SYSTEM PROBLEM EXPERIENCE IN MULTIPLE RECIPROCATING PUMP INSTALLATIONS

by

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ABSTRACT

Installations utilizing multiple reciprocating pump equipped with common suction and discharge headers can experience severe problems including cavitation, piping vibration and fatigue failure, or destruction of pump components. Typically, the source of these problems is the interaction between naturally pulsating reciprocating pumps and the piping system. In the past, field testing was used to define the problems which were eliminated by trial and error methods, usually by installing suction and discharge dampeners or modifying system piping. However, advances in analytical techniques and data acquisition equipment have lead to a better understanding of the system/pump relationship. This information is now available for use in designing reciprocating pump installations, thus eliminating the pulsation problems of the past.

INTRODUCTION

Typically, the problem most commonly associated with the installation of reciprocating pumps is cavitation, specifically a system Net Positive Suction Head Available (NPSHA) which is equal to or lower than the pump's Net Positive Suction Head Required (NPSHR). In addition to cavitation, reciprocating pump installations may also experience piping vibration problems, piping fatigue failures, and damage to pump components such as valves, fluid cylinders, bearings and connecting rods. Most of these problems can usually be traced to the same source: the interaction between the pulsating flow characteristics of the pump and the acoustical response of the piping system.

Field evaluation of problem systems usually consists of measuring the complex pressure waveforms at various locations within the piping system. These waveforms are measured using standard pressure transducers. The electrical signals generated are then displayed on oscilloscopes, analyzed for frequency content using real-time analyzers, stored on magnetic tape, and plotted or recorded using digital plotters.

Once the field data has been obtained, standard methods of analyzing the interaction between reciprocating pumps and their systems can be used to discover the cause of the problem and suggest required solutions. This analysis is conducted by using either electroacoustical analysis or digital computer simulations of the piping system [1].

In general, the interaction between the pump and system are worse in multiple pump installations because of the higher flowrates, interaction between parallel pumps and the larger, more complicated piping systems used. However, these same problems can occur in single pump installations; but the shorter pipe runs, simplicity of piping design, and lower flow rates usually minimize their effects. All of the discussions herein can be applied to either single or multiple pump installations experiencing pulsation related problems.

Basic Reciprocating Pump Operation

A reciprocating pump is a simple slider-crank mechanism consisting of a crankshaft, connecting rod, crosshead assembly, and plunger or piston. The crankshaft transmits the torque from the driving motor to the connecting rods, which change the rotating motion of the crankshaft to the reciprocating motion of the crosshead assembly. The crosshead assembly then transmits this reciprocating action to the plungers or pistons.

The pump's fluid end consists of a fluid cylinder, valves, suction (intake) and discharge (outlet) manifolds, and the plungers or pistons which convert the reciprocating motion into hydraulic horsepower.

By nature, a reciprocating pump will produce a constant pulsating flow of fluid. The magnitude of this flow pulsation is dependent upon the number of plungers in the pump and will decrease as the number of plungers increases. Unlike a centrifugal pump with its variable flowrate based on discharge pressure (head), a reciprocating pump develops a constant pulsating flowrate independent of pressure. Reciprocating pump flowrate is dependent upon fluid compressibility, pump size, displacement, number of plungers and speed [2].

On the other hand, the operating pressure of a reciprocating pump is strictly a system related function. System pressure is generated by the friction losses through piping and/or the pressure requirements for flow through restrictions, into pressurized vessels or injection into underground rock formations [3]. A detrimental aspect of the constant flow characteristics of reciprocating pumps is that these units do not have a "shut-off" head similar to that occurring in centrifugal pumps. Instead, a reciprocating pump discharging into a closed system will continue to deliver fluid, constantly increasing system pressure, until a relief valve opens, the driver is overloaded, the pipe ruptures, or the pump fails mechanically.

However, there is a relationship between the flowrate of the pump and system pressure. Since reciprocating pumps produce a pulsating flow, the pressure produced by the system will pulsate because the frictional pressure loss in a pipeline is a function of the square of the fluid velocity [3]. The typical pulsation pressure developed by reciprocating pumps is illustrated in Figures 1 and 2. These flow generated pulsations should occur at the frequency of pump operation, or the pump speed. Unfortunately though, these pressure pulsations also interact with the piping system, sometimes producing high frequency pulsations of extremely large magnitudes. This amplification of the pressure pulsation is due to the natural acoustical resonance of any piping system. By means of organ pipe acoustic theory, the acoustical resonance of any pipe length can be obtained [1]. If this acoustical resonance coincides with a multiple of the pump's flow generated pulsation frequency, the pressure pulsations could be amplified significantly.

