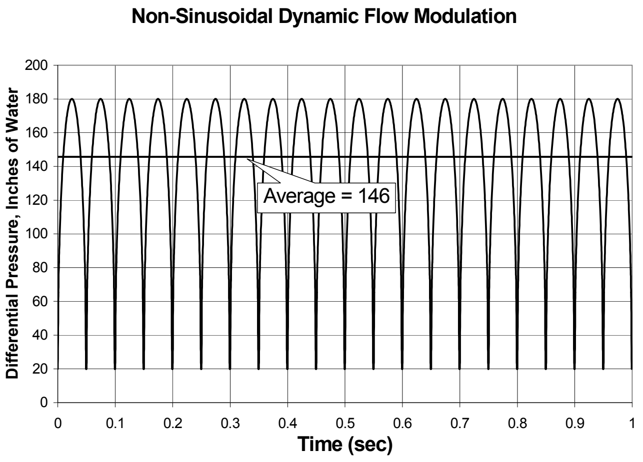

Figure 3 – Non-Sinusoidal Dynamic Differential Pressure Wave

Some statistics about this wave are shown in the table below:

Peak-to-Peak Differential Pressure	160 inches of water
RMS Differential Pressure	35.7 inches of water
Minimum Differential Pressure	20 inches of water
Maximum Differential Pressure	180 inches of water
Average Differential Pressure	145.6 inches of water

For this case, let us assume that the orifice *C* value is 1, so that the flow is simply the square root of the differential pressure. There are several techniques that we might use to estimate the flow that is represented by this differential pressure:

1. We could assume that the DDP is due to flow through the orifice. We could then apply a square-root correction to obtain a better estimate of the flow.
2. We could assume that the DDP is due to gage-line acoustical resonance. In this case, we would use the average differential pressure for the flow calculation.
3. We could use the measured peak-to-peak pulsation, and use Figures 4 and 5 to obtain an estimated SRE value.
4. We could use the measured rms pulsation, and use Figures 4 and 5 to obtain an estimated SRE value.
5. We could average the square root of the peak and minimum differential pressures to obtain an estimate of the flow. This would be similar to the equation used by the AGA to compute the corrected differential pressure [1].

The results of each of these techniques are shown in the table below:

Correction Technique	**Indicated Flow**
1. SRE Correction Using Instantaneous Pressures	11.95
2. Using Average Differential Pressure	12.06
3. SRE Correction Using Peak-to-Peak Differential Pressure	11.82
4. SRE Correction Using RMS Differential Pressure	11.97
5. Using Min/Max Differential Pressures	17.88

As shown in the table above, each potential correction technique computes a different value of indicated flow. Which value is correct? Although some techniques will always be better than others, the answer is that you do not know which flow is correct. The correction technique that must be applied depends on the causes of the differential pressure. Without a good understanding of the causes of the dynamic differential pressure, it is impossible to know how to minimize its effects.

The AGA states that "accurate measurement of flow with an orifice meter operating under pulsating flow conditions can be ensured only when the root mean square (rms) of the fluctuating differential pressure amplitude normalized over differential pressure time mean does not exceed 10%".

$$\Delta P_{\mathrm{rms}} / \Delta P_{\mathrm{avg}} \le 0.10 \qquad (8)$$

In other words, the dynamic differential pressure rms amplitudes should not exceed 10% of the average differential pressure. For a pure sine wave, rms values can be converted to peak-peak values by multiplying by $2\sqrt{2}$, or 2.828. Therefore, for a pure sine wave, the AGA allowable dynamic differential pressure peak-peak amplitudes would be approximately 28% of the average differential pressure.

To illustrate the sensitivity of the SRE to dynamic differential pressure levels, SRE values were computed for a range of dynamic pressures from 0 - 2.4 times the mean differential pressure (DDP Ratio). The calculations were made for rms and peak-peak dynamic differential pressures of a single frequency sine wave, and are plotted in Figure 4.

