Managing Liquid Transients and Vibration within Pump Facilities

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ABSTRACT

Fluid transients causing pressure surge or water hammer are well known to create damaging effects on pipeline systems. It is common for pipeline designers to evaluate transient surge scenarios for their pipeline projects by looking at the pipeline in its entirety from end to end. Any pump facilities located on the pipeline are often considered as a point on the pipeline, with little attention given to the specific piping details of the pump station at a local level.

Pressure transients passing through a pump facility can encounter many piping elbows, risers, and piping segments that have small bore attachments for instrumentation, vents, and drains. As the transients pass through the facility, high vibration on the main lines and their associated small bore attachments can lead to fatigue failures with damaging consequences. This paper highlights the importance of considering liquid transient effects on facility vibration for main pipes and small bore attachments using test data from field measured vibrations during known transient events.

INTRODUCTION

In today's world of increasing regulation and serious environmental concerns the incentive for fluid transport companies to minimize the risk of leaks and spills is greater than ever. No industry has felt the pressure of this more than the hydrocarbon pipeline industry in the past few years. With almost daily headlines of pipeline politics and the constant threat of possible leaks and spills within the public eye, there is a pressing need for pipeline companies to analyze and assess the risk of their assets. One prominent risk of leaks and spills is vibration related fatigue failure within pipeline pumping facilities.

Transient response of the piping system due to water hammer events can lead to vibration induced fatigue failures over time. These water hammer events can be caused by pumps starting or stopping, valve swings, transient events from up or down stream of a facility, check valve slam, or operational changes in flow rate. Each transient event has the potential of exciting vibrations of the main pipe, as well as corresponding small bore attachments such as drains, vents, instrument ports, thermal bypass piping, and others. The resulting vibration and stress due to transients can be excessive, as will be shown in this paper.

Water hammer or transient surge analysis within facilities is one area of design where Civil and Mechanical Engineering scopes begin to blur. Often water hammer analysis at the design stage will focus on the pipeline in its entirety, considering a facility as "dot" along the line. The intention of this paper is to shed some light on how a water hammer analysis can be extended toward the mechanical side of this overlap. It highlights some of the transient issues present in facilities, illustrates how the identification and mitigation of these "local risks" is quite different than the transient design analysis typically performed for an entire pipeline, and presents approaches to predict vibration and stress resulting from transient vibrations in pumping facilities.

FATIGUE LIFE, TRANSIENT VIBRATION, AND MEASUREMENT

Fatigue life in steel components is related to its endurance limit, the amplitude of dynamic stress on the component, stress concentration factors, and welding quality. In general, the fatigue life of a component is related to the dynamic stress it experiences. For steel subject to dynamic stresses below the endurance limit, the fatigue life is considered infinite. Any cycles spent at stress levels higher than the endurance limit are said to reduce the components fatigue life (EN 13445).

Fatigue analysis is typically divided into high cycle fatigue (HCF) and low cycle fatigue (LCF). Vibrations and pulsations typically create low amplitude high frequency stresses which lead to HCF. Pressurization, thermal expansions, and transient forces typically create high amplitude low frequency stresses, and lead to LCF.

One problem with transient vibrations is that often a component will only see high dynamic stresses during the transient event itself, which is usually only for a short period of time. This means that each time the transient occurs, a portion of the components fatigue life will be spent. In this way components that have functioned well for many years can suddenly fail without warning once their fatigue life is finally spent.

Another problem with water hammer (transient) induced vibrations is they often do not last long enough for anyone to notice. For these reasons transient vibrations can be thought of as a "silent killer".

In order to measure and evaluate transient vibrations, you need to be at the right place at the right time or you will miss it. For that, an advanced understanding of water hammer transients is required. Also, operations limited ability to perform transient test events adds to the complexity of their identification and evaluation;] so even if you want to test and measure it, there are limited opportunities to do so.

Figure 1. Example of data collection equipment required to measure transients' vibrations on hundreds of simultaneous test points

Figure 1 shows a temporary instrumentation setup to measure transient vibrations at hundreds of test points simultaneously at a pipeline pump facility. A setup like this allows for the collection of many points at facilities with limited transient test opportunities.

VIBRATION EFFECTS OF TRANSIENTS ON PUMP FACILITY PIPING

Generally water hammer analysis is concerned with transient induced pressure surges causing over or under-pressure of pipelines and piping systems. An additional concern for facilities is how water hammer transients will make the piping structures move. This movement, or vibration, is caused by unbalanced forces created in spans of pipe between elbows, and changes in pipe size, as pressure surges pass by. A simple example of this is shown in Figure 2 (top), where a travelling pressure wave between two elbows has a peak-to-peak pressure differential of 60 psi. This causes an unbalanced dynamic force toward to the right side of the diagram, which can be calculated for a 6" pipe with area about 28 in^2 (Force = 60 psi x 28 in^2 = 1,680 lb). As this pressure surge travels by (at the speed of sound of the fluid) the pressures will reverse, causing a similar force in the opposite direction (bottom of Figure 2). This transient force event is applied to the structure to create transient vibration.