Therefore, any adverse pressure pulsations which exist in a reciprocating pump system are caused by the interaction between the pump and the acoustical response of the piping system. Because of this interaction, the best way to eliminate adverse pressure pulsations is to isolate the pump's pulsating characteristics from the piping system. Typically, suction and discharge dampeners are used to perform this function.

Typical Suction System Problems

The pulsating flow characteristics of a reciprocating pump cause variable feed or inlet requirements in the suction system. As stated previously, this pulsating flow results in pulsating pressure, which can generate cavitation, water hammer, valve knock, or possibly damage to pump components.

Water hammer is the generation of a pressure spike due to the collapsing of voids at the plunger/fluid interface. These voids are formed by the separation of the plunger from the fluid, due to the inertia of the fluid and its inability to accelerate as quickly as the plunger during the start of the pump suction stroke [4]. Cavitation on the other hand, results in the generation of

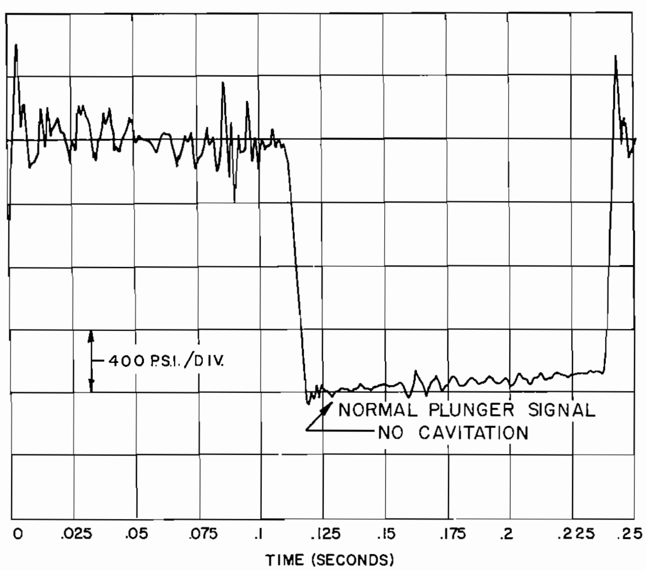

Figure 1. Typical Pressure Signal within Pump Working Barrel.

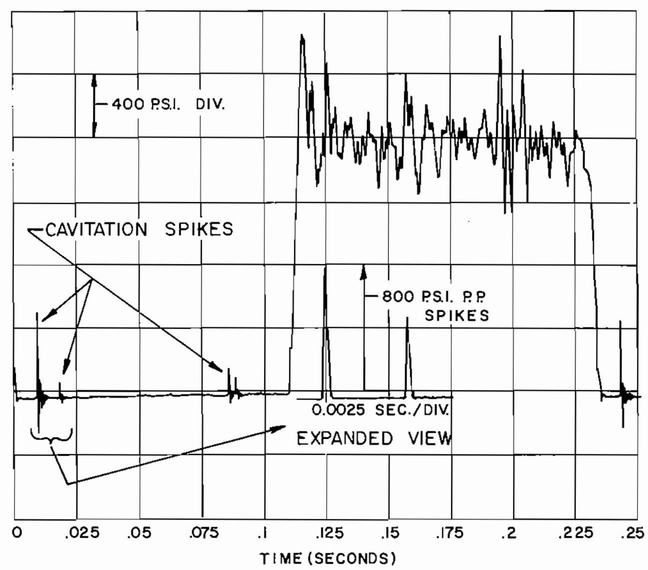

Figure 3. Typical Pressure Signal within Working Barrel Experiencing Cavitation.