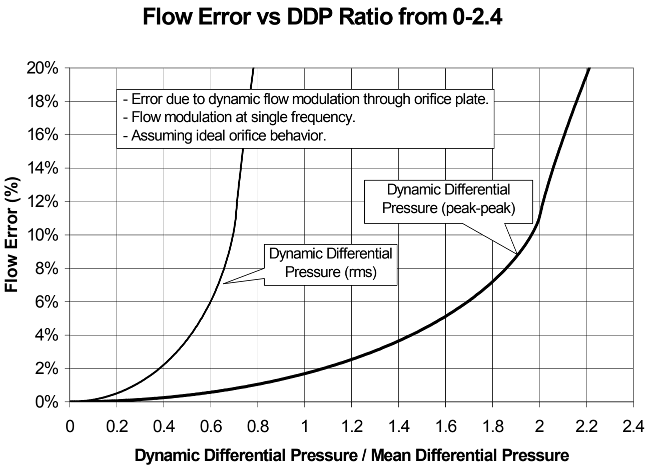

Figure 4 – Flow Error vs. DDP Ratio from 0 - 2.4

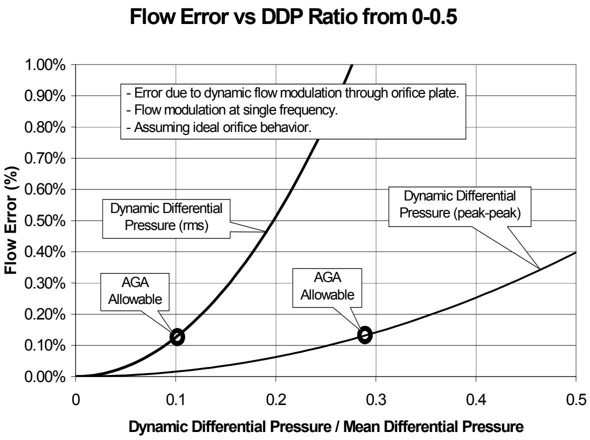

Figure 5 – Flow Error vs. DDP Ratio from 0 – 0.5

Figure 5 is the same data plotted for the 0 – 0.5 DDP Ratio range. This illustrates that the AGA allowable dynamic differential pressure of 10% *rms* results in an SRE of approximately 0.13%. Similarly, the allowable dynamic differential pressure of 28% *peak-peak* also results in an SRE of approximately 0.13%.

The plots in Figures 4 and 5, can be used to estimate the SRE for a measured dynamic differential pressure. Conversely, the plots can be used to estimate the dynamic differential pressure amplitude for a given SRE value. For example, some companies have an allowable SRE value of 0.25% for flow rates above 250 MMSCFD, which means that the allowable dynamic differential peak-peak pressure levels would be approximately 40% of the average differential pressure.

When the dynamic differential pressures exceed the average differential pressure (peak-peak pressures = 200%, and rms pressures = 70% of average differential pressure), the instantaneous differential pressure is negative and flow reversal occurs. As shown in Figure 4, the SRE equals approximately 10% when the flow reversal occurs. Also, note that the flow reversal causes the shape of the curves to change at SRE values greater than 10%.

Some references have reported SRE values well over 10% (in some cases up to 37%). As shown in Figure 4, to obtain an SRE value of 37%, the peak-peak dynamic differential pressures would have to be approximately 2.8 times the average differential pressure. The data presented in these cases is limited; therefore, it is difficult to determine the exact cause(s) for the excessive SRE values. However, a review of these cases, suggest that these were not classical SRE problems, but were due to excessive pressure drop when an acoustic filter was installed in the system.

6. Estimating DDP Error

The above calculations demonstrate how DDP problems can occur in instruments that average the differential pressure signals before computing the square root. This group of instruments includes analog transmitters and chart recorders. DDP errors can also occur as a result of gage line resonances.

Special instruments, such as the SRE-4 Indicator and the GLE/SRE Indicator [13,14], have been specifically developed to estimate DDP error. These systems include a portable differential pressure transducer which is installed near the transmitter or chart recorder. The signal from the differential pressure transducer is digitized and analyzed with a laptop computer, which estimates the DDP error values.

If one of these special instruments is not available, the DDP error can be estimated using a differential pressure transducer, and a digital voltmeter or an oscilloscope. The differential pressure transducer should be installed near the transmitter or chart recorder. The signal from the pressure transducer can then be analyzed using a voltmeter or an oscilloscope (or suitable A/D data acquisition system).

Volt Meter – The DC voltage represents the average differential pressure and the AC voltage represents the dynamic differential pressure in rms units. The ratio of the dynamic differential pressures and the average differential pressure can be computed and the DDP error can be evaluated based on the AGA limit of 10% rms.

Oscilloscope – Again, the DC voltage represents the average differential pressure. The ratio of the peak-to-peak voltage and the average voltage is computed. The DDP error can be evaluated by comparing with the 28% peak-peak guideline.

If the raw signal from the permanently installed analog transmitter is available, then that signal can be analyzed directly without installing the portable differential pressure transducer. In this case, the signal from the transmitter can similarly be analyzed using the voltmeter or oscilloscope as described above. If the transmitter includes a feature for adjusting the damping of the output signal, the damping should be turned off to obtain the maximum dynamic signal.

7. Digital Flow Meters

As discussed, digital flow meters are not usually subject to classical square root error problems. These devices typically compute the instantaneous flow rates every second and then compute minute-average flow rates.

These devices have potential problems when the dynamic differential pressures are greater than the static differential pressure, such as when the pulsations in a gage line are excessive. As previously discussed, when the dynamic differential pressures exceed the average differential pressure, the instantaneous pressure is negative indicating that flow reversal occurs. Depending upon how the flow computer is configured, the computer may or may not compute the flow if the differential pressures are negative (below zero). If the flows are not computed for that sample, the measured flow rates will be much smaller than the actual flow rates.

8. Case History No. 1 – Classical Gage Line Resonance Problem

This case history deals with orifice meter problems at a gas storage facility. Three compressors operating at 300 rpm (5 Hz) are used to inject gas into storage caverns. The injection flows are measured with five orifice meters located on the suction side of the compressors, Figure 6. The indicated flow rates between the five orifice meters were considerably different, especially Meter No. 5, which always read higher flows compared to the other tubes.

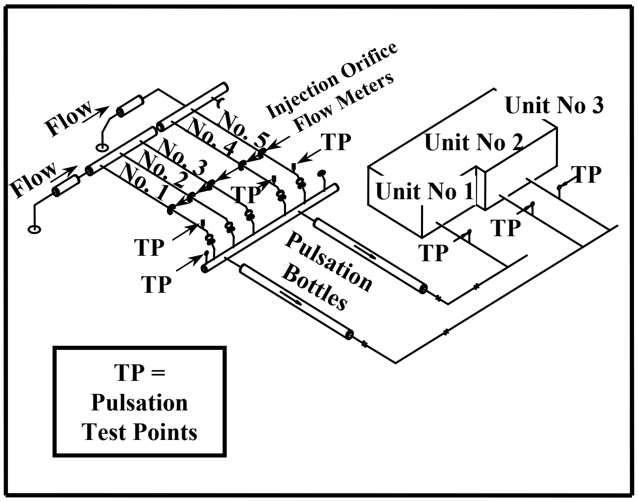

Figure 6 – Station Suction Piping and Meter Piping

Field tests at the compressor station indicated that the flow meter errors were due to a combination of the following problems.

