# Case Study: Torsional Vibration Assessment and Mitigation

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## Abstract

It is known that torsional vibrations in reciprocating compressors can cause issues throughout the entire skid package, having negative effects not only on the compressor frame, but on other components such as safety devices (e.g. PSVs), bottles, and scrubbers. It is also known that, without proper measurements, torsional vibrations will go undetected until catastrophic failures, such as broken couplings or failed crankshafts occur, as most operational personnel are not familiar with this phenomenon and can rarely pinpoint to specific concerns of such an issue.

This paper outlines one of those rare cases where torsional vibration was suspected after an initial field visit that yielded measurements that did not appear to be associated with common problems such as mechanical resonance or pressure pulsation-related problems. As such, a unique approach had to be taken toward finding a solution.

Following the initial site visit, an acoustical study confirmed that the vibrations were not pressure pulsation driven. A torsional study was conducted that gave confirmation to the suspicion of elevated torsional vibration. Torsional vibration was further confirmed during a second visit to site where it was measured directly on the compressor crankshaft using a torsional encoder system designed and built by AP Dynamics. A second method of measuring torsional vibration using strain gauges is highlighted in this paper, as well.

Working with the OEM, an active damper was specified and later installed on the auxiliary end of the compressor crankshaft. This successfully reduced the torsional vibration and consequently the lateral vibration seen throughout the package. A follow-up survey was performed to validate the mitigation measure and reduced vibrations due to torsional oscillation were confirmed.

# 1 Introduction

This paper highlights the importance of assessing and mitigating torsional vibration in reciprocating compressors and provides a rare case study that covers the entire process of observing the issue, mitigating, and finally validating the implemented solutions.

Torsional vibration problems are typically not evident from the operational standpoint until catastrophic failures occur, such as broken couplings or crankshafts. Only such failures distinctly show probability of elevated torsional oscillation; however, other areas of the skid can be negatively affected and are rarely thought to be associated with torsional vibration. AP Dynamics wants to highlight the effects that torsional vibration can have on compressor packages, not only on the drive train, but on other components within the package.

Evidence of lateral-torsional vibration coupling in reciprocating machinery, which was studied by Ariel Corporation (Newman et al., 2012), will be discussed in the case study within this paper. Due to the severity of impact that such vibration can have on operation, it is critical that all stakeholders be aware of the potential consequences along with the methods of how to detect and mitigate them.

It is not common practice to measure torsional vibration on site. This paper server to change this habit and emphasize the importance of performing torsional vibration measurements as part of baseline measurement surveys during commissioning phase to complete a full assessment of the unit.

# 2 Case Study

## 2.1 Background

AP Dynamics was approached by an Oil and Gas producer stating that field operations were reporting elevated vibration throughout two inherently identical compressor packages at a gas plant in the area surrounding Grande Prairie, Alberta, Canada. The packages in question were two 6-throw Ariel KBZ/6 compressor units powered by Caterpillar G3616 engines.

AP Dynamics performed a full baseline vibration survey on both packages, covering all critical areas of each package.

These areas included, at a minimum:

- Engine
- Compressor Frame
- Suction and Discharge Bottles
- Scrubbers
- Process Piping
- Safety Devices
- Fuel Gas Filter and Piping
- Skid

## 2.2 Initial Field Survey

During the field each unit was run from 900 – 1000 RPM. Elevated vibration levels on numerous areas on both packages were found

Several areas were determined to experience mechanical resonance, at either 1X or 2X run speed which is not unusual for reciprocating compressor packages. Other areas, however, exhibited an above-guideline 7X vibration that was not consistent with signs of potential resonance or elevated pressure pulsation issues. Moreover, the direction of vibration was not consistent, meaning that it was neither parallel to the flow or perpendicular to it. It was varying in direction among locations.