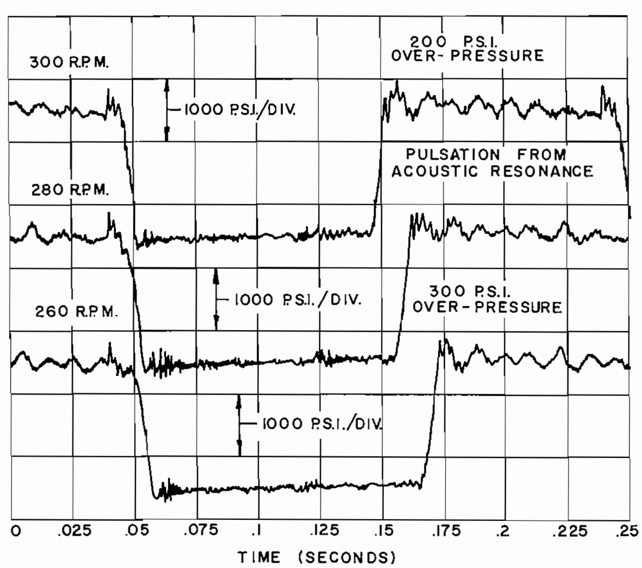

Figure 2. Illustration of How Pressure within Working Barrel Varies with Speed.

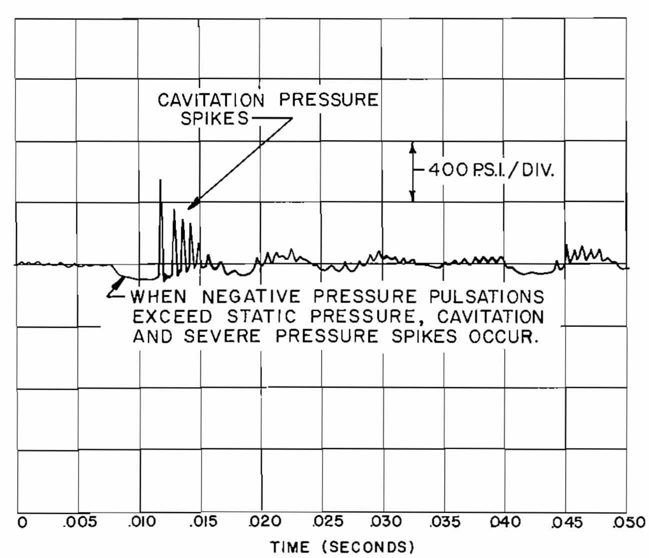

Figure 4. Typical Pressure Signal within Pump Suction Manifold (note cavitation).

pressure pulses because of the collapse of vapor pockets formed when system pressure drops below the fluid vapor pressure [5]. If system suction pressure is not high enough to compensate for the fluid inertia and overcome the fluid vapor pressure, water hammer and/or cavitation will occur. Reproductions of actual field data indicating cavitation are shown in Figures 3 and 4.

By definition, each of these phenomena produce pressure spikes or shocks. These shocks can then lead to valve knock or more serious damage to pump components. Valve knock usually results from inadequate valve response due to abnormal dynamic pressure conditions causing valve lag, reverse flow through valves, and slamming of the valve on its seat. In either case, all of these problems can be eliminated by properly designing suction systems with adequate NPSHA.

Historically, system NPSHA is defined as the static pressure plus atmospheric pressure at the pump suction flange minus lift losses, frictional pressure losses, fluid vapor pressure, and the acceleration pressure loss through the system [2]. In this definition, the pressure drop due to acceleration effects is used to compensate for the fluid inertia and the interaction between the pump and the piping. However, for piping lengths greater than approximately five feet, the normal methods of determining acceleration loss loses validity [3].

Also, the above definition of NPSHA does not include any terms to account for the acoustic resonance characteristics of the piping. If the normal pressure pulsations are acoustically amplified, they will consist of a postive and a negative peak. The negative peak, or pressure reduction, must be subtracted from the system static pressure when determining system NPSHA [5]. By disregarding the pressure pulsations arising from acoustical resonance when determining system NPSHA, it is easy to design a system with "adequate NPSHA," only to discover the pumps cavitate or the piping vibrates during system operation.

Therefore, a more realistic definition of system NPSHA is the static plus atmospheric pressure at the pump suction flange, minus the frictional pressure loss, fluid vapor pressure, nominal acceleration pressure loss, and one half of the peak-to-peak pressure pulsations due to acoustical resonances of the system. Unfortunately, the amplitude or nature of the acoustical pressure pulsations cannot be determined by simple calculations. Complex analog or digital computer simulations of the piping system are required to determine acoustical resonances.

Typical Discharge System Problems

The same type of pressure pulsation which can cause cavitation in the suction system of a pump can generate other problems in the discharge piping. Typically, discharge system piping problems include excessive piping vibration, piping fatigue failures, valve hammer, and, possibly destruction of pump components.

