PULSATION REDUCTION BY ACOUSTIC FILTERS FOR METERING APPLICATIONS

Robert J. McKee
Ray G. Durke

Southwest Research Institute®
6220 Culebra Road
San Antonio, TX 78238

INTRODUCTION

Because of the adverse effects of pulsations on orifice and other types of flow meters, there is a need at many installations to decrease the amplitude of pulsations in the piping. This task has been the primary domain of acoustical piping designers who have had both theoretical and practical field experience in such areas. The most common and effective treatment for pulsation control is the design and installation of acoustic filters. However, poorly designed filters can be ineffective or expensive to operate. This paper discusses the basic principles and considerations in acoustic filter design.

There are many small compressors, such as wellhead gathering compressors, that cannot justify the cost of a thorough acoustic analysis in order to protect the nearby orifice meter from excessive pulsations and accompanying square root error. This paper will make an effort to demonstrate design procedures related to a specific type of acoustic filter to be used to reduce pulsations for a simple metering application. The specific filter is a symmetrical in-line low pass filter. The important elements of this filter can be summarized in the following points:

1. The inlet line is located at the acoustic center of the first chamber of the filter.
2. The first chamber of the filter, the choke tube, and the last chamber are all the same acoustical length.
3. The choke tube connects the acoustical centers of each filter chamber.
4. The outlet line is located at the acoustical quarter point of the final chamber.

It is fully realized that this is a specialized filter design and other types of designs could be recommended, but this particular filter design was chosen for simplicity of discussion. It should be pointed out that the approach outlined in this paper does not predict pass-band frequencies that occur above the filter natural frequency nor the shift in the filter natural frequency caused by the piping. In many installations, the above effects are minor. Drawings of the physical aspects of the acoustic filter piping are shown at the end of this paper.

WHERE DO PULSATIONS COME FROM?

Pulsations of concern in metering applications can be generated by reciprocating compressors, centrifugal compressors, flow induced phenomena, or turbulent sources. The primary focus of this paper is directed toward filtering the most persistent pulsations that are produced by reciprocating compressors.

A reciprocating compressor produces pulsation at compressor crankshaft RPM and its multiples. Pulsation frequencies are generally expressed in cycles per second (Hertz). A 300-RPM compressor produces pulsation at 5 Hertz, 10 Hertz, 15 Hertz, and higher multiples. Most compressors (for natural gas services) are double-acting and compress gas on the head and crank end of the cylinder. Double-acting cylinders produce more pulsation at the even multiples of RPM and less at the odd multiples. Therefore, a 300-RPM double-acting cylinder will produce its strongest pulsation at 10 Hertz. When compressors have more than one cylinder, the crankshaft phasing of the cylinders will also cause certain multiples to be higher than others. For example, if two double-acting cylinders are phased 90 degrees apart, they will produce a significantly higher pulsation level at four times RPM. In the case of a 300-RPM machine and two double-acting cylinders phased 90 degrees apart, there will be a high fourth harmonic or 20 Hertz. Generally, the higher multiples (sometimes called compressor harmonics or compressor orders) will contain less energy than the lower orders.

WHAT ARE THE IMPORTANT CHARACTERISTICS OF LOW PASS FILTERS?

The single most important characteristic of a low pass acoustic filter is its acoustic natural frequency. The volume-choke-volume configuration exhibits a relatively low natural frequency compared to the acoustic half-wave natural frequencies of the chamber and choke tube lengths. At frequencies below the filter natural frequency, there will be no attenuation of pulsations passing through the filter. There will be a sharp reduction of pulsation at about 20 to 40 percent above the natural and extending out to several hundred Hertz. It is very important to understand that pulsations at the natural frequency of the filter will actually be magnified by as much as 10 to 40 times. Therefore, it is very important to ensure sufficient separation between the natural frequency of the filter system and the compressor harmonics. This can be accomplished in two ways. The filter natural frequency can be placed 20 to 40 percent below the minimum RPM of the compressor or, where adequate separation exists between compressor harmonics, the response can be placed midway between the first order at maximum RPM and second order at minimum RPM.

The degree of separation between the filter response and compressor harmonics is determined by the damping in the acoustic filter and the pulsation characteristics. In this paper, a separation of 40 percent is used. For less separation, an acoustic model or the expertise of an experienced designer should be used.

HOW TO CALCULATE THE FILTER NATURAL FREQUENCY

The following procedures show the design process for an acoustic filter with a natural frequency below the fundamental RPM or between the first and second RPM orders of the compressor. The following two cases illustrate the calculations and limitations:

Case 1: Placing the filter natural frequency F_0 below the fundamental order.

$$F_0 = \frac{RPM_{min}}{(60)(1.4)}$$

Where:

F_0 = filter natural frequency of filter system
RPM_{min} = the minimum actual operating RPM of the compressor

Case 2: Placing the filter natural frequency between the first and second orders.

$$F_0 = \frac{RPM_{min} * 2 + RPM_{max}}{(60) \quad (2)}$$

This frequency F_0 should be at least 40 percent separated from $\frac{RPM_{max}}{60}$ and $\frac{RPM_{min} * 2}{60}$. This 40 percent separation helps ensure that excitation of the acoustic filter response by the compressor is avoided.

