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VALVE-INDUCED PIPING VIBRATION

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ABSTRACT

While going through the startup process of a 600MMSCFD Gas Processing Plant, the piping downstream of a gas expander bypass valve and supporting structure was observed to be shaking abnormally. The shaking was significant enough that plant personnel limited the valve flow rate to well under the design capacity and at a level that limited the plant startup. The initial assumption was that the piping or the piping supports had been improperly designed. An investigation revealed no unusual looseness in the piping supports and no significant piping natural frequency at the observed vibration frequency.

Further investigation revealed that the root cause of the problem was a flow-generated pulsation in the discharge of the bypass valve that excited the piping and structural supports. Changing the valve flow path and applied valve opening limits provided a temporary work-around that allowed the plant to operate at sufficient flow rates to complete the startup. Subsequent replacement of the valve with one using the same trim but with different gas flow path characteristics proved to be the ultimate solution to the problem.

INTRODUCTION

During the initial startup and operation of a natural gas processing and Natural Gas Liquids extraction plant, the piping and structural supports associated with the gas expander turbine bypass valve - commonly called the Joule Thompson (JT) valve - was shaking significantly. The pipe shaking increased as the gas flow through the JT valve increased and was considered excessive at 25% to 33% of the design plant throughput. The plant startup was initially curtailed as a precaution. Piping shaking was investigated using a typical frequency and magnitude methodology and the resulting data was reviewed. Modifications to piping supports were considered; however, no conclusive information as to the cause of the vibration was evident at the time.

Some of the piping supports were modified and the plant restarted. The piping, however, continued to shake.

Additional vibration data was collected and the data was compared to the natural frequencies of the piping. This analysis did not indicate the piping was shaking at a significant natural frequency of the piping system. Additional data and analysis taken at several operational conditions indicated the vibration frequency did not change significantly. The amplitude of the vibration appeared to be in proportion to the plant throughput (flow rate).

It was apparent that a more detailed engineering analysis was necessary. Additional pipe vibration data was taken in conjunction with the gas pulsation measurements within the piping. Based on this additional data, it was determined that the JT valve was the source of the pulsation. The observed gas pulsation values just downstream of the JT valve were determined to be significant in providing a forcing effect that was sufficient enough to excite the piping system resulting in the observed valve and pipe shaking. The valve- induced pulsations were surprising in that the valve met all of the normal criteria intended to prevent vibration problems [1] [2] [3]. Although pulsations upstream of a control valve are discussed in the literature [4], downstream, low frequency pulsations due to vortex shedding are not normally anticipated [3].

PLANT DESCRIPTION

The natural gas processing and Natural Gas Liquids extraction plant owner is Phoenix Park Gas Processors Ltd. (PPGPL) located in Trinidad and Tobago. The new plant was similar in design to an older gas processing plant on site, both using the same process technology. The older plant had not experienced any significant pipe shaking in the piping system associated with the JT valve, even though the plant layout and pipe routing were similar to the new unit.

The JT valve (normally closed during the expander operation) is used to bypass the gas expander until the operation is suitable for expander operation and also, when necessary, to shut down the expander and continue operating the plant in the JT mode. Due to the pipe shaking conditions, the plant's initial startup was restricted to a reduced throughput that did not accommodate the use of the expander or allow the balance of the plant to be commissioned. The plant startup could not be completed until the pulsation forces from the JT valve were reduced significantly.

ORIGINAL OBSERVATIONS

The piping associated with the JT valve (12 inch body) was a nominal 16 inch (400 mm) diameter that then interconnected with 24 inch (600 mm) diameter piping with a design operating pressure of approximately 600 psi (41 bar). The piping was supported by typical structural steel pipe racks. At the reduced plant throughput, the pipe shaking was observed to excite portions of the supporting pipe rack. The pipe shaking was also considered to be sufficient enough to be a concern that it might trip the expander vibration monitoring system during initial operation. Because the older similar plant did not display JT valve-associated piping shaking, the obvious question was what was different. It was noted that the JT valve was of a different type. It was also noted that the pipe routing and piping supports were similar in the two plants but not identical. This led to an initial attempt to resolve the pipe shaking condition by modifying the JT area piping supports. These modifications did not significantly reduce the pipe shaking problem.