Once again, the pulsating flow generated by the pump results in pulsating pressure in the system. These pulsations can be either amplified or attenuated by the acoustical response of the piping system. The amplitude of the pressure pulse becomes dependent upon the interaction of the pump with the acoustical response of the piping. If the two are in phase, then pulsation amplification in excess of two to three times normal can be obtained.

Piping motion arises from a shaking force equal to the pulsating pressure times the projected area. The pulsating pressure causes a pulsating force resulting in vibration. Increased pressure causes the magnitude of the shaking forces to increase, resulting in higher vibrations; thus, vibrations are more of a problem in discharge systems. Furthermore, if the pressure pulsations are amplified by the acoustic resonance of the piping, subsequent vibrations will be increased accordingly.

Additional problems can arise from the mechanical resonance of a piping system. Because all piping has a unique mechanical resonance, this resonance can be excited by pulsations resulting in possible piping vibrations as high as 20 times the normal values. Also, if a mechanical resonance coincides with an acoustical resonance, additional piping vibrations of over 300 times normal can be experienced [1]. Thus, if the amplitude of the pressure pulsations present in a piping system are not minimized, piping fatigue failures can quickly occur.

Regarding pump component failures, the same pulsation amplification which results in excessive piping vibration generates shock loads which must be absorbed by the pump. Given the fatigue loading experienced by reciprocating pump components, shock loads will reduce the endurance limit of the parts resulting in component failures. While piping may be rigidly supported to reduce vibration and fatigue failures, only reduction of the pulsations can eliminate the pump breakdowns caused by shock loads. In order to reduce these pulsations, their amplitude and frequencies have to be determined, using analog or digital computer techniques. The amplitude and frequency signals mesured in the suction manifold of a pump experiencing cavitation are illustrated in Figure 5.

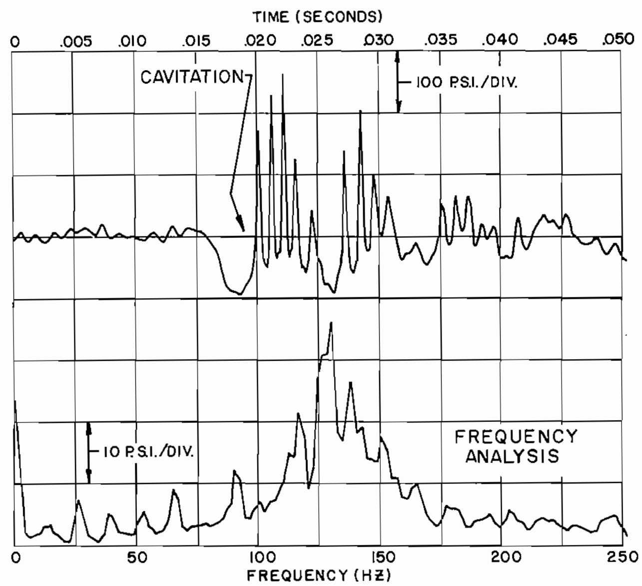

Figure 5. Dual Trace Showing Pressure Signal within Pump Suction Manifold with its Frequency Spectra Shown.

Methods of Analysis

Given all of the problems that can occur if the pulsations generated by reciprocating pumps are amplified by the acoustical resonance of the piping system, methods for determining the magnitude of these pulsations are required. As mentioned previously, the acoustical resonance of a piping system can be determined by organ pipe acoustic theory. Discussion of this method of analysis is beyond the scope of this study, but is more than adequately described in the references.

The determination of the acoustical resonance in piping systems is done by either electroacoustic analog or digital computer methods. In the first method of analysis, analogies are made between piping systems and electric circuits. Using alternating current theory, one can study the mechanical or acoustic response of the piping in terms of the equivalent electrical system [6]. In the latter method, classic fluid mechanics theory is used (Navier-Stokes equation, continuity equation, and the thermodynamic equation of state) [7]. Only the rapid advance of computer technology has made this method practical and cost effective. Whichever of these methods is used to evaluate the acoustic response of the system, field testing should be done to verify or validate the analytical results.

Pressure measurement is accomplished using piezoelectric or strain gage type pressure transducers, whereas vibrations can be measured with accelerometers. In either case, the resulting signals are displayed on oscilloscopes or via real-time analyzers with digital plotters to record the data. By reviewing the data collected during field testing, the source or cause of any pulsation problems can usually be discovered. Then by using the analytical techniques described, a solution can be found. Usually, this solution involves the design or selection of some type of pulsation suppression device.

