

# Root Cause of Piping Failures: Reliability Issues for Compressor Systems

By

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## Abstract

Based on recent field vibration inspection audits of its compressor units, Williams has identified that vibration induced piping failures represent a consistent integrity risk to their operations. This finding is surprising given that technical information and recommendations are available to avoid problems on compressor packages.

To address this integrity and reliability challenge, the authors have identified the factors contributing to the problem's true root cause, including practical considerations that occur during procurement, design, and testing phase.

This paper includes the perspectives of the Owner, Engineering Consultant, Packager, and Vibration Engineer, and offers recommendations to improve the situation. Field and design examples will be used to illustrate this common industry problem.

## 1. Introduction

Williams Pipeline (“Williams”) field inspection programs have identified vibration issues with various compressor stations. Vibration is an important reliability/integrity issue due to piping fatigue failure, production downtime, safety/environmental issues, and higher maintenance costs.

The purpose of this paper is to identify the root causes that contribute to these reliability issues and share these observations with industry so that others can benefit and improve their operations as well.

Note that a formal Root Cause Analysis (RCA) project was not undertaken. The following findings are based on an initial evaluation of contributing factors facing the engineering, technical services and operations teams.

Section 2 introduces the problems found in a recent vibration audit/inspection of 27 compressors. A variety of factors contribute to these problems and these root causes are identified in Section 3. The authors also provide suggestions to address these reliability/integrity gaps. An Appendix is also provided, showing more details on the causes found.

## 2. Problem Description

To identify vibration risks and problems, Williams conducted a vibration inspection program on its compressor fleet. A third party vibration engineering specialist (Beta Machinery Analysis, or “BETA”) conducted these inspections, provided a detailed assessment of each unit, and defined an implementation/remediation plan.

For purposes of this Root Cause Analysis (RCA), Williams has shared the inspection results from 27 different compressors located at 10 different stations in the Northeast United States. Figure 1 on page 3 defines the general inspection areas focused on during the vibration inspections (labeled inspection areas 1 through 12). These inspection areas are grouped together because components in these areas tend to have similar type problems. A description of these inspection areas and the typical problems found in them is shown in Table 1 on page 3.

Table 2, on page 5, lists the actual problems BETA and Williams found in these inspection areas, for each compressor and at each location. The areas flagged are considered problems because high vibration amplitudes were measured. These areas are at risk of vibration induced piping failure. Some of the inspection areas did not have any problems. These areas are left in the chart to show successes in the compressor design.

