TAKING THE PLUNGE

Kelly Eberle and Cajetan Ijeomah, Wood Group, Canada, outline a case study of vibration-induced cracks in a plunger pump piping system.

Plunger pumps are used in a wide variety of applications, such as LPG storage facilities, well injection for oil recovery, slurry pumps for mining, liquid condensate pumps, and specialty refinery applications. Given their common application in the oil and gas industry, plunger pumps are sometimes viewed as simple commodities and shortcuts can be taken when planning this equipment into the overall design of new facilities. All too often new plunger pump installations experience serious operational and safety problems after start-up because of design oversight. The case study shared in this article highlights the vibration problems encountered at a new pump installation for an LPG pipeline, caused by poor design and installation.

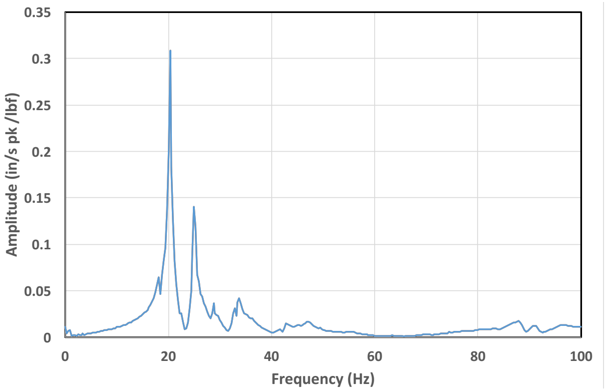

Figure 1. Modal measurement.

Table 1. PSV vibration measurement details

Location	Direction	Percent guideline	Amplitude (ips Pk)	Frequency (Hz)
PSV top	A	1192	9	24.1
PSV top	H	883	6.9	24.7

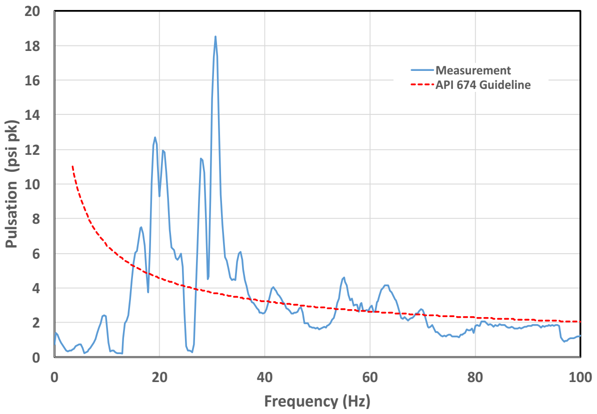

Figure 2. Discharge pulsation near the pump.

Plunger pump system

In this case, the system includes two quintuplex plunger pumps that deliver 416 gal./min. at the rated speed of 400 rpm. The pumps are driven by a variable frequency drive (VFD) controlled motor that provides a maximum of 350 hp to the pumps, and designed to operate over a range of 200 – 400 rpm. The pumps receive liquefied propane from several charge pumps that take the propane from large storage bullets at the terminal and boost the pressure from approximately 100 psig to 1100 psig as the propane is sent to a pipeline.

Early operating problems and field tests

Once start-up and commissioning was complete, some piping vibration problems were noted by operating personnel. Vibrations became more severe as the pump operation increased over the first six months of the plant's operation. Site assessments confirmed that the issues were a significant safety concern.

Wood Group conducted a field vibration test for the customer, sending specialist field engineers to the site to measure vibrations and pressure pulsations on both pumps over the operating speed range. Vibration amplitudes of more than 12 times the standard industry guideline levels were measured, indicating a significant risk to the integrity and safety of the pump system.

The API 674 design guideline for mechanical natural frequencies is 1.2 times plunger passing frequency. Therefore, for this installation, all mechanical natural frequencies had to be greater than 40 Hz. Modal testing was carried out to determine the mechanical natural frequencies of the piping system components and to determine the cause of the high vibration.