1. The differential flow transmitters and computers were installed in individual housings where chart recorders were originally installed. The gage lines between the orifice plates and the differential flow transmitters were very long and ranged from approximately 25 feet on Meter No. 1 to 55 feet on Meter No. 5.
2. The pulsations generated by the compressor were amplified by the quarter-wave acoustic natural frequencies of the gage lines. As shown in the table in Figure 8, the acoustic natural frequencies of gage line No. 1 and No. 2 were near 2× running speed, and gage line No. 5 was near 1× running speed. These resonances amplified the pulsation in the meter tubes, which in turn caused the measured flow rates to be too high.
3. The acoustic filter bottles between the compressors and the meter tubes attenuated the pulsation generated by the compressors at frequencies above 5 Hz; however, the filter bottles did not attenuate the pulsation at the compressor speed of 5 Hz. This indicated that the Helmholtz frequency for the filter bottles was too high.
4. The compressors often operated at load conditions where the head-ends and crank-ends of the cylinders were not equally balanced, which caused the pulsation levels to be increased at 1× running speed.
5. The measured peak-peak dynamic differential pressures at the transmitter on meter No. 5 were approximately 8 times larger than the average differential pressure, which resulted in negative differential pressures. The flow computers did not measure the flow when the differential pressures were negative, which caused the total computed flow times on Meter No. 5 to be much less than the actual flow times. For example, the indicated flow time (minutes/hour) for Meter No. 5 would be as low as 45 minutes/hr when it had actually been in service for the entire hour (60 minutes).
6. Due to the combined effects of not reporting the actual flow times and of reporting excessive flow rates when the meter did

record the values, it was almost impossible to compute the actual meter error. The data indicated that for some operating conditions, the flow variances could be as much as 30—40 percent.

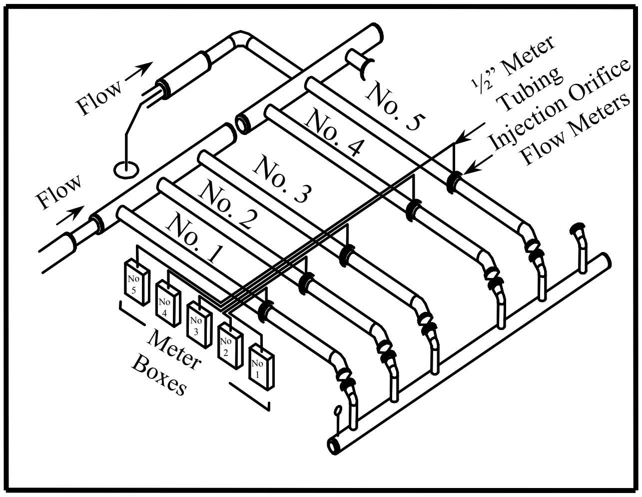

Figure 7 – Sketch of Gage Lines

Meter No.	Effective Gage Line Length*	Acoustic Natural Frequency
1	30 ft	11.3 Hz (near 2× running speed)
2	30 ft	11.3 Hz (near 2× running speed)
3	39 ft	8.6 Hz
4	48 ft	7.0 Hz
5	60 ft	5.6 Hz (near 1× running speed)

Figure 8 – Calculated Gage Line Resonances

* The effective gage line length was equal to the actual measured length between the orifice tap and the transmitter housing plus an additional 5 feet to account for the additional tubing in the housing and the effects of the various tubing fittings and valves.

During the tests, the average differential pressures across the orifices were approximately 50 inches of water, which would mean that the allowable dynamic differential pressure would be approximately 14 inches of water peak-peak.

The dynamic differential pressure at the transmitter on meter No. 5 (see Figure 9) was approximately 400 inches of water peak-peak, or approximately 28 times greater than the allowable level. The levels at the transmitter were approximately 7—8 times larger than the levels at the orifice taps. The pulsation levels were significantly modulated due to the beating between the three compressors as the pulsation from the units came in and out-of-phase. Note that the modulations were much lower on Meter Tube No. 4 where the gage line resonance was not coincident with the pulsation frequencies generated by the compressors.

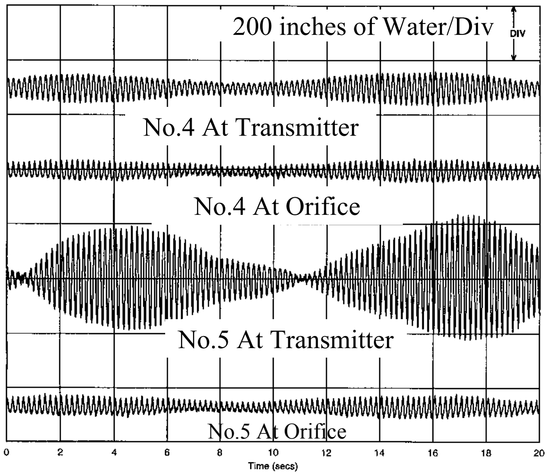

Figure 9 – Dynamic Differential Pressures at the Orifice Meters and Transmitters for Meter Tubes No. 4 and No. 5

Frequency spectra of the pulsation measured in several of the meter tubes and the suction piping are shown in Figure 10. The pulsation in the meter tubes and in the underground manifold piping at 1× running speed were similar to the levels measured near the compressors, which meant that the pulsation bottles were not effective in attenuating the pulsation at 1× running speed.