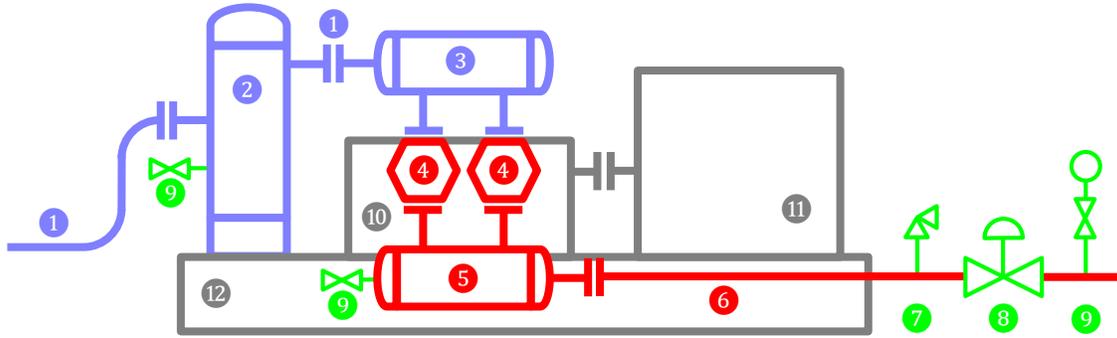


Figure 1. Problem Areas on Compressor System

Table 1. Summary of inspection areas and typical problems

Inspection Area	Typical Problems
1 Suction ("Cold") Piping	<ul style="list-style-type: none"> <li>Elevated piping is difficult to support and has high vibrations.</li> <li>Piping between scrubber and suction bottle can be short which makes fit up difficult.</li> <li>Difficulty fitting up flanges or clamps leads to pipe strain.</li> </ul>
2 Scrubbers, Separators, Vessels	<ul style="list-style-type: none"> <li>Small bore attachments on vessels can have high vibrations.</li> <li>Tall skinny scrubbers can have low natural frequencies (which don't meet API 618 guideline) and can have high vibrations.</li> <li>Inadequate scrubber skirt thickness, skid grouting, or scrubber skirt welding.</li> </ul>
3 Suction Pulsation Bottles	<ul style="list-style-type: none"> <li>High bottle vibrations leading to cracked nozzles.</li> <li>Oversized or overhung suction bottles can have low natural frequencies, be difficult to support and may vibrate.</li> <li>Short pulsation bottle nozzles have high stresses perpendicular to compressor crankshaft.</li> <li>Poorly designed small bore attachments resulting in high vibrations of the attachments and/or cracks at the connection.</li> </ul>
4 Compressor Cylinders	<ul style="list-style-type: none"> <li>High axial vibrations due to resonance and insufficient support at the crosshead guide (or cylinder head-end).</li> <li>Misalignment causing rod runout.</li> <li>Normal horizontal motion of compressor cylinders can cause high frequency vibration on small bore attachments or plate-type cylinder head-end supports.</li> </ul>
5 Discharge Pulsation Bottles	<ul style="list-style-type: none"> <li>High bottle vibrations leading to cracked nozzles (however supporting discharge bottles is easier).</li> <li>Poorly designed small bore attachments resulting in high vibrations of the attachments and/or cracks at the connection.</li> <li>Wedge supports come loose (due to thermal growth or vibration) and result in high bottle vibrations.</li> <li>Thermal growth of nozzles causes pipe strain or loose wedge supports.</li> </ul>
6 Discharge ("Hot") Piping	<ul style="list-style-type: none"> <li>Poorly supported piping near discharge bottle can have high vibration.</li> <li>Difficulty fitting up flanges or clamps, leading to pipe strain.</li> <li>Thermal expansion of piping, due to high temperature, can result in pipe strain and high pipe support loads.</li> <li>Pipe supports are removed or modified to reduce pipe static stress and/or equipment loads, but are not adequate for vibration design, resulting in high vibration.</li> </ul>

Inspection Area	Typical Problems
7 Relief and Blowdown Valves	<ul style="list-style-type: none"> <li>Isolation valves results in tall lines with high vibrations.</li> <li>Heavy valves can results in high vibrations and cracks at connection to mainline piping.</li> <li>High forces caused by valve activation can cause high deflections and stress.</li> <li>Thermal growth on mainline can cause stress on connection if relief header is not allowed to move also.</li> </ul>
8 Control and Recycle Valves	<ul style="list-style-type: none"> <li>High pressure drop and flow through pressure reducing valves can lead to noise (vortex shedding) and high-frequency acoustic vibration problems.</li> <li>Deadlegs created when valves are closed can create acoustical resonance in pipe, which can lead to high pulsation-induced forces and vibrations.</li> </ul>
9 Small Bore Piping	<ul style="list-style-type: none"> <li>Heavy unsupported cantilevered valves have high vibrations.</li> <li>Excessive small bore attachments are used but not necessary, resulting in more areas with failure risk.</li> </ul>
10 Compressor Frame	<ul style="list-style-type: none"> <li>Poor mounting to skid pedestal or concrete block results in high frame vibrations.</li> <li>Torsional vibrations can cause driveshaft failures or, in some specific cases, lateral vibrations of frame.</li> </ul>
11 Engine or Motor	<ul style="list-style-type: none"> <li>Poor mounting to machinery pedestal or concrete block results in high machinery vibration.</li> </ul>
12 Skid, Mounting, and Foundation	<ul style="list-style-type: none"> <li>Local flexibility in skid (baseplate) near machinery mounting feet can cause high vibration of machinery. Flexibility can be decreased by adding gussets or plate to skid.</li> <li>Inadequate grouting or concrete fill.</li> <li>Poor connection between skid (baseplate) and foundation (concrete, piles, platform deck, etc.) can cause high skid vibrations.</li> </ul>

The potential sources of the problem areas were flagged in Table 2. They included:

- **L**oose or poorly designed supports. These supports are not creating adequate stiffness at that location. A well-functioning support should have minimal vibration (< 0.1 in/s peak) at the support location. Support problems affected 59% of the units.
- High vibration due to base **M**otion of the main piping, vessels, or machinery. This tends to indicate the vibration is a symptom of high vibration of another component; therefore the fix should start at that component first. Base motion affected 18% of units.
- High vibration due to **R**esonance. Resonance is when the natural frequency of the components, like a suction bottle or small bore attachment, coincides with the frequency of the energy created by the rotating machinery. Resonant components can have their vibration amplified 20-40 times. Resonance was an issue on 93% of the units, with 41% of the units having resonance issues on small bore connections only.
- Pipe **S**train is internal strain in piping systems caused by misalignment and static deflections. It has been seen to increase vibrations, particularly high frequency ones. Pipe strain was an issue on 41% of the units.

Other areas which can potentially cause problems are misalignment of drive-train shafts, pulsation-induced unbalanced forces, and machinery unbalanced forces and moments. These sources were not found to cause vibration problems at these Williams locations, but are commonly found at other compressor installations.

