University of Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/Specialization: Marine- and Offshore Technology	Spring semester, 2021 Open
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Thesis title: **Flow Introduced Turbulence & Pulsation Assessment for Subsea Spools**	
Credits (ECTS): 30	
Key words: FIV LoF Flow-Induced Turbulence Energy institute Subsea spools Flow induced vibrations	Pages: 107 + enclosure: 0 Stavanger, 29.06.2021

Acknowledgment

First and foremost, I would like to thank my supervisor, Dr. Qiang Chen, who supported me on every problem that occurred while writing this thesis. I appreciate his great assistance and accurate comments, which were critical important during my work. I thank him for his motivational eagerness to help me accomplish the thesis. It inspired me and helped me to perform at my best. This thesis would have never been accomplishment without his dedicated involvement and his encouragement.

Secondly, I would send a special thanks to my other supervisor, Professor Daniel Karunakaran for helping me with setting up an office space at the subsea 7. I will also be grateful for his valuable help, guidance and follow-up during my time working on the thesis.

The last people I want to thank is my family. Without their support and love, this thesis would have been a lot more difficult. They showed a profound interest in what I did and facilitated everything else, so I could solely focus on the project.

Abstract

Submarine Spools are essential elements of a submerged structures. Subsea technology is a widely specialised field with new developments, the production of oil and gas is becoming possible at increasingly deeper water depths and harsher environment.

A high level of reliability and safety is therefore required for subsea structures to deter failures which possible can cause adverse crisis but also ensure secure and steady production of hydrocarbons.

A tie-in spool is a short section of pipe that connects and transports production fluid between subsea components. Spools can run between a pipeline and a manifold/template or wellhead, or even between two pipelines, and are often connected to different types of structures at either end. A spool primarily serves two purposes. (Yong & Qiang, 2014)

1. Ensures the connections between subsea systems and pipelines and compensating for the misalignment from installations.
2. It also reduces or mitigates axial expansion of flowlines. Therefore, to prevent expansion propagation to an adjacent system, Spools with curves are situated to contain and prevent high loads being transferred to an adjacent structure.

Loads imposed on the spool connecting hubs due to misalignments during tie-in as well as the pipe expansion normally set the limitations for the spool design. However, the O&G industry start to be aware of the fact that Flow induced vibrations (FIV), may be another limitation for spool design.

FIV for subsea structures is a contemporary topic in the industry. It is an industry trend to put valves/piping on spools which has a potential to trigger the VIV. The main objective of this thesis is to perform some screening checks for typical spool arrangements with piping/valves and perform some sensitivity cases for FIV. The first step is identification of potential excitation mechanism which are based on geometry of the spool arrangement. When the excitation mechanism is determined and an initial screening check is done to calculate the likelihood of failure, the LOF number. Detailed analysis using finite element method will be described for situations when the LoF number are above a certain threshold.

Contents

List of figures

List of tables

List of Abbreviations

FIV	Flow induced vibrations
FIT	Flow Induced turbulence
LoF	Likelihood of failure
O&G	Oil and Gas
EI	Energy institute
FIP	Flow-Induced Pulsations
HFAE	High-Frequency Acoustic Excitation
VIV	Vortex induced vibrations
PSD	power spectral density
PFD	process flow chart (PFD),
ROV	Remote operated vehicle
SBC	Small bore connection
N	Number of cycles
OD	Outer diameter
RMS	Root mean square

Chapter 1

1.1 Introduction

Integrity is a worrying issue for oil and gas industry since assets grow old and are considered more and more into the design phase of new subsea systems to ensure the reliability of those structures.

Whereas most of subsea facilities' integrity issues are dealt with during the design stage, flow induced vibrations is more of a forgotten problem or pushed further down the agenda. Nevertheless, the failure of this kind is considered dangerous, and the outcome is a complex and costly repair.

Many things have been accomplished in the subsea arena to address and ensure the mitigation of Vortex induced vibrations from environmental loading on unsupported pipe spans and risers. Vibration caused by internal flow such as process excitation received less attention. However, problems have come to light recently on some manifolds and jumpers, in part associated with increasing flow rates, leading to failures of piping, instruments, and valves.

FIV is considered a complicated phenomenon activated by numerous sources that engage with each other, the piping systems and with the flow itself. Moreover, the appliance is more complex by feedback from the structure back onto the sources. Several aspects like piping alignment, the flow speed, and liquid components affects the severity of FIV.

The greatest challenge when it comes to vibration induced fatigues on subsea systems is the treat being a hidden one and there is no indication topsides of vibration of subsea structures. The only possible exception is flow-induced pulsation from a riser, sometimes known as the "singing riser" phenomenon, which may be heard topsides. For a top side piping system, the vibrations are visible for crew working at that facility and they can deal with the treat accordingly. However, by the increased use of ROV in the industry, it will be good opportunities to utilize ROV to visualize FIV.

Although the likelihood of vibrations induced fatigue is consider small and rare, the impact and overall risk for the subsea spools and systems is deemed to be significant.

Increased production rates with higher pressure and temperature along with the trend of the development of complex and sophisticated subsea processing are the new norm in the industry, resulting in the possibility of FIV on subsea structures. Hence, there is a good reason for the subsea community to assess the existing State of the art for FIV assessment and highlight the present constraints and enhancements required. (Swindell, Hidden integrity threat looms in subsea pipework vibrations, 2011)

1.2 Scope and objectives

The thesis will conduct certain screening checks for spool alignment built on the methods outlined in GUIDELINES FOR THE AVOIDANCE OF VIBRATION-INDUCED FATIGUE. The guideline outlines numerous screening strategies to rank and identify vulnerable components in subsea structures by using a likelihood of failure score.

The screening is focused on basic fluid-process data and pipework geometric parameters, and it quickly assesses the advantages and disadvantages of any simple design changes.

In occasions where the anticipated LoF stays high, it can be essential to undertake more detailed analysis, to establish the dynamic stress levels by using finite element methods.

There will also be done some sensitivity analysis on the spools to see how FIV and be mitigated or the occurrence of FIV to be reduced. The main focus of this sensitivity analysis is to assess the change that stiffening the pipes through the addition of supports, change of chosen diameter, reduction of free spans will have on the LOF score.

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1.3 Structure of the Thesis

The subject that the master's thesis is based on a subject that has not been very focused on either in education or in industry. The available literature on Flow induced vibrations on subsea equipment's is limited, although the oil and gas industry are now beginning to realize the effect it can have on the integrity of their assets. That is why this thesis is structured accordingly with the lack of available literature in mind as the need for a comprehensive literature review before any analytical work can commence is important.

At the beginning of each chapter there will be a small introduction that will describe the content of that chapters.

Part 1		
Chapter 1- Introduction	Chapter 2- Literature Review	Chapter 3- Methodology

Chapter 1 - This chapter introduces:

- Introduction
- Scope and objectives

Because of the limited literature on FIV on subsea components, there has been a desire to create a document that addresses this. Therefore, relevant information on FIV gained through the literature study, have been presented at chapter 2. All the various excitation mechanism will be described in this chapter.

In Chapter 3 The Methodology used for this thesis will be covered. The methodology used are screening assessment based on "guidelines for the avoidance of vibrations induced fatigue failure in subsea systems" by Energy institute (EI). The excitation mechanism that will be covered in this chapter will only be the Flow induced turbulence and flow induced pressure pulsations.

Part 2
Chapter 4- Case study

As a part of the thesis, two LoF values have been calculated for Flow-Induced Turbulence (FIT). One were the assessment check was passed and one that didn't pass the assessment check. How to perform detailed analysis will then be demonstrated. Pulsation will also be done before the chapter is concluded with a comprehensive sensitivity analysis.

Part 3	
Chapter 5- Discussion	Chapter 6- Conclusion and recommendation

This part will consist of two important chapters. The findings of the thesis are discussed here. Furthermore, there will be some concluding words and recommendations for future work.

Chapter 2 Literature review

This chapter describes in detail the phenomena of Flow induced vibrations and the various excitation mechanism. All are described in detail, however the most critical for subsea industry are the flow induced turbulence and pulsations due to dead leg. Mechanical Excitation from Reciprocating/Positive Displacement Pumps and Compressors can pose greater challenge in the future when more of the processing structures are moved to subsea.

2.1 Basics Flow-Induced Vibration Physics and Analysis

Various sources are responsible for flow-induced vibration (FIV) in piping systems. These can be together with fluid-structure interactions. The various sources of FIV are shown in figure 1 below.

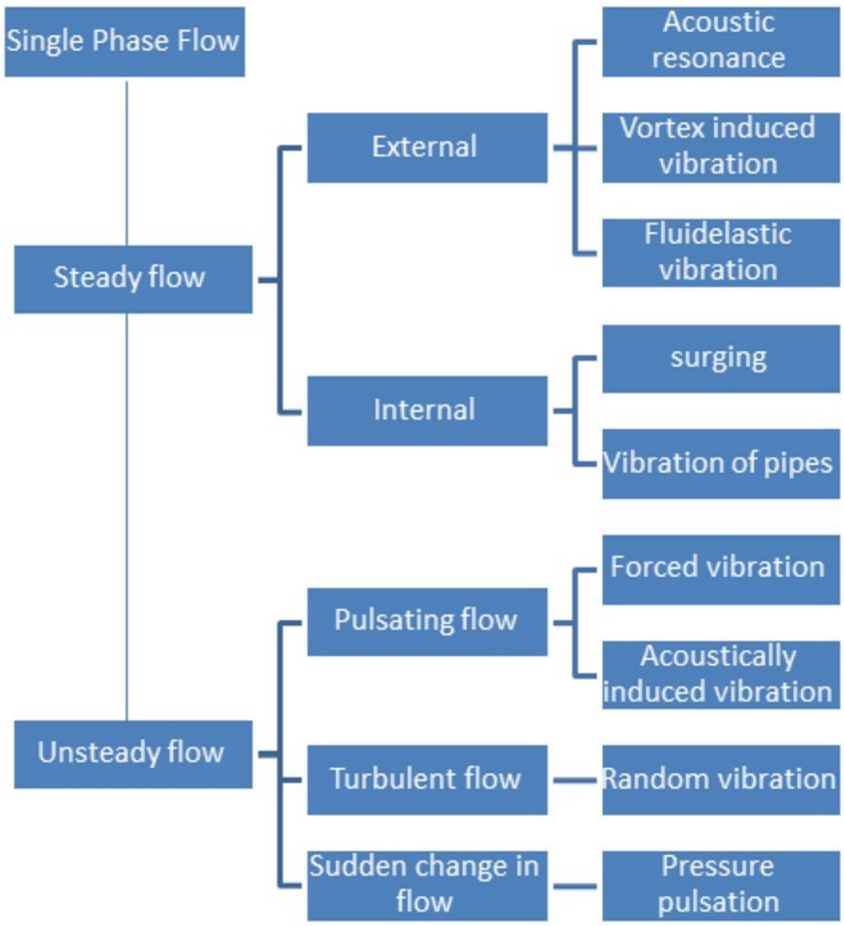


Figure 1: Multiple excitation mechanism (Nakamura, et al., 2013)

Many problems in industrial plants occur as a result of vibrations and noise caused by fluid flow. These hinder the smooth processes in a plant and some instances increase the cost of maintenance and repair thus affecting productivity and causing losses. Flow-related vibrations are categorically considered to be 'flow-induced vibrations' (FIV). On the other hand, flow-induced vibration and noise' (FIVN) is applied if noise is present in the phenomena. Flow unsteadiness has been documented to cause variation in the fluid force acting on an obstacle which in turn causes vibration of the obstacle. For instance, in reciprocating fluid machines, the piping connected oscillating flow causes an excitation force in the piping which results in vibration. However, vortex shedding behind obstacles and other issues can cause vibration problems even for steady flow conditions. An example is the symmetric vortex shedding that caused a vibration problem in the fast-breeder reactor at Monju in Japan where the drag direction vibration of the thermocouple well is evident behind the well. Such a form of self-excited FIV takes place even in steady flow resulting in difficulties in identifying the underlying mechanism rendering it the most complex problem to address during design or troubleshooting stages. (Nakamura, et al., 2013)

Common problems and failures are often associated with fluid-structure interactions within the internal fluid flows. Because the excitation generated by these turbulent flows are sometimes in significant levels, they result in similar levels in piping and associated structure vibrations. Various forms of flow instabilities, cavitation effects transient pulses, and strong vibration often are generated by valves, piping systems, and other devices. Such significant problems that have been documented include cavitation-induced vibrations, turbulence-induced vibrations, fluid hammer, and other vortex shedding problems.

In essence, the analysis of flow-induced vibration of piping entails the connection of piping structural vibration and fluid dynamics. The issue is complex, stimulating, and not straightforward. Such is of immense significance in the piping systems particularly when the flow-induced vibration can result in extreme vibration, fatigue, operational problems, and even failure. (Nakamura, et al., 2013)

2.1.1 Flow-induced vibration

For several decades, flow indicated vibration in piping systems has remained a documented phenomenon. Known as turbulence-induced vibration in some instances, small-bore piping connections are some systems that are often affected by such phenomenon. However, various types of flow-induced vibration can be described as unique and independent phenomena resulting from certain mechanism including:

- An abrupt change in fluid properties or conditions when a valve is opened, cavitation, and changes in pressure resulting in the variation of fluid conditions. For instance, pressure-reducing devices are known to produce such changes.
- Also, fluctuating flow past obstacles in the flow such as piping fitting, tees, thermowell as well as other intrusions.

2.1.3 Simplified physics

Friction is generated from the interaction of the fluid particles and the roughness of the inside of the piping wall. As a result, the velocity of flow is reduced, and the pressure declines significantly. These roughness in the inside of the piping walls which can be described as little valleys and ridges are responsible for the reduction in the velocity of the flowing fluid since they act against the motion of the fluid particles. The particles interacting with the surface of the wall are significantly affected. At the microscopic level, one can consider these valleys and ridges to be acting against the fluid particle motion which results in three-dimensional excitation forces and causing the piping vibration in the process. In piping, such simplified physics explains the development of flow-induced vibration.

2.1.4 Phenomenon and key parameters

FIV is essentially a low-frequency phenomenon resulting from turbulence and high flow velocity at piping branch connections or bends which excite low-frequency winding modes in the system. FIV is a characteristic of flow velocity. (Gharaibah, Barri, & Tungen, 2016)

The primary element includes the dynamic pressure which is a factor of density multiplied by the square of velocity (ρv2). Such a vibration usually occurs from the turbulence in the mixture within separation layers and pulsating pressure at piping bends, tees, reducers among others. The resultant low-frequency vibration (30Hz or below) is caused by the shaking forces at such discontinuities and beam modes which can be visible in piping shaking. Piping with a low natural frequency, small diameters, flare, or vent system are mostly affected by this phenomenon. Elements including the range of piping flexibility. wall thickness, piping diameter, and dynamic pressure (ρv^2) are used to evaluate the possibility of FIV in modern screening.

2.1.4 Natural frequencies and modes

Natural frequencies are those frequencies that result from the vibration of the piping system at any certain level. These vibrations have a defined and unique shape referred to as a mode shape which is assumed by the replica dynamic deformation vibrating at a similar frequency. The distribution of mass and stiffness in the piping system influences natural frequencies and modes. However, elements such as material properties, piping diameter, wall thickness, fluid density location of valves, and piping supports affect the distribution. Zero motion (node) and maximum motion (anti-nodes) are the locations of the mode shape. Moreover, the connection between excitation pattern and frequency to the systems natural frequencies influences the response of the piping to an excitation applied. A significant amount of system stress and displacement usually results from a dynamic excitation carrying a similar frequency to that of systems natural frequencies, a phenomenon referred to as resonance, which also tends to cause high vibration even failure. In the piping work, vibration can result in high cycle fatigue of key apparatus including small-bore connections or main piping welds suffering from a failure. The natural frequencies is used when detailed analysis is required after the initial screening check.

2.1 Excitation mechanism

2.2.1 Flow-Induced Turbulence (FIT)

Critical flow discontinuities in the piping system generate turbulent energy usually 30Hz or lower. Excitation is higher for low frequencies. These discontinuities can be tees or reducers, metered bends or partially closed valves, and a short radius.