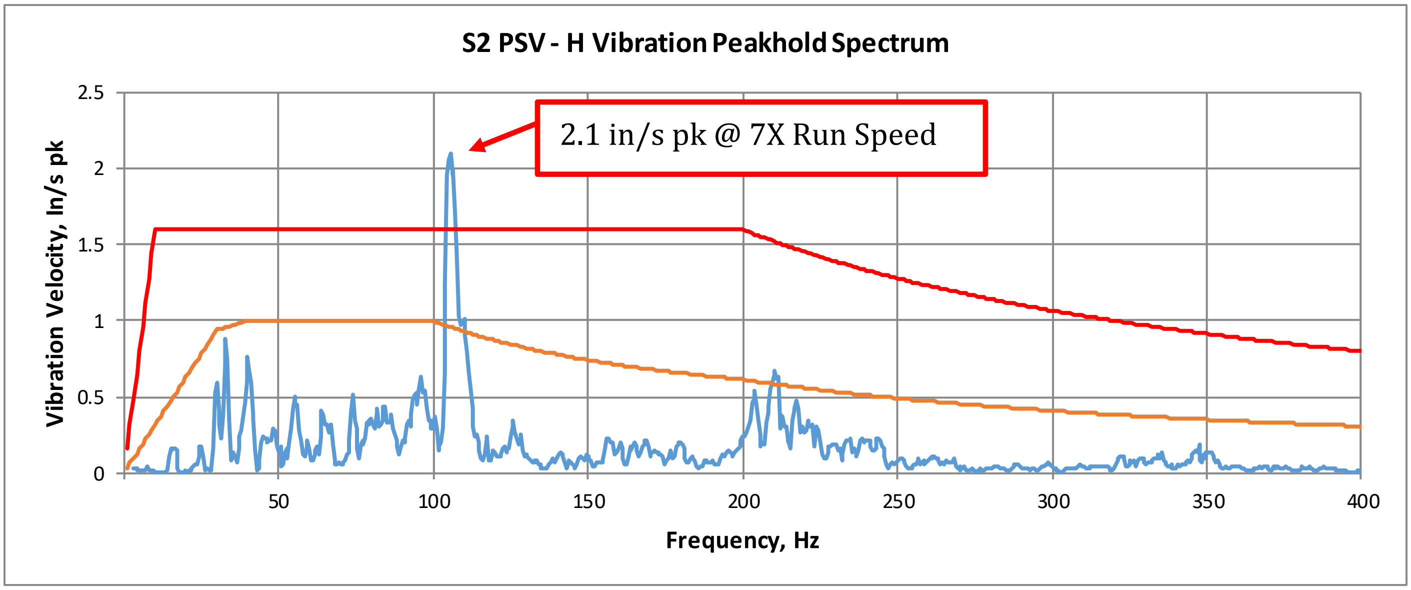


**Figure 1: Example of 7X Vibration Measured on Site**

At the time of the site visit there were no accessible ports on the process piping to be able to take pressure pulsation readings. Although these readings were not available, the data gathered and our initial analysis showed that pressure pulsation was unlikely the cause, because of the odd multiple of vibration (typically only even orders appear in a double-acting unit) and the varying directions of vibration that had no correlation with the direction of flow. Although there was no clear indication of a problem, AP Dynamics wanted to confirm that pressure pulsation-related issues were not causing this vibration and recommended that an acoustical study is performed.

Alongside the acoustical study, AP Dynamics also recommended that a torsional analysis was performed on both units, which was the primary suspect.

## 2.3 Acoustical Analysis

AP Dynamics performed an acoustical study to check if pressure pulsation could be the contributing factor to the 7X vibration seen in the system.

The study found that the pressure pulsation and the resulting shaking forces had no correlation to that of the vibration at 7X that was measured in the field. Additionally, there were no pressure pulsation-related issues found at other harmonics, therefore, no mitigation measures were needed.

## 2.4 Torsional Analysis

Following the acoustical study, AP Dynamics conducted a torsional analysis of both compressor units. The analysis found that the 2nd torsional natural frequency (TNF) lined up with the 6th harmonic of the compressor run speed, resulting in high angular deflection of the crankshaft.