**Table 2. Vibration Problems by Compressor**

Inspection Area	Compressor Unit (27 Compressor Packages at 10 Stations)																										
	A1	A2	A3	B1	B2	C1	C2	C3	D1	D2	D3	E1	E2	E3	F1	F2	G1	G2	H1	H2	I4	I5	I6	I7	J1	J2	J3
Stage 1	1 Suction piping			R					R			R							R	R	R		R		R		
	2 Scrubber			R																	R						
	3 Suction bottles					MR	R		R			R					L										
	4 Cylinders			R		L											L		R								
	5 Discharge bottles					M				L	L													L		L	
	6 Discharge piping																					S	S		S		
Stage 2, or left side stage 1	1 Suction piping																										
	2 Scrubber																										
	3 Suction bottles				R	MR	MR	MR	R			R	R	R				L	R								
	4 Cylinders			LR		L	L	L									L	L	R								
	5 Discharge bottles									L	L						L	L	L								
	6 Discharge piping																					S			LS	R	
	7 Relief valves	LS	S	LR	R		MRS	MRS	MRS	RS	R	R	R	R	R	MR	MR			S	S					R	
	8 Control valves										R	R												R	R	R	
	9 Small bore piping	R	R	R		LR	R	R	R								R	R		R	R		R	R	R	R	R
	10 Compressor frame																										
	11 Engine														L												
	12 Skid																										

Legend: L=loose/poor support, M=base motion, R=Resonance, S=pipe strain

### 2.1. Conclusions from Vibration Inspection Program

The conclusion from this field inspection program includes:

- Resonance on piping and vessels is a consistent issue.
- The compressor design addressed pulsation forces but did not address mechanical resonance problems, support design, or base motion. This indicates a gap in the vibration design.
- There are many fit-up or installation issues which occur at the compressor fabrication shop, during site construction, etc.
- Many of the problems require expensive field modifications. Addressing these problems in the design stage would result in significant financial savings.

There are three direct benefits of the vibration inspection program:

1. Williams can identify high risk integrity/reliability issues across its operating area. This is a critical requirement for an effective integrity management program.
2. For each unit, the maintenance team has a plan and recommendations to solve the problem.
3. Identify gaps in the engineering, fabrication and commissioning process (root cause analysis).

### 3. Root Causes and Lessons Learned

Problems can occur at different stages of the process, including the initial project planning, detailed design, construction, and ending with the site commissioning. Some of the contributing factors are technical/engineering related issues. These problems can be mitigated through changes in Williams’ specification, engineering and inspection activities. But many other contributing factors stem from communication, training, and project management activities.

Table 3 identifies the root cause issues affecting William’s compressor facilities, and recommendations for improvement. These observations reflect the authors’ “lessons learned” for improving the asset reliability. While these observations are focused on William’s operations, it is likely that many other owners/operators face similar challenges.

**Table 3. Root Causes and Improvement Ideas (Lesson’s Learned)**

<p><b>Lack of Standards</b></p>	<p>Existing engineering standards are inadequate and contain gaps relating to vibration engineering and analysis.</p> <p>Williams is updating its engineering specifications including:</p> <ul style="list-style-type: none"> <li>• Design requirements (pulsation, mechanical, torsional, skid, pipe stress analysis)</li> <li>• Consistency in required analyses and support design for on-skid and off-skid piping</li> <li>• Small bore piping specification</li> <li>• Packaged compressor mechanical completion checklist</li> <li>• Site installation and mounting</li> <li>• Testing and Inspection</li> </ul> <p>Note: GMRC High Speed Compressor Guideline is valuable source for specifications.</p>
<p><b>Limited Education or Awareness</b></p>	<p>Many project managers, project engineers, engineering contractors, inspectors, construction companies, and technical staff are unfamiliar with vibration engineering requirements. A lack of education in this discipline directly affects the unit’s reliability. Typical areas where education is needed are proper pipe support installation, pipe strain, small bore piping, operating conditions and their effect on performance and pulsations, and required design analyses (like pulsation studies).</p>

### 1. Define Project Team and Roles

Williams has identified a gap in how these compressor projects are managed. Engineering and Construction (E&C) project teams can be relatively inexperienced and are driven heavily by optimistic cost and schedule goals. The lack of experience combined with the fast project pace has shown that critical individuals are left out of the equipment selection, bidding, and design review process. Many times the Subject Matter Expert (SME) hears about equipment that has been purchased or scheduled design reviews from our vendors rather than the internal E&C group. By the time the SME's hear about a project, the cost and schedule are already set and the major equipment is on order with exceptions accepted. Every drawing or package modification from that point onward is a cost and schedule risk. This affects the E&C project manager's goals directly which creates pushback and conflict.