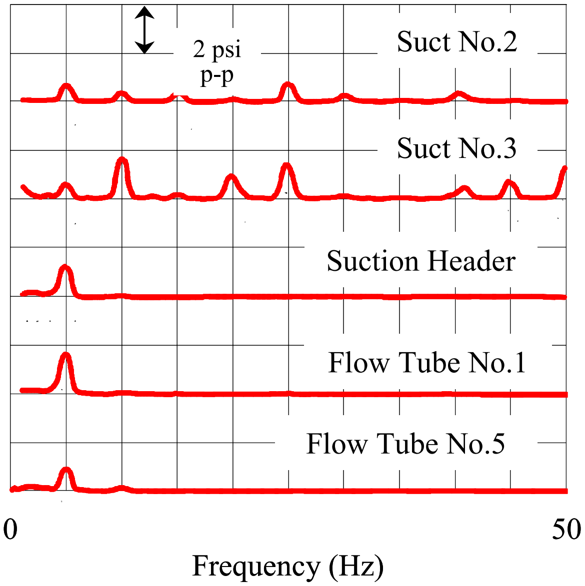

Figure 10 – Frequency Spectra of the Pressure Pulsation Measured in the Meter Tubes and in the Suction Piping

8.1 SRE Correction

Although the digital flow meters at this location were not subject to classical SRE problems, SRE values were computed at the orifice taps and at the transmitter for Meter No. 5 with various combinations of compressors in service to illustrate the magnitude of the dynamic differential pressures at the transmitter, Figure 11.

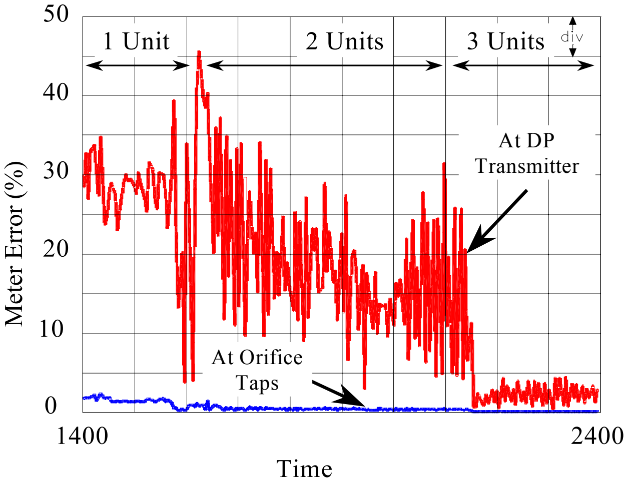

Figure 11 – Computed Meter Error for Meter No. 5 at the Differential Transmitter and at the Orifice Taps with Different Combinations of Units in Service

This illustrates that the SRE values were reduced as the number of compressors in service was increased, because the flow rates and the differential pressures were increased in each meter tube. The minimum SRE values were measured with all three units in service. Depending upon the number of units in service, the SRE on Meter No. 5 was as high as 45% at the transmitter. As shown in Figure 4, these SRE values are off the scale and are so high that they could not be due to actual flow modulation in the meter tube. Therefore, these calculations provided another indication that the flow errors had to be due to a phenomenon like a gage line acoustic resonance.

The effect of increasing the differential pressure on the SRE can also be clearly seen in Figure 12. With one engine in service, data were obtained with all five meter tubes open, and then two tubes were closed to increase the flow rate and differential pressure in the other three tubes. The data indicated that closing the two tubes slightly changed the pulsation levels; however, the indicated SRE values were reduced because the differential pressures in the other three tubes were increased.

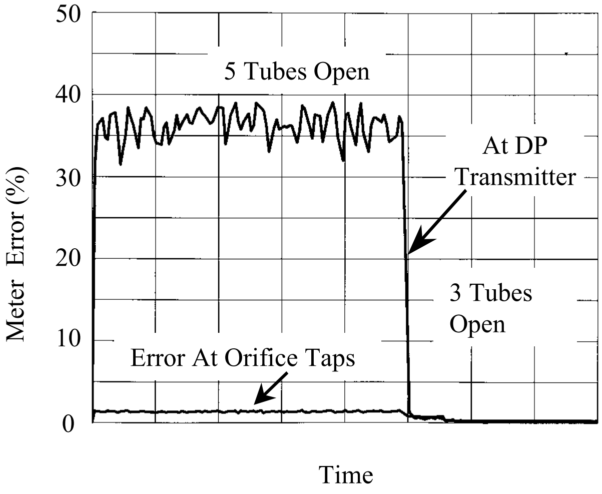

Figure 12 – Computed Meter Variance for Meter No. 5 at the Differential Transmitter and at the Orifice Taps with One Compressor in Service with Different Combinations of Meter Tubes in Service

Although these tests indicated that increasing the differential pressure in the meter tubes could reduce the SRE values, this modification was not desirable at this location because it could cause the safety valves to vent during certain operating conditions.

8.2 Case History No. 1 - Recommendations

The following recommendations were made based upon the results of the field tests.