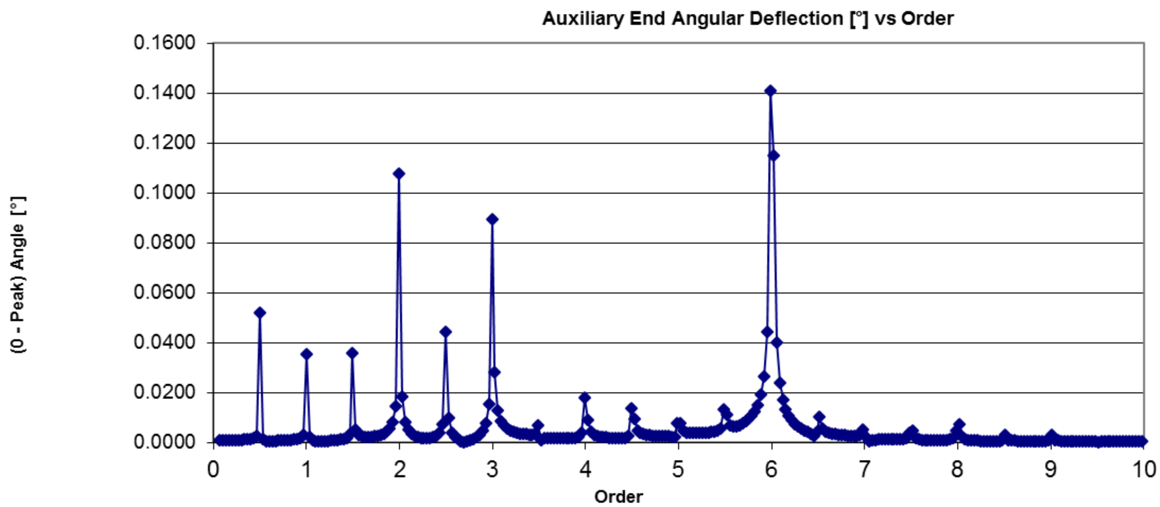


**Figure 2: Predicted Angular Deflection on Auxiliary End of Compressor Frame Crankshaft**

Studies conducted by Ariel (Newman et al., 2012) have shown that lateral vibration stemming from torsional vibration occurs at side band frequencies of the torsional oscillation, not at the same frequency as the torsional vibration. By this account the 6X torsional vibration occurring in the crankshaft could be correlated to the 7X lateral vibration seen throughout the package. This is termed lateral-torsional vibration coupling.

Working closely with Ariel, AP Dynamics came up with two possible solutions to mitigate the 6th order vibration within the crankshaft:

1. Shift the 2nd TNF out of the resonance range of any 6th harmonic by means of detuning, using an internal flywheel on the auxiliary end of the compressor.
2. Reducing the torsional vibration by means of an active internal damper installed on the auxiliary end of the compressor crankshaft.

It was found that the addition of the large inertia on the auxiliary end of the compressor by using an internal flywheel (Option 1) would have resulted in exceeding the allowable engine crankshaft torsional stress guideline. Additionally, the coupling torque would have been increased to the allowable limit (99.9%).

Forced response analysis showed a very significant reduction in torsional vibration at the 6th harmonic when the internal damper (Option 2) on the auxiliary end of the compressor was used. The torsional analysis also showed the system passing the following requirements and criteria:

1. TB Woods coupling torque criteria

2. Ariel vibratory torque requirements
3. Ariel vibratory velocity requirements
4. Caterpillar crankshaft torsional stress requirements
5. Damper torque and thermal load requirements

As a result of the analysis and discussions with Ariel, AP Dynamics concluded that the Ariel D7580 torsional damper installed on the internal auxiliary end of the compressor crankshaft would be the most effective alternative to reduce the vibration seen at the 6$^{th}$ harmonic. This solution was brought forth to the client as a method to reduce vibration levels throughout the packages.