Turbulent flows are found in a majority of piping systems although discontinuities such as tees and bends harbor high turbulent kinetic energy as shown in figure 2 below. As a result, pressure oscillations distribute the turbulent kinetic energy in wide broadband with the lower frequencies (100Hz or below) having the largest share of kinetic energy. As energy is transferred to the wall, it excites vibration in low frequency which can manifest in the form of visible pipe motion or even motion in pipe support.

In a bid to improve heat and mass transfer, the majority of plant process designs take into consideration high levels of turbulent flow, however, the variation in pressure fields resulting from turbulent flow still generate FIV in such plants. Probabilistic methods are ideal for analyzing turbulence-induced vibration because it is a random process with experimental data useful in formulating power spectral density (PSD) plots. Moreover, the random response of components affected by turbulence can be assessed by standard methods of probabilistic structural dynamics. (Gharaibah, Barri, & Tungen, 2016)

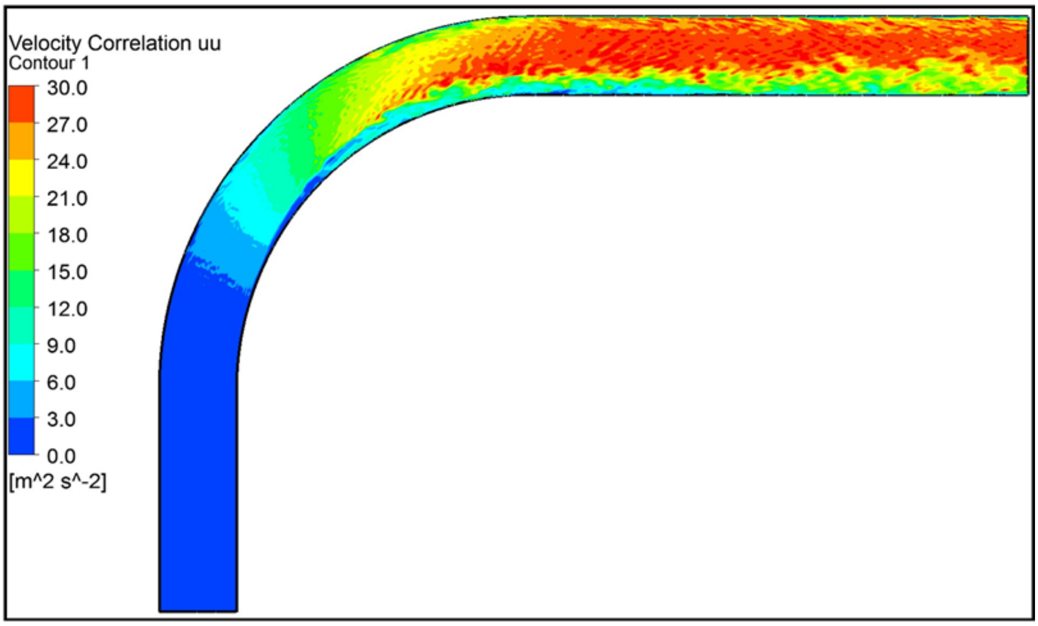


Figure 2: Flow induced turbulence at a bend (Gharaibah, Barri, & Tungen, 2016)

2.2.2 Flow-Induced Pulsations (FIP) In Dead Legs

In high-velocity gas systems, pulsations are often created bypassing the flow in the mouth of the branch connection with a “deadleg” or zero flow through the interaction between acoustic resonances and vortices as shown in figure 4 in next page. Vortices result from passing the flow on the mouth of the dead leg on a frequency based on equation 1 while acoustic resonances amplify them defined by Equation 2. A coincidence in the two frequencies results in a FIP.

The source of FIP can be difficult to identify in the field because the systems often have many dead legs. However, field measurements can be essential to determine the length of the dead leg and a starting point to investigate the source of FIP. The difference in frequency head-to-head harmonics and various FIP peaks can indicate the length of the dead leg. For instance, in figure 3 below, 95.9 Hz and 113.4 Hz are points of occurrence, and based on equation below one can determine the length of the dead leg. Taking sound speed to be 396 m/s [1300ft/s] s] in the gas medium, from second equation below the length of the deadleg will be 11.3 m [37.1 ft]. (Harper, 2016)

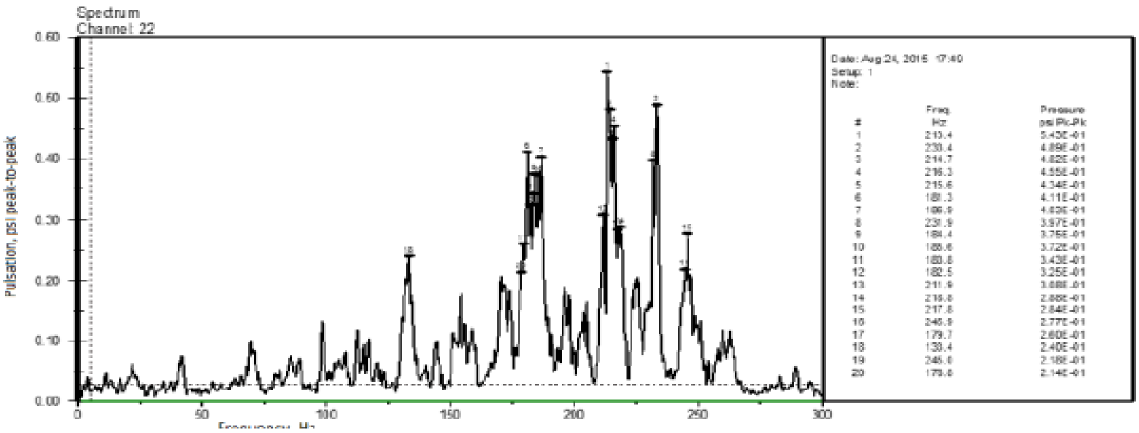


Figure 3: Frequency range due to FIP

$$F_V = \frac{S * v}{d} \quad (1)$$

$$F_S = \frac{(2n-1)}{4} * \frac{c}{L_{branch}} \quad (2)$$

From this point, one can look for likely sources of FIP including using the identified solutions to FIV problems listed below.

i. Altering the length of the dead leg, for instance, shortening
ii. Ignoring typical gas flow rates.
iii. Permit certain flow through dead leg.
iv. Prevent generation of vortices by adding spoilers to dead leg's mouth.
v. Reduce vibrations by providing additional support and bracing.

Figure 4 below shows how vortices are generated from flow past closed side branches and causing shear layer instability. The creation and destruction of vortices at different frequencies create tonal fluctuation of pressure. A frequency usually in the range of 500-1000 Hz (8) is dependent on the velocity of the fluid. However, any coincidence between this frequency and the natural piping system frequency would result in the generation of pressure pulsations at high levels. Moreover, severe vibration and cyclic stress may occur if the frequency is the same as mechanical eigenfrequency.

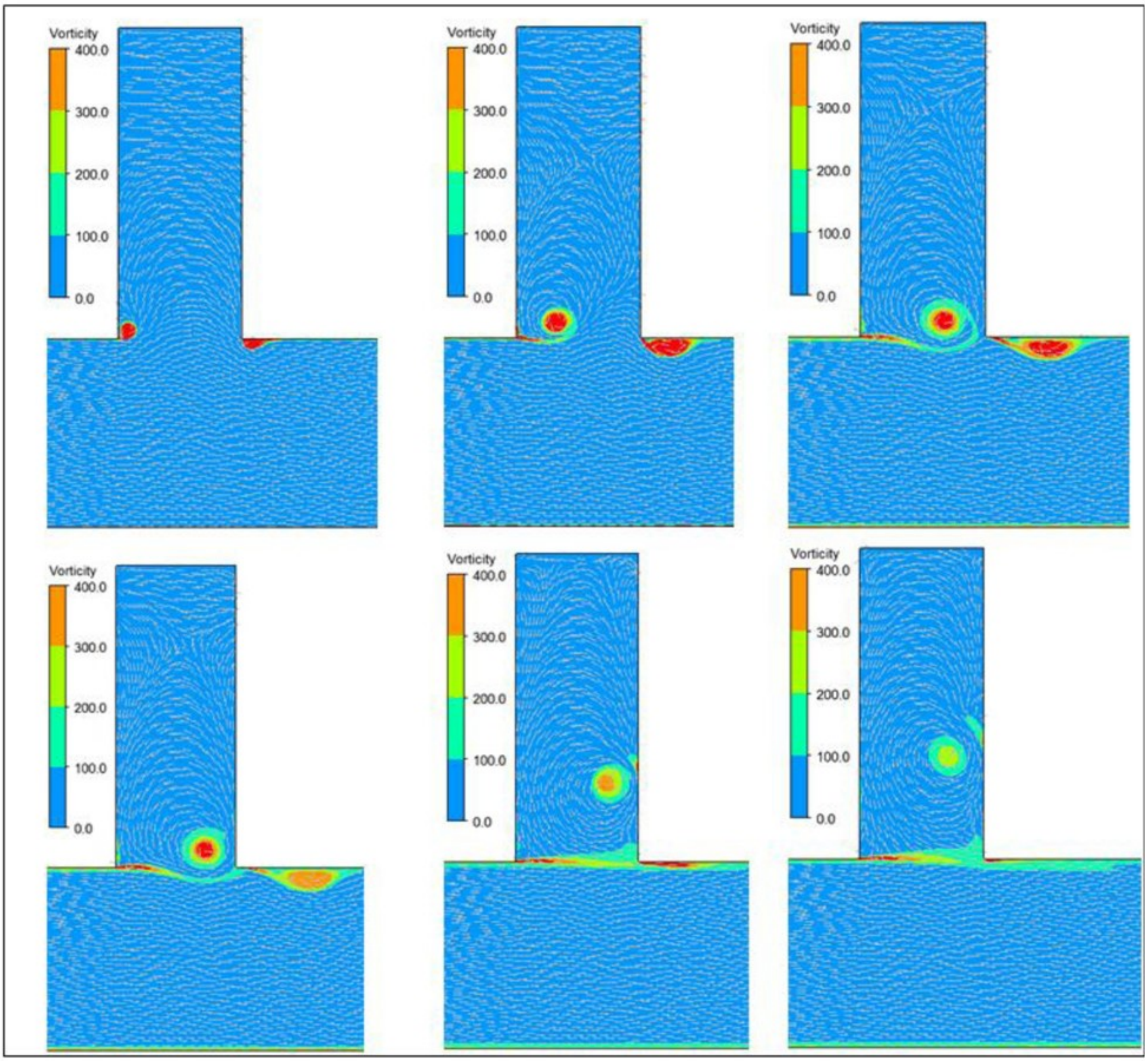


Figure 4: Vortices at dead leg (Gharaibah, Barri, & Tungen, 2016)

ANSYS acoustic is one of the tools useful in determining the acoustic pulsations and related forces in dead legs of piping systems since it allows for 3D pulsation evaluation through multiple sources and various piping structures. In this manner, one can calculate the acoustic frequency levels and related forces resulting from standing wave effects. Although various sources can be used, predicting their interaction is difficult since it depends on the phase shift and the distance between sources. The former is usually unknown. (Gharaibah, Barri, & Tungen, 2016)

The 3D capabilities are essential for higher frequencies where the pressure waves are not only flexural modes. Although it does not happen for dead leg pulsating, it is essential for devices such as choke valves that reduce pressure and their High-Frequency Acoustic Excitation. Figure 5 shows the use of ANSYS Acoustic where the source strength is 7 percent of the kinetic energy flow. In the analysis, CFD together with various flow directions past a closed branch were utilized. Also, a Strouhal number equal to 0.4 was typically used as the source frequency which is common practice. (Gharaibah, Barri, & Tungen, 2016)

The system's total acoustic response is determined from the superposition of the individual source's acoustic response. Induced shaking forces, resultant acoustic pressure can be determined from the difference in pressure between the opposing bends which can be Mechanical Response Analysis (MRA) input. In figure 5, acoustic pulsation levels in piping lines are determined from the acoustic model for a similar structure as in Figure 6. (Gharaibah, Barri, & Tungen, 2016)

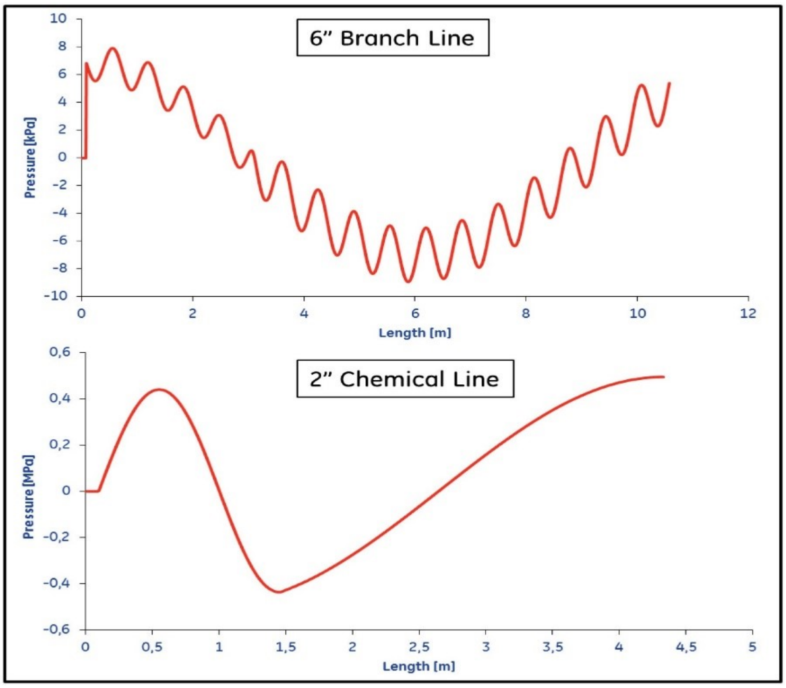


Figure 5: Acoustic pulsation levels

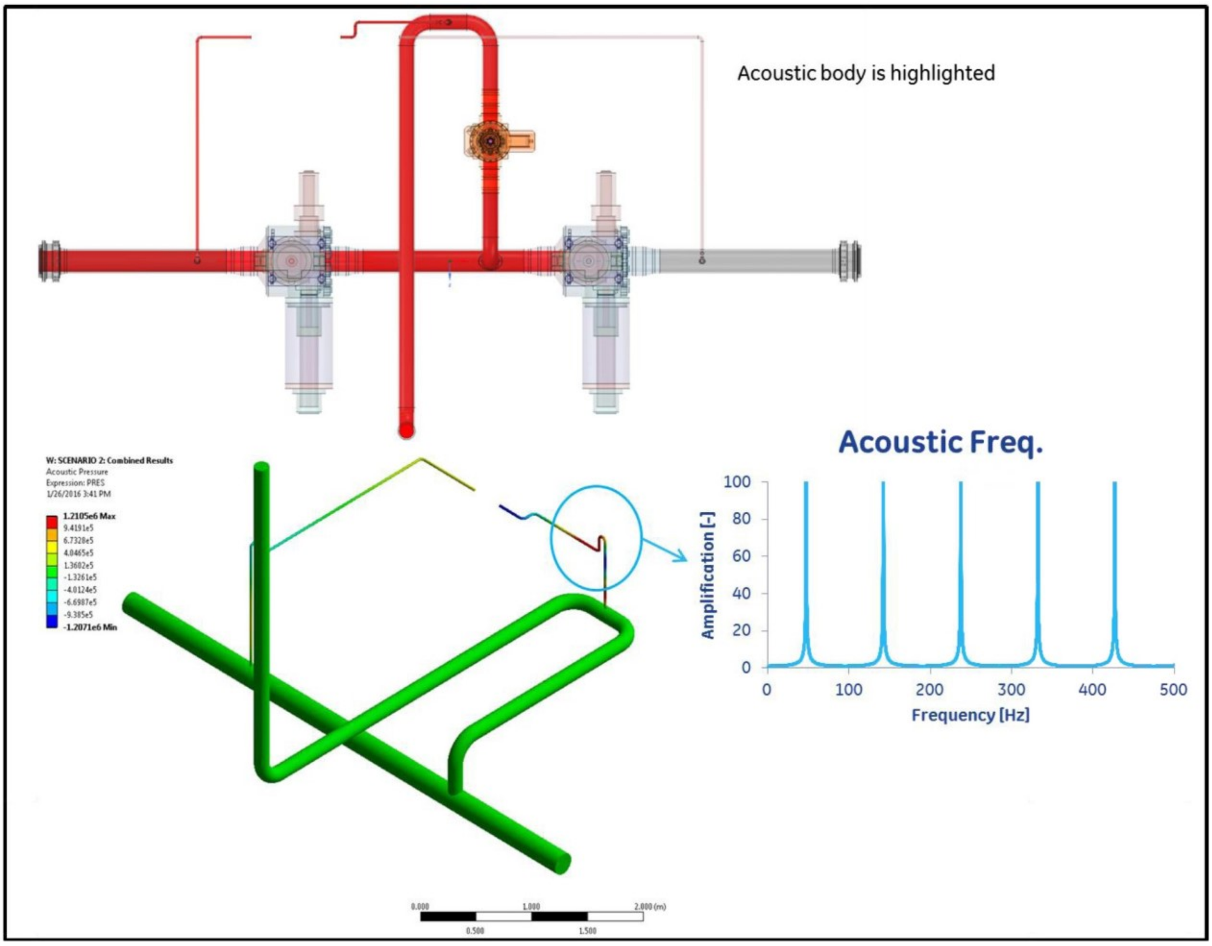


Figure 6: The source strength from ansys acoustic (Gharaibah, Barri, & Tungen, 2016)