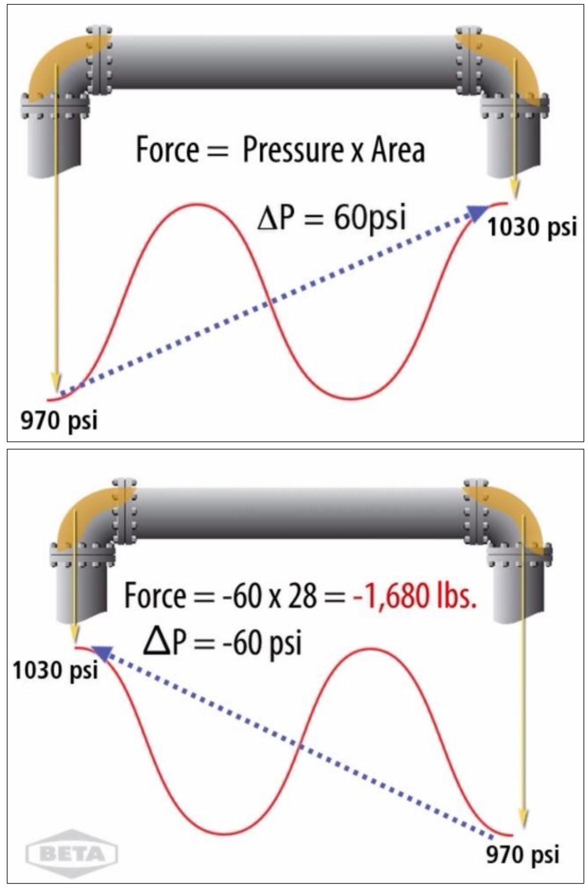

Figure 2. Example of unbalanced force in a piping system

It is possible to determine the transient forces on a given pipe span by calculating the force at each time step of a water hammer calculation (see an example force-time plot in **Error! Reference source not found.**). Some water hammer software's available on the market have this capability.

Discussing dynamic force on its own, however, does not paint a complete picture. Vibration can be described by the following equation:

$$V = \frac{F_d}{K_d} \ (1)$$

Where:

- F_d = *Dynamic Force*
- K_d = *Dynamic Stiffness*

As such, in order to predict the vibration a dynamic force may cause on the structure, we also need to know the dynamic stiffness of the piping structure.

Calculating the dynamic stiffness of a piping structure can be a complicated task that often involves finite element modeling. It is therefore desirable to design a system with a transient force guideline to limit the amount of force a system will see. The idea is that by keeping transient forces low (F_d in Eq.1), transient vibrations will also be kept low. Transient force guidelines in the industry are rare, but one can be found in the Energy Institute standard "Guidelines for the Avoidance of Vibration Induced Fatigue Failure in Process Pipework" (Section T2.8.3.3).

In cases where high transient forces exist, but suitable modifications to reduce these forces are not practical, transient vibration and stress of the piping system must be calculated to evaluate the severity of the issue.

Applying time varying forces to calculate vibration in structures is not a simple task; it involves a combination of water hammer analysis to produce transient forces, and finite element software to determine the dynamic stiffnesses. Combining these two pieces into a forced response analysis can produce predictions of vibration and stress on a particular component. Many approaches are available to do this; one specific example using common commercially available software packages was given by Wilcox and Walters (2012).

An example of how high vibration levels can be on main pipes subjected to water hammer transients is shown in Figure 3. This vibration data was collected on an 18” riser going into a 36” header during a transient that followed a pump shutdown. It can be seen in the figure that transient vibration levels reached over 6 inches per second 0-peak (over 12 inches per second peak–to-peak) during the event. A common rule of thumb guideline for piping is to keep vibration below 1 inch per second 0-peak.