Figure 1 and Table 1 show an example of the modal test results for the pressure safety valve (PSV). The measurements in Figure 1 illustrate that the mechanical natural frequencies were measured as 20.3 Hz and 25 Hz, which does not meet the minimum API 674 guideline of 40 Hz. The maximum PSV vibration was measured at 24.1 Hz. This excessively high vibration was, in part, due to the nearby mechanical natural frequencies. The mismatch in the frequency measured by the modal test and the vibration test also indicated high shaking forces from pressure pulsations. Pressure pulsations were also measured in the suction and discharge systems. Figure 2 shows a pulsation model of a portion of the suction system.

The results of the field testing concluded that the high vibration resulted from excessive pressure pulsations and excess pipe flexibility, due to the pipe layout and support design. Recommendation from the field testing included a redesign of the pipe support and a pulsation design study to reduce pressure pulsations and shaking forces.

Design work and simulations

The first step in the redesign was to conduct a pulsation simulation of the pump suction and discharge system. A computer model of the pump system was created with Wood Group's Mechanical Acoustical Package (MAPAK) simulation software. Figure 3 shows a portion of the pulsation models of the suction and discharge systems.

This pump performance simulation included the field test conditions, as well as a complete range of summer and winter operating scenarios. The range of pump performance was simulated with the software, as well as simulating combinations of single pumps operating and dual pump operation. One of the key findings from the simulations was that excessive shaking forces were acting on the piping. The shaking forces were the result of the high pressure pulsations acting on bends and tees (pressure x area = force) and would need to be controlled to minimise vibration.

Figure 4 and Table 2 show an example of the extreme shaking forces that were calculated. The force was calculated to be as high as 22 000 lb pk-pk, 10 to 20 times higher than recommended by the design guidelines.

Cavitation

Piping systems are also put at risk to cavitation through persistent high pressure pulsations. If pressure pulsations reach a certain limit, the instantaneous pressure can drop below the vapour pressure of the liquid, resulting in gas bubbles. As the instantaneous pressure increases, the bubbles collapse, resulting in a microjet of liquid at the site of the bubble collapse. This dramatic change in pressure due to the gas bubbles, along with the formation of the microjet, can cause high forces on the pump components and damage to the pump fluid end. Wood Group's suction system pulsation simulations calculated excessive pulsations in the pump and suction piping near the pump, causing significant cavitation and putting the integrity and safety of the pump suction system at risk.

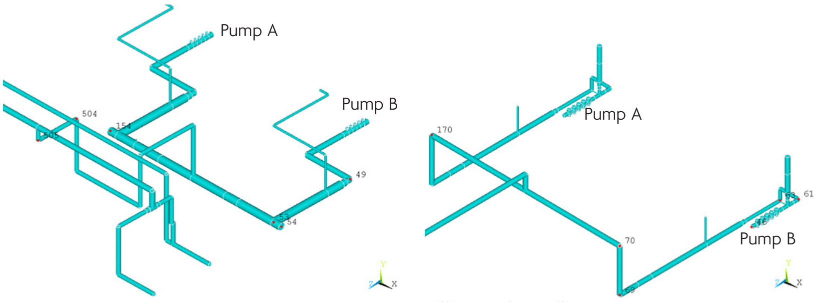

Figure 3. Part of the suction (left) and discharge (right) pulsation models.