Additionally, because the SME's were not contacted before the equipment was ordered, an out-of date specification might have been used from the previous job to purchase the equipment or facility vibration studies were not included in the cost estimates. Making sure that the correct people are notified early in the process is crucial for a successful project. Williams has implemented a Stage-Gate process that our Project Managers (PM's) follow to ensure all groups are allowed input on projects.

### 2. Vibration Review during Project FEED/Planning.

A vibration review is a worthwhile activity for new installations, or when re-vamping an existing unit. This activity is typically very short duration, but useful for evaluating applicable specifications, piping layout, foundation options, etc. Currently, this is not performed due to timing, lack of site information, and uncertainty of the cost/benefit of such a study.

### 3. Owner to Retain Vibration Specialist.

Best Practice also involves the owner retaining a vibration specialist to perform the required engineering and to work closely with the Engineering, Procurement and Construction contractor (EPC), compressor packager, and other team members. This has several benefits as compared to delegating the pulsation/vibration analysis to the compressor packager:

- The pulsation study will size and design the pulsation bottles, which can be included in the bid package.
- The full operating range can be analyzed and optimized, not the few design points provided to packagers.
- Recommendations about foundation and support structure can be communicated to the EPC.
- On-skid piping stress results can be integrated into the off-skid results, the latter typically done by the EPC. This avoids conflicts and rework later.
- If the scope changes, the pulsation/vibration study can be updated quickly. For example, off-skid piping can be added to the piping model once it is finalized, or new operating scenarios can be investigated for their impact on pulsations and performance.

<p><b>Gaps When Procuring The Compressor Package</b></p>	<p>The compressor packaging industry is highly competitive. If the owner is solely focused on the lowest cost, then careful attention must be paid to the vendor bids and contracting terms. Effective project management (as outlined above in <i>Project Execution Gap</i>) is needed to closely monitor the “bid exceptions” and how these exceptions can affect the unit’s costs and operation. Accepting the lowest cost unit and the vendor’s exceptions may not turn out to be the best approach.</p> <p>Some specific areas that Williams is working on to address this gap include:</p> <ol style="list-style-type: none"> <li>1. Supply preliminary bottle sizing for the bid. The vibration specialist can use specialize tools to calculate preliminary bottle sizes. Including this in the specification will save change fees later on and help tighten the bid comparison.</li> <li>2. Closely manage bid documents and exceptions to the bid. Some exceptions may have significant consequences to the operational reliability and flexibility of the unit.</li> <li>3. Participate in milestone meetings. There are important milestone meetings that require input/approval from the owner, and participation with the EPC/packager/Vibration Specialist.</li> <li>4. Monitor the design details to ensure they comply with the owner’s requirements.</li> </ol>
<p><b>Design Details – Small Bore Attachments</b></p>	<p>Rules of Thumb for improved design (technical observations):</p> <ol style="list-style-type: none"> <li>1. Avoid putting small bore attachments (SBA) within 10 mainline pipe diameters of valves (recycle, relief, control, etc.) and fittings (elbows, tees, and reducers).</li> <li>2. Location SBA within 2 mainline pipe diameters of supports.</li> <li>3. SBA should be schedule 80 thickness, as a minimum.</li> <li>4. Avoid putting SBA on elevated piping (due to geometric amplification of vibration).</li> <li>5. Heavy valves (including isolation valves, double block and bleed, and gate valves) should not be used on SBA. Use low profile valves instead, like monoflange valves. If large valves are required, use gussets on the SBA or brace the valve back to the mainline pipe.</li> <li>6. Cantilevered type SBA should be as short as possible.</li> <li>7. Use proper dynamic clamps on gas pipe rather than U-bolts (see Appendix A.6).</li> <li>8. Minimize the use of redundant gauges on- and off-skid</li> <li>9. Minimize the use of unused vent, hydrotest, or purge valves. <ol style="list-style-type: none"> <li>a. Many times the compressor package is following the best practice on pipe nipples but the pipe that bolts to the package skid edge connections (from the EPC or contractor) might have several unused pipe Female-to-Female (FxF) valves connected to the base pipe with a 6” long pipe nipple.</li> </ol> </li> <li>10. Use only Male-to-Female valves on pipe and vessel connections rather than a FxF with nipple.</li> <li>11. If pipe nipples are used, ensure they are schedule 160, as short as possible, and well supported. “Close” nipples are unacceptable due to inadequate stiffness.</li> <li>12. All instrument and vent tube is well supported.</li> </ol>
<p><b>Fabrication Details</b></p>	<p>Good communication between the EPC and compressor packager.</p> <ol style="list-style-type: none"> <li>1. Recommend regular shop visits to inspect compressor fabrication details.</li> <li>2. Check fit-up and tolerances of key joints.</li> <li>3. Vibration check including impact (bump) testing to identify potential resonances.</li> <li>4. Checklists for key items to look for.</li> </ol>

## Site Installation, Start-Up, Testing

During site installation a number of key activities take place that can affect the unit's reliability (e.g., piping fit-up and impact on pipe strain, mounting, grouting, and other site issues). There is typically good control of installation details on the package in the shop, but poor installation in the field beyond the package skid-edge. Items not routed on the drawings, like instrument supply lines to valve operators, are typically completely unsupported and left for premature failure.