Solution to Typical Problems

Pulsation problems are usually solved by trial and error methods such as raising system suction pressure, lowering pump speeds, installing some type of pulsation dampener, or rigidly supporting piping to minimize vibrations. If any pump problems exist, these are usually referred to the pump manufacturer for solution. Only after these solutions fail, or repair costs become prohibitive, are pulsation consultants contacted. If these consultants are involved during the design phase of the piping system, or at least at the first sign of pulsation problems, a lot of time, money and lost production can be avoided.

As explained previously, pulsation problems are caused by the interaction between the reciprocating pump and the acoustic response of the piping system. Therefore, the best method of solving these problems is to modify the acoustic characteristics of the system. This change can be accomplished by the installation of correctly sized pulsation dampeners, possibly with orifice plates, or by changing the operating parameters of the system. The effects of changing pump speed on pulsation amplitudes are illustrated in Figures 6 and 7. However, system design requirements usually prohibit any modification to system operating parameters. If a flowrate of 1500 gpm is required, pump speed cannot be reduced, thereby reducing pulsations, because system flowrate will also decrease.

In the majority of cases, the installation of properly sized pulsation dampeners will reduce pulsations for even the worst piping systems. Pulsation dampeners are of two types: energy

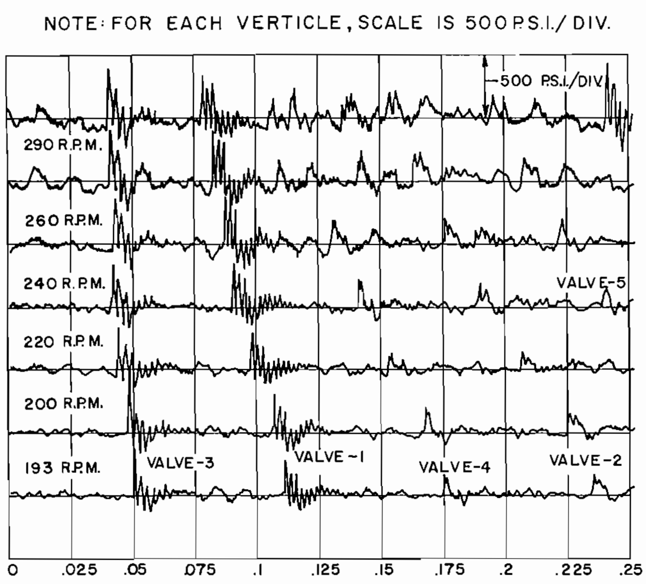

Figure 6. Pressure Traces within Suction Manifold Illustrating Effects of Speed on Pressure Pulse.

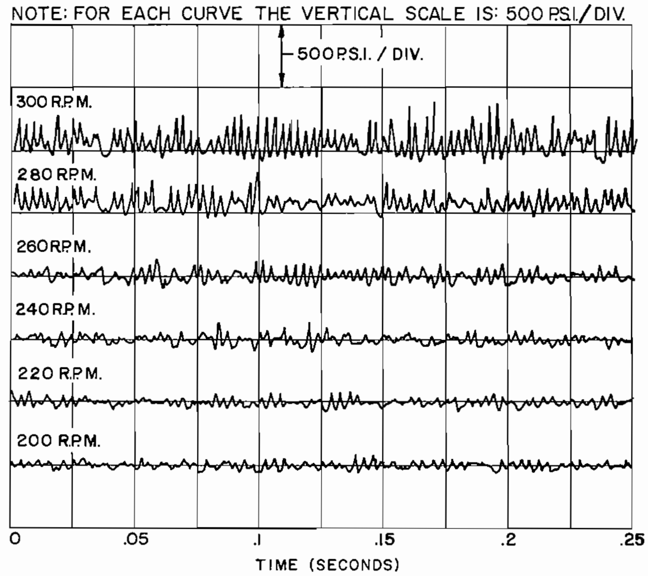

Figure 7. Typical Pressure Traces within Pump Discharge Manifold (note how pressure pulses increase with speed).

absorbing devices and acoustic filters [8]. The first type, also referred to as side branch accumulators, are most effective in absorbing low frequency pulsations such as those associated with flow induced pulsations [8]. Since this type of dampener relies on some type of gas filled bladder, it becomes ineffective in eliminating high frequency pulsations. The bladder must actually flex to absorb any detrimental pulsations, and, at frequencies above 50-75 Hz, the bladder cannot respond fast enough. Thus, this type of device loses its effectiveness as pulsation frequencies increase.

