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# Introduction to pipeline flow-induced vibration

Pipeline and piping vibration can cause a range of issues from reduced process efficiency and unplanned shutdowns to decreased equipment life or even loss of containment. It is an issue for engineers designing systems in many industries and has been of specific concern in subsea oil and gas in recent years. This article focuses on the phenomenon termed flow-induced vibration (FIV), where the internal flow of process fluids within a pipeline or piping system causes some form of vibration of the pipe.

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# Executive summary

Flow-induced vibration is a complex mechanism and one in which engineering design has traditionally relied on empirical methods for its avoidance. Empirical design methods are often, necessarily, conservative. High levels of conservatism can result in engineers identifying vibration risks that constrain designs or limit operations. Here we aim to present how computer-based simulation of flow and structural behavior can offer engineers greater understanding in cases where empirical approaches have identified potential vibration issues.

# Causes of flow-induced vibration

The most critical aims of pipeline and piping system design are to minimize the risk of pipe vibration and to improve safety, reliability and efficiency of process and production operations. Through engineering simulation, we may be able to meet these aims while reducing conservatism and cost.

Flow-induced vibration of pipelines and piping can be caused by a number of mechanisms including:

- Pumps and compressors which could produce pressure pulsations, exciting a response in nearby piping
- Fluctuating flow past obstructions or objects in the flow (for example, thermowells or other intrusions in the flow) and piping dead legs
- Multiphase flow – for cases with multiple phases flowing (for example, gas and liquid), specific multiphase flow regimes and flow frequencies through piping may drive vibration (for example, slug flows where packets of liquid impact the walls of the pipe at bends, elbows and obstructions)
- Rapid changes in flow conditions or fluid properties caused by opening valves, cavitation or other large pressure variations leading to changes in state, for example, flashing of liquids to vapor.

# Identifying flow-induced vibration risk

The seminal guidance document used in the field of flow-induced vibration is published by the Energy Institute (EI). This provides a very clear method to determine the likelihood of Flow Induced Vibration (FIV) when designing new plant, assessing or modifying existing pipework or assessing an identified problem of an operating system.

But what happens in the event that an unacceptable vibration risk is identified? Using the Energy Institute approach the engineer has three options:

- Redesign or resupport the pipe section
- Perform detailed analysis
- Carry out vibration monitoring during operation

While redesign may be possible for new facilities, the number of options available for design modifications in existing facilities is often severely limited. In cases where designs cannot be changed, the options are limited to detailed analysis or monitoring vibration in operation.

If the monitoring approach is taken, it could be costly to install the equipment needed and, if vibration is subsequently observed, it could result in operating restrictions with significant economic impact on a process or the production rates.

The option of performing detailed analysis could be the preferable choice, offering engineers greater understanding of the vibration risk or the actual response of the system to the required operating conditions.

The challenge here is “what is detailed analysis?” While there is very little in terms of industry best practices currently available, there are analysis and simulation approaches that engineers can turn to in order to further assess the risk of vibration.

# Vibration assessment using energy institute guidelines

Figure 1 shows a piping system that was initially investigated using the Energy Institute guidelines.

The system is based on piping at an existing process facility being reviewed to accommodate an upgrade in the process with the aim of increasing process flow rates through the system.

Table 1 summarizes the findings of the empirical assessment for three operating cases assessed. For a number of vibration mechanisms, the pipe work is identified as having vibration risk and requires more detailed investigation. Flow-induced pulsation, vortex-induced vibration (VIV) from flow past intrusive elements (the thermowells) and small bore

connections were all identified as limiting at least two of the three operating cases assessed. Using multiphase flow maps, the flow regime was estimated to be dominated by annular flow (where a liquid film forms and flows along the pipe walls) and so slug flow was not identified as a potential vibration mechanism.

The failure to meet the requirements of the EI guidelines means we need to redesign the system, perform detailed analysis or install monitoring equipment. In this case, we will look into detailed analysis and assess how an engineer could gain further information to make an informed decision as to how to proceed.

