Positive Displacement Pump Vibration

Pulsation and poor valve design are primary culprits.

Inadequate pulsation control and poor valve performance, along with faulty mechanical piping design, are the primary causes of excessive vibration in positive diplacement (PD) pump systems. Therefore, a working knowledge of how pulsation and valve dynamics influence PD pump vibration is essential for the design and operation of safe and reliable systems.

PULSATION

High vibration levels resulting from inadequate pulsation control usually correlate with high maintenance and poor machinery reliability. In addition, pressure pulsation acting on unbalanced areas such as elbows and closed valves will generate dynamic shaking forces that can cause high vibration levels in spite of adequate mechanical supports.

A less obvious effect of high pulsation is the potential for cavitation even when the static pressure has a sufficient margin above the vapor pressure. Pulsation may cause the pressure to drop instantaneously to the vapor pressure, (Figure 1) resulting in severe pressure spikes from bubble collapse as illustrated by Figure 2, which represents actual field data. These pressure spikes can damage pump internals, such as valve plates, plungers and working barrels. With severe pulsation, this phenomenon has been documented even in the discharge of pumping systems.

A feature article in the June 1994 issue *Pumps and Sytems* magazine (Ref. 1) discussed gas-charged pulsation dampeners as a means of pulsation control, and a comprehensive discussion of how these devices work can be found in reference 2. Since the gas charge offers an acoustical compliance characteristic that yields an effective volume many times larger than the same volume of liquid, these devices can be very compact. The effective volume can be computed as follows:

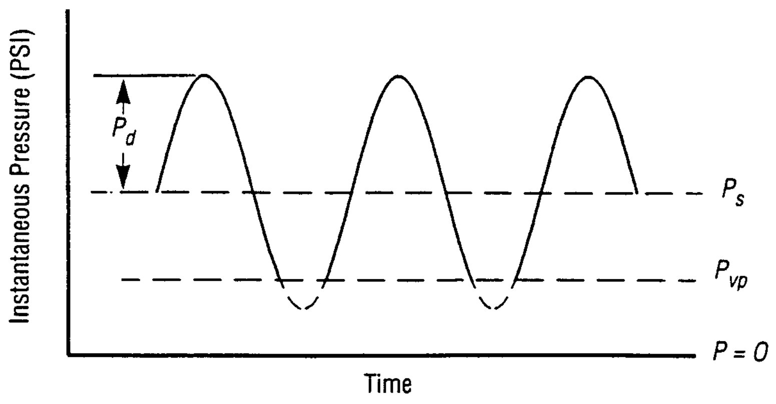
$$V' = \frac{K_{liquid} V_{gas}}{K_{gas}} = \frac{(\rho c^2)_{liquid} V_{gas}}{(\rho c^2)_{gas}}$$

where:

K = bulk modulus (psi)

c = speed of sound (ft/sec)

FIGURE 1. CAVITATION DUE TO PULSATION PRESSURE



If $P_d > P_s - P_{vp}$: then cavitation will occur.

P_s = *Static Pressure*

P_d = *Dynamic Pulsations, 0 - p*

P_{vp} = *Vapor Pressure*

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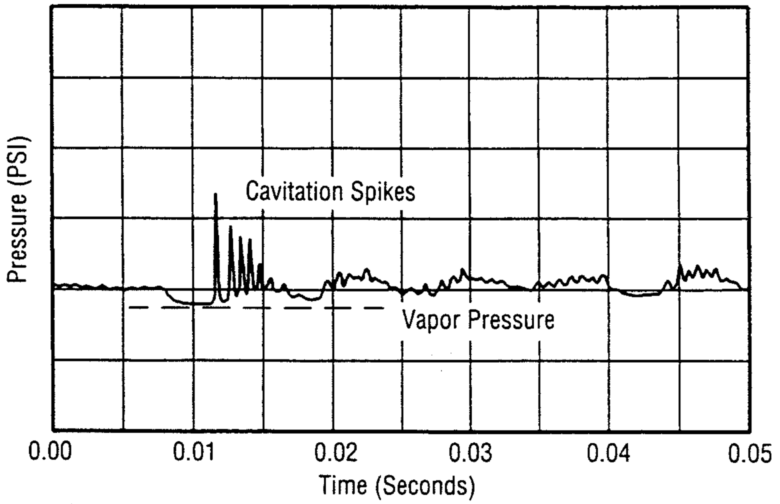
FIGURE 2. FIELD DATA SHOWING CAVITATION SPIKES



ρ= density (lb/ft^3)

V = volume (ft^3)

V' = equivalent liquid volume (ft^3)

Unfortunately, the performance of gas-charged devices can be degraded due to several factors, including:

- neck restriction (which reduces the compliance effects)
- bladder stiffness
- absorption of gas in non-bladder devices
- sensitivity to charge pressure
- bladder fatigue failures
- permeability of bladder materials to certain liquids.