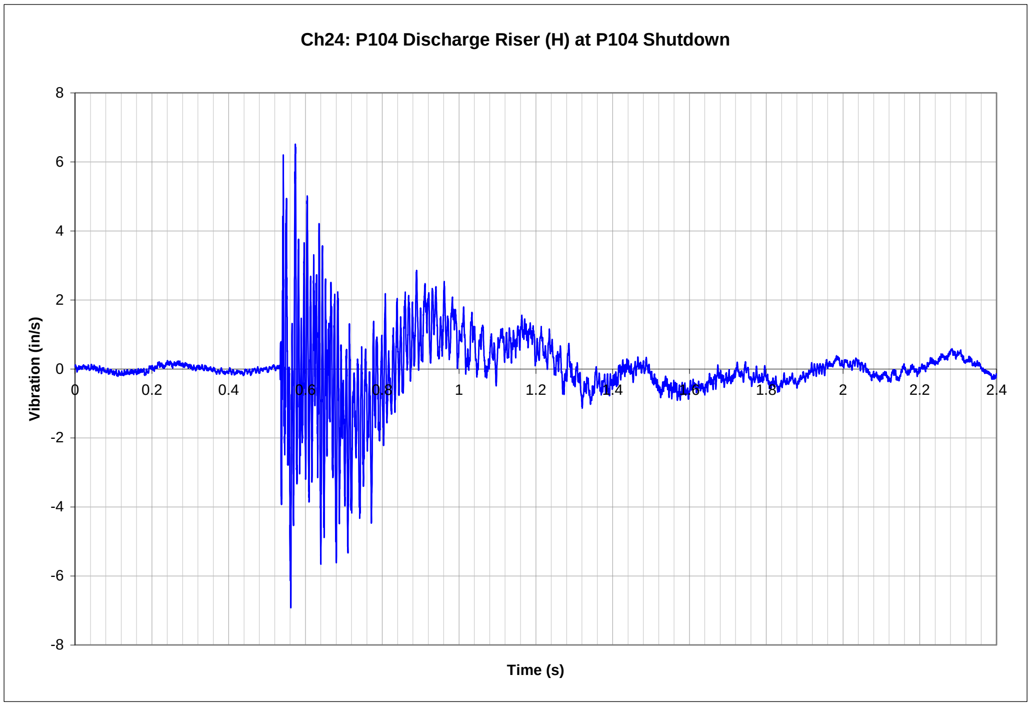

Figure 3. Transient piping vibration of a discharge pump riser after pump shutdown

Transient vibration levels such as those shown in Figure 3 must be evaluated for risk of high stress, fatigue life, and ultimately failure. If found to be high, solutions can involve reducing water hammer transient forces, increasing dynamic stiffness, or both.

VIBRATION EFFECTS OF TRANSIENTS ON SMALL BORE PIPING

Another high risk area for leaks and spills to occur in a pipeline pump facility is small bore piping. The previous section described how transient vibrations are created from water hammer events on main piping, this section describes problems and considerations for small bore connections (SBCs) to the main pipe.

An SBC is defined as a branch connection on the mainline piping that is NPS 2” and smaller. For larger bore pipes (above 24”), connections of up to NPS 4” are also considered to be SBC’s. They come in the form of instrumentation ports, vents, drains, inspection ports, and more. Some examples are shown in Figure 4.

Figure 4. Examples of small bore attachments in pipeline systems.

As described by Harper (2014), it is rare to have design specifications requiring SBC vibration audits during the design stage, or even during field commissioning. Most specifications occur on P&ID's or isometric drawings without suitable design details. As such, it is left to the field installers' whim to decide what the SBC design will be. It is thus common at pump facilities to see every SBC on a site being different. This makes an assessment of transient vibration risks very difficult. Given this, the author has witnessed some pipeline operators beginning to standardize its SBC designs in the wake of many costly failures and challenges mitigating the risks.

In considering SBC transient vibration we must be aware of the main line pipe the SBC is attached to. When the main line pipe is subjected to transient vibrations, anything attached to it is also subjected to those vibrations, including SBC's. The interesting point with SBC's however, is that their vibration characteristics operate somewhat independently of the main pipe's characteristics. For instance, a particular SBC will often have a very different mechanical natural frequency (MNF) than its parent main pipe. And so, even when the main pipe appears not to vibrate significantly, the attached SBC can be quite the opposite.

An example of this is shown in Figure 5, where the blue vibration trace is the small bore vibration, and the red trace is the main pipe vibration. The transient event in this case was a pump startup. Notice how the blue SBC vibration is up to 4 inches per second 0-peak maximum vibration during a transient, while the red main pipe vibration remains relatively low through the transient.