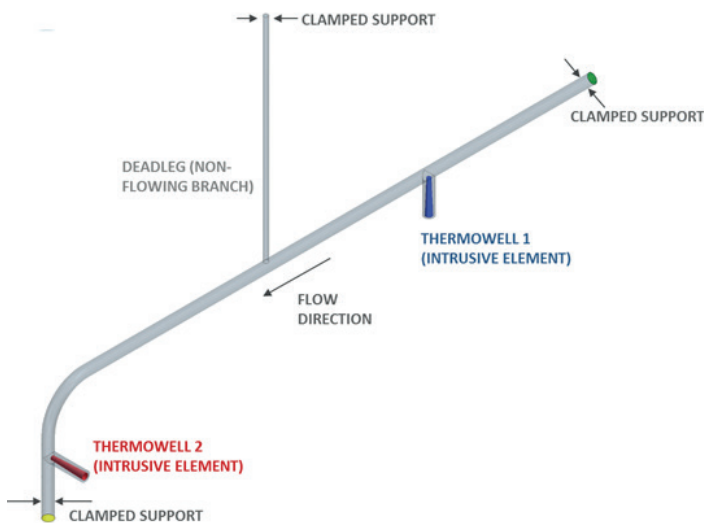


Figure 1: Pipe section layout

Mechanism	Case 1	Case 2	Case 3
Flow induced turbulence	-	-	!
Flow induced pulsation	!	!	!
Slug flow			
VIV from intrusive elements	-	!	!
Small bore connections	!	!	!

! Further action required: redesign, further detailed analysis and/or vibration monitoring  
 - Further action: only visual inspection for good, as analysed construction

Table 1: Results from EI guidelines assessment of three operating conditions for pipe section considered. The slug flow condition was not required to be assessed in this case.

# Full system flow and structural analysis

With modern computing capabilities, it is now more practical than ever to simulate flow and structural responses of larger systems; even using desktop workstations. In this case, we will demonstrate how the flow field within the piping can be simulated and used to predict the subsequent structural response of the system.

The two modeling approaches used for the piping system (shown in figure 1) were:

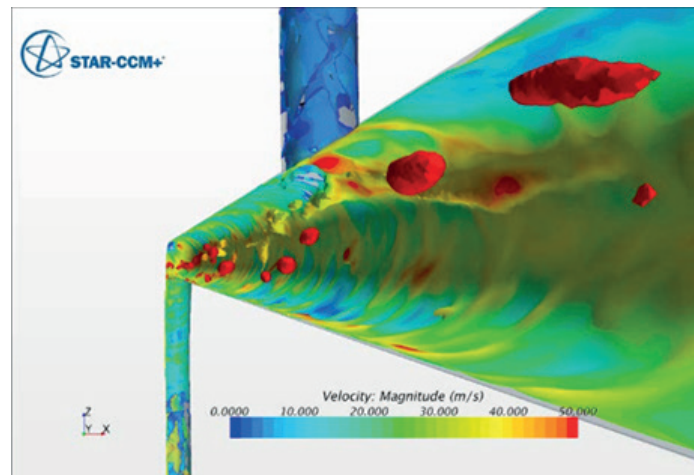
- a) Computational fluid dynamics (CFD) to simulate the flow. This was performed using the STAR-CCM+® software (by Siemens PLM Software)
- b) Finite Element Analysis (FEA) to assess the structural response. This used wave6 FEA software (by wave6), a frequency domain vibro-acoustic software package designed specifically to assess noise and vibration.

In the situation where flow-induced pipe deflections are large it may be necessary to perform a two-way coupled fluid-structure simulation where the flow-driven deflections of the pipe feedback to impact the flow through pipe. However, in the case presented, this approach was not necessary and the flow results were used to predict structural response but this was not fed back to the flow simulation since it would have negligible effect, a one way coupling approach.

CFD simulation of the multiphase flow through the piping confirmed the flow regime was dominated by annular flow for all three operating cases with some liquid carried in a dispersed manner (as large droplets).

Figure 2 shows results from the CFD analysis, illustrating contours of liquid speed on interfaces that exist between the gas and liquid phases present in the flow. It is clear that there is a gas-liquid interface near the pipe wall, confirming the dominant annular flow regime. In addition, large droplets of liquid are carried along in the gas through the main bore of the pipe, shown in red. The CFD simulation demonstrated that no slug flow occurred through the system, which corroborated the empirical assessment made during the EI guidelines approach.