2.2.3 Rough Bore Flexible Risers Carrying Dry Gas

Similar to pulsation generated in dead legs, the corrugated inner surfaces also produce vortices in flexible piping particularly in pipes carrying dry gas where its velocity is greater than the start velocity. Various elements influencing onset velocity include carcass geometry and speed of sound. Ongoing studies posit smoother surfaces could minimize the problem. (Gharaibah, Barri, & Tungen, 2016)

2.2.4 High-Frequency Acoustic Excitation (HFAE)

Pressure reducing devices including orifice plates and choke valves create HFAE. Turbulent mixing. fluid impingement on the pipe wall and choked flow shockwaves are responsible for noise in the locality of these devices. Typically, the frequency would be between 500 Hz and 2000 Hz and they usually create high-frequency flexural vibration modes resulting in dynamic stress at tees, welds, or other weak sections. (Gharaibah, Barri, & Tungen, 2016)

2.2.5 Surge Associated with Fast Acting Valves

Pipe transporting fluid can face or pressure surges due to variations in the velocity of flow, for instance, where there are a rapid valve opening and closing. A rapid increase in pressure results from a sudden closure of the valve when the fluid is in motion because of upstream compression of the valve. However, downstream the pressure will decline rapidly and cause the fluid column to separate temporarily and likely flow back towards the valve where the pressure gradient is sufficient. It could result in damage to the pipe and the valve. Pressure surges often occur due to power failure which causes operating pumps to suddenly stop. Because pressure and velocity changes are not limited to trouble point, it continues downstream and upstream the pressure wave propagation.

The conditions of the boundary influence the extent to which waves are replicated at points of non-steady flow such as valves leading to versal of amplitude or phase. The superposition of the waves arriving at a certain point and time determines their observed location and time. Moreover, the variations of pressure and resulting high pressure usually create a system with high loads.

The minimum pressure level is the vapor pressure and cannot go lower. Any situation that results in elongated time creates a cavitation zone which ensures liquid column separation and flows separation. Their change in velocity direction causes the columns to reverse and collide resulting in pressure surge as illustrated in Water hammer, the sudden collapse of vapor-filled cavities. The sudden pressure rise often dwarfs the original increase. In sudden valve closure, a surge in pressure traveling in the opposite direction of the fluid flow is created due to the sudden stop of fluid motion as shown in figure 7. Huge dynamic forces often arise from the transient pressure fluctuation in the piping system. (Ksb, u.d.)

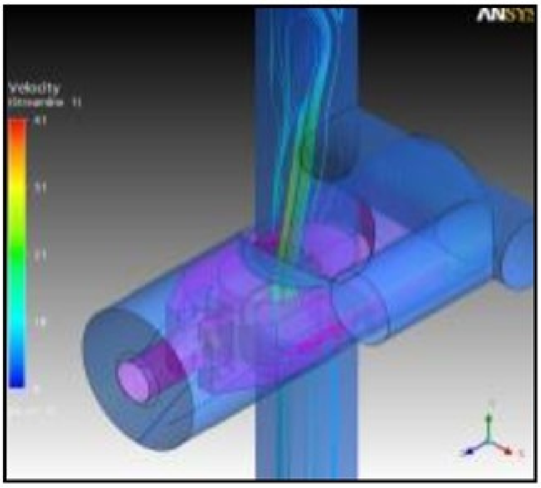


Figure 7: Sudden stop of fluid motion

2.2.6 Cavitation and Flashing

Cavitation happens through an abrupt drop in liquid pressure generating suddenly collapsing bubbles and resulting in huge local pressure fluctuations. Also, liquid changes its state to vapor if its pressure decreases below the vapor pressure of a liquid (Flashing). Turbulent forces result from the instability of the process. (Gharaibah, Barri, & Tungen, 2016)

Why flashing occurs in piping systems and industrial processes?

Any liquid that encounters a restriction such as a port valve must maintain a constant volumetric flow rate by accelerating its velocity. However, any decline in pressure within the restricted area to below the vapor pressure of the liquid, the liquid vaporizes through the "vena contracta" process. Moreover, flashing occurs if the pressure remains below the vapor pressure of fluid downstream whereas the vapor phase will occur at the outlet. Such a situation causes erosive damage to valve components even when abrasive solids are absent in the liquid. (piping, 2018)

Cavitation

Where the upstream pressure is higher than the vapor pressure of the fluid, and below the downstream pressure, the result is the formation of vapor bubbles which suddenly collapse as pressure increases. The process is often energetic and can damage piping and valve components. Moreover, the collapse of the bubble generates fluid "micro-jets" that impinge valve surfaces at high speeds and shockwaves of 100,000 psi could be generated. The process of cavitation takes place in liquid systems affected by variation in pressure. Near the liquid's vapor pressure, the bubbles collapse suddenly to create microjets and localized shock waves. When these affect the adjacent valve, pump, or pipe surfaces they create severe erosive damage, and wall thickness reduces as a result.

Besides, high levels of vibration and noise are created from cavitation which occurs across various frequencies. Extreme vibration leads to lose bolting, damage to supporting structures, and destruction of piping process equipment. Also, the noise is unhealthy for people and their surroundings. Control valves have a pressure-reducing feature that also makes them vulnerable to cavitation. However, minimizing these negative effects may involve combining material selection, valve selection, and system design. Flashing noise and vibration are often minimal in comparison to cavitation, however, extreme vibration generated in the process results in high-velocity flow. Erosion-resistant materials, reduction of velocity, and design strategies are ways of minimizing the flashing damage. (piping, 2018)

2.2.7 Vortex Shedding Around Thermowells or Other Intrusive Elements

Fluid flows product aerodynamic and hydrostatic forces around objects inserted into any moving fluid. In some situations, a wake is created when a fluid flows around the cylindrical thermowell. Vortices rotating in the opposite direction results from the wake and then they shed in a process referred to as Kármán vortex street. The process results in a periodic drag and periodic lift force. The force is normal to the direction of the flow whereas the drag is in line with the flow and causes the shaking of the thermowell. Wake's frequency determines the vortex-induced vibrations (VIV)' frequency while it is influenced by the fluid's velocity and the diameter of the thermowell.

Small velocity increase often results in stronger forces because induced forces surge with the square of the velocity in comparison to linearly increase of shedding frequency in relation to fluid velocity. Thermowell goes into resonance when its natural frequency is similar to shedding frequency a process that increases the force of vibrations. Mechanical failures often occur sooner when bluffy bodies are exposed to vibrations, in the case of the thermowell, the failure is the base where it is facing the most stress. The bending stress is so high that failure often occurs at its base. As shown in figure 8 and figure 9, the boundary layer separation and vortex shedding occur at the downstream surface in Thermowells. The vortices generate variation in pressure on the surface of the body it comes into contact and where the frequency coincides with the structural eigenfrequency of that object, vibration resulting from a high level of dynamic stress is likely. (DeLancey, 2018)

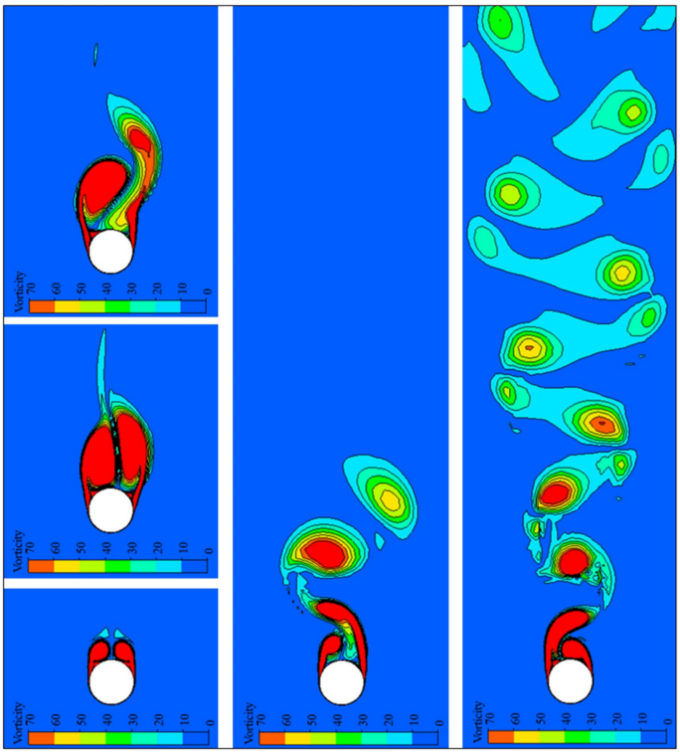


Figure 8: The boundary layer separation and vortex shedding due to thermowells

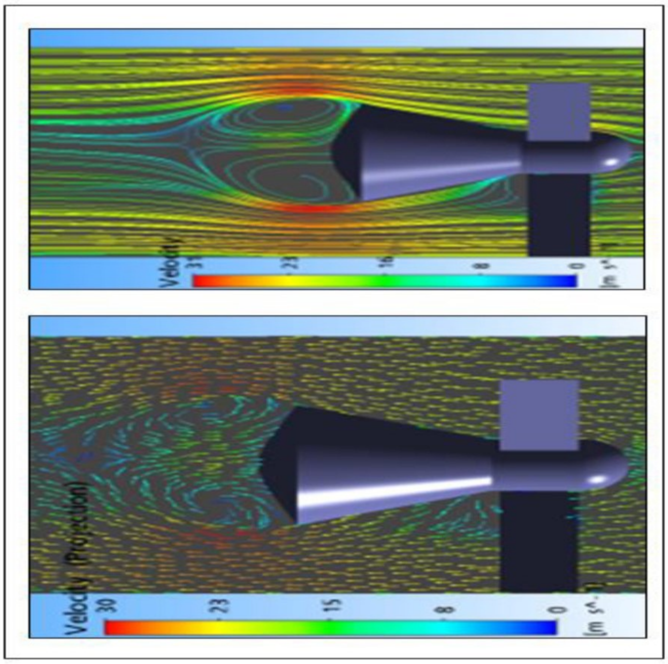


Figure 9: The boundary layer separation and vortex shedding due to thermowells

2.2.8 Mechanical Excitation from Reciprocating/Positive Displacement Pumps and Compressors

In linked piping systems, vibrations often result from rotating or reciprocating processes. Little is known about rotating/reciprocating equipment in subsea although a gas compressor at Gullfaks field multiphase became the pioneer in 2015 at subsea in Norway. Future problems with vibration are likely and thus the need to address the issue sufficiently. (Gharaibah, Barri, & Tungen, 2016) Fatigue failure, leaks, downtimes, and explosions are some of the major issues associated with vibrations in reciprocating machinery and piping systems in petrochemical plants. The vibration typically happens when machinery's natural frequency is excited by the pulsation energy at various harmonics making the problem common. Lateral vibration modes and structural modes are usually affected by fatigue failures. Also, the safety and reliability of the system is often influenced by compressor/pump vibrations, for instance, bearing and crankshaft failures are common where there is an extreme dynamic misalignment of the compressor. (Wachel & Tison)

Chapter 3. Methodology: Screening Assessment

This chapter details the methodology that were utilised for this thesis. The methodology is a screening assessment based on the "guidelines for the avoidance of vibration induced fatigue failure in subsea systems". This guideline is provided by the Energy institute, a chartered professional membership body for the energy industry.

The screening consists primarily of evaluating the causes of vibrational impulses that may occur following the flow of fluid. The actual response of a subsea system depends on the location of the sources, the matching mode damping of natural frequencies, and the mobility of pipes and other system components. Vulnerability to fatigue failure depends on the presence and location of vulnerable components (welding, etc.). (Swindell & Hill, Guidelines for the avoidance of vibration-induced fatigue failure in subsea systems, 2018)

The main goal in assessing the impact of flow-induced vibrations on the design of an underwater structure is to identify design issues related to FIV. The first step is to define possible drive mechanisms based on the process flow chart (PFD), process design and all possible process routing systems. For application, each of these mechanisms must be considered:

1. Flow-induced turbulence due to pipeline gas and liquid flow
2. Flow induced pulsation from gas lines with closed branches
3. Flow induced pulsation (FLIP) from rough bore flexible jumpers/gas that carries dry gas
4. High frequency acoustic excitation from pressure reducing devices on gas lines.
5. Momentum changes or surges due to fast acting valves.
6. Flashing and cavitation both for liquid and multiphase lines
7. Vortex shedding around thermowells on liquid and gas lines
8. Mechanical excitation for liquid and gas lines

Table 1: Mechanism category and likelihood classification (excerpt from EI guideline) (Swindell, Hidden integrity threat looms in subsea pipework vibrations, 2011)

Item	Aspect	Applicable process fluids	Likelihood classification			Excitation mechanism
			Low	Medium	High	
	What is the maximum value of kinetic energy $\rho * v^2$ of the process fluid within the system under consideration?	All	$\rho v^2 < 5\,000$ kg/m s^2	Between 5000 and $\rho v^2 \leq 20000$ kg/m s^2	$\rho v^2 \geq 20000$kg/m s^2	Flow induced turbulence (all fluids).Flow induced pulsation (Gases only).
2	Is there a rough bore flexible in the system?	Gas	No	—	Yes	FLIP (roughbore flexible)
	Is choked flow possible or are sonic flow velocities likely to be encountered?	Gas	No	—	Yes	High-frequency acoustic excitation
	Are there any systems with fast-acting opening or fast-closing valves?	All	No	—	Yes	Surge/ momentum changes
	Are there any systems that may exhibit flashing or cavitation	Liquid/ multi-phase	No	—	Yes	Cavitation and flashing
	Are there intrusive elements in the process stream?	All	No	—	Yes	Vortex shedding from intrusive elements
	Is there any rotating or reciprocating machinery?	All	No	Rotating equipment only.	Reciprocating equipment.	Mechanical excitation

Semi-quantitative assessment of each mainstream using method described below for flow induced turbulence and pulsation for each identified excitation mechanism should be conducted. Many of these methods were obtained in Technology Module 2 of the EI Guidelines for avoiding vibrations induced fatigue failure in process pipework.