Acoustical filters, on the other hand, can be specifically designed to attenuate pulsations from low to high frequencies. This type of dampener consists of a series of choke tubes and surge volumes and is always filled with fluid [6]. By using the correct series and size of chokes and volumes, any frequency pulsation can be reduced. Unfortunately, the size of the dampener is inversely proportional to the pulsation frequency that has to be attenuated. Therefore, acoustic dampeners required for pulsations less than 50 Hz are usually very large and often cost prohibitive. Also, because acoustic filters are liquid filled devices, this type of dampener can be very expensive in high pressure systems.

Although most pulsation problems can be corrected with dampeners, the different types, sizes, and effectiveness of the units available make it necessary to select these devices for the pulsation frequencies to be attenuated. Typically, pulsation dampener manufacturers determine dampener size based on pump speed, fluid flow, and system operating pressure. Since no consideration is given to the pulsation frequencies which may exist in the system, other methods of determining dampener size are required. Not only is the type or size of the dampener important, the location of dampener in the system is critical. A properly sized dampener that is incorrectly placed within the system can result in increased pulsations due to an undesirable frequency shift of the system acoustic resonance. Ideally, pulsation dampeners should be located as close as possible to reciprocating pumps—usually attached to the pump flanges. The correct method of determining the size, type, and location of any required dampener is through acoustic analysis.

When pulsation problems occur in existing systems with pulsation dampeners, sometimes it is possible to reduce the pulsations by installing an orifice plate in series with the dampener. However, as with the selection of dampeners, the orifice size must be carefully selected and it must be properly located within the system. An orifice acts as an restriction in the piping and will reduce the amplitude of pulsations. Also, orifice plates can act as separators between the pump and piping helping to reduce the acoustic interaction between the two. Once again, an acoustic analysis should be used to determine the orifice size and location required to reduce pulsations.

In some cases, modification of the pump valves may result in a reduction of pressure pulsations. As mentioned previously, abnormal conditions can result in pump valve lag or valve knocking. Modification of the valves by either increasing spring loads, changing spring rates, or varying valve flow areas sometimes results in reduced pulsations. This method of tuning the pump valves for a specific piping system is not easy. Trial and error methods of determining the best valve modifications are required. Also, some modifications may result in decreased valve life.

Finally, when cavitation is a problem, it can be eliminated some of the time by raising the system suction pressure. This method of correction does not reduce the pulsations which may have caused the cavitation—it only raises the static system pressures to a point where the pulsations will not induce cavitation. This solution can result in other problems, however, because now the fluid pulsations occur at higher static pressures. Raising suction pressure can lead to increased piping vibration and/or additional shock loads in the pump. Prior to instituting this solution, an analysis should be completed to determine the possible detrimental aspects of raising system pressures.

Summary

In conclusion, the majority of system pulsation problems are the consequence of the relationship between the reciprocating pump pulsating flow and the acoustical characteristics of the piping system. When flow induced pulsations match the acoustic resonance of the piping system, their magnitude increases drastically. If these pulsations are not attenuated or eliminated, they can lead to a variety of problems in both the suction and discharge systems of the pumps. Suction system problems include cavitation, water hammer and valve knock. The usual discharge system problems are piping vibrations, fatigue failures and increased shock loading of pump components. Both suction and discharge system pulsations can lead to damage of the reciprocating pump, increasing maintenance costs.

Experience has shown that the best method of reducing detrimental pulsations in reciprocating pump systems is through the installation of properly sized pulsation dampeners, either of the energy absorbing or acoustical filter type. The best method of determining the size, type and location of a pulsation dampener is with either analog or digital acoustical analysis.

Field testing of systems experiencing pulsation problems will provide the amplitudes and frequencies of the detrimental pulsations. After these conditions are known, standard acoustical theory can be used to design adequate pulsation dampeners or determine whether other piping modifications are required.

The most reliable means of ensuring that a reciprocating pump system will not experience pulsation problems is to perform either an analog or digital acoustical analysis of the system in the design stage. Selection of required pulsation dampeners should not be done until after the acoustic analysis has been completed. Finally, once the system is built, field testing should be conducted to verify the recommendations implemented as a result of the acoustic analysis. If this simple addition to the design process is made, field problems should decrease. The cost of this additional analysis will pay for itself in increased production and reliability of the piping system.

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