CFD simulation suggested that some flow-induced pulsation was occurring, both in the thermowell housing as well as in the main vertical dead leg. This was indicated by the fluctuating pressures recorded in the relevant areas. Detailed analysis of the flow around the thermowells (not presented here) showed no signs of adverse response or loading through the onset of vortex-induced vibration, which is contrary to the findings of the EI method.



**Figure 2:** Contours flow speed on gas-liquid interfaces clearly shows a layer of liquid along the pipe walls and some dispersed (large) droplets in the flow

# Full system flow and structural analysis

Figure 3 shows the frequency content of the flow-induced pressures on the pipe wall. Two dominant spectral peaks can be observed as generated by the flow at 4 Hz and 32 Hz.

These two spectral peaks were investigated further and it was identified that the:

- 4 Hz peak was the characteristic frequency of the large liquid droplets passing through the pipe
- 32 Hz peak was related to the liquid film interaction with the first thermowell housing (deadleg)

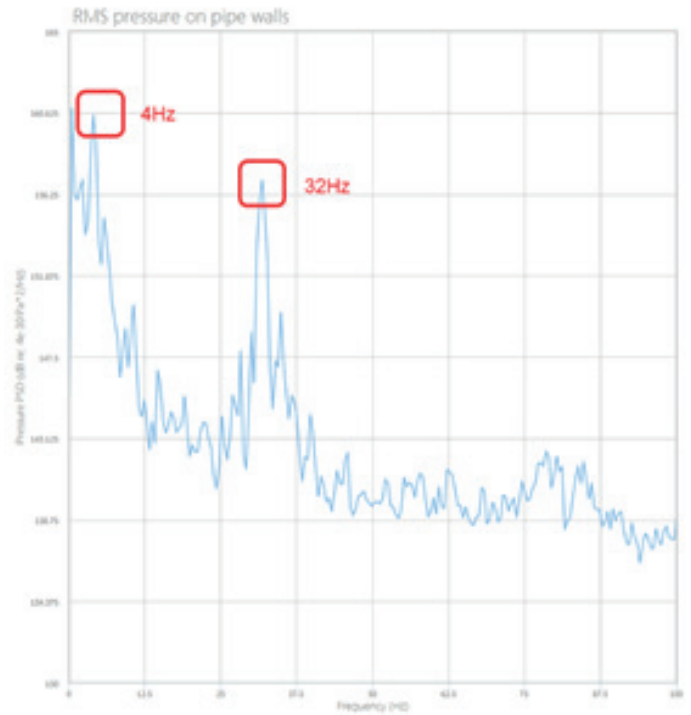


Figure 3: Surface-average RMS pressure on internal pipe wall



# Full system flow and structural analysis

The frequency content of the flow-induced forcing on the pipe can be compared to the natural frequencies of the pipe system, which were calculated using wave6. The natural frequencies of the system are shown in figure 4 and are generally higher than much of the spectral content in the flow-induced pressure signal captured on the pipe walls from the flow simulations. This indicates that the forcing function induced by the flow on the pipe system is unlikely to excite these natural structural modes.