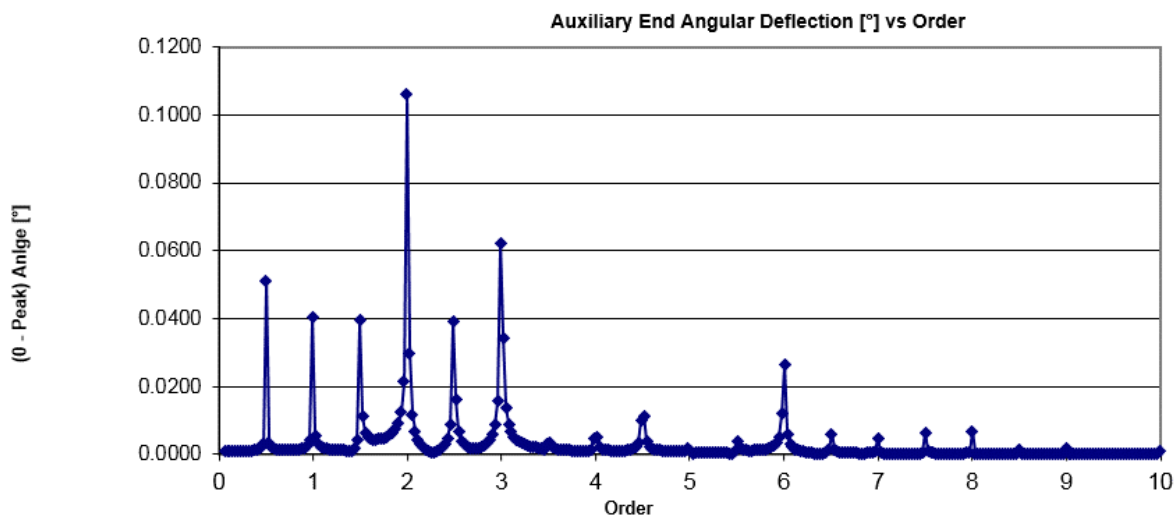


**Figure 3: Predicted Angular Deflection on Auxiliary End of Compressor Crankshaft with Internal Damper (D7580)**

## 2.5 Torsional Vibration Survey

In order to validate the results of the torsional analysis, AP Dynamics made a second trip to site to perform a torsional vibration survey on one of the two identical packages.

A custom designed torsional encoder was used. The encoder was designed and built in-house. This piece of hardware allows AP Dynamics to directly connect to the crankshaft of an Ariel compressor frame on the auxiliary end through an access port on the frame and is designed to work with most Ariel stock models. The system is designed in such a way to minimize compressor downtime required for installation and removal. It takes approximately 30 minutes of downtime to install, compared to the roughly 2 hours required for strain gauges. Additionally, it works together with tachometers to directly correlate vibration with the RPM of the unit.


**Figure 4: Torsional Encoder Installation on Auxiliary End of Compressor Frame**

One has to be aware of torsional deflection nodes that vary per mode shape. Nodes are defined as points along the crankshaft that undergo zero deflection at a given mode shape. As an illustration for the $2^{nd}$ mode shape in this application a node can be seen at CP2 (coupling) location in Figure 5. It is important to consider the results of the torsional analysis when validating it by conducting the torsional vibration survey. It should be used to help ensure that the location selected for measurement does not fall on a node. Taking this into account, measurements performed on either end of the compressor will typically give representative results. By referring to Figure 5 below, we can see that the auxiliary end is an anti-node for the $2^{nd}$ torsional natural frequency.