Based on these observations, the available field vibration data, and the failure of the piping support modifications to resolve the pipe shaking, a more extensive investigation was initiated.

FIELD DIAGNOSIS

The problem, as determined from the initial observations, involved vibrating piping in a region of the system where it was not expected. Additionally, the vibration was not at a significant mechanical natural frequency of the piping system. Due to the pressure drop across the JT valve, significant broad band turbulent energy was introduced into the system. This energy was a suspected source, perhaps driving a resonance in the system. However, there was not enough information to either confirm or deny such a driving source. Thus, it was decided that an on-site diagnostic measurement and analysis program was required. In order to provide the fastest possible response, one member of the Porter McGuffie, Inc. (PMI) analysis team traveled to the plant immediately while another member assembled the necessary measurement instrumentation.

As has been mentioned, several rounds of vibration measurements at various flow rates were originally conducted on the piping system. While these measurements determined the frequency and magnitude of the piping vibration, they did not provide any information about the vibration source. To this end, the measurement team came equipped with pressure transducers to evaluate possible pressure pulsations within the piping as well as accelerometers to measure the vibrations.

MEASUREMENT PROCEDURES

Field measurements were conducted on July 9, 12 and 14, 2009, at the PPGPL plant site. The primary measurements were conducted at the JT valve as indicated on Figure 1. The vibration associated with the valve was monitored in the vertical and transverse directions on the downstream side of the JT valve with accelerometers mounted on the flange bolts.

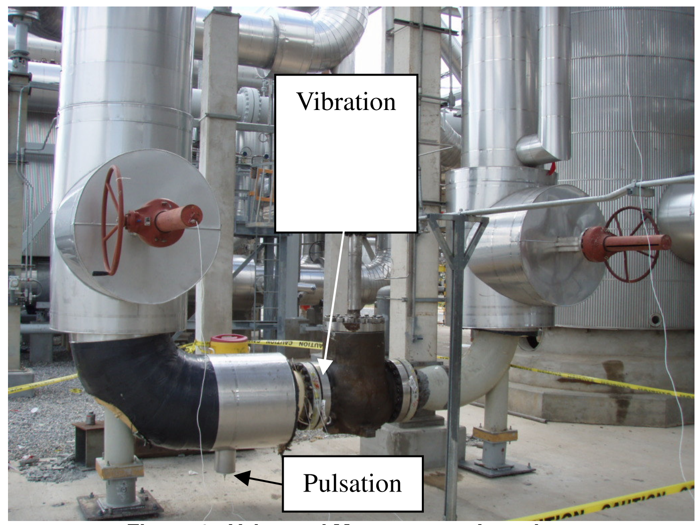

Figure 1 - Valve and Measurement Locations

The dynamic pressure was monitored using a pressure transducer located in the drain valve just downstream of the JT valve. In addition, another pressure transducer was located in the line between the upstream cold separator vessel and the JT valve. The accelerometers used were PCB model 338B35 with a nominal sensitivity of 100 mV/g. The pressure transducers were PCB model 112A21 with a nominal sensitivity of 50 mV/psi. The output of the transducers was monitored with a Data Physics Dynamic Signal Analyzer. In general, data in the range of 0-160 Hz were collected using record length of approximately 13 seconds to achieve a 2000 line Fast Fourier Transform from the time domain to the frequency domain. Ten records were averaged with an overlap of 90% to produce the resultant spectra. Additional measurements of the piping vibration were conducted at numerous locations around the JT valve and the expander. The pulsations were also monitored periodically at a drain valve on the outlet side of the expander.