1. Effective site inspection is a critical during this activity, including access to a trained site inspector.
  - a. Inspector needs to be knowledgeable in proper clamp use, lessons learned, tube routing/support, SBA supports, proper torqueing procedures, proper bolt stretch requirements (e.g., not epoxying in foundation studs), proper studs for the application, etc.
2. Baseline vibration audit including checking pulsations, resonance across speed sweep, skid, driver, piping, small bore attachments, etc.

## 4. Summary

An inspection of 27 compressor units at 10 different compressor stations revealed trends in the types of problems found. The main areas of concern were small bore attachments, most of which were resonant, had pipe strain issues, or were due to loose supports and braces. Next were suction pulsation bottles, which were almost all due to resonance. Discharge bottles were also a vibration concern, mostly due to loose wedge supports.

Areas that were successfully designed and installed were the compressor skid, the compressor itself, and the engine. This was due to well-designed foundations and good installation procedures. Scrubbers were also well designed and installed. This is positive because scrubber tend to be resonant (therefore have high vibrations) and have many small bore attachment (which can be a failure risk).

Many of the problem areas can be solved through better procedures and practices, many of which were outlined. These include better education of the vibration risks to owners, packagers and EPCs, better evaluation of the bids for details that will affect the ultimate design, and better specs to make the expectations on all parties clearer throughout the project life-cycle.

## 5. References

- GMRC Guideline for High-Speed Reciprocating Compressor Packages for Natural Gas Transmission & Storage Applications, Gas Machinery Research Council & ACI Services, Rev. 0, August 2013.
- B. Howes, G. Maxwell, "Piping Misalignment and Vibration Related Fatigue Failures," Gas Machinery Conference 2013.
- C. Harper, "Integrity Evaluation of Small Bore Connections (Branch Connections)", 9th EFRC Conference, September 2014.

## Appendix A: Examples of Problem Areas

### A.1. Small Bore Attachment

#### A.1.1. Example #1

A resonant small bore attachment had high vibration at its natural frequency (Figure 2). It was flagged as a potential failure risk during the vibration audit, and failed shortly after the vibration audit report was received.

The original design had a FxF valve, which necessitated a small MxM coupling between the fitting and the valve. An MxF valve was recommended in the vibration audit report, which would have reduced the length, but the broken attachment was replaced with a similar design (Figure 3).

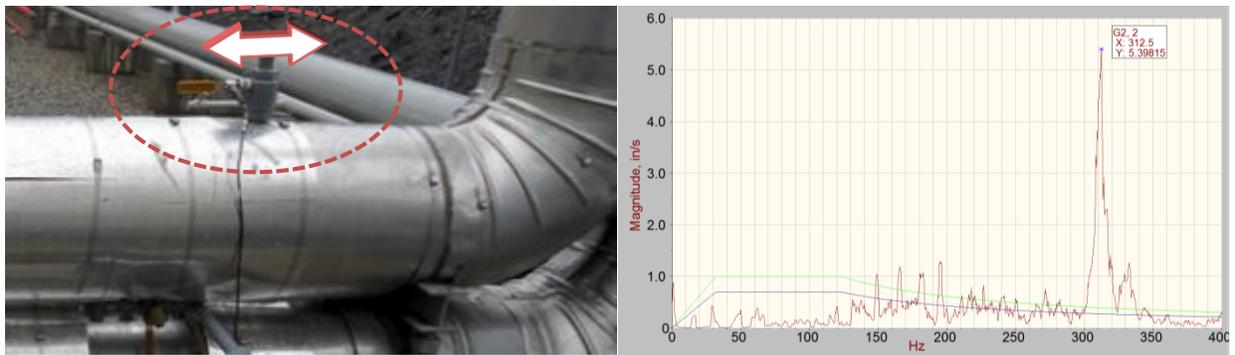


Figure 2. Small bore attachment with high vibration (left) and vibration spectrum (right)



Figure 3. Original small bore attachment (left) and crack detail (right)

#### A.1.2. Example #2

A small bore attachment, directly upstream of a suction scrubber, was found to have high vibrations (Figure 4). During the vibration audit, it was discovered that the fitting was leaking. The fitting was replaced after BETA left the site with a similar designed fitting and failed again.

Finally, the fitting was replaced with a design with a longer nipple, which also broke and contributed to a fire that destroyed the machine.