1. The pressure transmitters should be installed directly on the orifice taps, which would reduce the effects of the gage line resonances.
2. If possible, the compressors should be operated at load steps which would reduce the pulsation at 1× running speed. This would reduce the pulsation at the orifice taps, especially the pulsation at 1× running speed, which was not attenuated by the pulsation bottles.
3. The long-term recommendation was to evaluate the suction piping system to determine modification to reduce the pulsation from the compressors.

It was reported that relocating the differential transmitters to the orifice taps corrected the flow meter errors. At this time, no other modifications have been made to the piping system.

9. Case History No. 2 – Internal Gage Line Resonance Problem

This case history deals with orifice flow meters where the flow transmitters were mounted directly on the orifice taps as recommended in the previous case history. Although mounting the transmitters on the orifice taps eliminated classical “external” gage line resonance problems, the meters experienced high dynamic differential pressure levels at the “internal” gage line acoustic natural frequency. No major meter problems had been reported at this station; however, the field tests indicated there were several minor problems, which could affect the accuracies of the flow measurements.

These meters were also installed at a gas storage facility. Three 9600 hp compressors operating at 300 rpm (5Hz) are used to inject gas into storage caverns. The injection and withdrawal flows are measured with five bi-directional orifice meters located on the suction side of the compressors. The photograph in Figure 13 illustrates digital transmitters which are installed on each tube to measure the injection and withdrawal flows. The transmitters are installed on a common tee above the vertical orifice taps.

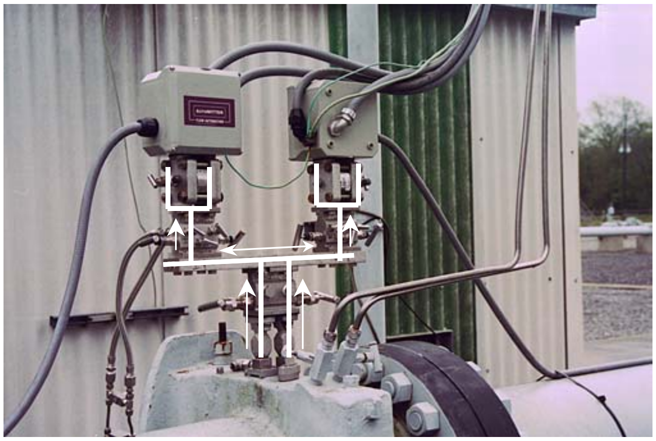

Figure 13 – Bi-Directional Orifice Meter (Internal gage lines are indicated by overlay)

The pulsations in the meter tubes were lower at this station compared to those measured in Case History No. 1. These orifice meters are effectively isolated from pulsation generated by the compressors by two large suction scrubbers located between the meters and the compressors.

During the field tests, data were obtained over a large range of injection flow rates with one and two engines in service. The measured pulsation levels in the meter tubes were low, and the dynamic differential pressures due to the pulsation in the meter tubes were also low. However, the dynamic differential pressures at the acoustic natural frequency of the internal gage lines were considered to be high and in some cases were near the AGA allowable levels.

The digital flow computers installed near the orifice tubes sample the data every second and compute the flows at that instant in time. The total flow over a given time period is the summation of these individual flows. Sampling the data every second and computing the flows based upon the instantaneously captured data should eliminate the classical SRE problems, which can occur when pulsation due to flow modulation is present.

However, if the differential pressures are modulated by "false pulsation", such as pulsation due to gage line resonances that are not caused by actual flow modulations in the meter tube; then the computed flow rates will be incorrect. Therefore, since the sampling process cannot correct for the effects of the false pulsation, it is important to minimize the pulsations at the differential pressure transmitter.

The exact dynamic differential pressures at the flow transmitters were unknown because the raw signals from the transmitters were not available. Therefore, in order to estimate the dynamic differential pressures at the transmitter, a differential pressure transducer was temporarily connected to the manifold just below the pressure transmitter. The pressure transducer was connected using 18-inch long flexible hoses, Figure 14. This arrangement is similar to that used in the SRE-4 Indicator [14].

Figure 14 – Temporary Differential Pressure Transducer Installed with Flexible Hoses

The differential pressure data obtained with the transducer attached with the flexible hoses is shown in Figure 15. The dynamic differential pressure was approximately 20 inches of water peak-peak with occasional pressure spikes of almost 40 inches of water peak-peak. The maximum peaks exceeded the AGA allowable levels.

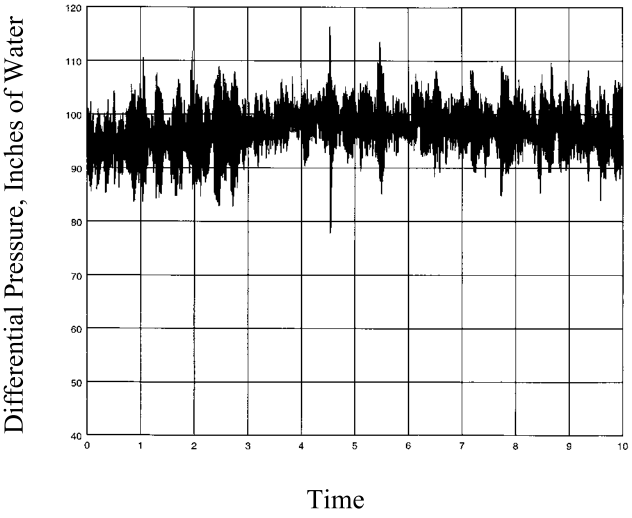

Figure 15 – Differential Pressure Measured with Flexible Hoses and Two Units in Service Flowing Through One Meter Tube

The frequency spectra of the differential pressure signal indicated that the pulsation at multiples of the compressor speed was low and that the maximum pulsation was due to the gage line resonance near 74 Hz, Figure 16. In this case, the gage line resonance was due to the combined system of the flexible hoses and the internal passages between the orifice taps and the transmitter. The gage line resonance appeared to be excited by broadband flow turbulence.

