Flow-Induced Vibration Problems
in
Process and Power Plants

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Stress Engineering provides analytical and testing services to process industries faced with flow-induced vibration (FIV) problems. This class of plant vibration problems is relatively complex and requires in-depth understanding of fluid dynamics and structural dynamics concepts, fluid-structure interaction, and specific knowledge of the machinery and equipment under consideration. It has been said that FIV is often viewed as some kind of "black art" – too mysterious for the typical plant engineer to understand. Stress Engineering engineers have the skills and engineering tools required to solve FIV problems that can threaten availability of plant equipment and machinery. A few of the more common FIV problems in process and power plants are discussed in more detail below.

Pulsations from Fluid Machinery

It is common for fluid machinery to experience noise, vibration, and failures that can be traced back to dynamic phenomena occurring in the machine and the connected piping system. All fluid machinery generates periodic fluctuations in flow and pressure (pulsations) that are related to the rotational speed; in some cases these flow variations and pulsations lead to excessive vibration, noise, and component failures.

For reciprocating machinery, API 618 (for gas compression systems) and API 674 (for liquid pump systems) specify engineering analysis techniques aimed at controlling the harmful effects of flow-induced vibrations. Both standards utilize acoustical simulation techniques that study the system dynamics interaction of the machinery signals and the piping acoustics. Some of the key issues that are addressed as part of an API acoustical simulation include:

Some of the key issues that are addressed as part of an API acoustical simulation include:

- Predict pulsation levels in the machinery and connected piping system.
- Design pipe layout and support systems to prevent structural resonance and fatigue failures.
- Gas Systems: custom design bottles to control pulsation levels, study the effect of pulsations on compressor performance, and study the interaction of several parallel machines under various operating conditions.
- Liquid Systems: Prevent cavitation by calculating pulsation waveforms with respect to vapor pressure levels, and custom design accumulators to control pulsation levels.

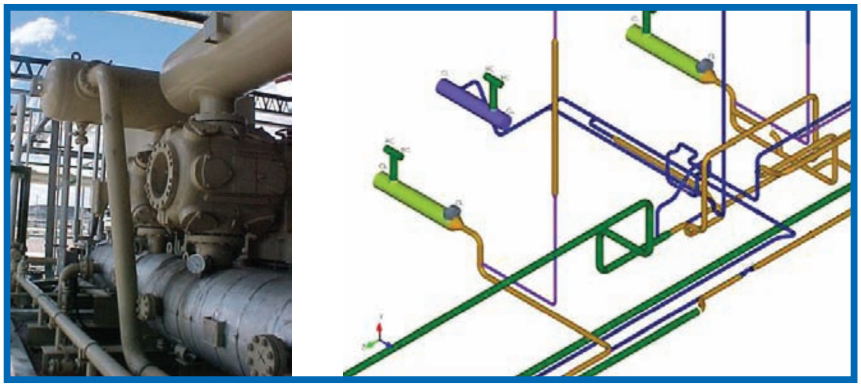


Figure 1: Digital pulsation simulation of a refinery treat gas compressor system.

Vortex-Induced Vibration

Vortex shedding occurs when steady fluid flow passes over stationary objects in the flow field, resulting in boundary layer separation and alternating pressure field applied to the structure. When the vortex shedding frequencies approach the structural natural frequencies, the fluid-structure interaction becomes strongly coupled and dangerous levels of vibration and fatigue failure can occur. Similarly, excessive pulsation and noise occur when the vortex shedding frequencies match acoustic natural frequencies.

- Pulsations and noise generated by flow through restrictions and side branches
- Vibration of instrument connections inserted into the flow field
- Vibration of heat exchanger tubes
- Pulsations and noise in shell-side heat exchanger cavities
- Wind-induced vibration of tall towers & structures

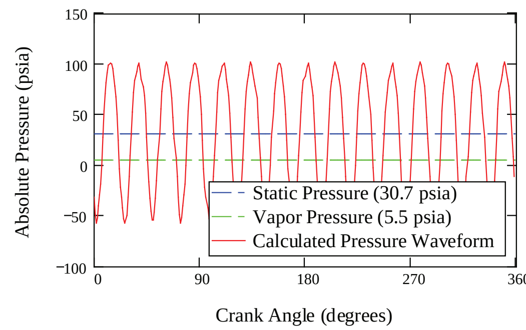


Figure 2: Quintuplex pump simulation indicating a cavitation problem – negative pulsation peaks reach the vapor pressure limit.