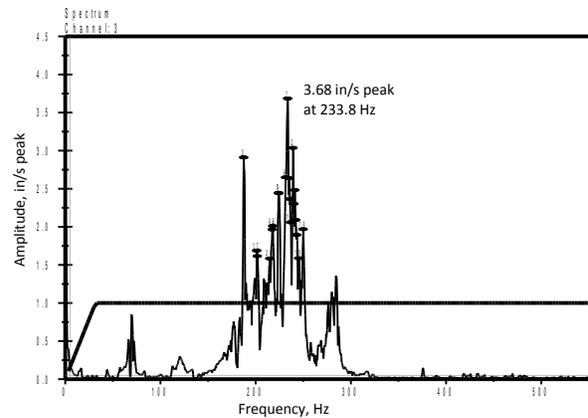
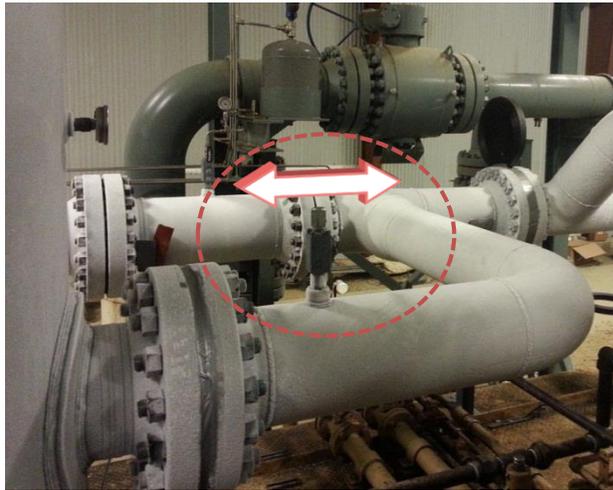


Figure 4. Small bore attachment upstream of scrubber with high vibration (left) and vibration spectrum (right)

### A.1.3. Example #3

Several small bore attachments were resonant and vibrating excessively. The problem was due to the tall design of the small bore attachment, its location near a control valve (which creates acoustic energy when partially closed), and the flexible main piping support design (Figure 5).



Figure 5. Small bore attachment

### A.2. Pressure Safety Valves

The Pressure Safety Valve (PSV) was gusseted but poor shimming caused pipe strain which lead to high vibrations (Figure 6). When the supports were loosened, shimmed, and retightened, the vibration levels were reduced.

### A.3. Base Motion

On compressor “C1” (Table 2 on page 5), a suction bottle was found to be vibrating a 2.9 in/s peak in the horizontal direction at its closed end. Further investigation found that the nearby cylinder vertical vibration was 1.1 in/s peak. The flexibility was traced to either the inboard support connection or loose wedge supports. Fixing those, or installing outboard cylinder supports, will fix the suction bottle vibration, which was due to base motion of the cylinders (Figure 7).



Figure 6. PSV

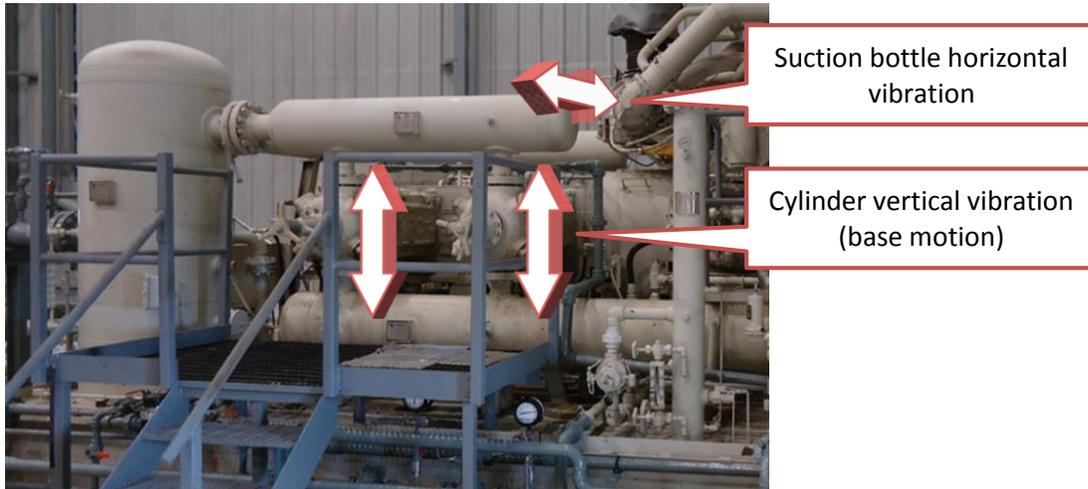


Figure 7. Suction bottle vibration caused by cylinder vibration

#### A.4. Discharge Bottles

On compressor “D2” (Table 2 on page 5), wedge supports were found loose and in some cases missing (Figure 8). These wedge supports were reinstalled and tightened, and vibration levels were found to actually increase. When all wedge supports were removed completely, the vibrations did not change significantly, therefore it was decided to leave them off.