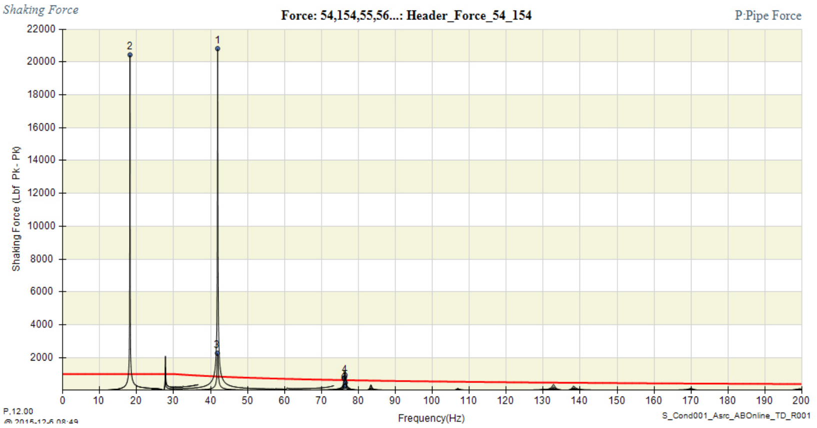

Figure 4. Example shaking force calculated by the pulsation simulation.

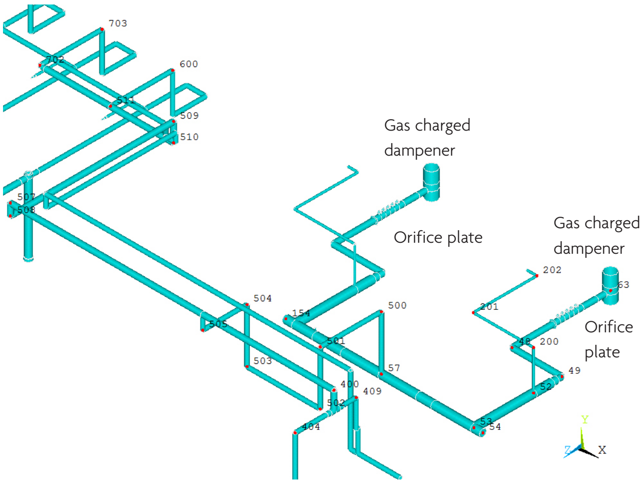

Figure 5. Short-term suction system recommendations.

Table 2. Harmonics peak points

Number	Frequency	Shaking force (lbf Pk – Pk)
1	41.9	2.08E + 04
2	18.2	2.04E + 04
3	41.8	2.27E + 03
4	76.3	7.82E + 02
5	76.5	4.71E + 02
6	76.2	2.44E + 02

Design simulations

Through its detailed studies, the company determined that the original pulsation control design was insufficient and recommended new pulsation control devices. It evaluated and presented several design options to the customer.

Because of the wide range of operating speeds and variability in the liquefied propane properties, the system required significant modifications. Figures 5 and 6 illustrate the recommendations that were determined for the suction system. The combination of a gas-charged dampener on the non-flow end of the pump manifold and an orifice plate at the pump inlet was effective in reducing pressure pulsations and shaking forces for the limited speed range operation. To ensure operability over the complete speed range, Wood Group recommended using a pulsation filter near the pump inlet to prevent pulsations from being transmitted to the piping system. This pulsation filter design is maintenance free and does not require a gas charge.

Cracks in piping

Due to concerns about possible cracks in the piping caused by the extreme vibration and shaking forces, a comprehensive, non-destructive inspection of the piping system was also conducted. More than 20 crack locations were identified.

These cracks represented a significant risk to the site and required costly repairs. There were concerns

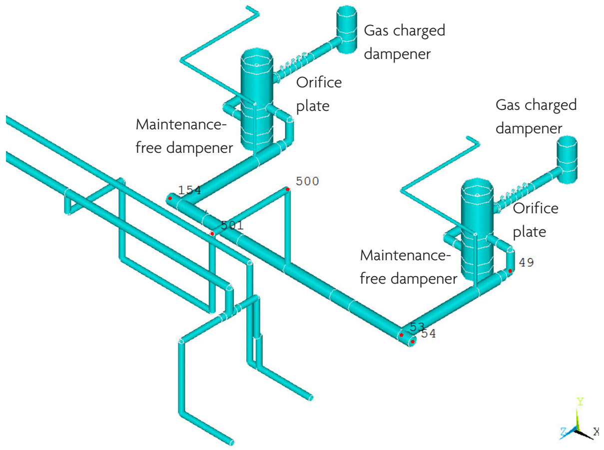

Figure 6. Long-term suction system recommendations.