MEASUREMENT CONDITIONS

The initial measurements on the JT valve system were conducted on July 9, 2009. For this series of test runs, the JT valve was operated at plant operating conditions similar to when the original vibration measurements were taken. The flow rate through the JT valve was varied from approximately 25% to 50% of the plant design throughput and the pressure drop across the valve ranged from approximately 16 to 115 psi.

A second set of measurements was conducted on July 12, 2009. For this set of measurements, the original extensive noise reduction trim in the JT valve was replaced with a standard noise reduction trim. The flow rate through the JT valve was varied from approximately 25% to 50% plant design throughput and the pressure drop across the valve ranged from approximately 42 to 148 psi. The pipe shaking was reduced to some extent with the installation of the standard noise reduction trim. The continued shaking, however, remained a concern and was expected to become excessive if throughput rates were increased.

The final set of measurements was conducted on July 14, 2009. For this test, the standard trim remained in the JT valve. However, the JT valve was rotated 180 degrees so that it was operating in a down flow condition as opposed to the up flow condition as originally installed (see Figure 2). The flow rate through the JT valve was varied from approximately 25% to 70% plant design throughput and the pressure drop across the valve ranged from approximately 58 to 173 psi. Although the pipe shaking was reduced further, the concern remained for excessive pipe shaking as the flow rate approached 70% of the plant design throughput. The valve body reversal also generated excessive noise levels.

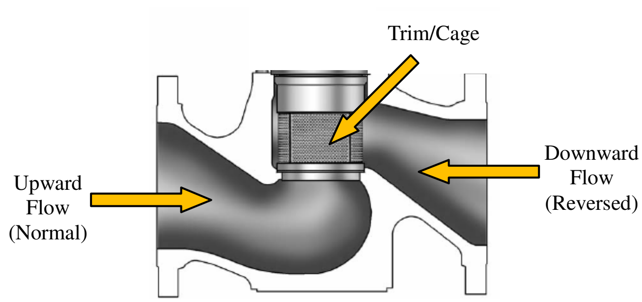

Figure 2 – JT Valve Body Flow Directions

MEASUREMENT RESULTS

As indicated in the previous section, measurements were conducted on three different days with differing flow rates, pressure drops and valve configurations. The results obtained and the path forward developed from each of the measurement sessions are discussed in the following sections.

July 9, 2009

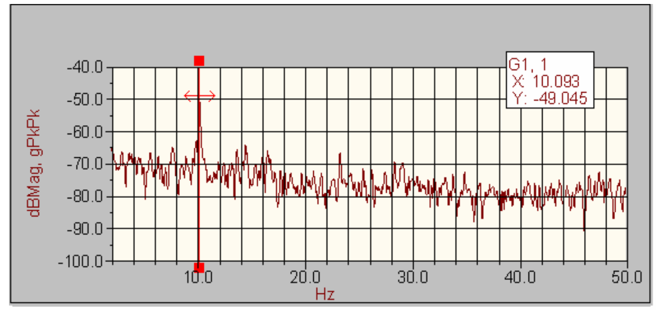

Figure 3 – No Flow Vibration

Figure 3 illustrates a spectrum measurement on the JT valve taken on the morning of July 9, 2009, before gas flow was started through the valve. As indicated by the red cursor, a strong peak was observed in the spectrum at approximately 10 Hz. This peak is an indication of the piping system being excited by ambient conditions at a natural mechanical frequency vibration mode.