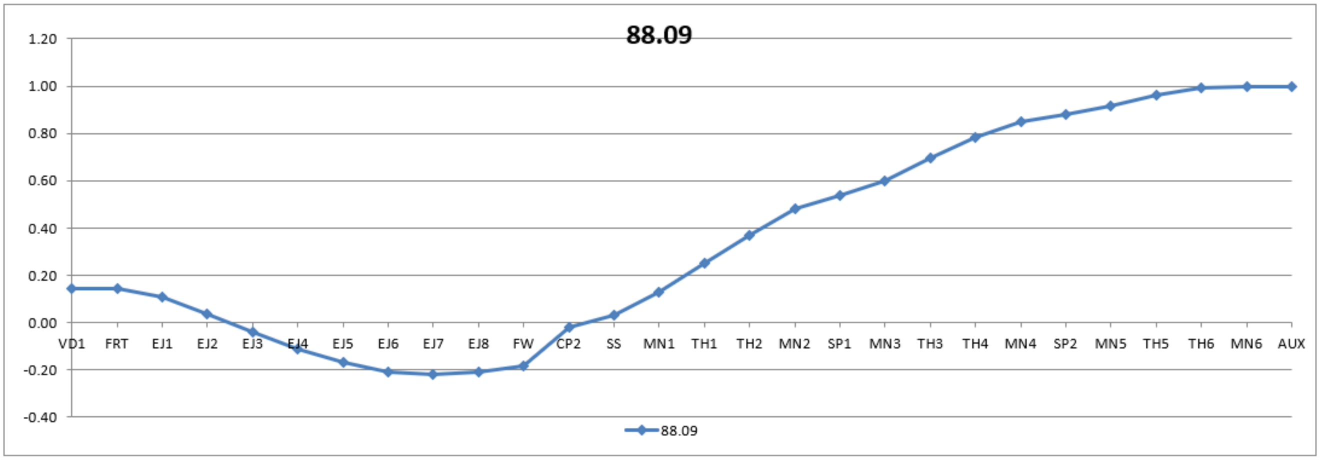


**Figure 5: 2nd Torsional Mode Shape**

The unit was run through its operating speed range (850 – 1000 RPM) and the torsional vibration was captured on a cascade plot. The results are shown in Figure 6 below.