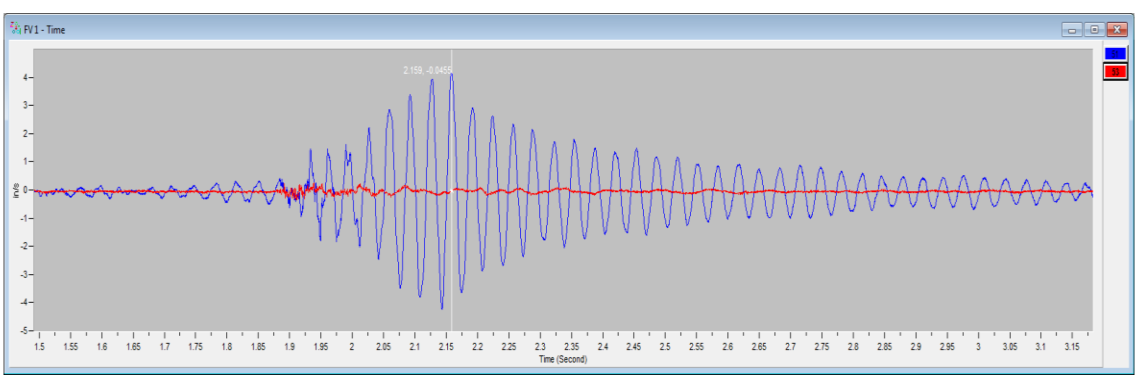

Figure 5. Example transient vibration levels of small bore attachments (blue) compared to main line vibration (red)

Once a vibration level has been measured, it must be compared to a suitable guideline to gauge its severity. Small bore connection guidelines are very sensitive to the layout of the connection and therefore change based on the SBC design. However, using 1 in/s 0-peak as a screening guideline is appropriate in many cases (Harper, 2014). In the case of Figure 6, this vibration was flagged as needing investigation.

The next step is to determine if the measured vibration causes high stress and is at risk of failure. There are several approaches to determine this. One useful method is to calculate an allowable vibration limit given an endurance limit. The results of this method are shown in Figure 6 using finite element analysis (FEA) on the subject SBC of Figure 5. The calculation determined an allowable vibration for this particular small bore of 2.1 inches per second 0-peak. It should be noted that this is a high cycle fatigue analysis, and the allowable vibration limit of 2.1 in/s 0-peak will ensure an infinite life of the component. Figure 5 clearly shows that this particular SBC is at risk of HCF failure.

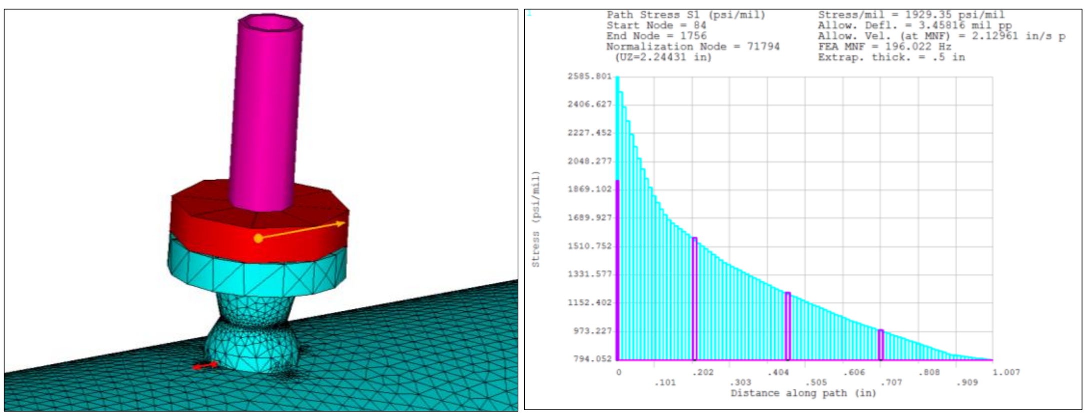

Figure 6. FEA model of small bore attachment with resulting allowable vibration calculations

The analysis can be continued with a LCF analysis to determine the number of cycles to failure, and a prediction can be made of the time, or of how many transient events this particular SBC can survive before failure. In the case of the above example, the client opted to modify the SBC to prevent the high transient vibration in the future.

SUMMARY

Water hammer transients in pumping facilities entail many failure risks. Consequences of these risks are magnified in pipelines transporting hazardous materials such as hydrocarbons which are under increasing regulatory pressure to minimize loss of containment.

Facilities have special considerations of water hammer effects that are not normally considered by analyses used to design an entire pipeline. These "local" facility considerations include:

1. Transient vibrations of main pipes induced by water hammer events. These vibrations are influenced by:
    a. Transient water hammer dynamic unbalanced forces in pipe spans

b. Pipe system dynamic stiffness

Both can be combined in a forced response analysis to calculate resulting vibration and stress.

2. Transient vibrations of small bore connections by water hammer events. Small bore risks are influenced by:
   a. Availability of SBC design specifications
   b. Installation practices
   c. SBC mechanical natural frequencies, and their interactions with water hammer unbalanced forces

Including these considerations in a pump station design will significantly reduce the risk of failure, leading to reduced incidences of leaks, spills, and significant loss of containment of transport fluids.

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