The screening assessment provides a Likelihood of failure (LoF) score for each excitation mechanics on each line that are assessed. However, it is important to understand that LoF is not to be taken as an absolute probability of failure or a measure of absolute failure. These calculations are conservative and are based on a simplified model to ensure easy application and attention. If LoF scores are predicted to be out of the tolerable range, then various corrective actions can be considered. Sensitivity analysis can be done and simple changes such as unsupported span length, pipe diameter, wall thickness, fluid densities and velocities can be incorporated into the screening assessment to determine their effect. This can be used when in the design phase of new spool or pipework. However, it is recognised that the options for system modifications are severely limited for an existing subsea system. Action that can be carried based on the calculated LoF score is shown in Table 2. (Swindell, Hidden integrity threat looms in subsea pipework vibrations, 2011)

Table 2:Action to be taken based on LoF(excerpt from EI guidelines) (Swindell & Hill, Guidelines for the avoidance of vibration-induced fatigue failure in subsea systems, 2018)

Score	Action
LoF ≥ 1,0	***The main line should be redesigned, re-supported or a detailed analysis of the main line shall be conducted. A suitable safety factor shall be applied tothe fatigue life*** ***If a satisfactory fatigue life cannot be demonstrated, further redesign andre-analysis or detailed vibration analysis shall be undertaken*** ***Small bore connections on the main line shall be assessed***
1,0 > LoF ≥ 0,5	***The main line should be redesigned, re-supported or a detailed analysis of the main line should be conducted. A suitable safety factor should beapplied to the fatigue life*** ***If a satisfactory fatigue life cannot be demonstrated, vibration monitoring of the main line may be undertaken using a fit-for-purpose instrumentationsystem and/or ROV visual monitoring when appropriate. The latter may offer early information for low frequency excitation, which results in visible motion of the piping*** ***Small bore connections on the main line shall be assessed.***
0,5 > LoF ≥ 0,3	***Small bore connections on the main line should be assessed*** ***A visual survey should be undertaken to check for poor construction and/or geometry and/or support for the main line and/or potential vibration transmission from other sources.***
LoF < 0,3	***A visual survey should be undertaken to check for poor construction and/or geometry and/or support for the main line and/or potential vibration transmission from other sources***

3.1 Detailed Fatigue Life Assessment

In the case of a simple design review marked with a high LoF value (≥0.5) at the first screening, if it does not go down to the acceptable range, a series of detailed analyses should be performed. The detail analysis is performed to predict dynamics response and associated dynamic stress range of the structure. These things are determined using a software system, and the outcome of the detailed analysis is used to estimate the fatigue life of the spool or the pipework. If the fatigue life is limited in detailed vibration analysis and the analysis is accompanied by a lot of uncertainty, vibration monitoring can be performed instead of the new design.

For thick pipes, acoustic simulations are required to predict the condition of the gas sound in the piping system and the magnitude of possible vibration forces.

Wherever there is anticipating of excessive pressure pulsations from flow past closed branch the necessity to undertake an acoustic simulation in order to provide the acoustic modes of the gas within the pipework and predict the shaking forces magnitude that will be generated.

For excessive pressure pulsation caused by flow past closed branches, acoustic simulations will provide a range of force and phase relationships at different frequencies that can be applied directly to the structural model. For broadband excitation including turbulent flow, two-phase or high-frequency acoustic excitation, the transfer function of the unit applied force (dynamic response) is usually determined at each source site in the entire frequency band. The amplitude and density of the power spectrum can be used to extend the force response of the element by using a magnitude and power spectral density. The amplitude and density of the power spectrum depends on the actual process conditions of the excitation mechanism. Once the dynamic RMS stress ranges have been determined at critical locations (typically welds), it is possible to estimate the corresponding number of cycles to failure and hence the fatigue life. The probability density function is then used to simulate changes in the response to any stimulus caused by vibration. (Swindell & Hill, Guidelines for the avoidance of vibration-induced fatigue failure in subsea systems, 2018)

3.2 FLOW-INDUCED TURBULENCE

3.2.1 Degree of excitation

The energy of turbulence is generated by the flow of liquid. Therefore, the scope of evaluation is limited to the main line containing moving liquids. The minimum diameter is 10" and the flow are a single-phase gas or liquid. The different inputs to calculate the LoF is tabulated in table 3, shown in figure 10 and described in detailed in this sub-chapter.

3.2.1.1 Inputs

Table 3: Input parameters for flow induced vibrations

Input	symbol	Units	Comments
External pipe diameter	D_o	mm	
Maximum Span length between supports on line of interest	L_{span}	m	Definition is described chapter 3.2.4.
Wall thickness of main pipe	t	mm	
Fluid velocity	v	$\frac{m}{s}$	
Gas dynamic viscosity	u_{gas}	$pa * s$	Only required for gas systems.
Fluid density	ρ	kg/m^3	

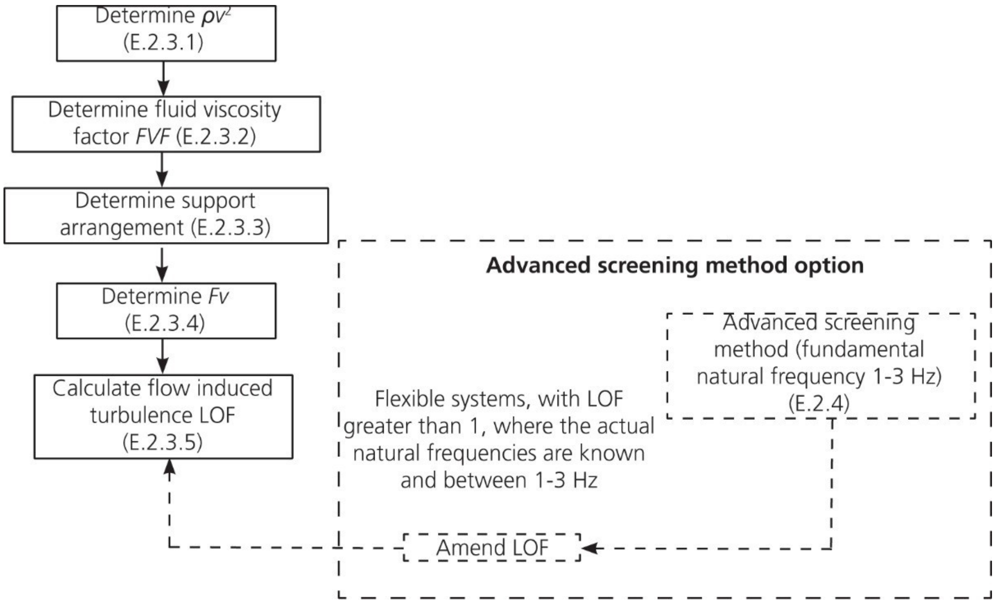


Figure 10: Process of calculating LoF for FIT (Swindell & Hill, Guidelines for the avoidance of vibration-induced fatigue failure in subsea systems, 2018)

3.2.2 Determining ρv²

Calculating $\rho * v^2$ using the relevant equation depending on whether the fluid is single phase or multi-phase flow. Important parameters is listed in table 4.

Table 4: Determining ρv2 (Swindell & Hill, Guidelines for the avoidance of vibration-induced fatigue failure in subsea systems, 2018)

	$\rho * v^2$	Comments
For a single-phase flow	$(actual\ density) * (actual\ velocity)^2$	SI units applied, $\rho * v^2 = Kg/ms^2$
For multi-phase flow:	$(effective\ density) * (effective\ velocity)^2$	SI units applied, $\rho * v^2 = Kg/ms^2$
Effective density	$\frac{total\ mass\ flow\ rate}{total\ volumetric\ flow\ rate}$	Actual values and not those from standard temperature and pressure
Effective velocity	$\frac{total\ volumetriic\ flow\ rate}{pipe\ internal\ cross\ sectional\ area}$	Actual values and not those from standard temperature and pressure
Total mass flow rate	$\sum(actual\ volumetric\ flow\ rate\ for\ each\ phase) * (phase\ density)$	
Total volumetric flow rate	$\sum(actual\ volumetric\ flow\ rate\ for\ each\ phase)$	

3.2.3 Determination of the liquid viscosity coefficient (FVF)

The size of turbulence depends in part on the viscosity of the liquid. The liquid viscosity coefficient (FVF) takes this into account. For a liquid, the FVF is 1.0. The FVF for multiphase where the no-slip hold up is larger than 0.01 is equal to 1. While for gases where the no slip liquid hold up is less than 0.01 the FVF is given by; $\frac{\sqrt{\mu_{gas}}}{\sqrt{1*e-3}}$. The definition of the No-slip hold up is as follows: $\frac{liquid\ volumetric\ flow}{mixture\ volumetric\ flow}$ under actual conditions.

Dynamic viscosity (μ) is required to determine the FVF of the gas system. For some general process gases of pressure under 35 barg, general values for dynamic viscosity is illustrated in figure 11. The gas dynamic viscosity should be determined by other methods if the pressure is greater than 35 barg. (Swindell & Hill, Guidelines for the avoidance of vibration-induced fatigue failure in subsea systems, 2018)

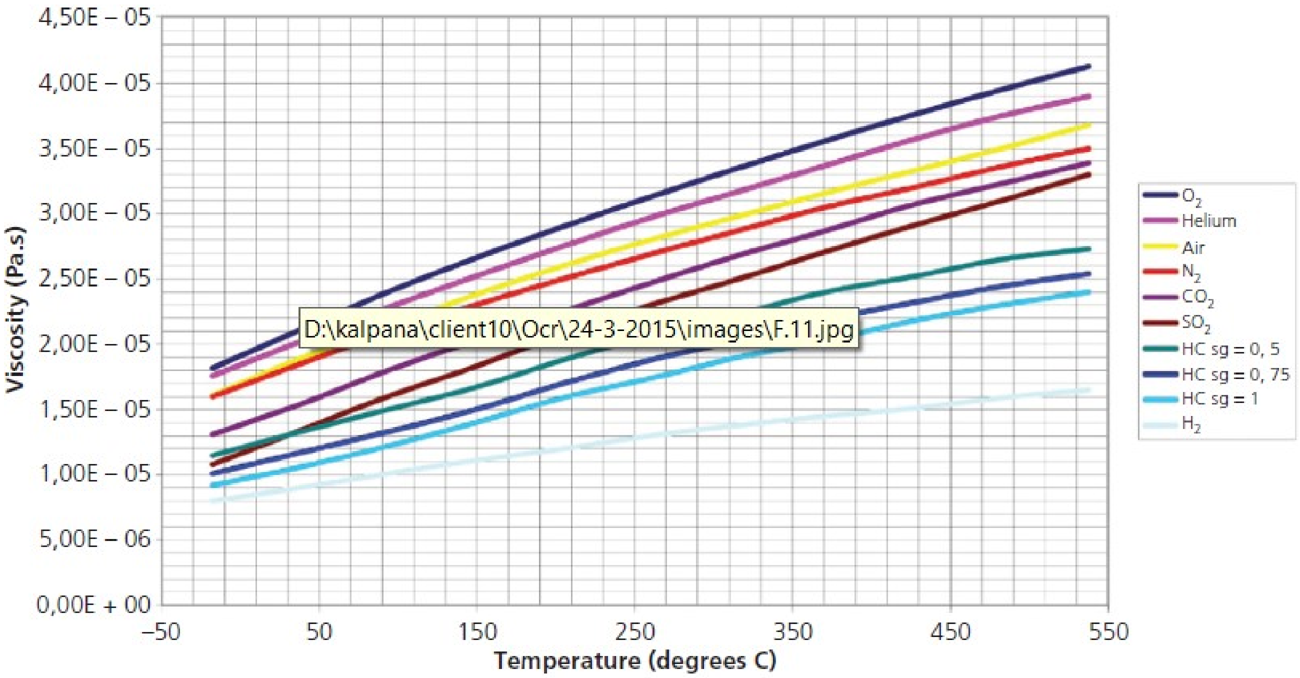


Figure 11: Dynamic viscosity for various substances with varying temperature (Swindell & Hill, Guidelines for the avoidance of vibration-induced fatigue failure in subsea systems, 2018)

3.2.4 Determining support arrangement

The span length in this guideline is defined as the distance between effective supports. It is the distance between fixed support and/or partially fixed support. For a partially fixed support, on or two translations degrees of freedom of the main pipe are fixed while the remaining degrees of freedom are set to be free. Likewise, for a fixed support of main pipe, the three transitional degrees of freedom is fixed, that is pipe anchor.

There are some items that are part of pipe structures that are not considered to be pipe supports. These items include: Shock arrestors, viscous dampers, spring hangers.

It is assumed that the structure to which the support is attached is effectively rigid. Long goal-post systems, for example, may result in significantly less effective support in particular scenarios.

It is important to be aware of the possibility that main line supports can be difficult to inspect in some locations, like heights, providing difficult to verify if there is good contact and the support is effective. It can be less effective if, for example, the line has lifted from the support. The line should be assed as if a support is not present if there is a question related to effectiveness of the support.

How to determine the support arrangement is presented in Table 5 with relevant equations. Figure 12 shows the relationship between outside diameter, span between major supports and the resulting support arrangement. arrangement (Swindell, Hidden integrity threat looms in subsea pipework vibrations, 2011)

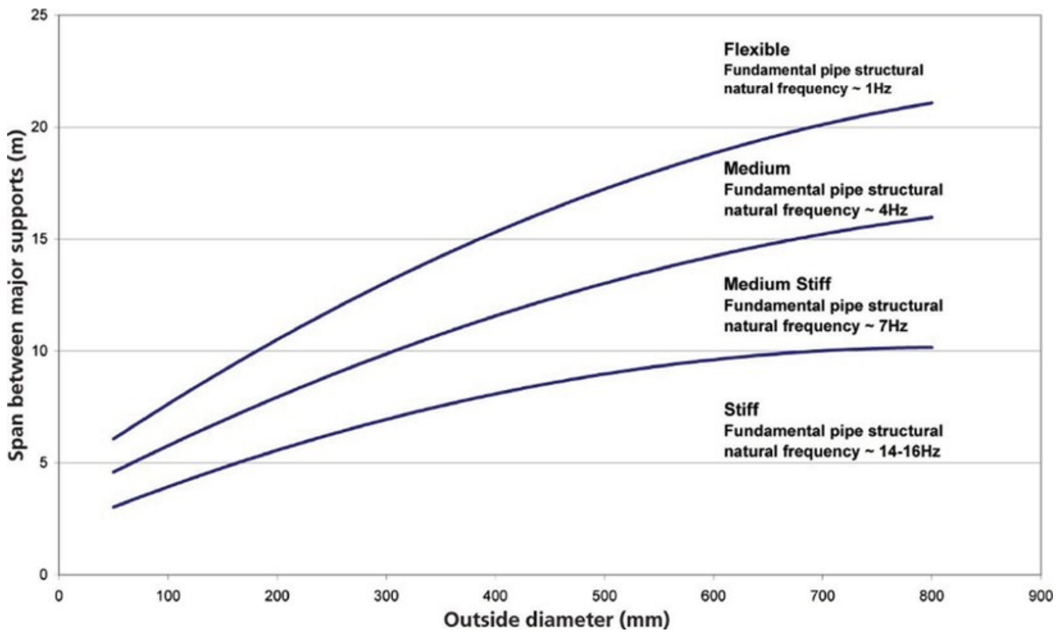


Figure 12: Relationship between span length, diameter, and support arrangement. (Swindell & Hill, Guidelines for the avoidance of vibration-induced fatigue failure in subsea systems, 2018)

Table 5: Support arrangements

Support arrangement	Span length criteria	Typical fundamental natural frequency
Stiff	$L_{span} \leq -1.2346 * 10^{-5} * D_{ext}^2 + 0.02 * D_{ext} + 2.0563$	14-16 Hz
Medium stiff	$L_{span} > -1.2346 * 10^{-5} * D_{ext}^2 + 0.02 * D_{ext} + 2.0563$ $L_{span} \leq -1.1886 * 10^{-5} * D_{ext}^2 + 0.025262 * D_{ext} + 3.3601$	7Hz
Medium	$L_{span} > -1.1886 * 10^{-5} * D_{ext}^2 + 0.025262 * D_{ext} + 3.3601$ $L_{span} \leq -1.5968 * 10^{-5} * D_{ext}^2 + 0.033583 * D_{ext} + 4.429$	4Hz
Flexible	$L_{span} > -1.5968 * 10^{-5} * D_{ext}^2 + 0.033583 * D_{ext} + 4.429$	1 Hz

Table 6: Method of calculating Fv, α and β

Support arrangement	**Range ofoutside diameter**	$\mathbf{F_V}$	α	β
Stiff	60 mm-762 mm	$α*(\frac{D_{ext}}{t})^{B}$	$446187 + 646 * D_{ext} + 9.17 * 10^{-4} * D_{ext}$	$(0.1 \ln(D_{ext}) - 1.3739$
Medium stiff	60 mm-762 mm	$α*(\frac{D_{ext}}{t})^{B}$	$283921 + 370 * D_{ext}$	$0.1106 \ln(D_{ext}) - 1.501$
Medium	273 mm-762 mm	$α*(\frac{D_{ext}}{t})^{B}$	$150412 + 209 * D_{ext}$	$0.0815 \ln(D_{ext}) - 1.3269$
Medium	60 mm-219 mm	$\exp(α*(\frac{D_{ext}}{t})^{B})$	$13.1 - 4.75 * 10^{-3} * D_{ext} + 1.41 * 10^{-5} * D_{ext}^{2}$	$0.132 + 2.28 * 10^{-4} * D_{ext} - 3.72 * 10^{-7} * D_{ext}^{2}$
Flexible	273 mm-762 mm	$α*(\frac{D_{ext}}{t})^{B}$	$41.21 * D_{ext} + 49397$	$0.0815 \ln(D_{ext}) - 1.3842$
Flexible	60 mm-219mm	$\exp(α*(\frac{D_{ext}}{t})^{B})$	$1.32 * 10^{-5} + D_{ext}^{2} - 4.42 * 10^{-3} + D_{ext} + 12.22$	$2.84 * 10^{-4} * D_{ext} - 4.62 * 10^{-7} * D_{ext}^{2} - 0.164$

3.2.5 Calculation of likelihood of failure (LoF)

The LoF for flow-induced turbulence is then determined by the equation.

$$Flow\ induced\ turbulence\ LoF = \frac{\rho v^2}{F_v} * FVF$$

An additional check that can be performed on each control valve in the system is to assess the level of kinetic energy of the liquid at the outlet of the bar. For single-phase fluid, the value should be no more than 480kPa. For multiphase fluids, the value should be no more than 275 kPa.