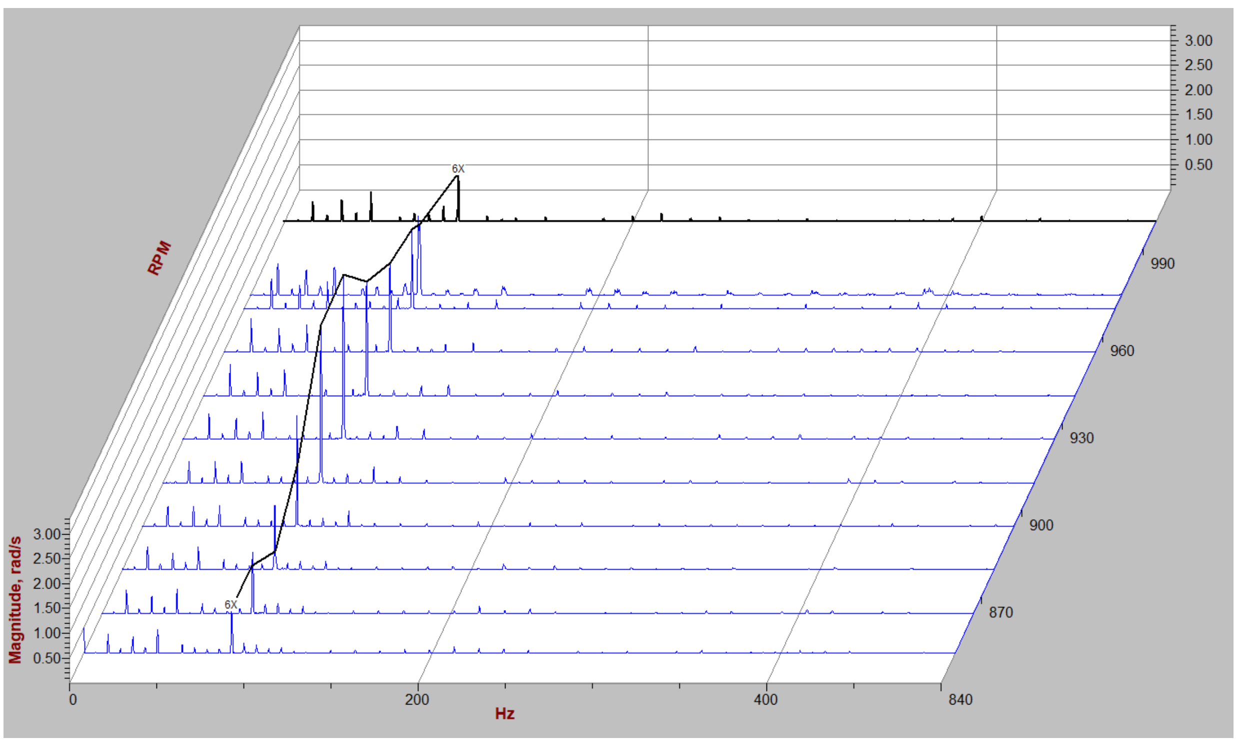


**Figure 6: Torsional Survey Plot**

The plot showed that the dominant frequency was found to be 6X the run speed. This validated the results of the torsional analysis performed prior to the survey and confirmed the suspicion of a lateral-torsional vibration coupling.

### 2.5.1 Alternative Method of Measuring Torsional Vibration

A commonly used alternative to the torsional encoder is strain gauges. Unlike the torsional encoder, strain gauges are mounted on the coupling. Both the strain gauges or torsional encoder prove as effective means in capturing torsional vibration, however, installation of strain gauges takes considerably more time due to the requirements of perfectly clean surfaces and a more complex installation procedure. In some cases, and depending on the equipment available, up to 4 strain gauges are required to be adhered to the coupling. Adequate training in installation and wiring is required in order to accurately capture strain gauge data.

The strain gauge signal is read using a wireless system that allows for a safe and robust installation, sometimes without the need to remove the coupling guard during operation.

Historically, strain gauges were the primary method of measuring torsional vibration and are an effective solution. The encoder method is a simplified technique offering faster installation and easier set-up; however, if it is unavailable or cannot be installed, strain gauges provide an accurate and comprehensive method of measurement.

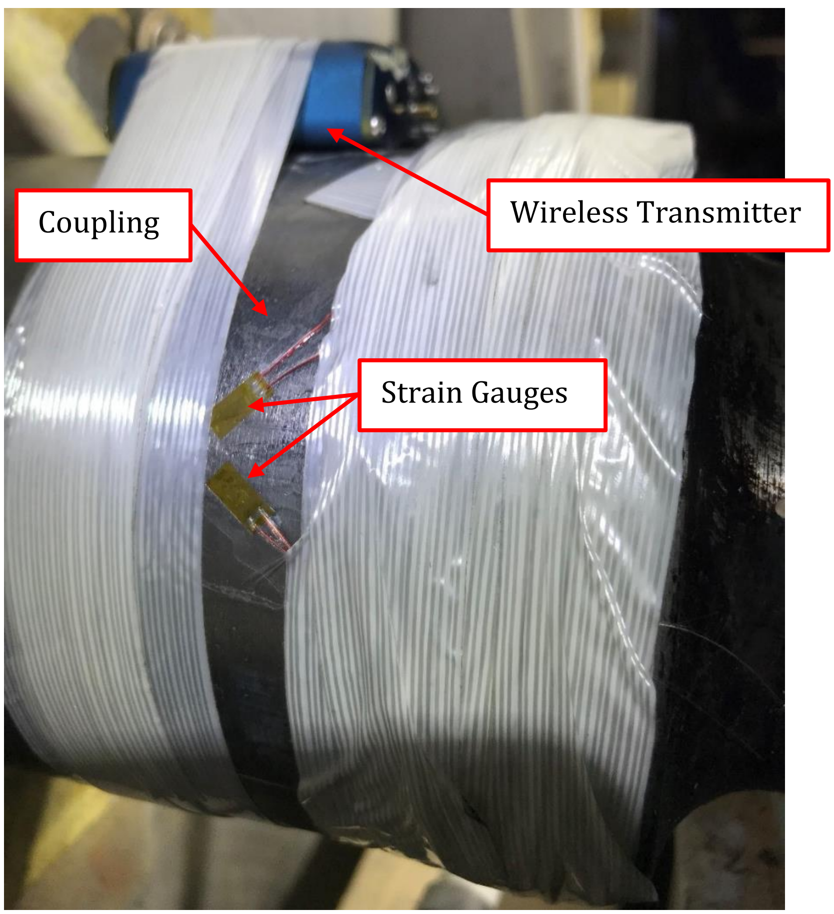


**Figure 7: Example of Strain Gauge Installation for Torsional Vibration Measurements on Coupling**

## 2.6 Installation of Damper and Follow-up Visit

Once the modification was reviewed and approved by Ariel, the client proceeded with the installation of the damper in one of the units. This unit was the worst of the two in terms of vibration.

