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## Fundamental Specifications for Eliminating Resonance on Reciprocating Machinery

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### Abstract

When performing acoustical studies, companies have asked for accompanying mechanical analysis. Presently, no specific mechanical guideline exists in API Standard 618, which is the most commonly used standard for acoustical studies. API Standard 618 concentrates on the affects of pulsations only. There are many more forces associated with a reciprocating separable compressor, other than just pulsations, that can result in unacceptable vibrations. This paper discusses the main sources of forces and presents a mechanical guideline which will help to avoid mechanical resonance due to these sources.

- 1- we will explore what forces are in a reciprocating compressor and at what frequencies they occur at, and
- 2- we will develop a mechanical guideline to avoid resonance with these high forcing functions.

### Vibration Definition

Is the periodic movement of a body about an equilibrium position?

Vibration amplitude is a function of an applied force and the dynamic stiffness at a given frequency:

$$\text{Vibration} = \frac{\text{Dynamic Force}}{\text{Dynamic Stiffness}}$$

In controlling vibration, both aspects of the vibration equation must be considered.

### Introduction

Question: What is the purpose of performing an acoustical analysis?

Answer: To ensure a smooth running compressor package.

Question: Why do you want a smooth running compressor?

Answer: To avoid component failure leading to worker injury or equipment loss.

Knowing what unbalanced forces and moments are present in a separable reciprocating compressor package, and avoiding coincident mechanical natural frequencies, will greatly increase your chances of having a smooth running compressor.

Beginning with the fundamental equation of vibration:

### Forcing Functions

Several main forcing functions (ie: dynamic forces) are found in reciprocating machinery. Most are a function of the machine make and model rather than operating conditions. Pulsation induced shaking forces are more a function of operating conditions and piping geometry.

The forcing functions of concern in a reciprocating compressor installation are given in the following table along with the frequency at which the forces are largest and what can be done, if anything, to minimize the force.

Forcing Function	Dominant Frequency (Multiple of Run Speed)	How to Minimize Response
Mass Unbalance	<u>1X</u> , 2X	Minimize opposing mass unbalance (eg: 0.5 to 1 lbs for 1000 RPM, 6" stroke unit).
Moment/Couple	<u>1X</u> , 2X	Inherent in design.
Alignment	1X, 2X	Check angular and parallel alignment.
Pulsation *	<u>1X</u> , <u>2X</u> , 3X, 4X, ....	Control pulsations using acoustical simulation techniques.
Cylinder Stretch *	<u>1X</u> . 2X, 3X, 4X, ....	Inherent in design but check that cylinder assembly bolts are properly torqued.
Coincidence of torsional and acoustical natural frequency	At torsional natural frequency	Avoid coincidence of torsional and acoustical or mechanical natural frequencies.
Torque Fluctuations *	.5X, 1X, 1.5X, 2X, ....	Minimize torsional vibration using/replacing torsional dampener. Keep engine balanced properly.
<b>NOTE: * - On average these forcing functions decrease with increasing multiples. - The most significant forcing functions occur at 1X and 2X compressor run speed.</b>		

### Terminology

Mass Unbalance:	Mass unbalanced in opposing reciprocating components and rotating component unbalance.
Moment/Couple:	Created by the offset of opposed reciprocating components.
Alignment:	Angular and parallel alignment of driver and compressor shafts.
Pulsation:	Pulsation induced shaking forces.
Cylinder Stretch:	Elongation/shortening of cylinder assembly due to internal gas forces.
Coincidence of torsional and acoustical natural frequencies:	Coincident acoustical and torsional natural frequencies feed on one another to produce additional cylinder stretch vibrations and pulsations
Torque Fluctuations:	Changes in torque loading. Frequencies to be concerned with: -.5X,1X,1.5X.. for 4 cycle engines -1X,2X,3X.. for 2 cycle engines, motors and compressors.

If engine power cylinder pressures are perfectly balanced, then the highest torque input frequency will be N/2 times run speed for a 4 cycle engine and N times run speed for a two cycle engine, where N is the number of power cylinders.