Another common method of pulsation control is the "all-liquid filter." This method differs conceptually from the gas-charged device. The gas-charged device acts simply as a large compliance (volume). The all-liquid device is usually designed as a low-pass filter to attenuate pulsation levels at frequencies above a specified cutoff frequency. Acoustic elements such as volumes, choke tubes, and orifice plates are used to design the filter characteristics to accomodate particular applications.

The filter itself actually creates an acoustic resonance (Helmholtz frequency). But, the device works to attenuate pulsation levels at frequencies well above this resonance. Consider a triplex pump operating at 250 rpm. The plunger frequency can be calculated as follows:

$$\text{Plunger Frequency} = \frac{3 \times 250\text{rpm}}{60\text{rpm/Hz}} = 12.5\text{Hz}$$

An all-liquid filter can be designed with a Helmholtz frequency of 6 Hz. This device would create an acoustical resonance at 6 Hz; but since the lowest excitation frequency is 12.5 Hz, pulsation levels at the plunger frequency and its harmonics would be effectively attenuated. Generally, the lower the Helmholtz frequency, the better the pulsation filter.

All-liquid filters can be configured to achieve various characteristics. A symmetrical volume-choke-volume arrangement is shown in Figure 3. The following equation gives the relationship between filter frequency and the dimensions of the filter arrangement.

$$f = \frac{c}{\sqrt{2}\pi L}\left(\frac{d}{D}\right)$$

where:

f = frequency (Hz)

c = speed of sound (ft/sec)

d = choke diameter (ft)

D = diameter of each bottle (ft)

L = acoustic length of bottles and choke (ft)

As indicated by the equation, lower filter frequencies require either larger bottle chambers or smaller diameter choke tubes. Larger volumes cost more to build initially, but smaller choke tubes result in higher pressure drops and therefore higher operating costs.

However, this equation does not take into account the effect of attached piping networks on the filter performance. Because this effect does not generally follow a simple mathematical relationship, critical systems should be simulated using digital or analog techniques to ensure adequate pulsation control. This modeling also allows the trade-offs between installation costs (volume bottle size), pressure drop, and pulsation attenuation to be optimized, and it should be done regardless of whether gas-charged devices or all-liquid filters will be used.

A commonly employed all-liquid filter configuration for PD pump sys-

FIGURE 3. SYMMETRICAL VOLUME-CHOKE-VOLUME ALL-LIQUID FILTER

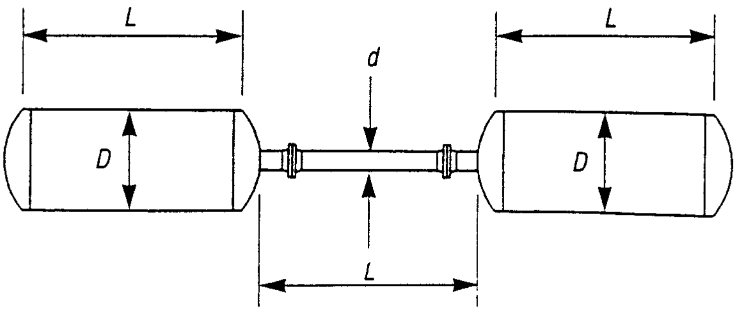


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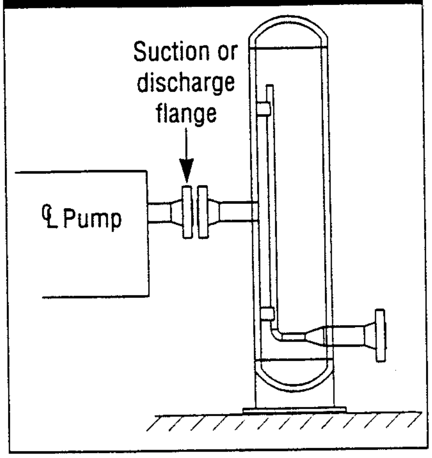
FIGURE 4. VOLUME-CHOKE ALL-LIQUID FILTER



tems is illustrated by Figure 4. This configuration is referred to as a volume-choke all-liquid filter and utilizes a single volume (bottle) near the pump flange and a choke tube that may be internal or external to the bottle. The choke tube connects directly to the larger suction or discharge piping through a reducer. This configuration does not cut off higher frequency pulsation components as sharply as the volume-choke-volume filter does. However, it is effective in pump systems since, unlike compressor systems, higher pressure drops may usually be tolerated. As a result, this volume-choke configuration often provides a good compromise between initial cost and pressure drop concerns.