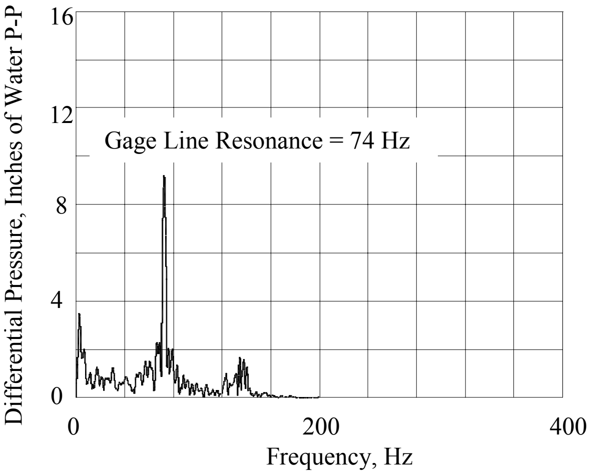

Figure 16 – Frequency Spectra of Differential Pressure Shown in Figure 15

To reduce the effects of the flexible hoses on the gage line resonance, the differential pressure transducer was connected to the manifold using short sections of tubing, Figure 17.

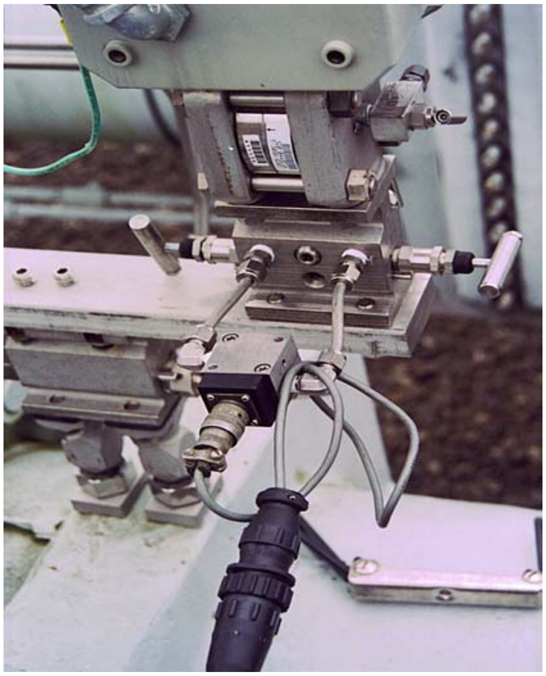

Figure 17 – Temporary Differential Pressure Transducer with Short Sections of Tubing

The effect of installing the pressure transducer with the short pieces of tubing can be seen in Figure 18. This reduced the overall dynamic amplitudes to approximately 20 inches of water peak-peak.

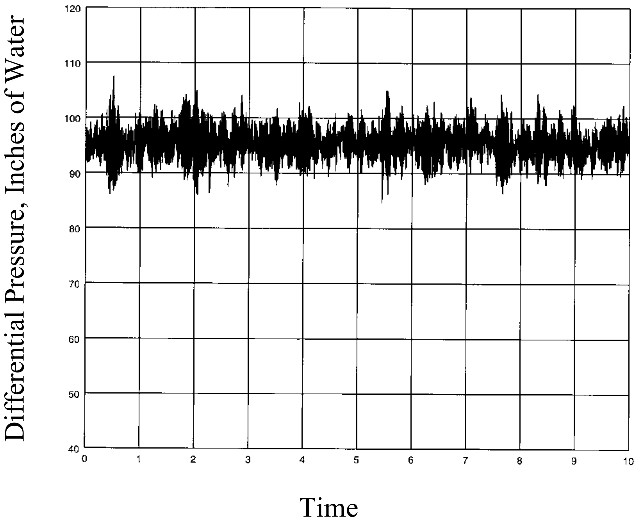

Figure 18 – Differential Pressure Measured with Short Sections of Tubing, Two Units in Service Flowing Through One Meter Tube

Installing the pressure transducer with the short sections of tubing raised the gage line resonance from 74 Hz to approximately 94 Hz, Figure 19. As shown, the gage line resonance was still the predominant response. Again, the response appeared to be excited by broadband flow turbulence.