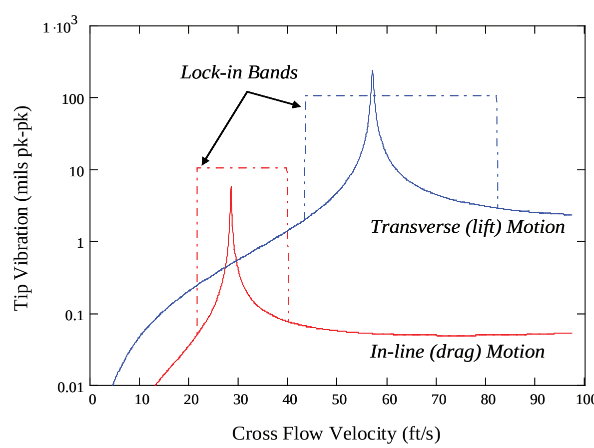


Figure 4: Simulation of a thermowell subject to vortex-induced vibration.

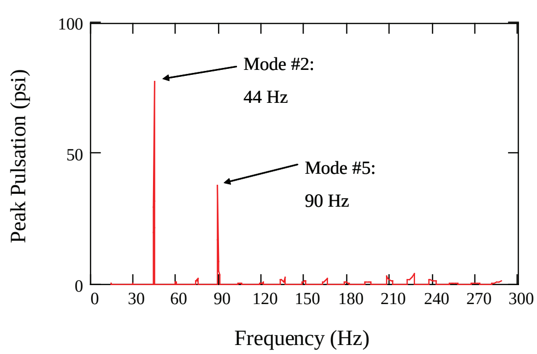
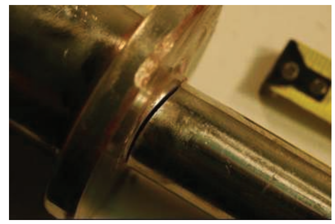


Figure 3: Frequency domain view of the same signal illustrating the excitation of specific piping acoustic modes.

Turbulence-Induced Vibration

Most plant processes are designed for high levels of turbulent flow in order to enhance heat and mass transfer; unfortunately the fluctuating pressure fields generated from turbulent flow also provide a source of FIV in plant components. Turbulence-induced vibration is a random process that must be analyzed with probabilistic methods. In most analysis problems, experimental data is used to formulate the turbulent forcing function in the form of power spectral density (PSD) plots; standard methods of probabilistic structural dynamics are then used to estimate the random response of components subject to turbulence. Common situations of turbulence-induced vibration include:



Fatigue failure of a thermowell due to vortex-induced vibration.

- Vibration of heat exchanger tubes (external cross flow)
- Vibration of pipes and ducts (internal parallel flow)
- Wind-induced vibration of towers

Self-Excited Vibration

This special class of vibration problems is distinctly different when compared to vortex-induced and turbulence-induced vibration where a forcing function can be defined. The common feature that exists for all self-excited vibration problems is a de-stabilizing effect that leads to a threshold of stability, such as a critical flow velocity or rotating speed, below which self-excited vibrations will not occur. Some common examples of self-excited vibration in process and power plants include:

- Fluidelastic whirling of heat exchanger tubes (the leading of cause of exchanger tube vibration)
- Non-synchronous shaft orbits in rotating machinery: oil whirl, oil whip, and cross-coupling fluid forces
- High-velocity flow in flexible piping systems