### Stiffness and Mechanical Natural Frequencies

All groups of components, (piping, pulsation bottles, scrubbers, cylinders, etc.) in a reciprocating compressor installation will have several mechanical natural frequencies below 200 Hz. The mechanical natural frequency of a component is the frequency at which the component naturally wants to vibrate. For example, a spring-mass system will oscillate at a constant frequency if the weight is pulled down and then released. Another example is when a guitar string is plucked it will vibrate at its natural frequency to produce the sound we hear. The mechanical natural frequencies of a pipe or piping system depends on lengths, schedules, diameters, elbows, supports, etc.

The static stiffness of a component helps to determine its mechanical natural frequencies (ie. the frequencies of the different scrubber modes that are excited when a scrubber is struck once with a hammer). The dynamic stiffness of the component approaches zero at its mechanical natural frequencies (ie: the effective stiffness of a scrubber when it is excited by an oscillating force at its natural frequency).

Remembering the basic vibration equation, as the dynamic stiffness approaches zero the potential for high vibration increases.

Mechanical resonance of a piping component occurs when a forcing function is applied at a frequency corresponding to a mechanical natural frequency of the component.

If an oscillating force of constant amplitude is applied to a system over a frequency range, the resulting vibration of the systems will vary. A schematic of a typical suction system is shown in Figure 1. Figure 2 – Response of Suction Line Upper Elbow, illustrates the response of the suction line.

- When the oscillating force is applied at a frequency below the natural frequency of the component there will be some response.
- As the frequency of the input force approaches the first mechanical natural frequency of the component the response of the system is greatly amplified. At this point the component is “resonant”.
- The shape and the magnitude of the response peak is a function of the damping (analogous to electrical resistance) in the system. The more damping in the system the broader and lower the peak will be. Damping comes from flanged and bolted connections, clamping, material characteristics, etc.
- When the forcing frequency is greater than the natural frequency of the component, the response of the system drops to very low levels.
- As the frequency of the input force approaches the second mechanical natural frequency of the component the response of the system may again be greatly amplified.

Considering the typical response curve, components of a compressor system will have less response if the natural frequencies are below compressor speed (components that have their natural frequencies below compressor speed are said to be undertuned). However, undertuning is not always possible in cases where the static stiffness is high. Also, by undertuning the first mode, higher modes may become a problem.

As well, the magnitude of the forcing function typically decreases as frequency increases. If the component natural frequencies are above the frequencies of greatest input (ie. one and two times compressor speed) the vibration levels should be acceptable, assuming the forcing functions are reasonably controlled.

When a system, or part of a system, is mechanically resonant, normal (or even low) pulsation induced unbalanced force levels can couple with the system geometry to produce very high vibration levels.

**NOTE:** Beta Machinery Analysis' field experience shows that the majority of the vibration problems encountered in reciprocating compressor installations is related to mechanical resonance, with most of the remaining problems related to acoustical resonance.

### Mechanical Guideline

To avoid resonance at the predominant force input frequencies, the mechanical natural frequency of any piping component must not be in the range of 1X or 2X run speed. With over 25 years of experience, Beta Machinery Analysis concludes that a minimum natural frequency of 30 Hz should be applied to piping closely coupled to the cylinders (ie: bottles, scrubbers and piping to the second pipe support). This is due to the interaction of cylinder stretch, pulsation, torque and torsional input forces. For all other piping and vessels there is one of the following two mechanical guidelines to consider.

#### Variable Speed Mechanical Guideline:

A mechanical analysis is to be performed on all systems included in the acoustical models. A finite element program is to be used to determine the mechanical natural frequencies of all vessels and attached piping. All predicted mechanical natural frequencies are to be greater than 2.4 times run speed. The minimum mechanical natural frequency on piping closely coupled to the cylinders is to be greater than 30 Hz, or 2.4 times run speed, whichever is higher.

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**Fixed Speed Mechanical Guideline:**

A mechanical analysis is to be performed on all systems included in the acoustical models. A finite element program is to be used to determine the mechanical natural frequencies of all vessels and attached piping. All predicted mechanical natural frequencies for high speed units (900 RPM or over) are to be less than .8 times run speed or between 1.2 and 1.6 times run speed or greater than 2.4 times run speed. For low speed units, avoid mechanical natural frequencies below 30 Hz that are within  $\pm 20\%$  of harmonics of run speed.