AP Dynamics followed up by performing a second measurement survey to determine the effectiveness of the damper. Measurements were conducted on areas previously highlighted with 7X vibration to determine if levels at that frequency were eliminated or reduced to acceptable levels. Due to operational restrictions, the torsional encoder was not installed during this visit because it required the unit to be shut down briefly for installation and the client was not able to accommodate it at the time. Although torsional measurements were not acquired, comparing lateral vibration measurements taken during the follow-up survey with the initial baseline survey, the client was pelased with the reduction in vibration levels.

The results from the survey showed drastic improvements in 7X vibration where the vibration levels were greatly reduced after the damper was installed. A comparison of the vibration occurring on Stage 3 Discharge PSV before and after the damper was installed can be seen in Figure 8 and Figure 9, respectively. Table 1 shows three locations that had the biggest improvements in vibration levels at 7X vibration.

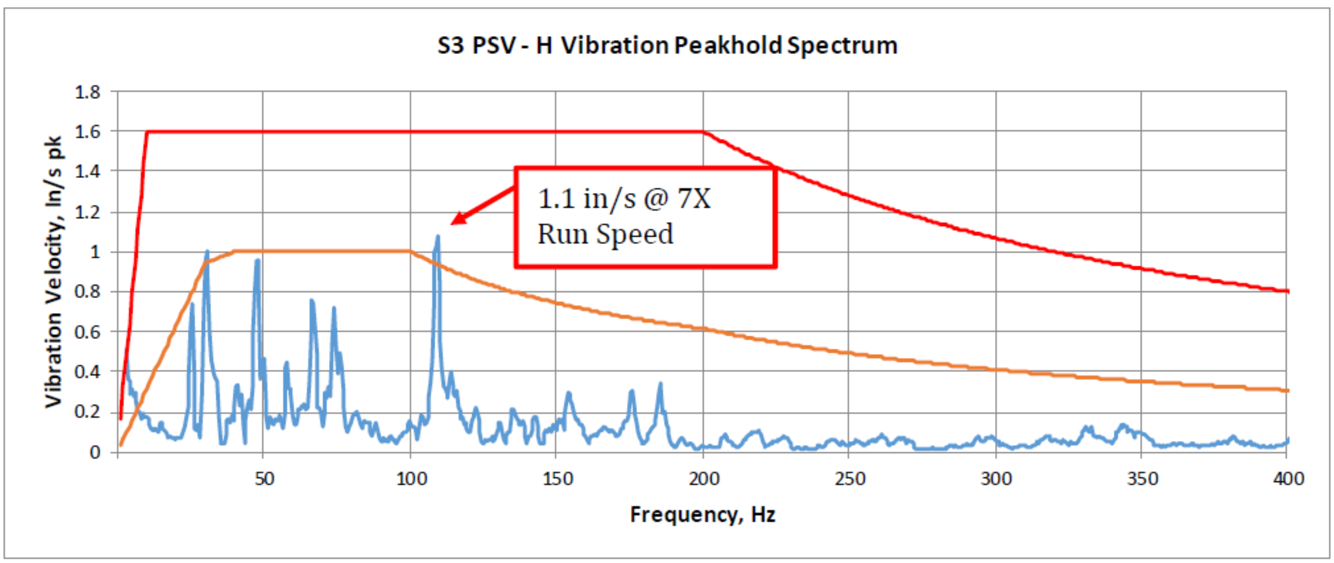


**Figure 8: 7X Vibration Prior to the Installation of the Internal Damper – 7X at 940 RPM**

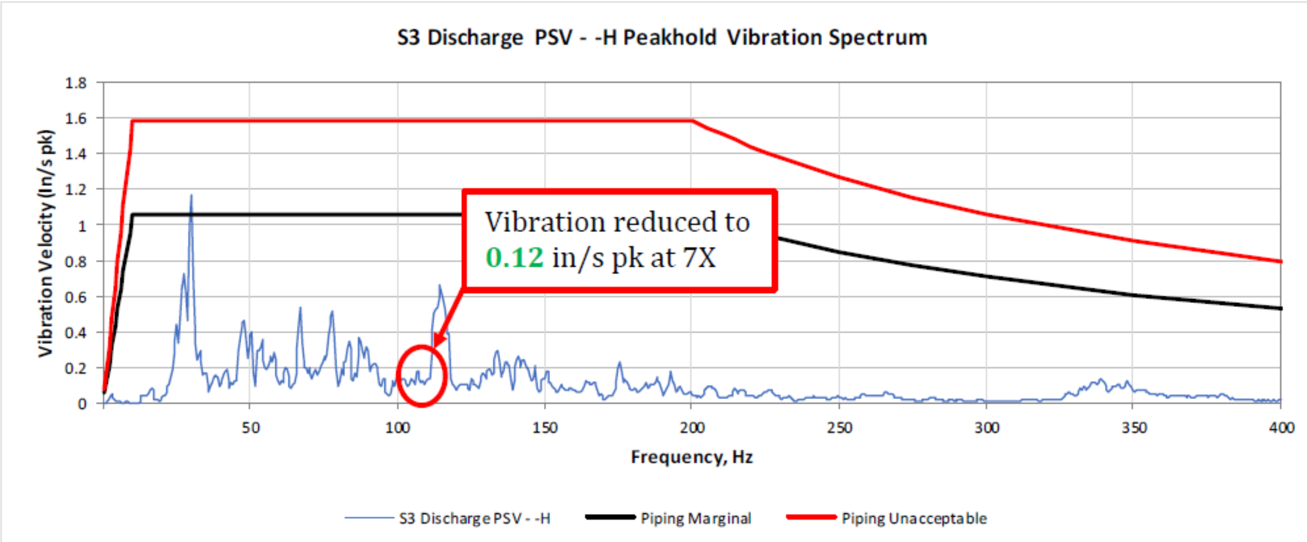


**Figure 9: 7X Vibration After the Installation of the Internal Damper – 7X at 940 RPM**

**Table 1: Comparison of Vibration Levels Pre- and Post- Damper Installation (Unit 2250)**

| Location (Direction) | Frequency (Hz) | Before Damper Amplitude (in/s) | After Damper Amplitude (in/s) | Running Speed of Unit (RPM) |
|---|---|---|---|---|
| Stage 3 Discharge PSV (H) | 109.5 | 1.1 | 0.12 | 940 |