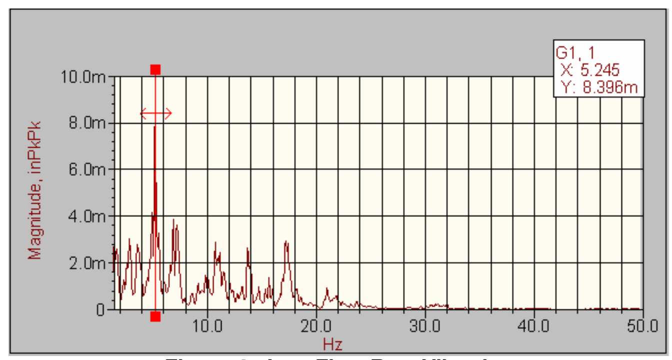

Figure 4 - Low Flow Rate Vibration

Figure 4 illustrates the spectrum measured on the same day with the flow going through the valve at approximately 50% of design plant throughput with a pressure drop of approximately 112 psi. The cursor indicates that the peak displacement is at a frequency of approximately 5.2 Hz. There is no indication of significant piping system motion in the vicinity of 10 Hz ss noted in the no-flow vibration signature.

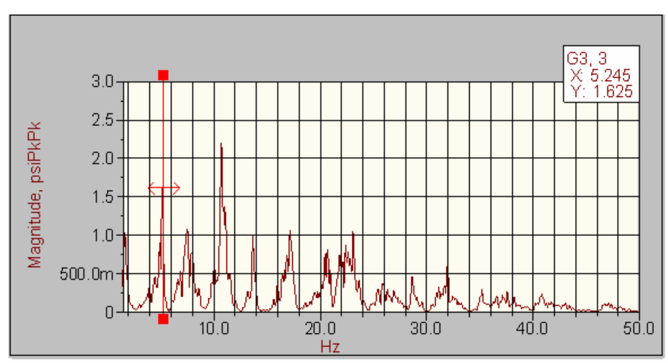

Figure 5 – Pulsation Downstream of Valve

Figure 5 illustrates the pulsation levels measured just downstream of the JT valve at the same time that the vibration measurement was conducted. The cursor indicates a strong peak in the pulsation signature at approximately 5.2 Hz, matching the frequency of the peak in the vibration signature. Note as well that the strong pulsation peak at about 10.8 Hz (Figure 5) results in a weak response at the same frequency in the vibration spectrum (Figure 4). Very little motion is observable at the 10 Hz natural frequency of the JT valve piping.

The observed displacement on the piping was on the order of 8 mils with a pulsation level of 1.5 psi. Personnel at the PMI office in Lawrence, Kansas, constructed a piping model of the system. By subjecting this piping system to a driving force of 1.5 psi at 5.2 Hz at the JT valve location and using a damping value of 5%, a displacement of 10 mils was computed. Thus, the pulsation level was consistent with the measured vibration.

A strong correlation between the measured pulsations and the piping vibration was observed under all flow conditions observed on July 9, 2009. Both the pulsation levels and the vibration levels were observed to increase with gas flow and with pressure drop across the valve. The fact that the piping system was vibrating at the same frequency as the pulsations and that it was not exhibiting significant vibration levels at the 10 Hz natural frequency of the piping system led to the conclusion that the gas pressure pulsations generated in the valve were driving the vibration in the piping system. This conclusion was further supported by the anecdotal reports that little vibration was observed when the JT valve was replaced with a straight though spool piece during the original observation activities.

July 12, 2009

In order to test the conclusion that the source of the unwanted pulsations was the JT valve, it was decided that a different trim would be obtained and installed in the valve. A standard noise reduction trim cage with a special pattern of ¼" holes was located at another facility on the island of Trinidad and installed in the valve. The OD of this trim cage was smaller than that of the original noise reduction cage, allowing more clearance between the cage and the valve body. The increased clearance changed the characteristic pulsation output of the JT valve.