CALCULATING THE INSIDE DIAMETER OF THE CHOKE TUBE

The inside diameter (ID) of the choke tube should be as small as pressure drop limits will allow in order to create as small a filter as possible. Larger diameter choke tubes create less pressure loss but require larger filter volumes. For many applications, a common procedure is to limit the gas flow velocity to 100 feet per second as implemented in the following equations:

$$q\left(\frac{ft^3}{\sec}\right) = 0.327\frac{MMSCFD(T + 460))Z}{P}$$

$$IN_c = 1.354\sqrt{q}$$

Where:

MMSCFD = flow through the choke tube in million standard feet^3 per day
T = gas temperature (°F)
P = gas pressure (PSIA)
Z = real gas correction factor
q = flow rate (feet^3 per second)
ID_c = inside diameter of choke tube (inches)

The cost of pressure loss should be carefully considered as the price is paid over the life of the installation. Flow increases can cause significant increases in pressure loss. Reduction of choke tube pressure drop can be reduced by the use of a bell mouth entrance fitting. Bell mouths are common when a single-bottle design is selected.

CALCULATING THE FILTER CHAMBER INSIDE DIAMETER

To ensure sufficient attenuation of pulsation above the filter natural frequency, the bottle or filter chamber ID_B should be 2.5 times the choke tube diameter lD_C or larger. A larger bottle diameter will improve the filter response characteristics.

$$ID_B = 2.5 * ID_C$$

CALCULATING THE FILTER ELEMENT ACOUSTIC LENGTH

For ease in calculations, the acoustic bottle length and the acoustic choke length are equal. This length is calculated based on the following equation.

$$L_f\,(ft) = \frac{c}{\pi\sqrt{2}}\frac{ID_C}{ID_B} = 0.225\frac{c}{F_0}\frac{ID_C}{ID_B}$$

Where:

c = gas velocity of sound (feet per second)

An equation and method for calculating gas velocity of sound is shown below.

Because of acoustic end effects, the physical length of the choke tube should be slightly shorter than the calculated acoustic length. An approximation of the end effect is 1.2 times the ID of the choke. Therefore, the choke length is set to $L_f - 0.4 * \frac{ID_c}{12}$ so that the physical length has the proper acoustic effect.

Speed of Sound Calculation

The velocity of sound can be approximated by:

$$c\left(\frac{ft}{\sec}\right) = 1.354\sqrt{\frac{kTZ}{G}}$$

Where:

c = velocity of sound (feet per second)
k = ratio of specific heats
T = gas temperature (degrees R)
G = gas specific gravity
Z = real gas correction factor

Variations in velocity of sound from operating temperature or pressure, or from changes in gas composition, can shift the response of the acoustic filter. Both the minimum and maximum acoustic velocities should be considered in the design. One approach is to use the median velocity of sound to size the filter and realize that the response can vary by the percent change in acoustic velocity.

EXAMPLE CALCULATIONS (CASE 1)

General Information

A set of reciprocating compressors operating over a speed range from 350 to 440 RPM is causing pulsation at a metering site approximately 500 feet downstream of the compressors. The compressors single-act on occasion. The maximum flow rate through the meter site is approximately 31.5 MMSCFD. The discharge temperature is 84°F, and the pressure is 925 PSIA. The ratio of specific heats is 1.32. The gas specific gravity is 0.62, and the compressibility is estimated to be 0.947. The velocity of sound is calculated to be 1,371.9 feet per second.

Solution

For best results, the natural frequency of the filter system should be placed below the fundamental compressor frequency, since single-acting is possible. The highest possible filter natural frequency placement for 40 percent separation is 4.17 Hertz.

The choke tube volume flow rate is 5.735 feet^3 per second. The choke inside diameter of 3.548 inches is selected. The minimum bottle inside diameter is calculated to be 8.87 inches, but this would produce a very long installation; therefore, a 22.626-inch inside diameter is selected instead. This will produce a bottle chamber acoustic length of 11.62 feet (per single chamber). To account for the acoustic end effects, 1.2 times the choke diameter is subtracted from the characteristic filter length to give a choke tube length of 11.26 feet.

EXAMPLE CALCULATION (CASE 2)

General Information

A reciprocating compressor operating at a fixed speed of 300 RPM is causing pulsation at a metering site approximately 200 feet downstream of a compressor. The compressor has no mechanism to single-act. The maximum flow rate through the meter site is approximately 10.5 MMSCFD. The discharge temperature is 120°F, and the pressure is 925 PSIA. The gas specific gravity is 0.62, and the compressibility is estimated to be 0.947. The ratio of specific heats is 1.32. The velocity of sound is calculated to be 1416.5 feet per second.