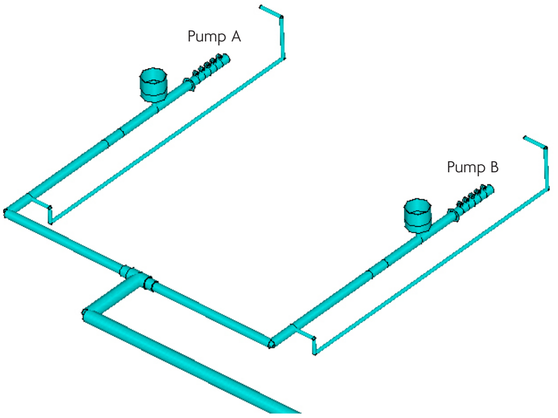

Figure 7. The new suction system layout.

about other possible cracks that were too small to detect but may have led to future failures. The tests also indicated that the existing pipe layout and support arrangement were too flexible. Even though the system had only been operating for around six months, the customer made the decision to redesign and replace all suction and discharge piping in the pump area to ensure the ongoing and long-term safety of the installation.

Redesign

Wood Group conducted the analysis for a redesign of the piping system with a scope that included adequate layout and support to minimise pipe flexibility and vibration, as well as a pipe stress analysis to ensure the piping system was not too stiff in consideration of the stress and equipment nozzle loads from pressure, temperature and other static loads. This scope carefully considered the competing factors of low flexibility to control vibration and low stiffness to control static load effects.

Figure 7 shows the pulsation model for the new suction system. The original suction piping had several elevated sections of piping, as well as numerous bends and tees, which caused excessive flexibility. The new design routed the piping close to the top of the pump skid and grade level and included a reduced number of bends. Changes to the pipe support and pipe restraints were also implemented in the new design; the pipe support structures were mostly large beams with gussets provided at restraint location, and flat bar clamps were used as pipe restraints to minimise vibration caused by residual shaking forces remaining in the system.

Short-term pulsation control devices, pipe layout and pipe support changes were made to both the suction and discharge systems. The pumps were recommissioned and Wood Group returned to site to measure vibrations. All vibration measurements on the main process piping and equipment were reduced to acceptable levels.

Small-bore connection issue

The field test found marginal to high vibration on some small diameter piping for drains and vents, as well as some instrumentation vibration connections. These small diameter connections were not included in the design study as the devices were added after the initial design of the main piping had been completed, as well as design changes made during site construction. Remedial measures to reduce the projection and weight of these small connections, as well as supports, were recommended as follow-up measures.

Conclusions and recommendations

This case study highlights the risk for vibration and fatigue failures on plunger pump installations when the design for control of pressure pulsations and their effects has not been duly considered. Wood Group recommends that a pulsation study is conducted on a reciprocating pump installation with a power of 50 hp or more, especially for variable speed applications.

The company's analysis in this case found that an orifice plate was required to control pressure pulsations and reduce the potential for cavitation in the suction system. While the orifice plate increases the pressure loss in the suction system, this pressure loss is offset by a significant reduction in pulsation.

The routing of piping and supports is another significant factor to consider in a reciprocating pump design. Piping must be routed as low as possible to the skid or ground level, the number of bends and tees must be minimised, the pipe supports must have sufficient stiffness to avoid resonance at 1x plunger passing frequency, and pipe restraints must be robust enough to withstand vibration, particularly near elbows and tees.

Finally, the company would always recommend a start-up vibration check for all new and retrofit pipe installations to ensure the mainline piping is within acceptable vibration limits. The main purpose of the start-up vibration check is to develop a baseline for vibration, assess installation techniques and review small-bore piping and instrumentation connections to ensure the future integrity and operability of the plant.