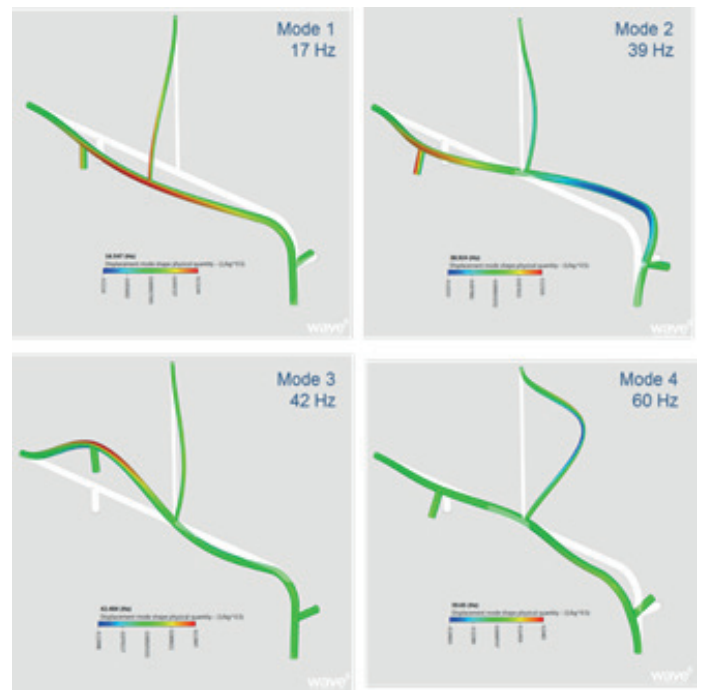


Figure 4: Pipe work natural mode shapes and frequencies

# Full system flow and structural analysis

To complete the investigation, a one-way coupled analysis was undertaken. Here the forcing functions predicted from the CFD analysis were applied to the wave6 FEA model to assess the response. A vibro-acoustic model was solved to yield the forced response of the system, taking into account both the forcing function obtained from the CFD model and the impedance of the structure and fluid.

Figure 5 shows the pointwise maximum Von Mises stress for one of the operating cases. It can be seen that the peaks correspond to the structure's modal frequencies (shown in figure 4) and that there are no "line-up" effects, where a forcing frequency (from the fluid) and a modal frequency coincide, to produce excessive vibration.

While results presented are for a single operating condition, the same process (CFD and FEA) was undertaken across the operating range and no significant changes in system response was observed. This insensitivity to flow conditions suggests that the overall levels and peak values in the structural response are being sustained by wall turbulence rather than by specific mechanisms exciting structural modes. No significant vibration risks were identified by the analysis.

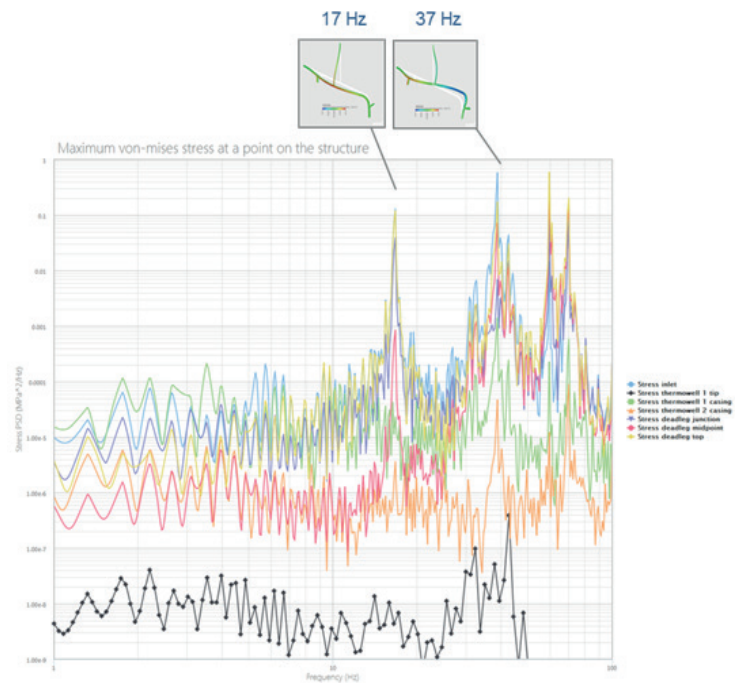


Figure 5: Pointwise maximum Von-Mises stress

# Conclusion

Detailed analysis was selected as the way to further assess the identified vibration risks identified by the assessment using the Energy Institute approach. This work aimed to present how a combined approach using computational fluid dynamics and finite element methods can offer the opportunity to more fully understand vibration risks. The detailed analysis presented briefly here suggested that there was no significant vibration risk in the system.

The starting point for a flow-induced vibration assessment will continue to be based on desktop studies and empirical approaches. In cases where a vibration risk is identified, flow and structural analysis has the potential to inform engineers of options available. Analysis best practices are not yet widely available but the tools are there and methods exist to help make well informed decisions and to enable the design and operation of safe and efficient pipelines and piping systems.

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