- Kinetic energy in KPa is given by $\frac{\rho v^2}{2000}$
- $\rho\left(\frac{\mathrm{kg}}{\mathrm{m}^3}\right)$ is the density of the fluid
- $v(\frac{m}{s})$ is the velocity at which the liquid exits the valve trim.

. (Swindell, Hidden integrity threat looms in subsea pipework vibrations, 2011)

3.3 PULSATION: FLOW-INDUCED EXCITATION

3.3.1 Extent of excitation

This form of mechanism considered in this subchapter is caused by the passage of gas at the branch with closed pipe-end, the so-called dead leg branch of the main pipeline. It can occur in a gas system with a vacuum ratio (volume gas flow/mixed gas volume flow under real conditions) of less than 0.95. The induced pulse can propagate upstream and downstream of the side branch to the first large change in the main pipe diameter. The main change is defined as a pipe diameter change of more than double (large tank or enlargement / reduction). In addition, it is important to be aware at the excitation characters can vary under certain operations with different flow rate. This will affect the acoustic modes changes in pressure, temperature, and molecular weight. Therefore, the range of expected operation conditions should be considered as part of the evaluation. (Swindell, Hidden integrity threat looms in subsea pipework vibrations, 2011)

Table 7: Input for pulsation excitation

Input	Symbol	Units
Speed of sound in gas	C	$\frac{m}{s}$
Internal diameter of branch	d_{int}	mm
Internal diameter of main line	D_{int}	mm
Length of side branch	L_{branch}	m
Reynolds Number	R_e	
Gas density	V	$\frac{m}{s}$
Gas density	ρ	$\frac{kg}{m^3}$

3.3.2 Calculation of likelihood of failure (LoF)

The screening analysis is shown in the figure 13. Firstly, the relationship between d_{crit} and internal diameter D_i of the dead leg branch is evaluated. If the dead leg branch have an internal diameter that is larger than d_{crit} then it passes the check, with no further and detailed analysis required. The expression for d_{crit} is as follows:

$$\boldsymbol{d_{crit}} = \left(\frac{\mathbf{400}}{\boldsymbol{\pi * \rho * v^2}}\right)^{\mathbf{0.5}}$$

However, if it doesn't pass the first check, then it should be evaluated further as described in figure 13. The evaluation method is to assign main line LoF score for each side branch of the main line. After calculating the LoF of all side branches coming out of the main line, the highest LoF point is used as the representative LoF score for the main line. This screening methodology is used if the geometry of the side branches are not complicated. That is, the side branch itself does not part single line from the main pipe to the edge of the closed pipe. A typical example is a safety pipe separating two or more safety valves for oil supply. In this case, a detailed analysis must be performed to accurately determine the acoustic frequency (i.e. Fs) for the side branch. It is recommended to perform a more efficient analysis for each flanking side branch with a LoF $\geq$ 1.0 score (Swindell & Hill, Guidelines for the avoidance of vibration-induced fatigue failure in subsea systems, 2018)

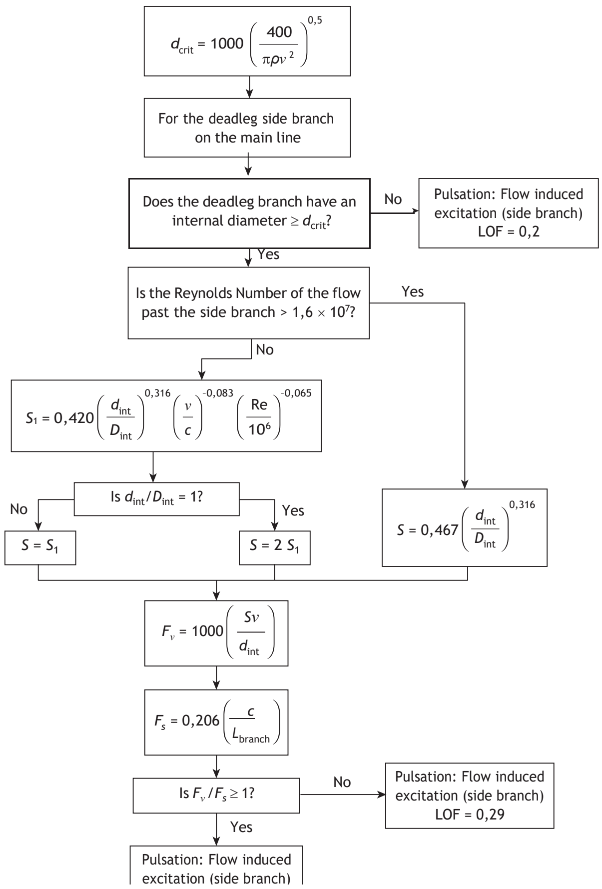


Figure 13: Screening Method for Pulsation

Chapter 4 Results

This chapter will deal with the calculation of LoF for the two mechanisms that are most common and important for O&G industry. These mechanism are the turbulent and pulsation assessment. Firstly, a LoF calculation for turbulence that passes the check will be performed, secondly a LoF calculation that doesn't pass the check will be performed. How the detailed analysis is performed is also discussed for cases that don't pass the screening check . Lastly a calculation will be performed for a pulsation case; a detailed analysis is not the scope for this master thesis for the pulsation mechanism.

4.1 Flow-Induced Turbulence (FIT) Calculation for case 1

When calculating the LoF for a spool or pipe section, the parts of pipe-sections with bends or geometry change are analysed.

Table 8: Spool parameters

Outer diameter	$D = 219\, mm$
Wall thickness of the pipe	$t = 14.3\, mm$
Maximum span length between supports on line	$L_{span} = 6m$
Effective fluid velocity	$v = 3\, m/s$
Effective fluid density	$\rho = 150\, kg/m$^3
LMVratio	0.001
Gas dynamic viscosity only used	$\mu_{gas} = 1.3 * 10^{-5}\, pa * s$

Calculation

$$\rho * v^2 = 1.35 * 10^3 Pa$$

From the EI guidelines the input parameters should be made dimensionless.

$D = 219\frac{mm}{mm} = 219$	$t = 14.3\frac{mm}{mm} = 14.3$
$L_{span} = \frac{4m}{m} = 4$	$v = \frac{3\frac{m}{s}}{\frac{m}{ms}} = 3$
$\rho = \frac{150\frac{kg}{m^3}}{\frac{kg}{m^3}} = 150$	$\mu_{gas} = 1.3 * 10^{-5}5\frac{pa * s}{pa * s} = 1.3 * 10^{-5}$

$F_V = Fluid\ viscosity\ factor$ is equal to 1 if the LVM ratio is less than 0.01.

Span length upper limits:

$L_{stiff} := -1.2346 10^{-5} \cdot D^2 + 0.02D + 2.0566$	$L_{stiff} = 5.845$
$L_{medstiff} := -1.1886 10^{-5} \cdot D^2 + 0.025262D + 3.3601$	$L_{medstiff} = 8.322$
$L_{medium} := -1.5968 \times 10^{-5} \cdot D^2 + 0.033583D + 4.429$	$L_{medium} = 11.018$

Classification of support arrangement:

- $Stiff\ if\ L_{span} \leq L.stiff$
- $Medium\ stiff\ if\ L_{span} > L_{stiff}\ and\ L_{span} \leq L_{medstiff}$
- $Medium\ if\ L_{span} > L_{medstiff}\ and\ L_{span} \leq L_{medium}$
- $Flexible\ otherwise$

$$Support = L_{span} > L_{stiff}\ and\ L_{span} \leq L_{medstiff} = 6 > 5.845\ and\ 6 \leq 8.322 = \boldsymbol{medium\ stiff}$$

$\boldsymbol{\alpha}$

- $446187 + 646 * D + 9.17 * 10^{-4} * D^3\ if\ support\ is\ Stiff$
- $283921 + 370 * D\ if\ support\ is\ medium\ stiff$
- $150412 + 209 * D\ if\ support\ is\ medium\ and\ D \geq 246$
- $13.1 - 4.75 * 10^{-3} * D + 1.41 * 10^{-5} * D^2\ if\ support\ is\ medium\ and\ D\ <\ 246$
- $41.21 * D + 49397\ if\ support\ is\ flexible\ and\ D \geq\ 246$
- $1.32 * 10^{-5} * D^2 - 4.42 * 10^{-3} * D + 12.22$

$$\boldsymbol{\alpha} = 283921 + 370 * D = 283921 + 370 * 219 = 364951$$

β

- $0.01 ln(D) - 1.3739\ if\ support\ is\ stiff$
- $0.11061 ln(D) - 1.501\ if\ support\ is\ medium\ stiff$
- $0.08151 ln(D) - 1.3269\ if\ support\ is\ medium\ and\ D \geq 246$
- $-0.132 + 2.28 * 10^{-4} * D - 3.72 * 10^{-7} * D^2$ if support is Medium and D < 246
- $0.0815 ln(D) - 1.3842\ if\ support\ is\ Flexible\ and\ D >=\ 246$
- $2.84 * 10^{-4} * D - 4.62 * 10^{-7} * D^2 - 0.164\ if\ support\ is\ flexible\ and\ D < 246$

$$\boldsymbol{\beta = 0.11061 ln(D) - 1.501 = 0.11061 ln(219) - 1.501 = -0.905}$$

$\boldsymbol{F_V}$

- $\boldsymbol{\alpha * \left(\frac{D}{T}\right)^{\beta}\ if\ support\ is\ stiff\ or\ medium\ stiff\ \ or\ D \leq 246}$
- $\boldsymbol{e^{\alpha} * \left(\frac{D}{T}\right)^{\beta}\ if\ support\ is\ medium\ or\ flexible\ and\ D < 246}$

$$\boldsymbol{F_V} = 364951 * \left(\frac{291}{14.3}\right)^{\boldsymbol{-0.905}} = \boldsymbol{30882.5}$$

$$\boldsymbol{LoF} = \frac{\rho * v^2}{F_V} * FVF = \frac{150 * 3^2}{30882.5} * 0.0014 = 4.98 * 10^{-3}$$

4.2 Flow-Induced Turbulence (FIT) Calculation for case 2

$D\ =\ 273\ mm$	Outer diameter
$t =\ 14.3\ mm$	Wall thickness of the pipe
$L_{span}\ =\ 9m$	Maximum span length between supports on line
$v =\ 8\ m/s$	Effective fluid velocity
$\rho =\ 460\ kg/m^3$	Effective fluid density
$LMVratio =\ 0.05$	LMVratio
$\mu_{gas} =\ 1.3 * 10^{-5}\ pa * s$	Gas dynamic viscosity only used

Calculation

$$\rho * v^2 = 1.35 * 10^3 Pa$$

From the EI guidelines the input parameters should be made dimensionless.

$D = 219 \frac{mm}{mm} = 219$	$t = 14.3 \frac{mm}{mm} = 14.3$
$L_{span} = \frac{4m}{m} = 4$	$v = \frac{3\frac{m}{s}}{\frac{m}{ms}} = 3$
$\rho = \frac{150\frac{kg}{m^3}}{\frac{kg}{m^3}}$	$μ_{gas} = 1.3 * 10^{-5} 5 \frac{pa * s}{pa * s} = 1.3 * 10^{-5}$

- $F_V = Fluid\ viscosity\ factoris\ equal\ to\ 1\ if\ the\ LVM\ ratio\ is\ greater\ than\ 0.01$
- $otherwise\ FVF = \sqrt{\frac{μ}{10^{-3}}}$

Span length upper limits:

$L_{stiff} := -1.2346\,10^{-5} \cdot D^2 + 0.02D + 2.0566$	$L_{stiff} = 6.597$
$L_{medstiff} := -1.1886\,10^{-5} \cdot D^2 + 0.025262D + 3.3601$	$L_{medstiff} = 9.37$
$L_{medium} := -1.5968 \times 10^{-5} \cdot D^2 + 0.033583D + 4.429$	$L_{medium} = 12.409$

Classification of support arrangement:

$$\text{Support} = \ = L_{span} > L_{stiff}\ and\ L_{span} \leq L_{medstiff} = 9 > 6.597\ and\ 9 \leq 9.37 = \boldsymbol{Medium\ stiff}$$

$$\boldsymbol{\alpha} = 283921 + 370 * D = 283921 + 370 * 273.1 = 384968$$

$$\boldsymbol{\beta = 0.11061 ln(D) - 1.501 = 0.11061 ln(273.1) - 1.501 = -0.88049}$$

$$\boldsymbol{F_V} = 384968 * \left(\frac{273.1}{14.3}\right)^{\boldsymbol{-0.88049}} = \boldsymbol{28676}$$

$$\boldsymbol{LoF} = \frac{\rho * v^2}{F_V} * FVF = \frac{460 * 8^2}{28676} * 1 = 1.026$$

4.3 Detailed analysis

4.3.1 Developing structural finite element models

Fatigue content requires more detailed evaluation to predict the dynamic stress range associated with the pipe response of the piping system and to estimate the fatigue life. It involves developing structural finite element models and using them to determine responses to different types of excitation.

