The effects of pipe strain and flange misalignment on vibration in reciprocating compressor systems

by

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1. Abstract

Pipe strain and flange misalignment have been shown to lead to higher than normal vibrations in piping systems. The problem of high vibration due to pipe strain is more common on reciprocating compressor packages due to several factors such as high dynamic forces that are part of normal operation, compact design for equipment packages and improper piping assembly and installation processes.

This paper presents insights into the effects of pipe strain, measures to reduce pipe strain and case studies that show the effect of pipe strain and flange misalignment on piping vibration.
2. Introduction

Many vibration problems are the result of, or amplified by, pipe strain or flange misalignment. In some cases, the measured vibration amplitudes are double, triple or even higher when under pipe strain, compared to after relieving pipe strain. Pipe strain on the main line can intensify vibrations on small-bore attachments, which can lead to failures.

Although the effect of pipe strain on piping vibration is observed on many packages, particularly with units that are assembled on tight schedules or minimum quality control checks, this topic is rarely discussed at industry events. Howes and Maxwell (1) discussed pipe strain effects on vibrations and presented some examples in 2013. Some industry standards such as API 686 (2) and ASME B31.3 (3) include limits for pipe strain and flange misalignment. However, these limits are mainly set for increasing the reliability of the machinery, rather than reducing vibrations on the piping and attached components.

This paper summarizes the authors’ experience as well as work completed for a GMRC-funded research project (4) on this topic. This paper reviews several case studies. A theory on the reasons for higher vibrations due to excessive pipe strain is discussed. In addition, suggestions are made to reduce pipe strain in reciprocating compressor packages, and future studies are proposed.

3. Definitions and categories

Static deflection of the pipe from its neutral position, or zero-stress condition, is called pipe strain. By itself, pipe strain may not be sufficient to cause failure. However, when combined with the dynamic stresses from other sources such as unbalanced forces and pulsation-induced forces in reciprocating compressor systems, pipe strain becomes an element critical to the reliability of piping systems.

One of the major contributors of controllable pipe strain is piping misalignment. The root cause of misalignment can be attributed to deficiencies in design, fabrication, assembly and installation practices. Figure 3.1 and 3.2 show examples where pipe strain and flange misalignments were observed on real piping systems.

Improper support installation can induce pipe strain. Figure 3.3 shows 3 different scenarios where a pipe could be held away from its neutral position resulting in pipe strain.
Two flanges can have one or more types of misalignments:
- Axial offset
- Radial offset
- Angularity (not parallel)

See the excerpt below from API 686 (2) that shows three types of flange misalignment. The paragraph numbers in these plots refer to API 686 text.

Figure 3.4 – Types of flange misalignment (2)

4. Case study

This case study is about high vibrations on a reciprocating compressor unit. The 4-throw, 3-stage compressor was being driven by a reciprocating engine at 1250 to 1400 RPM. A fleet of 12 nominally identical reciprocating compressors was assembled in a very tight timeline. This led to many areas with excessive flange misalignment and pipe strain.

Figure 4.1 shows the piping between the suction scrubber and suction pulsation control bottle on the third stage for this compressor.

Figure 4.1 – Third stage suction piping

Our analysis showed high vibrations on test points 304 and 305. Signs of the pipe strain and flange misalignment were observed on the piping, and the operators were asked to loosen the clamps. Once the clamps were removed, up to 25 mm displacement was observed on some of the piping. Figure 4.2 shows the gap between the pipe and support once the clamp is loosened. In addition, the pipe was not parallel to the support base. When the clamp was removed fully, as shown in Figure 4.3, signs of forcing the pipe into position were visible on both pipe and flanges. Temporary shims were installed under some of the pipes to assess the effect of pipe strain. Figure 4.4 shows the temporary shims. Flange misalignment was also observed. Figure 4.5 shows a flange mating against a straight edge, which clearly presents the flange misalignment.