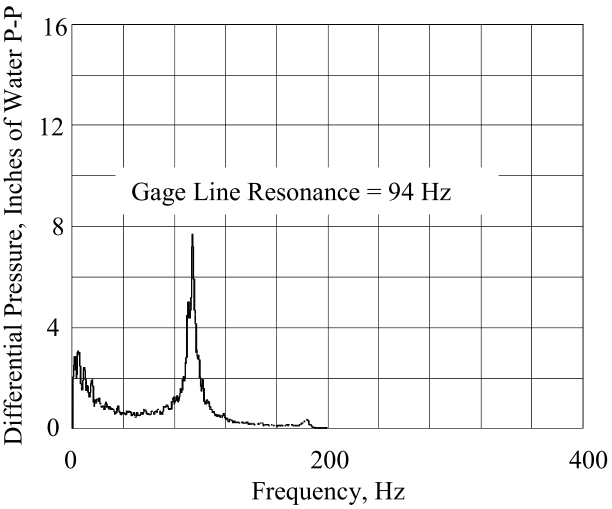

Figure 19 – Frequency Spectra of Differential Pressure Shown in Figure 18

Since the differential transmitters were installed on the vertical tee section, this would affect the quarter-wave acoustic natural frequencies and make it more difficult to compute using simple hand equations. Therefore to remove the effects of the tee section, it was decided to install the temporary pressure transducer directly on the auxiliary orifice taps, Figure 20. As shown in the photograph, the total effective length from the auxiliary taps to the transducer was similar to the length from the main orifice taps to the pressure transmitters.

Figure 20 – Differential Pressure Transducer Installed on the Auxiliary Orifice Taps

The differential pressure data measured at the auxiliary taps are given in Figure 21. The overall dynamic amplitudes were similar to those measured with the transducer installed in the manifold with the short pieces of tubing.

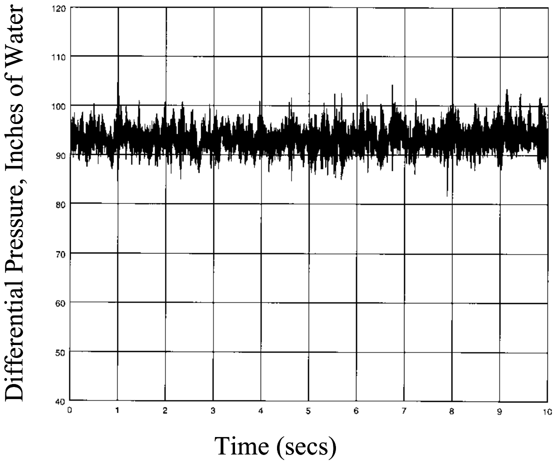

Figure 21 – Differential Pressure Measured at Auxiliary Taps with Two Units in Service Flowing Through One Meter Tube

A spectrum of the data measured at the auxiliary taps is shown in Figure 22. The gage resonance increased to approximately 213 Hz; however, the amplitudes were similar to those measured at the manifold. This test indicated that mounting the transmitters directly on the auxiliary taps would not eliminate the gage line resonance.

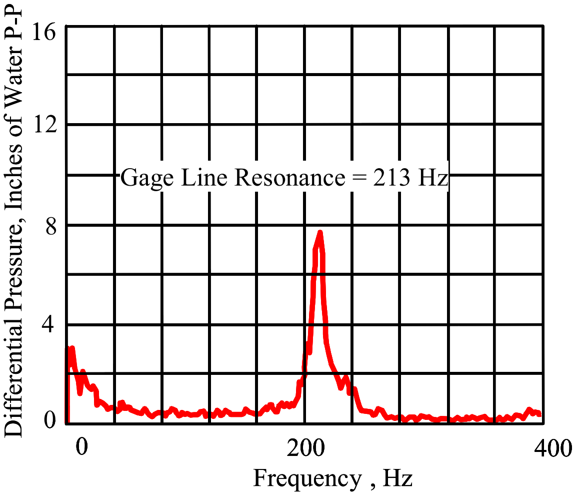

Figure 22 – Frequency Spectra of Differential Pressure Shown in Figure 21

One method to reduce the effects of the gage line resonance is to electronically filter the signal coming from the differential pressure transmitter. Electronically filtering the signal will not eliminate the pulsation in the gage line, but it will reduce the effects of the gage line pulsation on the meter readings.

To illustrate the magnitude of the false pulsation, the differential pressure data shown in Figure 21 were digitally filtered with a 100 Hz low-pass filter to remove the pulsation at the gage line acoustic natural frequency. Figure 23 shows that the low-pass filter significantly reduced the high-frequency dynamic differential pressures. The remaining dynamic differential pressures were due to actual flow modulation in the meter tube.

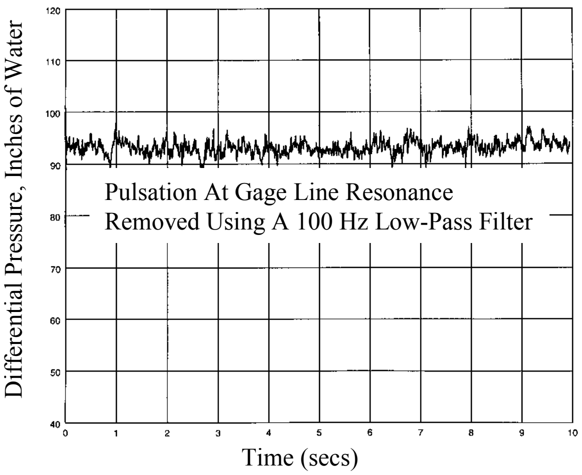

Figure 23 – Data Shown in Figure 22 with a 100 Hz Low-Pass Digital Filter

9.1 Linear Averaging

Another method to reduce the effects of the pulsation at the gage line resonance is to use linear averaging instead of the square root averaging. The data shown in the above figures indicated that the dynamic differential pressure pulsation due to the actual flow modulation in the meter tubes was very low, which means that square root averaging is not appropriate.