Appropriate SN data is used to estimate the number of cycle failure time for a specific stress range. Fatigue life is determined by the frequency characteristics of the vibration response. Other methods in the frequency domain are also possible, one of which is described in Pontaza (2016). This is primarily related to the imposed boundary conditions and pipe rack modelling methods. (Swindell, Hidden integrity threat looms in subsea pipework vibrations, 2011)

4.3.2 Boundary conditions

The most important elements in generation of structure finite element model is in relation to boundary conditions that are imposed on the modelled and how the pipe supports are modelled. In general, hub connections can be assumed to impose completely fixed boundary conditions on the pipe. Pipe supports (especially long columns and beams made supports) need to be fully modelled so that accurate stiffness is included in the simulation. Added mass should also be included so the effect of the external water loading is included. (Swindell, Hidden integrity threat looms in subsea pipework vibrations, 2011)

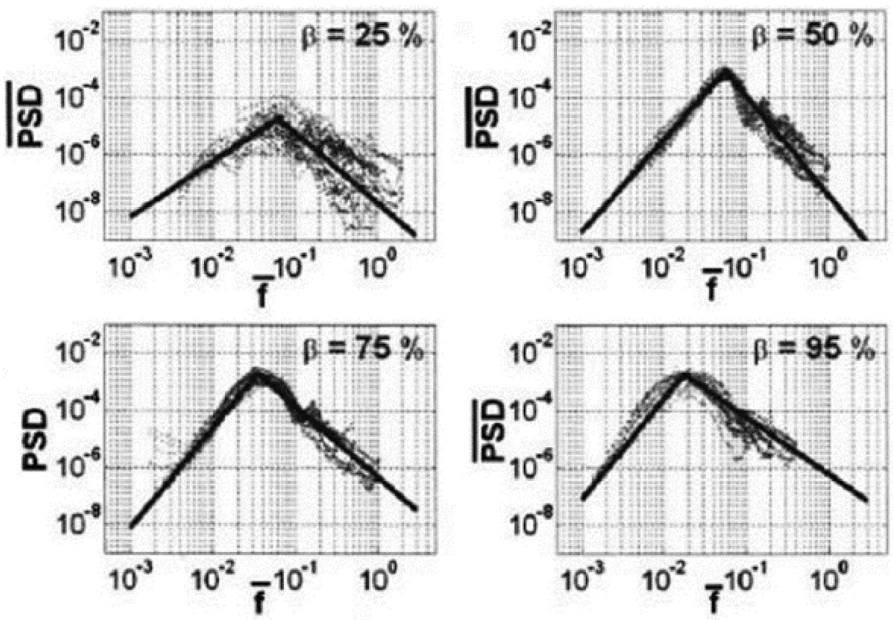
4.3.3 Prediction of Harmonic Response

Finite element model is applied with excitation forces that has known amplitudes, phases, and frequencies to determine the harmonic response (stress range) for each site of interest. The main assumption used to predict the harmonic response is the damping value used. If the uncertainty inherent in the prediction process allows the excitation frequency to be accurately predicted, then this frequency applies to all configuration modes within ± 10% of the excitation frequency (perfect assumption can be made). If not, it should be expanded to ± 20%. (Swindell & Hill, Guidelines for the avoidance of vibration-induced fatigue failure in subsea systems, 2018)

4.3.4 Two phase turbulence

When dealing with two phase flow a method developed by Rivering and Pettigrew (2007) can be used. The method is based on series of laboratory scale test where they used a two-phase mixture which contained air and water. 25 %,50 % 75 % and 95 % were the four gas volumetric ratios the test were performed at.

This yields a set of non-dimensionalized force power spectrum densities for two-phase excitation caused by a bend flow. The set of non-dimensionalized are then scaled by using the actual liquid density, homogenous void fraction, the interfacial surface tension (also called the weber number), the superficial velocity of the mixture and internal pipe diameter to obtain the Absolut power spectral density of the excitation.



$$f_F = \frac{fD}{j}$$

4.3.5 Prediction of overall RMS and maximum response

The response of a structure to random excitation (such as flow turbulence or 'steady state' two-phase flow) can be characterised in the frequency domain using the following expression:

A structure response to random excitations like steady state two phase flow or flow turbulence may be described in the frequency domain by using this formula:

$$\boldsymbol{S(f)_{response,1} = \left|H(f)_{1,2}\right|^2 * S(f)_{excitation,2}}$$

$S(f)_{response,1}$ = Where S(f) response,1 is the power spectral density (PSD) of the response at location 1 when a force power spectral density, $S(f)_{excitation,2}$, is applied at location 2 on the structure.

$\left|H(f)_{1,2}\right|^2$= Frequency response function that relates $S(f)_{response,1}$ and $S(f)_{excitation,2}$. It characterises as a function of frequency the response in location 1, when there is a unit force applied at location 2. When the excitation is in multiple locations like multiple bends in piping systems, the power spectral density can be described using this expression:

$$\boldsymbol{S(f)_{response,1} = \left|H(f)_{1,2}\right|^2 * S(f)_{excitation,2} + \left|H(f)_{1,3}\right| * (f)_{excitation,3} + \left|H(f)_{1,4}\right| * (f)_{excitation,4} + \cdots}$$

4.3.6 Damage calculation

When calculation damage for a spool or a pipe section, knowledge of the probability density function of the distribution of the stress range is required. This will enable the engineer to obtain an estimate of the number stress cycles that the pipe will experience a particular amplitude, zero up to maximum stress range, over the time it is exposed to the excitation. Rayleigh distribution is used when the response is narrow band which means the response is at single frequency. This is however not the case for most practical cases, since the response is not narrow band leading to conservative results. For a situation like this, Dirlick probability density function can be used with the benefits of giving fewer conservative results. This probability density function is calculating by taking the moments of the predicted stress PSD at every location of interest, then combine them to obtain a probability density function for each location on the model. The expected number of peaks per second, E(P), is also calculated.

The expected damage E[D] in time T can then be calculated by summing the damage for each set of stress ranges between zero and the maximum stress range:

$$E(D) = \sum_{.}^{i} \frac{E(P) * T * P(S_i) * \Delta_S}{N_1}$$

N= Number of cycles to failure S= Stress range, obtained from relevant S-N curve

By setting E(D)= 1, and solving for T, the fatigue life for the spool or the pipe section can be obtained. If this satisfies the lifetime intended for the spool or the pipe system, then this is good, and the spool or pipe system will not fail due to FIV.

4.4 Pulsation due to dead leg case

Table 9: Pulsation case input

$D = 273\ mm$	Outer diameter
$t = 14.3\ mm$	Wall thickness of the pipe
$L_{span} = 9m$	Maximum span length between supports on line
60.3mm	Outer diameter branch pipe
8 mm	Wall thickness of the branch pipe
$v = 4\ m/s$	Effective fluid velocity
$\rho = 150\ kg/m\text{^}3$	Effective fluid density

Calculations

$$\boldsymbol{\rho * v^2 = 1.35 * 10^3 Pa}$$

$$\boldsymbol{D_{int} = \frac{D_{main} - 2 * t_{main}}{mm} = \frac{273.1 - 2 * 14.3}{mm} = 244.5} \qquad \boldsymbol{d_{int} = \frac{D - 2 * t}{mm} = \frac{60.3 - 2 * 8}{mm} = 44.3}$$

$$\boldsymbol{d_{crit} = \left(\frac{400}{\pi * \rho * v^2}\right)^{0.5} = \left(\frac{400}{\pi * 150 * 4^2}\right)^{0.5} = 230.239}$$

Since the d_{int} is less than the d_{crit}, it passes the assessment check, and there is no need for further and detailed analysis.

4.5 Sensitivity Analysis

Sensitivity analysis model is utilizing for modelling analyses to evaluate the influence of various independent variables on particular dependent variables in some situations. Essentially, it can be useful across various industries.

The approach is essentially applied in the evaluation of the Black Box Process like calculating the LoF where several inputs have an opaque function.

In a sensitivity analysis, the input and output are evaluated thoroughly, and identify the movement of the variables as well as the influence of the target variable on the input. Thus, sensitivity analysis is critical for future design of spools, but it can be used on already existing spools and pipes to check if they have un-acceptable values and if they need further analysis or monitoring. Through an analysis of various variables and their likely outcomes, important conclusions can be made about the selection of geometry and layout of the spools.

KEY TAKEAWAYS

- The sensitivity analysis explains how an input variable like diameter, span length, velocity, density influences the LoF for various set (span) assumptions.
- It is a method that can be utilized to predict if a spool in design phase will have high LoF for a given input parameters. This will make it easier for an engineer to continue with the chosen parameters or if something needs to change.
- Historical data can be used for already build spools and pipe-system to check whether they are at risk for FIV.

4.5.1 Gas lines

The sensitivity analysis will be divided into two parts, one for gas lines and oil and multiphase lines. The table below, table 10 shows typical spools parameters and fluid property that will be used in the sensitivity analysis. The sensitivity analysis will be comprehensive since all the components will varied to get clearer on what effect they have on the LoF. The lines for gas will be started with. The sensitivity analysis is made of two tables. The first outlines the parameters like

- Pipe Diameter, OD.
- Wall thickness, t
- Support arrangement
- α, β, F_v

The second table is discussed in detail in the next page. It describes what the different rows and columns contains.

Table 10: Typical spool parameters and fluid properties

Spool size in Inches	Pipe OD (mm)	Typical wall thickness (mm)	Free span Length at Goose Neck (m)	Typical fluid property			
2	60.3	8.7	4-6	Oil line or multiple phase		Gas line	
6	168.3	11.0	4-8	Density (kg/m^3)	Velocity(m/s)	Density (Kg/m^3)	Velocity (m/s)
8	219.1	12.7	6-10	60-800	1-10	50-300	5-40
10	273.1	14.3	6-10				
12	323.9	15.9	6-14				
16	406.4	19.1	6-14				
20	508	20.6	8-14				
24	609.6	25.4	8-14				

Table 11: Sensitivity table explanation

1	
ρ, v	2
3	4
	4

1. Contains spool parameters like the outer diameter of the spool, the wall thickness, and the spool length.
2. This row shows the velocities that are used in this analysis.
3. This column contains the different densities used in this analysis.
4. These values are the calculated values for LoF. Depending on their value, they will have different colours. Furthermore, the value of the LoF will require actions in the design phase of a spool. The colours and the actions are as follows:
   - Green; The Small-Bore Connection (SBC) LOF Assessment should be performed in addition to the previous actions. When $LoF < 0.5$
   - Yellow; A detailed analysis should be performed in addition to the previous actions. When $0.5 < LoF \leq 1$
   - Red; The line shall be re-designed or and monitoring of the main line shall be undertaken, in addition to the previous actions. $Lof \geq 1$ (Swindell & Hill, Guidelines for the avoidance of vibration-induced fatigue failure in subsea systems, 2018)

Table 12: Output values, Do=60.3 mm and t=8.7 mm

$D_o = 60.3mm$ $t = 8.7\ mm$				
L_{span}	Support arrangement	α	β	F_v
4	Medium stiff	$3.062 * 10^5$	-1.048	40292
5	Medium	12.865	-0.12	27056
6	Medium	12.865	-0.12	27056

Table 13: LoF values, Do= 60.3 mm, t= 8.7 mm and Lspan= 4m, gas line

$D_o = 60.3\ mm$ $t = 8.7\ mm$								
$L_{span} = 4m$								
LoF:								
ρ, v	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
50	0.004	0.014	0.032	0.057	0.088	0.127	0.173	0.226
100	0.007	0.028	0.064	0.113	0.177	0.255	0.347	0.453
150	0.011	0.042	0.095	0.170	0.265	0.382	0.520	0.679
200	0.014	0.057	0.127	0.226	0.354	0.509	0.693	0.905
250	0.018	0.071	0.159	0.283	0.442	0.637	0.866	1.132
300	0.021	0.085	0.191	0.340	0.531	0.764	1.040	1.358

Table 14: LoF values, Do= 60.3 mm, t= 8.7 mm and Lspan= 5-6m, gas line

$D_o = 60.3\ mm$ $t = 8.7\ mm$								
$L_{span} = 5 - 6m$								
LoF:								
ρ, v	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
50	0.005	0.021	0.047	0.084	0.132	0.190	0.258	0.337
100	0.011	0.042	0.095	0.169	0.263	0.379	0.516	0.674
150	0.016	0.063	0.142	0.253	0.395	0.569	0.774	1.011
200	0.021	0.084	0.190	0.337	0.527	0.758	1.032	1.348
250	0.026	0.105	0.237	0.421	0.658	0.948	1.290	1.685
300	0.032	0.126	0.284	0.506	0.790	1.138	1.548	2.022

Table 15: Output values, Do=168.3 mm and t=11.0 mm

$D_o = 168.3\ mm$ $t = 11.0\ mm$				
L_{span}	Support arrangement	α	β	F_v
4	stiff	$5.593 * 10^5$	-0.861	53361
5	Stiff	$5.593 * 10^5$	-0.861	53361
6	Medium Stiff	$3.462 * 10^5$	-0.934	27084
7	Medium Stiff	$3.462 * 10^5$	-0.934	27084
8	Medium	12.7	-0.104	14168

Table 16: LoF values, Do= 168.3 mm, t= 11 mm and Lspan= 4-5 m, gas line

$D_o = 168.3\ mm$ $t = 11.0\ mm$								
$L_{span} = 4 - 5m$								
LoF:								
ρ, v	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
50	0.003	0.011	0.024	0.043	0.067	0.096	0.131	0.171
100	0.005	0.021	0.048	0.085	0.134	0.192	0.262	0.342
150	0.008	0.032	0.072	0.128	0.200	0.288	0.393	0.513
200	0.011	0.043	0.096	0.171	0.267	0.385	0.523	0.684
250	0.013	0.053	0.120	0.214	0.334	0.481	0.654	0.855
300	0.016	0.064	0.144	0.256	0.401	0.577	0.785	1.025

Table 17: LoF values, Do= 168.3 mm, t= 11 mm and Lspan= 6-7m, gas line

$D_o = 168.3\ mm$ $t = 11.0\ mm$								
$L_{span} = 6 - 7m$								
LoF:								
ρ, v	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
50	0.005	0.021	0.047	0.084	0.132	0.189	0.258	0.337
100	0.011	0.042	0.095	0.168	0.263	0.379	0.516	0.673
150	0.016	0.063	0.142	0.253	0.395	0.568	0.773	1.010
200	0.021	0.084	0.189	0.337	0.526	0.758	1.031	1.347
250	0.026	0.105	0.237	0.421	0.658	0.947	1.289	1.684
300	0.032	0.126	0.284	0.505	0.789	1.136	1.547	2.020

Table 18: LoF values, Do= 168.3 mm, t= 11 mm and Lspan= 8, gas line

$D_o = 168.3\ mm$ $t = 11.0\ mm$								
$L_{span} = 8m$								
LoF:								
ρ, v	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
50	0.010	0.040	0.091	0.161	0.251	0.362	0.493	0.644
100	0.020	0.080	0.181	0.322	0.503	0.724	0.986	1.287
150	0.030	0.121	0.272	0.483	0.754	1.086	1.479	1.931
200	0.040	0.161	0.362	0.644	1.006	1.448	1.971	2.575
250	0.050	0.201	0.453	0.805	1.257	1.810	2.464	3.219
300	0.060	0.241	0.543	0.966	1.509	2.173	2.957	3.862

Table 19: Output values, Do=219.1 mm and t=12.7 mm

$D_o = 219.1\ mm$ $t = 12.7\ mm$				
L_{span}	Support arrangement	α	β	F_v
6	Medium stiff	$3.65 * 10^5$	-0.905	27736
7	Medium stiff	$3.65 * 10^5$	-0.905	27736
8	Medium Stiff	$3.65 * 10^5$	-0.905	27736
9	Medium	12.736	-0.1	14507
10	Medium	12.736	-0.1	14507

Table 20: LoF values, Do= 219.1 mm, t= 12.7 mm and Lspan= 6-8, gas line

$D_o = 219.1\ mm$ $t = 12.7\ mm$								
$L_{span} = 6 - 8\ m$								
LoF:								
ρ, v	5	10	15	20	25	30	35	40
50	0.005	0.021	0.046	0.082	0.128	0.185	0.252	0.329
100	0.010	0.041	0.092	0.164	0.257	0.370	0.503	0.658
150	0.015	0.062	0.139	0.247	0.385	0.555	0.755	0.986
200	0.021	0.082	0.185	0.329	0.514	0.740	1.007	1.315
250	0.026	0.103	0.231	0.411	0.642	0.925	1.259	1.644
300	0.031	0.123	0.277	0.493	0.771	1.110	1.510	1.973

Table 21: LoF values, Do= 219.1 mm, t= 12.7 m and Lspan= 9-10 m, gas line

$D_o = 219.1\ mm$ $t = 12.7\ mm$								
$L_{span} = 9 - 10\ m$								
LoF:								
ρ, v	5	10	15	20	25	30	35	40
50	0.010	0.039	0.088	0.157	0.246	0.354	0.481	0.629
100	0.020	0.079	0.177	0.314	0.491	0.707	0.963	1.257
150	0.029	0.118	0.265	0.471	0.737	1.061	1.444	1.886
200	0.039	0.157	0.354	0.629	0.982	1.414	1.925	2.515
250	0.049	0.196	0.442	0.786	1.228	1.768	2.407	3.143
300	0.059	0.236	0.530	0.943	1.473	2.122	2.888	3.772