Also note that the beam under the wedge supports has no gussets, and is therefore very flexible in the axial direction (although the stiffness is reasonable in the horizontal and vertical directions). Gussets are always recommended for supports similar to this; see Figure 9 for a good example.

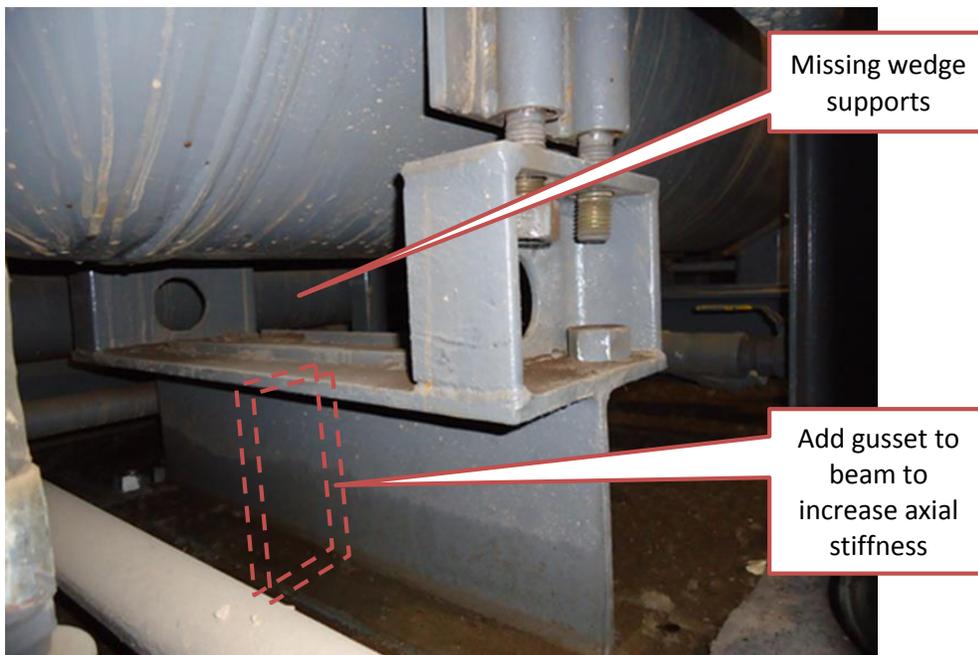


Figure 8. Discharge bottle wedge supports

## A.5. Pipe Strain

On compressor "14" (Table 2 on page 5), high vibration (1.5 in/s peak) was found (Figure 10) on piping that was well supported on well-design sleepers with gussets and good grouting (Figure 9). When the clamp was loosened, a gap opened up between the pipe and the support structure below it. Shimming this gap reduced the vibration of the piping, especially the high frequency vibration.



Figure 9. Discharge piping near discharge pulsation bottle

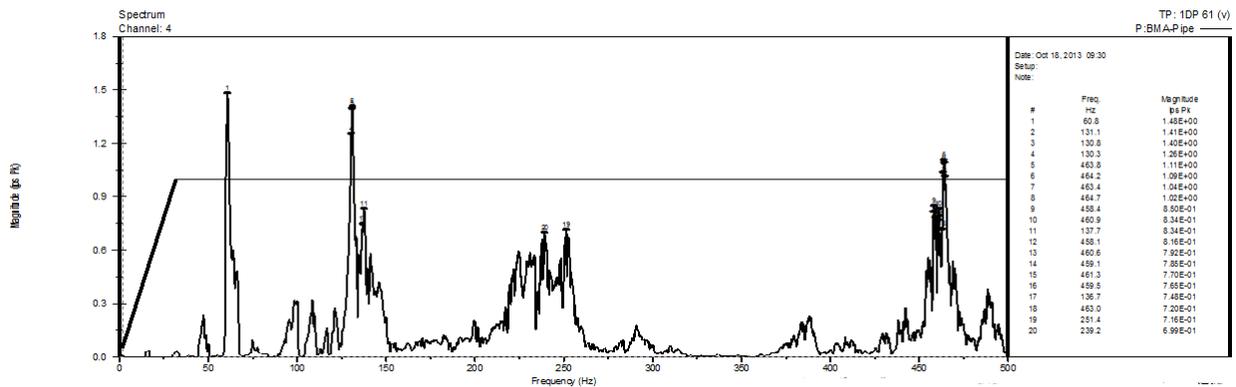


Figure 10. Vertical vibration of discharge piping, speed sweep from 900 - 1000 RPM

## A.6. Pipe Supports

Several common pipe support designs are shown in Figure 11. Comments on each of the designs are shown in Table 4.