Solution

The natural frequency of the filter system can be placed between the first and second compressor harmonics since single-acting is not possible. For a 40 percent separation from the second compressor harmonic, the filter response could be placed at 7.14 Hertz $\left(\frac{300*2}{60*1.4}\right)$. The separation is greater than 40 percent from the first order $\left(\frac{300}{60*1.4} = 7Hz\right)$. The choke tube flow rate is 2.038 feet^3 per second, and the choke tube inside diameter is calculated to be 1.933-inches. Selecting a 1.939-inch choke tube results in a minimum bottle diameter of 4.848. Such a small bottle diameter results in a long volume bottle, so a larger bottle of 13.124-inch ID is selected. The filter characteristic length of 6.59 feet is calculated, and the physical length of the choke tube is calculated to be 6.53 feet.

MECHANICAL CONSIDERATIONS

If a single-bottle design is selected, the internal choke tube should be restrained at both ends to ensure that the cantilever lengths on each side of the baffle are not resonant mechanically. The baffle should be a dished head with thickness approximately the same thickness as the bottle wall. If a two-bottle design is selected, the branch connections should be reinforced with saddles or pads. Weld-o-lets should be avoided because of the high stress riser they inflect on the bottle wall. Elbows in the choke tube are acoustically irrelevant as long as the centerline length is used for the length. Elbows do serve as acoustical to mechanical coupling points and should be avoided, if possible. The filter bottle(s) should be securely restrained to ensure mechanical stability. All external choke tubes should be restrained to ensure that the mechanical natural frequency is not coincident with the half-wave acoustic frequency of the choke tube.

OTHER PULSATION REDUCTION APPROACHES

In some cases, design of meter installations by selecting proper lengths and acoustic junctions can be effective in reducing or eliminating pulsation error. Meter installations should be designed so that the piping lengths are not acoustically resonant and so that the orifices or other meters are located at a velocity minimum. This involves selecting meter tube lengths that are not coincident with pulsation energy.

Restrictions or additional orifice plates installed at various locations can detune acoustic length responses and can dissipate some of the energy in pulsating waves. To be effective, these pulsation restrictions are sized to create pressure drops and, thereby, require an increase in compression horsepower. Orifice plate performance is dependent on acoustic responses of the piping system and the frequency content of the pulsations. In some cases, orifice plates can tune acoustic responses and cause increased pulsation amplitudes.

Surge volumes or single-bottle filters, such as scrubbers or separators, generally do reduce pulsation levels; however, depending on the placement in the standing wave, they may not be effective and can change the acoustic responses within the installation.

CONCLUSIONS

It is possible to reduce pulsations at metering sites with properly designed acoustic filters to minimize the influence of pulsations on flow measurement. A simple approach was illustrated for sizing two symmetrical acoustic filters. Development of filter designs for flow measurement applications generally involves cost of the filter, both installation cost and pressure drop or performance cost, versus the cost of living with pulsation-induced errors. Pressure drop costs can be reduced by building larger filters. It is advantageous to have an experienced acoustical engineer evaluate filter designs, particularly if the installation or the metering accuracy is critical. If the filter natural frequency is placed below the compressor fundamental, it is possible to be conservative with an oversized filter. However, if the natural frequency is to be placed between the first and second harmonics, it is important to be accurate in both calculations and physical construction, since placement of the filter too close to compressor harmonics can amplify pulsations.

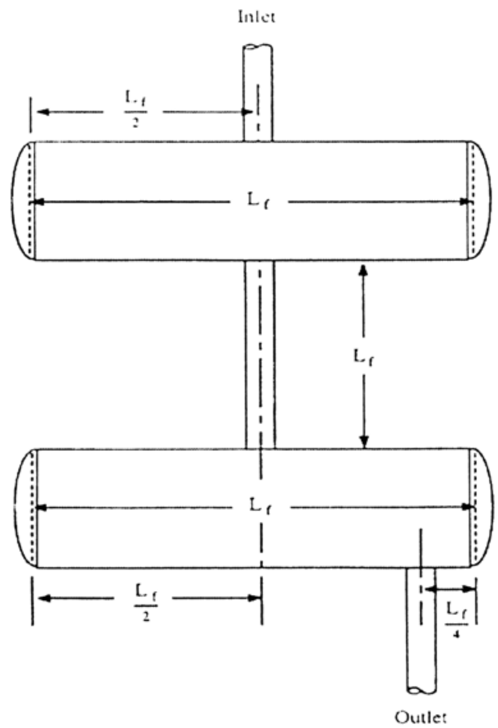

FIGURE 1. TWO BOTTLE LOW-PASS ACOUSTIC FILTER

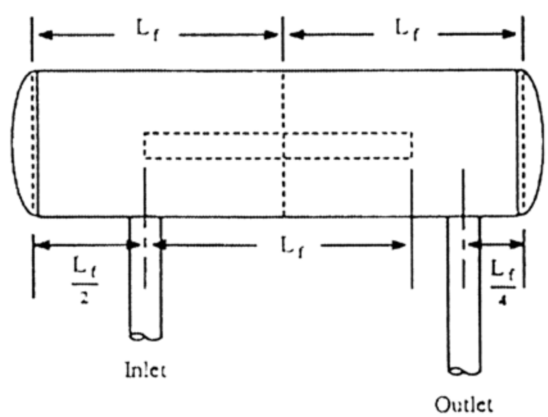

FIGURE 2. SINGLE BOTTLE LOW-PASS ACOUSTIC FILTER

Ray Durke

Robert McKee