Table 22:Output values, Do=273.1 mm and t=14.3 mm, gas line

$D_o = 273.1\ mm$ $t = 14.3\ mm$				
L_{span}	Support arrangement	α	β	F_v
6	Stiff	$6.413 * 10^5$	-0.813	58307
7	Medium stiff	$3.85 * 10^5$	-0.881	28671x
8	Medium Stiff	$3.85 * 10^5$	-0.881	28671
9	Medium Stiff	$3.85 * 10^5$	-0.881	28671
10	Medium	$2.075 * 10^5$	-0.87	15956

Table 23: LoF values, Do= 273.1 mm, t= 14.3 mm and Lspan= 6-7 m, gas line

$D_o = 273.1\ mm$ $t = 14.3$ $L_{span} = 6 - 7\ m$ LoF:								
ρ, v	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
50	0.003	0.010	0.023	0.041	0.064	0.093	0.126	0.165
100	0.005	0.021	0.046	0.082	0.129	0.185	0.252	0.329
150	0.008	0.031	0.069	0.123	0.193	0.278	0.378	0.494
200	0.010	0.041	0.093	0.165	0.257	0.370	0.504	0.658
250	0.013	0.051	0.116	0.206	0.321	0.463	0.630	0.823
300	0.015	0.062	0.139	0.247	0.386	0.556	0.756	0.988

Table 24: LoF values, Do= 273.1 mm, t= 14.3 mm and Lspan= 8 m, gas line

$D_o = 273.1$ mm $t = 14.3\ mm$								
$L_{span} = 8m$								
LoF:								
ρ, v	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
50	0.0051	0.0206	0.0462	0.0822	0.1284	0.1850	0.2517	0.3288
100	0.0103	0.0411	0.0925	0.1644	0.2569	0.3699	0.5035	0.6576
150	0.0154	0.0617	0.1387	0.2466	0.3853	0.5549	0.7552	0.9864
200	0.0206	0.0822	0.1850	0.3288	0.5138	0.7398	1.0070	1.3153
250	0.0257	0.1028	0.2312	0.4110	0.6422	0.9248	1.2587	1.6441
300	0.0308	0.1233	0.2774	0.4932	0.7707	1.1097	1.5105	1.9729

Table 25: LoF values, Do= 273.1 mm, t= 14.3 mm and Lspan= 9 m, gas line

$D_o = 273.1\ mm$ $t = 14.3$								
$L_{span} = 9m$								
LoF:								
ρ, v	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
50	0.0050	0.0199	0.0447	0.0795	0.1243	0.1789	0.2435	0.3181
100	0.0099	0.0398	0.0895	0.1590	0.2485	0.3579	0.4871	0.6362
150	0.0149	0.0596	0.1342	0.2386	0.3728	0.5368	0.7306	0.9543
200	0.0199	0.0795	0.1789	0.3181	0.4970	0.7157	0.9742	1.2724
250	0.0249	0.0994	0.2237	0.3976	0.6213	0.8946	1.2177	1.5905
300	0.0298	0.1193	0.2684	0.4771	0.7455	1.0736	1.4612	1.9085

Table 26: LoF values, Do= 273.1 mm, t= 14.3 mm and Lspan= 10 m, gas line

$D_o = 273.1\ mm$ $t = 14.3$								
$L_{span} = 10m$								
LoF:								
ρ, v	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
50	0.0089	0.0357	0.0804	0.1429	0.2233	0.3215	0.4376	0.5716
100	0.0179	0.0714	0.1608	0.2858	0.4465	0.6430	0.8752	1.1431
150	0.0268	0.1072	0.2411	0.4287	0.6698	0.9645	1.3128	1.7147
200	0.0357	0.1429	0.3215	0.5716	0.8931	1.2860	1.7504	2.2863
250	0.0447	0.1786	0.4019	0.7145	1.1164	1.6075	2.1880	2.8579
300	0.0536	0.2143	0.4823	0.8574	1.3396	1.9291	2.6257	3.4294

Table 27: Output values, Do=323.9 mm and t=15.9 mm

$D_o = 323.9\ mm$ $t = 15.9\ mm$				
L_{span}	Support arrangement	α	β	F_v
6	Stiff	$6.866 * 10^5$	-0.796	62360
7	Stiff	$6.866 * 10^5$	-0.796	62360
8	Medium Stiff	$4.038 * 10^5$	-0.862	30073
9	Medium Stiff	$4.038 * 10^5$	-0.862	30073
10	Medium stiff	$4.038 * 10^5$	-0.862	30073
11	Medium	$2.181 * 10^5$	-0.856	16536
12	Medium	$2.181 * 10^5$	-0.856	16536
13	Medium	$2.181 * 10^5$	-0.856	16536
14	Flexible	$6.274 * 10^4$	-0.913	4002

Table 28: LoF values, Do= 323.9 mm, t= 15.9 mm and Lspan= 6-7 m, gas line

$D_o = 323.9\ mm$ $t = 15.9\ mm$								
$L_{span} = 6\ and\ 7m$								
LoF:								
ρ, v	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
50	0.002	0.009	0.021	0.037	0.057	0.082	0.112	0.146
100	0.005	0.018	0.041	0.073	0.114	0.165	0.224	0.292
150	0.007	0.027	0.062	0.110	0.171	0.247	0.336	0.439
200	0.009	0.037	0.082	0.146	0.229	0.329	0.448	0.585
250	0.011	0.046	0.103	0.183	0.286	0.411	0.560	0.731
300	0.014	0.055	0.123	0.219	0.343	0.494	0.672	0.877

Table 29: LoF values, Do= 273.1 mm, t= 14.3 mm and Lspan= 8-10 m, gas line

$D_o = 323.9\ mm$ $t = 15.9\ mm$								
$L_{span} = 8 - 10m$								
LoF:								
ρ, v	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
50	0.005	0.019	0.043	0.076	0.118	0.171	0.232	0.303
100	0.009	0.038	0.085	0.152	0.237	0.341	0.464	0.607
150	0.014	0.057	0.128	0.227	0.355	0.512	0.697	0.910
200	0.019	0.076	0.171	0.303	0.474	0.682	0.929	1.213
250	0.024	0.095	0.213	0.379	0.592	0.853	1.161	1.516
300	0.028	0.114	0.256	0.455	0.711	1.024	1.393	1.820

Table 30: LoF values, Do= 273.1 mm, t= 14.3 mm and Lspan= 11-13 m, gas line

$D_o = 323.9\ mm$ $t = 15.9\ mm$								
$L_{span} = 11 - 13m$								
LoF:								
ρ, v	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
50	0.009	0.034	0.078	0.138	0.215	0.310	0.422	0.552
100	0.017	0.069	0.155	0.276	0.431	0.620	0.845	1.103
150	0.026	0.103	0.233	0.414	0.646	0.931	1.267	1.655
200	0.034	0.138	0.310	0.552	0.862	1.241	1.689	2.206
250	0.043	0.172	0.388	0.689	1.077	1.551	2.111	2.758
300	0.052	0.207	0.465	0.827	1.293	1.861	2.534	3.309

Table 31: LoF values, Do= 273.1 mm, t= 14.3 mm and Lspan= 14 m, gas line

$D_o = 323.9\ mm$ $t = 15.9\ mm$								
$L_{span} = 14m$								
LoF:								
ρ, v	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
50	0.036	0.142	0.320	0.570	0.890	1.282	1.745	2.279
100	0.071	0.285	0.641	1.139	1.780	2.564	3.490	4.558
150	0.107	0.427	0.961	1.709	2.671	3.846	5.234	6.837
200	0.142	0.570	1.282	2.279	3.561	5.127	6.979	9.115
250	0.178	0.712	1.602	2.849	4.451	6.409	8.724	11.394
300	0.214	0.855	1.923	3.418	5.341	7.691	10.469	13.673

Table 32: Output values, Do=406.4 mm and t=19.1 mm

$D_o = 406.4mm$ $t = 19.1\ mm$				
L_{span}	Support arrangement	α	β	F_v
6	Stiff	$7.703 * 10^5$	-0.773	72434
7	Stiff	$7.703 * 10^5$	-0.773	72434
8	Medium Stiff	$7.703 * 10^5$	-0.773	72434
9	Medium Stiff	$4.343 * 10^5$	-0.837	33640
10	Medium stiff	$4.343 * 10^5$	-0.837	33640
11	Medium Stiff	$4.343 * 10^5$	-0.837	33640
12	Medium	$2.353 * 10^5$	-0.837	18190
13	Medium	$2.353 * 10^5$	-0.837	18190
14	Medium	$2.353 * 10^5$	-0.837	18190

Table 33: LoF values, Do= 406.4 mm, t= 19.1 mm and Lspan= 6-8 m, gas line

$D_o = 406.4mm$ $t = 19.1\ mm$								
$L_{span} = 6 - 8m$								
LoF:								
ρ, v	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
50	0.0020	0.0079	0.0177	0.0315	0.0492	0.0708	0.0964	0.1259
100	0.0039	0.0157	0.0354	0.0630	0.0984	0.1416	0.1928	0.2518
150	0.0059	0.0236	0.0531	0.0944	0.1475	0.2125	0.2892	0.3777
200	0.0079	0.0315	0.0708	0.1259	0.1967	0.2833	0.3856	0.5036
250	0.0098	0.0393	0.0885	0.1574	0.2459	0.3541	0.4820	0.6295
300	0.0118	0.0472	0.1062	0.1889	0.2951	0.4249	0.5784	0.7554

Table 34: LoF values, Do= 406.4 mm, t= 19.1 mm and Lspan= 9-11 m, gas line

$D_o = 406.4mm$ $t = 19.1\ mm$								
$L_{span} = 9 - 11m$								
LoF:								
ρ, v	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
50	0.0042	0.0169	0.0381	0.0678	0.1059	0.1525	0.2076	0.2711
100	0.0085	0.0339	0.0762	0.1356	0.2118	0.3050	0.4151	0.5422
150	0.0127	0.0508	0.1144	0.2033	0.3177	0.4575	0.6227	0.8133
200	0.0169	0.0678	0.1525	0.2711	0.4236	0.6100	0.8303	1.0844
250	0.0212	0.0847	0.1906	0.3389	0.5295	0.7625	1.0378	1.3555
300	0.0254	0.1017	0.2287	0.4067	0.6354	0.9150	1.2454	1.6266

Table 35: LoF values, Do= 406.4 mm, t= 19.1 mm and Lspan= 12-13 m, gas line

$D_o = 406.4mm$ $t = 19.1\ mm$								
$L_{span} = 12 - 13m$								
LoF:								
ρ, v	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
50	0.0078	0.0313	0.0705	0.1253	0.1958	0.2820	0.3839	0.5014
100	0.0157	0.0627	0.1410	0.2507	0.3917	0.5640	0.7677	1.0027
150	0.0235	0.0940	0.2115	0.3760	0.5875	0.8461	1.1516	1.5041
200	0.0313	0.1253	0.2820	0.5014	0.7834	1.1281	1.5355	2.0055
250	0.0392	0.1567	0.3525	0.6267	0.9792	1.4101	1.9193	2.5069
300	0.0470	0.1880	0.4230	0.7521	1.1751	1.6921	2.3032	3.0082

Table 36: LoF values, Do= 406.4 mm, t= 19.1 mm and Lspan= 14 m, gas line

$D_o = 406.4mm$ $t = 19.1\ mm$								
$L_{span} = 14m$								
LoF:								
ρ, v	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
50	0.002	0.007	0.016	0.028	0.044	0.064	0.087	0.113
100	0.004	0.014	0.032	0.057	0.088	0.127	0.173	0.226
150	0.005	0.021	0.048	0.085	0.133	0.191	0.260	0.339
200	0.007	0.028	0.064	0.113	0.177	0.255	0.346	0.453
250	0.009	0.035	0.080	0.141	0.221	0.318	0.433	0.566
300	0.011	0.042	0.095	0.170	0.265	0.382	0.520	0.679

Table 37: Output values, Do=508 mm and t=20.6 mm

$D_o = 508mm$ $t = 20.6mm$				
L_{span}	Support arrangement	α	β	F_v
8	Stiff	$8.946 * 10^5$	-0.751	80618
9	Stiff	$8.946 * 10^5$	-0.751	80618
10	Medium Stiff	$4.719 * 10^5$	-0.812	34967
11	Medium Stiff	$4.719 * 10^5$	-0.812	34967
12	Medium stiff	$4.719 * 10^5$	-0.812	34967
13	Medium Stiff	$4.719 * 10^5$	-0.812	34967
14	Medium	$2.566 * 10^5$	-0.819	18579

Table 38: LoF values, Do= 508 mm, t= 20.6 mm and Lspan= 8-9 m, gas line

$D_o = 508mm$ $t = 20.6mm$								
$L_{span} = 8 - 9m$								
LoF:								
ρ, v	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
50	0.002	0.007	0.016	0.028	0.044	0.064	0.087	0.113
100	0.004	0.014	0.032	0.057	0.088	0.127	0.173	0.226
150	0.005	0.021	0.048	0.085	0.133	0.191	0.260	0.339
200	0.007	0.028	0.064	0.113	0.177	0.255	0.346	0.453
250	0.009	0.035	0.080	0.141	0.221	0.318	0.433	0.566
300	0.011	0.042	0.095	0.170	0.265	0.382	0.520	0.679

Table 39: LoF values, Do= 508 mm, t= 20.6 mm and Lspan= 10-13 m, gas line

$D_o = 508mm$ $t = 20.6mm$								
$L_{span} = 10 - 13m$								
LoF:								
ρ, v	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
50	0.004	0.016	0.037	0.065	0.102	0.147	0.200	0.261
100	0.008	0.033	0.073	0.130	0.204	0.293	0.399	0.522
150	0.012	0.049	0.110	0.196	0.306	0.440	0.599	0.782
200	0.016	0.065	0.147	0.261	0.408	0.587	0.799	1.043
250	0.020	0.082	0.183	0.326	0.509	0.734	0.998	1.304
300	0.024	0.098	0.220	0.391	0.611	0.880	1.198	1.565

Table 40: LoF values, Do= 406.4 mm, t= 19.1 mm and Lspan= 14 m, gas line

$D_o = 508mm$ $t = 20.6mm$								
$L_{span} = 14$								
LoF:								
ρ, v	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
50	0.008	0.031	0.069	0.123	0.192	0.276	0.376	0.491
100	0.015	0.061	0.138	0.245	0.383	0.552	0.752	0.982
150	0.023	0.092	0.207	0.368	0.575	0.828	1.127	1.473
200	0.031	0.123	0.276	0.491	0.767	1.104	1.503	1.964
250	0.038	0.153	0.345	0.614	0.959	1.381	1.879	2.454
300	0.046	0.184	0.414	0.736	1.150	1.657	2.255	2.945

Table 41: Output values, Do=609.6 mm and t=25.4 mm

$D_o = 609.6mm$ $t = 25.4\ mm$				
L_{span}	Support arrangement	α	β	F_v
8	Stiff	$1.047 * 10^6$	-0.733	102093
9	Stiff	$1.047 * 10^6$	-0.733	102093
10	Medium Stiff	$5.094 * 10^5$	-0.792	41148
11	Medium Stiff	$5.094 * 10^5$	-0.792	41148
12	Medium stiff	$5.094 * 10^5$	-0.792	41148
13	Medium Stiff	$5.094 * 10^5$	-0.792	41148
14	Medium Stiff	$5.094 * 10^5$	-0.792	41148

Table 42: LoF values, Do= 609.6 mm, t= 25.4 mm and Lspan= 8-9 m, gas line

$D_o = 609.6mm$ $t = 25.4\ mm$								
$L_{span} = 8 - 9m$								
LoF:								
ρ, v	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
50	0.001	0.006	0.013	0.022	0.035	0.050	0.068	0.089
100	0.003	0.011	0.025	0.045	0.070	0.100	0.137	0.179
150	0.004	0.017	0.038	0.067	0.105	0.151	0.205	0.268
200	0.006	0.022	0.050	0.089	0.140	0.201	0.274	0.357
250	0.007	0.028	0.063	0.112	0.174	0.251	0.342	0.447
300	0.008	0.033	0.075	0.134	0.209	0.301	0.410	0.536

Table 43: LoF values, Do= 609.6 mm, t= 25.4 mm and Lspan= 10-14 m, gas line

$D_o = 609.6mm$ $t = 25.4\ mm$								
$L_{span} = 10 - 14\ m$								
LoF:								
ρ, v	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
50	0.003	0.014	0.031	0.055	0.087	0.125	0.170	0.222
100	0.007	0.028	0.062	0.111	0.173	0.249	0.339	0.443
150	0.010	0.042	0.094	0.166	0.260	0.374	0.509	0.665
200	0.014	0.055	0.125	0.222	0.346	0.499	0.679	0.887
250	0.017	0.069	0.156	0.277	0.433	0.623	0.848	1.108
300	0.021	0.083	0.187	0.332	0.519	0.748	1.018	1.330

4.5.1.1 Varying wall thickness

When designing a spool, the Outer diameter is often of standards diameters with little room for changing. The wall thickness on the other hand can be fabricated more freely, hence the importance of the influence wall thickness has on LoF is important to study. From the Table below it shows that larger wall thickness yields a decrease in LoF value.