In linear averaging, the differential pressures are averaged over a long time period before taking the square root (equation 5). This type of averaging is normally not recommended, but in this case the linear averaging would be beneficial because it would essentially eliminate the dynamic differential pressure pulsation at the gage line frequency. The linear averaging would be similar to applying the low-pass filter to the data.

Therefore, for this particular installation, it would be better to average the differential pressure data for long periods of time before taking the square root. Some digital flow computers provide an option to select between square root averaging and linear averaging.

9.2 Case History No. 2 - Recommendations

The following recommendations were made based upon the results of the field tests.

1. The amplitudes of the false pulsation at the gage line resonance should be reduced. One possible modification would be to install electronic low-pass filters in the flow computers to filter the differential pressure signal before it is sampled. The low-pass filter should be set to approximately 60 Hz to filter the gage line resonance without attenuating the signal due to the actual flow modulation in the orifice meter tube.
2. The differential pressures across the orifice meters should be increased because the differential pressures were on the low end of the calibrated span. This could be accomplished by replacing the existing orifices with smaller orifices, and/or re-staging the meter tubes to minimize the number of tubes in service.

10. Suggested Modifications to Meters

These two case histories illustrated the need for two modifications to the differential pressure transmitters – (1) provide access to the raw signal from the differential pressure transducer and (2) provide a low-pass filter.

10.1 Provide Access to Raw Signal From the Differential Pressure Transducer

The basic objective in each of the field tests described in the above case histories was to obtain dynamic differential pressure data in the meter tube, in an effort to estimate the actual dynamic differential pressure at the flow transmitter. Since the transmitters do not provide access to the actual raw signal from the differential pressure transducer, transducers have to be temporarily installed at available pressure connections.

As shown in Case History No. 2, the dynamic differential pressures measured with temporarily installed transducers can vary significantly depending upon where the transducers are installed and how they are connected (long hoses, short tubing, etc.).

The field tests showed the importance of determining the modulation of the differential pressure signal. During the tests, data were obtained with several different brands of differential transmitters and pressure transducers, and yet none of them had a method for accessing the raw differential pressure signal. It is surprising that the raw differential pressure signal is not available for analysis. The differential pressure transducer is the heart of the transmitter, and yet the raw signal from that instrument is not available for independent analysis.

As a point of comparison between industries, almost all monitoring systems, such as vibration monitoring systems, allow the raw dynamic signal to be analyzed. Most vibration monitoring systems provide an electrical connection, such as a BNC connection, to obtain the raw signal from the vibration transducers. These are buffered outputs to prevent the raw signals from being affected by instruments connected to the monitor.

The following is a list of reasons for providing access to the raw differential pressure signal.

1. The meter error analysis would be made using the actual signal, rather than inferring what might be occurring at the differential pressure transducer.
2. It would eliminate the need to install temporary pressure transducers.
3. The DDP error values could be evaluated without the need for specialized instrumentation.
4. The actual dynamic signal could be monitored from remote locations.
5. It would provide another method to calibrate the differential pressure independently from the flow computer.
6. It would be much safer, since it would eliminate installing the temporary pressure transducers.
7. It would provide a signal for setting the range for the low-pass filter for eliminating the effects of the gage line resonance.

10.2 Low-Pass Filter to Eliminate the Effects of the Gage Line Resonance

As discussed in Case History No. 2, an electronic low-pass filter can be used to eliminate the effects of the gage line resonance, when the gage line resonance is well above the frequencies of the actual flow modulation (pulsation from the compressors). The frequency of the low-pass filter should be set to attenuate the gage line resonance without attenuating the flow modulation frequencies. The filter should be applied to the raw differential pressure signal before the signal is sampled.

At this time, the option of using an electronic low-pass filter to eliminate the gage line resonance is not available on currently installed flow computers. Again, one manufacturer indicated that it would be possible to install a low-pass filter as an option.

11. Summary

The following is a list of recommended guidelines that can be used when designing and evaluating orifice meters installations. Many of these guidelines are similar to those recommended by the AGA.

11.1 Installation Guidelines

1. Pulsation due to flow modulation in the orifice meter tube should be minimized.
2. Orifice meter tubes should be installed where large vessels, such as suction scrubbers and/or dehydrators are located between the meter tubes and the compressors.
3. Acoustic filters should be designed with the cutoff frequency below 1× running speed. This could possibly result in large diameter bottles for low speed compressors.
4. Operate the meter tubes with the highest possible differential pressure across orifice plates by reducing the orifice diameter and/or reducing the number of orifice tubes in service.
5. If possible, block both ends of non-flowing meter tubes.
6. Install differential pressure transmitters directly on orifice meter taps to eliminate long gage lines.
7. Use a frequency analyzer (FFT spectrum analyzer) to determine the predominant frequencies of the dynamic differential pressures. In particular, it should be determined if the pulsation response peaks are due to flow modulation in the meter tubes, or due to gage line resonances.
8. Compare the measured dynamic differential pressure to the AGA guidelines. If the measured levels exceed the AGA allowable values, then modifications may be required to reduce the amplitudes.
9. If the amplitudes of the gage line resonance are excessive, then a low-pass digital filter should be installed to filter the differential pressure signal before the computer samples it. Currently, the option of using a low-pass filter is not available. However, it is felt that this could be provided as an option by the equipment manufacturers.

In conclusion, it is highly recommended that the manufacturers of the differential flow transmitters and flow computers be requested to make the raw signal from the differential pressure transducer accessible for analysis. As discussed, in Section 10.1, access to this signal would provide a wealth of knowledge concerning the accuracy of the flow measurements.

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