**Summary**

Avoid resonance, avoid failure! The number one cause of piping failure in the oil and gas industry today is mechanical resonance. If you can avoid resonance at the frequencies that have the highest input forces, then you are well on the way to having a smooth running installation. The above guidelines, when followed correctly, do that.

FIGURE 1

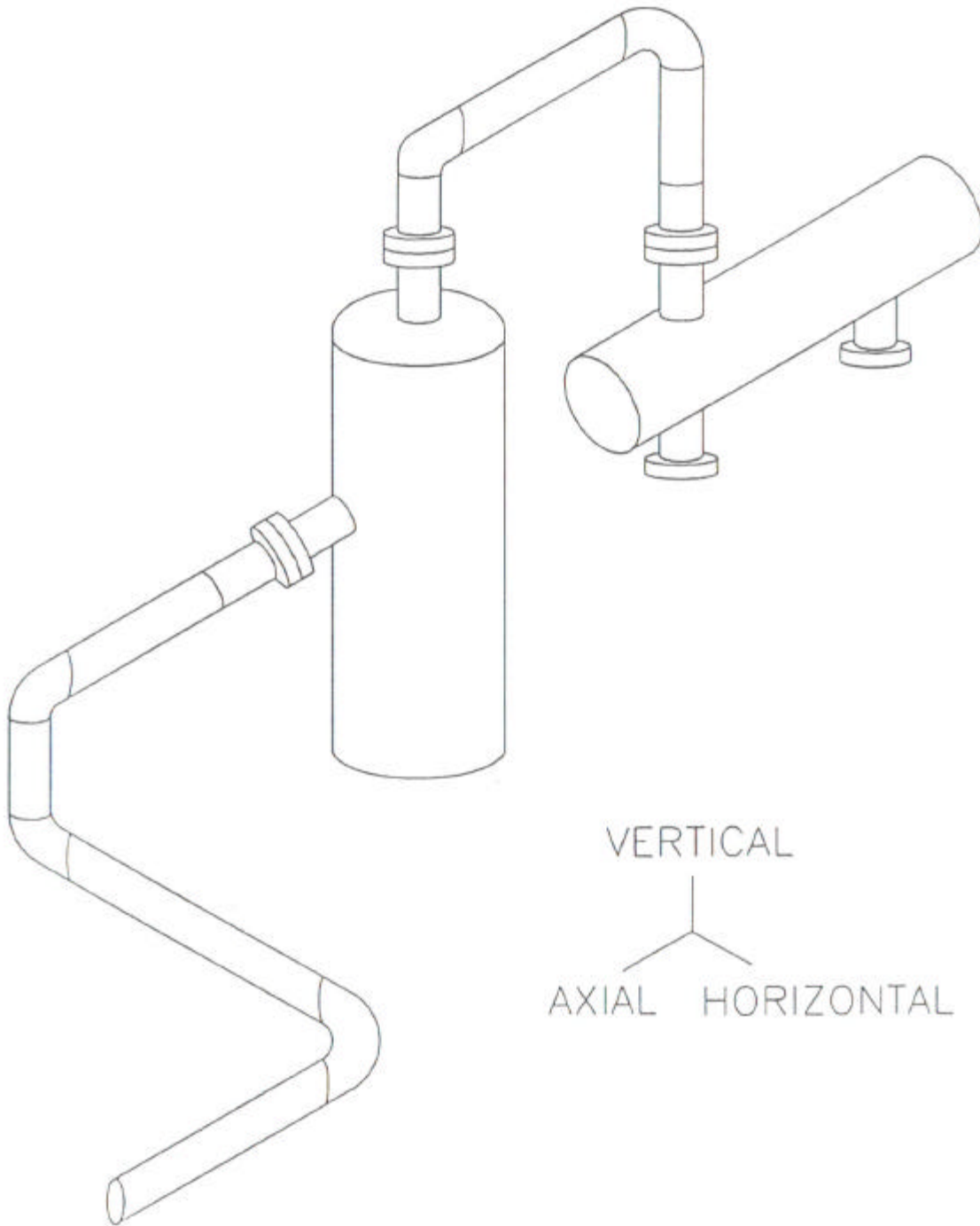


FIGURE 2