Figure 4.2 – Signs of pipe strain
The customer was recommended to remove all clamps and mitigate the pipe strain and flange misalignment, based on the procedure discussed in Section 7. After the pipe strain was mitigated, vibration was measured again. Figure 4.6 to Figure 4.8 show examples of before and after vibration plots. The vibration plots below show peak-hold vibration amplitudes when the units were run throughout the speed range. The modifications led to significant vibration reductions. The vibration amplitudes are compared against Wood (formerly BETA Machinery Analysis) vibration guidelines.

Figure 4.3 – Signs of pipe strain

Figure 4.4 – Temporary shims under the pipe

Figure 4.5 – Flange misalignment

Figure 4.6 – Comparison of before and after pipe strain is mitigated, TP 305, horizontal vibration

Figure 4.7 – Comparison of before and after pipe strain is mitigated, TP 305, vertical vibration

Figure 4.8 – Comparison of before and after pipe strain is mitigated, TP 304, horizontal vibration
5. Effects and mechanism

The effect of pipe strain, even if vibration does not increase, is that a higher static force is imposed on the piping. The static forces from pipe strain increases the static or mean stress that the pipe experiences. The combined stress, which includes both the mean stress and alternating stress, can be represented on a Goodman diagram. The Goodman diagram (Figure 5.1) shows that the allowable amplitude of alternating stress decreases as mean stress increases. Vice versa, the allowed amplitude of alternating stress increases as the mean stress is lower. In Figure 5.1, Y.S. is the abbreviation for yield stress, S_n is the fatigue life at 10^7 cycles, and U.T.S. is the abbreviation for ultimate tensile stress.

Pipe strain increases the static stress in the system. When static stress increases, the allowable dynamic stress, hence the allowable vibration levels, drop.

As demonstrated by the case study and many other field tests on compressor piping systems, high pipe strain tends to be associated with high vibration. Research into the fundamental mechanisms whereby pipe strain leads to higher vibration levels is required. One proposed theory is that pipe strain will lead to a reduction in damping. Damping results from many different mechanisms in a piping system. One method of damping is energy dissipating as two parts move relative to each other. For example, joints between the pipe, pipe clamps and pipe support have a small amount of relative motion under normal vibration. If the pipe is under a high static load, the mating surfaces between the pipe, clamp and support are distorted, and the same joints are fully closed. Less relative motion between these components occurs when the piping is subjected to dynamic forces, so there is less energy dissipated and less damping.

Reduced damping will cause increased vibration at the mechanical natural frequency (MNF). Figure 5.2 shows the vibration amplitudes and phase at different damping ratios at different frequencies. ξ represents the damping ratio, f is the frequency, f_n represents the mechanical natural frequency.

6. Assembly procedure to avoid pipe strain

Following is the suggested procedure to avoid pipe strain during the assembly. This procedure applies to the assembly process when none of the flanges are tightened and none of the clamps are installed.

1. For each system (first stage suction, first stage discharge, etc), start at the compressor cylinder. Installing pulsation control vessels (bottles), especially a bottle that is common to multiple cylinders,
requires special attention and precision. Start at the first pairs of flanges, for example, the flange set connecting the piping to the suction pulsation volume and bring the flanges to a neutral position by adjusting the shims and/or modifying the support structure and nearby pipe clamps. The misalignment should be kept within the limits suggested by ASME B31.3 guidelines between each two flange faces.

The information in B31.3 is further described by the Los Alamos National Laboratory (LANL) as shown below (6). ASME B31.3 does not provide any guidance on the axial offset of the flanges. In this case, it is recommended to use API 686 guideline of “Gasket flanging must be within ±1.5 mm (1/16 in.) of the gasket spacing” (2).

3. For each pipe clamp, place the clamp on the pipe, mark the neutral location of the pipe clamp on the sleeper, remove the clamp and then drill the sleeper. The holes should be drilled ¼” oversize to allow for hot alignment. Avoid clamp designs that require welding the studs or bolts to the sleeper. A welded stud design doesn’t allow for potential future corrections. Also, high bending loads can be imposed on the fastener and weld as the pipe goes through thermal cycles. When dealing with extreme temperature, special clamp types should be considered to avoid pipe strain problems due to thermal expansion. The clamp fastener must only be tightened enough so there is no relative vibration between the pipe, clamp and support. Overtightening the fastener limits small movement due to thermal cycles that will reduce pipe strain.