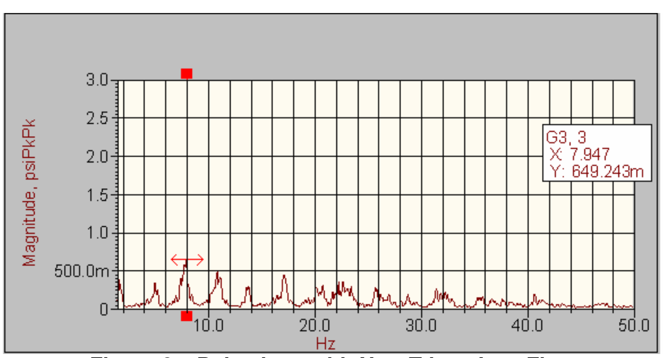

Figure 6 – Pulsations with New Trim – Low Flow

Figure 6 illustrates the pulsation levels observed just downstream of the JT valve on July 12, 2009. With nearly the same flow conditions as illustrated in Figure 5, the valve with the new trim exhibited significantly lower pulsation levels. In addition, the spectrum pattern changed. With increased flow and pressure drop, the peak level pulsation increased by almost a factor of two, as illustrated in Figure 7.

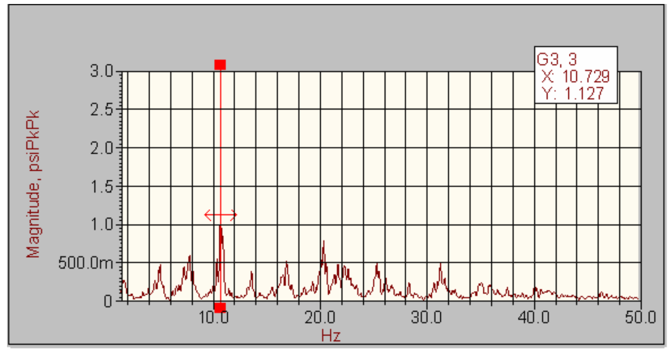

Figure 7 - Pulsations with New Trim – Increased Flow

The noise level generated by the standard trim was significantly increased above the original noise reduction trim. This was expected since the original noise reduction trim design was superior in noise reductions as compared to the standard noise reduction trim.

Developed from the July 12th measurements, the path forward was to find a means of further reducing the pulsations generated in the JT valve for long term operation of the plant.

July 14, 2009

Based on a consensus of the parties involved, it was determined that an additional test was desirable. For this test, the JT valve was rotated 180 degrees so that the valve was operating in a down-flow rather than the original up-flow direction. The standard noise reduction trim cage remained installed in the valve. The result was a gross change in the configuration of the downstream side of the valve's internal gas flow geometry. The pulsations and resultant vibrations were lower with the standard trim and with the valve rotated.

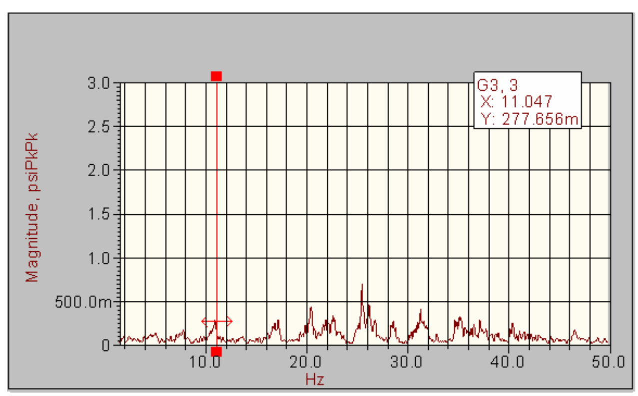

Figure 8 – Pulsations with Rotated Valve

Figure 8 illustrates the pulsations observed downstream of the valve in the rotated configuration. As can be seen, there is very little energy below 10 Hz. In general, the piping vibration was acceptable for all flows with the rotated valve.