Table 4. Common pipe support designs

Pipe Support Design	Comments
Resting support	<ul style="list-style-type: none"> <li>Not typically acceptable on reciprocating compressor installations.</li> <li>May be permitted away from the compressors, but not within 10 mainline diameters of elbows, tees, reducers and vessels.</li> </ul>
Single u-bolt clamp	<ul style="list-style-type: none"> <li>Not typically acceptable on reciprocating compressor installations due to tendency vibrate loose and/or wear into pipe wall.</li> <li>May be permitted away from compressor if lined to prevent pipe wear.</li> </ul>
Double u-bolt clamp	<ul style="list-style-type: none"> <li>Not desirable on reciprocating compressor installations.</li> <li>If used, have u-bolts lined to prevent pipe wear.</li> </ul>
Long bolt type pipe clamp	<ul style="list-style-type: none"> <li>Acceptable design for use on reciprocating compressor installations.</li> <li>Long bolt helps prevent vibratory loosening of clamp.</li> <li>Some axial thermal growth can be accommodated due to lower clamping force.</li> <li>If lateral thermal growth is required, slots can be cut in support structure underneath pipe clamp.</li> </ul>
Short bolt type pipe clamp	<ul style="list-style-type: none"> <li>Acceptable design for use on reciprocating compressor installations.</li> <li>Can be susceptible to vibratory loosening due to short bolt.</li> <li>If axial thermal growth is required, PTFE slide plates can be used.</li> <li>If lateral thermal growth is required, slots can be cut in clamp or support structure underneath pipe clamp.</li> </ul>
Short bolt type pipe clamp with disc spring washers	<ul style="list-style-type: none"> <li>Acceptable design for use on reciprocating compressor installations.</li> <li>Disc spring washers help prevent vibratory loosening.</li> <li>Axial thermal growth can be accommodated due to lower clamping force (disc spring washers).</li> <li>If lateral thermal growth is required, slots can be cut in clamp or support structure underneath pipe clamp.</li> </ul>

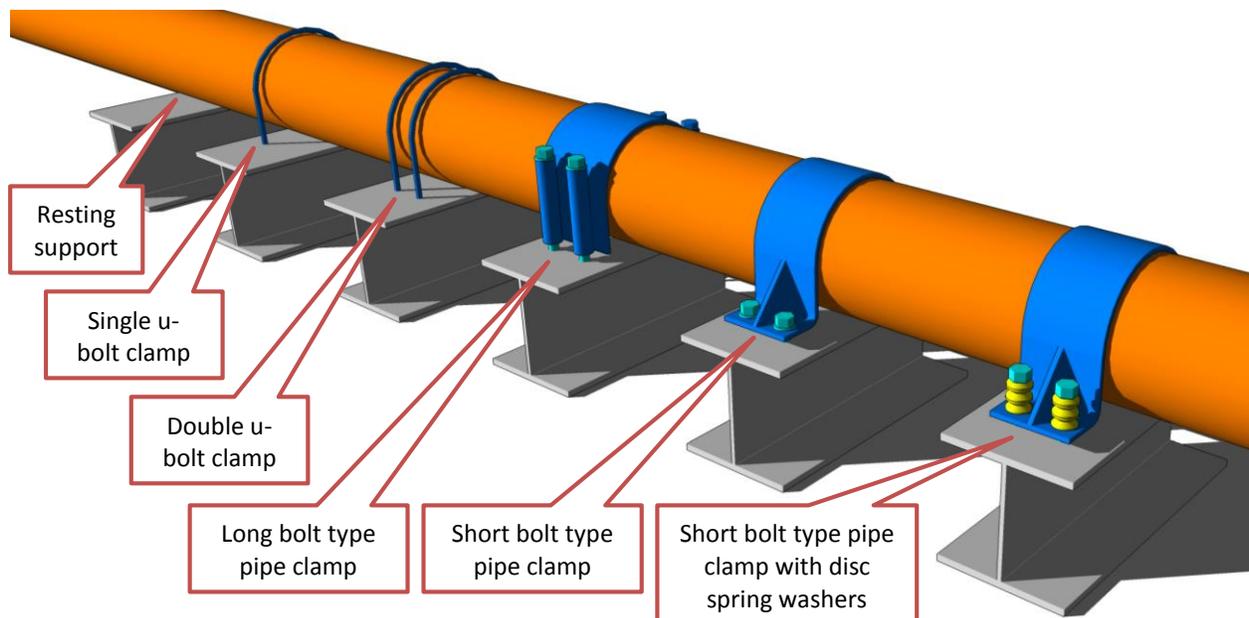


Figure 11. Pipe support designs