4. For each pipe clamp, make sure one ½ inch thick packing is placed under the pipe to allow for future pipe strain adjustments. The packing can be tack welded in place if needed. The number of shims under the pipe should be limited to three shims.

7. Mitigating pipe strain after assembly

The suggested procedure for assembling the piping system to avoid and minimize the pipe strain is discussed in the previous section. The list below explains the suggested procedure for checking for pipe strain on an existing assembled unit.

1. Shut down the unit and perform a thorough visual inspection:

   a) It is recommended to perform a systematic inspection throughout the whole package. For example, start with the compressor cylinders on the first stage suction system and move toward the off-skid edge. Once the inspection of the first stage suction system is done, move to the first stage discharge system.

   b) Loosen all the clamps. Document the movement of the pipe when the clamps are removed.

   c) Inspect the flange alignment for all flanges. Use a straight edge to inspect
the lateral alignment of flanges. Use a micrometer to make sure the flange faces are parallel.

d) Check if the pipe is pushing on the support by removing the shims, packers, spacers, or liner under the pipe.

2. Correct the pipe strain by adding or removing shims, modifying the pipe supports and structures.

3. If after all modifications have been completed, some pipe strain and flange misalignment are observed, breaking the flanges can be used as the last resort. Make sure to monitor the flange position before and after bolts are loosened.

4. In extreme cases, replacing the pipe spool and/or bottles may be required to remove the pipe strain.

5. The final pipe strain checks must be done after the unit and piping have reached a stable operating temperature. Depending on the system, the ambient temperature, compressor setup, operating temperature and other factors, the time to reach stable operating temperature may vary. Slight adjustments may be needed in shims and pipe supports when the unit has reached operating temperature. The ideal procedure includes bringing the unit up to temperature, shutting down the unit and then inspecting the line. However, a large-scope inspection may require multiple startups and shutdowns. If this is not feasible, the inspection can be done while the unit is operating.

6. Adjust shims and packing to place the pipe at its hot, neutral position.

8. Conclusions

The following conclusions can be made based on the authors’ experience with reciprocating compressor piping system vibration.

- Pipe strain has been shown to contribute to significant vibration problems including vibration-induced piping failures.
- The root cause of misalignment can be attributed to deficiencies in design, fabrication, assembly and installation practices. Installation and assembly procedures were identified as the most critical steps of the project to avoid pipe strain.
- By itself, pipe strain may not be sufficient to cause failure, but when combined with the dynamic stress related to reciprocating compressors, pipe strain becomes an element critical to the reliability of piping systems.
- It is believed that increased vibration occurs mainly due to a reduction in damping when pipe strain is present. However, more research is needed to find the exact mechanism that leads to higher vibrations when pipe strain is present.
- Existing standards can provide a minimum required level for preventing excessive pipe strain. However, more stringent criteria may be needed for reciprocating compressor applications. The application of existing standards in cases where multiple flanges are used in near vicinity of each other, or multiple nozzle pulsation control vessels (commonly known as multi-nozzle bottles) may be misleading.
- The existing body of knowledge is not sufficient to draw solid conclusions and develop a guideline. More research is required.

9. Future research

It is recommended to perform additional studies to investigate the effects of pipe strain on vibration. The following studies should be conducted for different configurations such as straight pipe, two nozzle bottles, head and shell nozzles and other piping and vessel configurations common to reciprocating compressor installations:

- Laboratory study on the mechanism that pipe strain leads to higher vibrations. The outcome of this work is the development of a set of laboratory measurements that can be used to develop and verify a theory and simulation approach to calculate the effects of pipe strain.
- Finite element analysis (FEA) to compare the change in static stress due
to various levels of flange misalignment and pipe strain, for different pipe sizes and configurations.

- FEA to compare the change in vibration and dynamic stress due to various levels of flange misalignment and pipe strain.
- Field measurements of real piping systems to verify the results from the FEA work for assessing static and dynamic effects of pipe strain and flange misalignment.

10. References