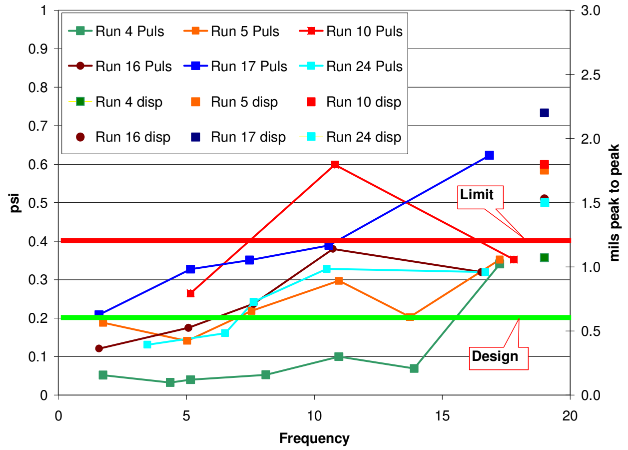

Figure 9 - Criteria

Figure 9 illustrates the simplified pulsation spectra and vibration levels measured at a number of operating conditions on July 14th. Based on these data, a pulsation limit level of 0.4 psi peak-to-peak was established for the valve-induced pulsations measured just downstream of the valve and corresponding to an acceptable level of piping vibration. In order to provide some margin of safety, a design level of 0.2 psi maximum peak-to-peak was selected. These levels are represented by the red and green horizontal lines on Figure 9.

The low frequency vibration levels observed on July 14th were deemed acceptable for continuing the startup operation, but not the expander operation at reduced plant gas throughput. This allowed the plant startup to progress while corrective action for a redesigned JT valve could be undertaken.

DISCUSSION

Low frequency (< 20 Hz) pulsations with magnitudes in the range of 2-3 psi peak-to-peak were initially observed just downstream of the JT valve. The pulsation levels observed upstream of the JT valve were nearly an order of magnitude lower and had an entirely different spectral signature than those downstream of the valve. When the noise reduction trim in the JT valve was replaced with a standard trim, the pulsation levels were significantly reduced. The reduction observed was somewhat less than an order of magnitude. Other than the trim, no other changes in the system were necessary to change the pulsation levels. Then the valve was rotated 180 degrees (see Figure 2), effectively switching the inlet and outlet ends of the valve. This resulted in very significant change in the valve outlet geometry and a very significant lowering of the pulsation levels.

As was noted earlier, there was anecdotal evidence that replacing the JT valve with a straight through spool piece resulted in an elimination of the pulsations and resultant vibrations. Changing the trim in the valve resulted in a lowering of the pulsation and vibration levels. Changing the trim and reversing the flow through the valve resulted in a dramatic lowering of the pulsation levels. It must be noted that the standard trim generated significantly greater noise than the original noise reduction trim.

CONCLUSIONS

Based on the series of measurements conducted during July 2009, it was concluded that the pulsations and resultant vibrations in the piping system associated with the JT valve were being generated in or by the JT valve. These pulsations were of a high enough magnitude that they were driving the piping system to an unacceptable level of vibration. The original observations and pipe vibration data gathering was not sufficient to determine the cause for the pipe vibration. Additional vibration testing with corresponding internal pressure pulsation data collection confirmed the JT valve was producing pressure pulsations that drove the pipe vibration. The additional testing included changing the valve trim and flow direction to provide a basis for determining the necessary corrective action.

Flow testing of the 12” and 16” valves was conducted at the valve manufacturer’s flow test lab. The lab results for the 12” valve yielded similar results confirming the field analysis. During the lab testing, the 16” valve was shown to yield a significant improvement in controlling the downstream pressure fluctuations. As a result of these tests, the original JT valve was replaced with a similar but larger body size (16 inch). The flow path remained the same as the original valve and the original noise reduction trim was maintained. The pulsations being generated by the replacement JT valve were reduced to an acceptable level. The subsequent reduction in the forcing function as the flow interacts with the piping network provided suitable operating behavior such that the piping system functioned properly at the design plant throughput rate. No follow-up pulsation measurements were conducted on the revised system.

Since the same trim was used in both the old and new valves, there was no indicated change in the kinetic energy exiting the valve trim. Only the gas flow path volume between the trim and the valve body was increased by the use of 16” valve body. The authors offer the comment that during the design stage, identification of the potential for the JT valve to produce sufficient low frequency pulsations to excite the piping system is perhaps beyond the current state-of-the-art for valve specification, sizing and selection and piping design practices.

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