| Stage 2 Suction Bottle NDE (H) | 109 | 0.9 | 0.24 | 930 |
| Stage 2 Suction Bottle (H) | 115 | 1.1 | 0.48 | 990 |

# 3 Closing Remarks

Torsional vibration is not always evident or thought of when elevated vibration is observed on a compressor package. As in the case study of this technical paper, there was no history of coupling or crankshaft failures, therefore lacking immediate evidence that torsional vibration was at the root of the vibration problem.

Few people are aware of the consequences such vibration can have and how it can directly impact tertiary equipment that is not directly connected to the compressor frame. As such, it is important to note that torsional vibration assessments are critical to safe and reliable operation of the machine.

AP Dynamics wants to emphasize that to avoid failure-related costs, in-situ torsional vibration measurements during commissioning or baseline surveys provide a tremendous value.

Some clients request torsional vibration measurements alongside vibration measurements during commissioning; however, this is a rare occurrence mostly due to lack of awareness in the particular area. AP Dynamics believes this knowledge should be shared amongst all stakeholders.

# 4 Acknowledgements

The authors would like to thank Ariel Corporation for their expertise and guidance when assisting with this project. We were fortunate to be given the opportunity by our client to solve their problem and their full support to perform a comprehensive evaluation of their units. This is a rare occurrence amidst typical budgetary and time constraints.

# 5 References

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