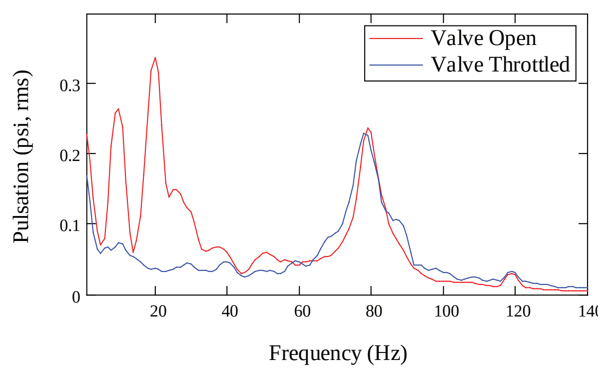
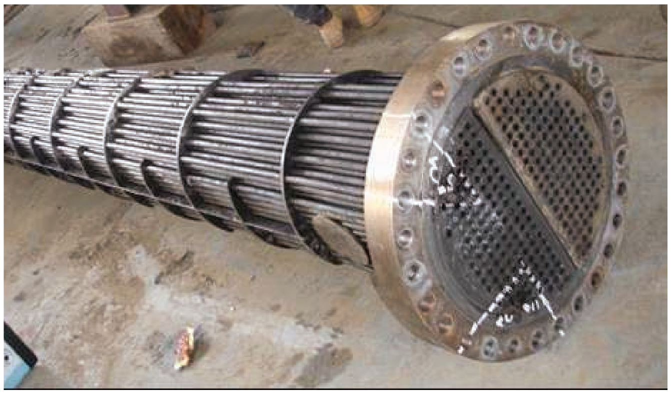


Figure 5: Field measurement of pressure pulsations at heater outlet piping – VIV problem solved by de-tuning the excitation source (valve position) from the system (piping acoustics).

The engineering analysis of these problems typically involves eigenvalue analysis of a linear system dynamics model - including the effects of fluid-structure interaction (e.g. rotordynamics models including hydrodynamic bearing forces). System stability, and hence protection from self-excited vibration, is predicted when all system eigenvalues have negative real components. When



Tube bundle failure

nonlinear effects must be considered (e.g. exchanger tubes in oversized baffle holes) time-domain simulations can be used to predict the onset of instability. For some applications stability diagrams such as the one shown in Figure 6 can be used to evaluate self-excited vibrations.

Vibrations Caused by Fluid Transients

Structural vibration resulting from fluid transients is better described as shock rather than vibration – due to the high-amplitude/short-duration loading of structures from fluid transient events. The most common sources of shock loads leading to structural vibration include:

- Rapid changes in valves and machines: water hammer and surge
- Sudden fluid release: relief valve exhaust and pipe whip
- Intermittent two-phase flows: slug flow and plug flow
- Sudden phase changes: flashing and cavitation

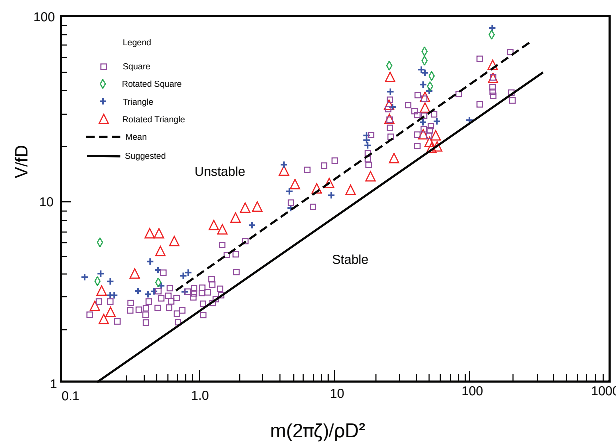


Figure 6: Fluid-elastic stability diagram for tube bundles (ASME Boiler Code, 1998)

This class of flow-induced vibration is often decoupled such that the fluid dynamics and structural dynamics can be analyzed separately. On the fluids side, analytical techniques are available to estimate the magnitude and duration of fluid shock loads. For example, waterhammer can be simulated with time-domain solutions to the fluid dynamics momentum and continuity equations. A time-domain analysis is then carried out using standard methods of structural dynamics such as response spectrum or time-history simulation.

Recent projects involving flow-induced vibration in process plants:

- Acoustic-induced vibration of refinery heater piping system
- Custom design of thermowells subject to vortex-induced vibration
- API 618 acoustical simulation for a refinery hydrotreater unit
- Forensic investigation of LNG pipe failure due to waterhammer loading
- Noise and vibration analysis of flood water pumping systems
- Fluid shock and vibration analysis of refinery heater piping system