All-liquid filters are relatively maintenance free when compared to gas-charged devices. They may also provide more effective pulsation control and are easily fabricated from typical piping components. The main disadvantage of all-liquid filters, relative to gas-charged devices, is their larger size.

VALVE PERFORMANCE

Valve dynamic effects can also cause large deviations in the pressures acting on a pump's working parts. The typical valve consists of a spring and a valve plug or plate that seals against a seat. An overpressure may occur once per cycle, producing dynamic stresses on pump components. Since the pressure required to open the valve is controlled by the spring forces and the differential pressure across it, the valve design can influence the magnitude of the overpressure.

The forces acting on a closed valve that can result in overpressure (illustrated by Figure 5) are described by the following equations:

1. Spring force

$$F_s = F_{preload}$$

2. Pressure forces

$$F_1 = P_cA_c \text{ (in cylinder)}$$

$$F_2 = P_mA_m + F_{preload} \text{ (in manifold)}$$

The valve will open when:

$F_1 > F_2$

or:

$P_cA_c > P_mA_m + F_{preload}$

$P_c > P_m(A_m/A_c) + F_{preload}/A_c$

where:

A_c = the area of the valve in contact with the cylinder pressure

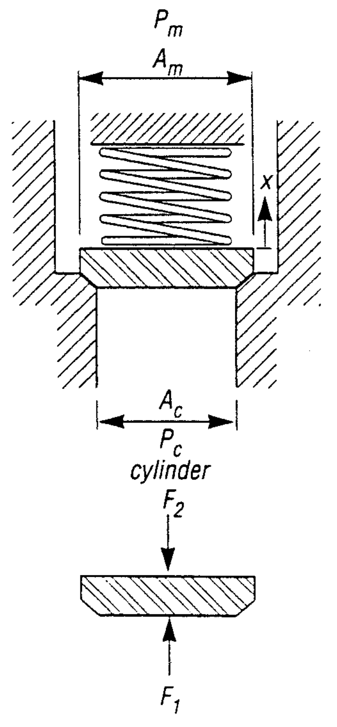
A_m = the area of the valve in contact with the manifold pressure

The differential area, required at the valve seat to seal the liquid, may cause an overpressure. For the valve to open, the cylinder pressure must be greater than the manifold pressure by the ratio of the areas A_m/A_c plus an additional factor to overcome the spring force. The area ratio A_m/A_c is typically 1.1-1.5 to yield a seating area sufficient to control valve impact stresses.

In addition to the spring, mass and differential pressure effects, there is a "sticktion" effect that opposes the separation of two lubricated flat surfaces (Ref. 3). This sticktion force is influenced by the initial fluid film thickness, the viscosity of the fluid and the geometry of the surfaces. The sticktion results in "overpressure" spikes on the discharge valves and "underpressure" spikes on the suction valves. Large overpressure spikes can cause various problems such as:

1. working barrel failure
2. crosshead guide and case failure
3. bearing damage

FIGURE 5. FORCES ACTING ON A CLOSED VALVE



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4. crankshaft and connecting rod failures
5. reduced valve life.

Another phenomenon related to valve performance is valve lag. The time required for a valve (suction or discharge) to return from a fully open position to its seat is dependent on the valve mass and return spring properties. Therefore, as the speed of a pump increases, the fixed finite time required for valve closure to occur results in a greater relative valve lag in relation to crank rotation. The lag of the discharge valve closing can actually cause backflow through the discharge valve. Likewise, a lag in the suction valve can allow backflow through the valve. This problem not only reduces pump capacity, but also changes the flow excitation characteristics of the pump. Since the pulsation levels are directly proportional to the flow modulation amplitudes, valve dynamic effects can increase the pulsation levels in a pump-piping system.

Valve dynamics effects can be computed using a time-stepped integration method (Ref. 4). This computation involves calculation of spring and mass properties, sticktion effects, and valve lag as well as calculations of pressure versus time to predict overpressure and underpressure spikes and valve lift versus time to define valve lag. Valve parameters (e.g., spring stiffness, mass, surface geometry, lift) can be optimized using this technique to minimize pressure spikes and valve lag.

CONCLUSION

Pulsation and valve dynamic effects should be of primary consideration when designing and troubleshooting PD pump systems. Careful attention to these factors, as well as to the mechanical support of the attached piping, will ensure a more reliable system. ■

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