Table 44: LoF values for different wall thickness, t

$D_o = 273.1\ mm$		
$L_{span} = 6 - 7\ m$		
$\rho = 100 \frac{kg}{m^3}\ and\ v = 5 \frac{m}{s}$		
t	F_v	LoF
$7.15mm$	33191	0.009
$10mm$	43598	0.007
$14.3mm$	58307	0.005
$20mm$	76587	0.004
28.6	102431	0.003

$D_o = 60.3mm$ $t = 8.7\ mm$				
L_{span}	Support arrangement	α	β	F_v
4	Medium stiff	$3.062 * 10^5$	-1.048	40292
5	Medium	12.865	-0.12	27056
6	Medium	12.865	-0.12	27056

4.5.2 Oil lines or multiphase line

4.5.3

This section deals with pipe sections that are used to transport oil. The main differences from gas lines are ;

- Velocities: The velocity are lower than the gas
- Density: Higher density values compared to gases
- The Fluid viscosity, FVF, is equal to 1 for oil lines.

The table below is identical to the one in gas lines, and the rest of these tables are also identical so they will be omitted from the rest of the sensitivity analyses.

Table 12: Output values, Do=60.3 mm and t=8.7

$D_o = 60.3mm$ $t = 8.7\ mm$				
L_{span}	Support arrangement	α	β	F_v
4	Medium stiff	$3.062 * 10^5$	-1.048	40292
5	Medium	12.865	-0.12	27056
6	Medium	12.865	-0.12	27056

Table 45: LoF values, Do= 60.3, t= 8.7 and Lspan= 4m, oil line

$D_o = 60.3\ mm$ $t = 8.7\ mm$										
$L_{span} = 4$										
LoF:										
ρ, v	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
60	0.001	0.006	0.013	0.024	0.037	0.054	0.073	0.095	0.121	0.149
110	0.003	0.011	0.025	0.044	0.068	0.098	0.134	0.175	0.221	0.273
160	0.004	0.016	0.036	0.064	0.099	0.143	0.195	0.254	0.322	0.397
210	0.005	0.021	0.047	0.083	0.130	0.188	0.255	0.334	0.422	0.521
260	0.006	0.026	0.058	0.103	0.161	0.232	0.316	0.413	0.523	0.645
310	0.008	0.031	0.069	0.123	0.192	0.277	0.377	0.492	0.623	0.769
360	0.009	0.036	0.080	0.143	0.223	0.322	0.438	0.572	0.724	0.893
410	0.010	0.041	0.092	0.163	0.254	0.366	0.499	0.651	0.824	1.018
460	0.011	0.046	0.103	0.183	0.285	0.411	0.559	0.731	0.925	1.142
510	0.013	0.051	0.114	0.203	0.316	0.456	0.620	0.810	1.025	1.266
560	0.014	0.056	0.125	0.222	0.347	0.500	0.681	0.890	1.126	1.390
610	0.015	0.061	0.136	0.242	0.378	0.545	0.742	0.969	1.226	1.514
660	0.016	0.066	0.147	0.262	0.410	0.590	0.803	1.048	1.327	1.638
710	0.018	0.070	0.159	0.282	0.441	0.634	0.863	1.128	1.427	1.762
760	0.019	0.075	0.170	0.302	0.472	0.679	0.924	1.207	1.528	1.886

Table 46: LoF values, Do= 60.3, t= 8.7 and Lspan= 5-6 m, oil line

$D_o = 60.3\ mm$ $t = 8.7\ mm$										
$L_{span} = 5\ and\ 6$										
LoF:										
ρ, v	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
60	0.002	0.009	0.020	0.035	0.055	0.080	0.109	0.142	0.180	0.222
110	0.004	0.016	0.037	0.065	0.102	0.146	0.199	0.260	0.329	0.407
160	0.006	0.024	0.053	0.095	0.148	0.213	0.290	0.378	0.479	0.591
210	0.008	0.031	0.070	0.124	0.194	0.279	0.380	0.497	0.629	0.776
260	0.010	0.038	0.086	0.154	0.240	0.346	0.471	0.615	0.778	0.961
310	0.011	0.046	0.103	0.183	0.286	0.412	0.561	0.733	0.928	1.146
360	0.013	0.053	0.120	0.213	0.333	0.479	0.652	0.852	1.078	1.331
410	0.015	0.061	0.136	0.242	0.379	0.546	0.743	0.970	1.227	1.515
460	0.017	0.068	0.153	0.272	0.425	0.612	0.833	1.088	1.377	1.700
510	0.019	0.075	0.170	0.302	0.471	0.679	0.924	1.206	1.527	1.885
560	0.021	0.083	0.186	0.331	0.517	0.745	1.014	1.325	1.677	2.070
610	0.023	0.090	0.203	0.361	0.564	0.812	1.105	1.443	1.826	2.255
660	0.024	0.098	0.220	0.390	0.610	0.878	1.195	1.561	1.976	2.439
710	0.026	0.105	0.236	0.420	0.656	0.945	1.286	1.679	2.126	2.624
760	0.028	0.112	0.253	0.449	0.702	1.011	1.376	1.798	2.275	2.809

Table 47: LoF values, Do= 168.3 mm, t= 11 mm and Lspan= 4-5m, oil line

$D_o = 168.3\ mm$ $t = 11.0\ mm$										
$L_{span} = 4\ and\ 5$										
LoF:										
ρ, v	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
60	0.001	0.004	0.010	0.018	0.028	0.040	0.055	0.072	0.091	0.112
110	0.002	0.008	0.019	0.033	0.052	0.074	0.101	0.132	0.167	0.206
160	0.003	0.012	0.027	0.048	0.075	0.108	0.147	0.192	0.243	0.300
210	0.004	0.016	0.035	0.063	0.098	0.142	0.193	0.252	0.319	0.394
260	0.005	0.019	0.044	0.078	0.122	0.175	0.239	0.312	0.395	0.487
310	0.006	0.023	0.052	0.093	0.145	0.209	0.285	0.372	0.471	0.581
360	0.007	0.027	0.061	0.108	0.169	0.243	0.331	0.432	0.546	0.675
410	0.008	0.031	0.069	0.123	0.192	0.277	0.376	0.492	0.622	0.768
460	0.009	0.034	0.078	0.138	0.216	0.310	0.422	0.552	0.698	0.862
510	0.010	0.038	0.086	0.153	0.239	0.344	0.468	0.612	0.774	0.956
560	0.010	0.042	0.094	0.168	0.262	0.378	0.514	0.672	0.850	1.049
610	0.011	0.046	0.103	0.183	0.286	0.412	0.560	0.732	0.926	1.143
660	0.012	0.049	0.111	0.198	0.309	0.445	0.606	0.792	1.002	1.237
710	0.013	0.053	0.120	0.213	0.333	0.479	0.652	0.852	1.078	1.331
760	0.014	0.057	0.128	0.228	0.356	0.513	0.698	0.912	1.154	1.424

Table 48: Table 46: LoF values, Do= 168.3 mm, t= 11 mm and Lspan= 6-7 m, oil line

$D_o = 168.3\ mm$ $t = 11.0\ mm$										
$L_{span} = 6 - 7\ m$										
LoF:										
ρ, v	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
60	0.002	0.009	0.020	0.035	0.055	0.080	0.109	0.142	0.179	0.222
110	0.004	0.016	0.037	0.065	0.102	0.146	0.199	0.260	0.329	0.406
160	0.006	0.024	0.053	0.095	0.148	0.213	0.289	0.378	0.479	0.591
210	0.008	0.031	0.070	0.124	0.194	0.279	0.380	0.496	0.628	0.775
260	0.010	0.038	0.086	0.154	0.240	0.346	0.470	0.614	0.778	0.960
310	0.011	0.046	0.103	0.183	0.286	0.412	0.561	0.733	0.927	1.145
360	0.013	0.053	0.120	0.213	0.332	0.479	0.651	0.851	1.077	1.329
410	0.015	0.061	0.136	0.242	0.378	0.545	0.742	0.969	1.226	1.514
460	0.017	0.068	0.153	0.272	0.425	0.611	0.832	1.087	1.376	1.698
510	0.019	0.075	0.169	0.301	0.471	0.678	0.923	1.205	1.525	1.883
560	0.021	0.083	0.186	0.331	0.517	0.744	1.013	1.323	1.675	2.068
610	0.023	0.090	0.203	0.360	0.563	0.811	1.104	1.441	1.824	2.252
660	0.024	0.097	0.219	0.390	0.609	0.877	1.194	1.560	1.974	2.437
710	0.026	0.105	0.236	0.419	0.655	0.944	1.285	1.678	2.123	2.621
760	0.028	0.112	0.253	0.449	0.702	1.010	1.375	1.796	2.273	2.806

Table 49: LoF values, Do= 168.3 mm, t= 11 mm and Lspan= 8m, oil line

$D_o = 168.3\ mm$ $t = 11.0\ mm$										
$L_{span} = 8m$										
LoF:										
ρ, v	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
60	0.004	0.017	0.038	0.068	0.106	0.152	0.208	0.271	0.343	0.423
110	0.008	0.031	0.070	0.124	0.194	0.280	0.380	0.497	0.629	0.776
160	0.011	0.045	0.102	0.181	0.282	0.407	0.553	0.723	0.915	1.129
210	0.015	0.059	0.133	0.237	0.371	0.534	0.726	0.949	1.201	1.482
260	0.018	0.073	0.165	0.294	0.459	0.661	0.899	1.174	1.486	1.835
310	0.022	0.088	0.197	0.350	0.547	0.788	1.072	1.400	1.772	2.188
360	0.025	0.102	0.229	0.407	0.635	0.915	1.245	1.626	2.058	2.541
410	0.029	0.116	0.260	0.463	0.723	1.042	1.418	1.852	2.344	2.894
460	0.032	0.130	0.292	0.519	0.812	1.169	1.591	2.078	2.630	3.247
510	0.036	0.144	0.324	0.576	0.900	1.296	1.764	2.304	2.916	3.600
560	0.040	0.158	0.356	0.632	0.988	1.423	1.937	2.530	3.202	3.953
610	0.043	0.172	0.387	0.689	1.076	1.550	2.110	2.756	3.487	4.305
660	0.047	0.186	0.419	0.745	1.165	1.677	2.283	2.981	3.773	4.658
710	0.050	0.200	0.451	0.802	1.253	1.804	2.456	3.207	4.059	5.011
760	0.054	0.215	0.483	0.858	1.341	1.931	2.628	3.433	4.345	5.364

Table 50: LoF values, Do= 219 mm, t= 12.7 mm and Lspan= 6-8m, oil line

$D_o = 219\ mm$ $t = 12.7\ mm$										
$L_{span} = 6 - 8m$										
LoF:										
ρ, v	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
60	0.002	0.009	0.019	0.035	0.054	0.078	0.106	0.138	0.175	0.216
110	0.004	0.016	0.036	0.063	0.099	0.143	0.194	0.254	0.321	0.397
160	0.006	0.023	0.052	0.092	0.144	0.208	0.283	0.369	0.467	0.577
210	0.008	0.030	0.068	0.121	0.189	0.273	0.371	0.485	0.613	0.757
260	0.009	0.037	0.084	0.150	0.234	0.337	0.459	0.600	0.759	0.937
310	0.011	0.045	0.101	0.179	0.279	0.402	0.548	0.715	0.905	1.118
360	0.013	0.052	0.117	0.208	0.324	0.467	0.636	0.831	1.051	1.298
410	0.015	0.059	0.133	0.237	0.370	0.532	0.724	0.946	1.197	1.478
460	0.017	0.066	0.149	0.265	0.415	0.597	0.813	1.061	1.343	1.658
510	0.018	0.074	0.165	0.294	0.460	0.662	0.901	1.177	1.489	1.839
560	0.020	0.081	0.182	0.323	0.505	0.727	0.989	1.292	1.635	2.019
610	0.022	0.088	0.198	0.352	0.550	0.792	1.078	1.408	1.781	2.199
660	0.024	0.095	0.214	0.381	0.595	0.857	1.166	1.523	1.927	2.380
710	0.026	0.102	0.230	0.410	0.640	0.922	1.254	1.638	2.073	2.560
760	0.027	0.110	0.247	0.438	0.685	0.986	1.343	1.754	2.219	2.740

Table 51: LoF values, Do= 219 mm, t= 12.7 mm and Lspan= 9-10m, oil line

$D_o = 219\ mm$ $t = 12.7\ mm$										
$L_{span} = 9 - 10\ m$										
LoF:										
ρ, v	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
60	0.004	0.017	0.037	0.066	0.103	0.149	0.203	0.265	0.335	0.414
110	0.008	0.030	0.068	0.121	0.190	0.273	0.372	0.485	0.614	0.758
160	0.011	0.044	0.099	0.176	0.276	0.397	0.540	0.706	0.893	1.103
210	0.014	0.058	0.130	0.232	0.362	0.521	0.709	0.926	1.173	1.448
260	0.018	0.072	0.161	0.287	0.448	0.645	0.878	1.147	1.452	1.792
310	0.021	0.085	0.192	0.342	0.534	0.769	1.047	1.368	1.731	2.137
360	0.025	0.099	0.223	0.397	0.620	0.893	1.216	1.588	2.010	2.482
410	0.028	0.113	0.254	0.452	0.707	1.017	1.385	1.809	2.289	2.826
460	0.032	0.127	0.285	0.507	0.793	1.142	1.554	2.029	2.568	3.171
510	0.035	0.141	0.316	0.562	0.879	1.266	1.723	2.250	2.848	3.516
560	0.039	0.154	0.347	0.618	0.965	1.390	1.892	2.471	3.127	3.860
610	0.042	0.168	0.378	0.673	1.051	1.514	2.060	2.691	3.406	4.205
660	0.045	0.182	0.409	0.728	1.137	1.638	2.229	2.912	3.685	4.550
710	0.049	0.196	0.440	0.783	1.224	1.762	2.398	3.132	3.964	4.894
760	0.052	0.210	0.471	0.838	1.310	1.886	2.567	3.353	4.243	5.239

Table 52: LoF values, Do= 273.1 mm, t= 14.3 mm and Lspan= 6 m, oil line

$D_o = 273.1\ mm$ $t = 14.3mm$										
$L_{span} = 6$										
LoF:										
ρ, ν	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
60	0.001	0.004	0.009	0.016	0.026	0.037	0.050	0.066	0.083	0.103
110	0.002	0.008	0.017	0.030	0.047	0.068	0.092	0.121	0.153	0.189
160	0.003	0.011	0.025	0.044	0.069	0.099	0.134	0.176	0.222	0.274
210	0.004	0.014	0.032	0.058	0.090	0.130	0.176	0.231	0.292	0.360
260	0.004	0.018	0.040	0.071	0.111	0.161	0.218	0.285	0.361	0.446
310	0.005	0.021	0.048	0.085	0.133	0.191	0.261	0.340	0.431	0.532
360	0.006	0.025	0.056	0.099	0.154	0.222	0.303	0.395	0.500	0.617
410	0.007	0.028	0.063	0.113	0.176	0.253	0.345	0.450	0.570	0.703
460	0.008	0.032	0.071	0.126	0.197	0.284	0.387	0.505	0.639	0.789
510	0.009	0.035	0.079	0.140	0.219	0.315	0.429	0.560	0.708	0.875
560	0.010	0.038	0.086	0.154	0.240	0.346	0.471	0.615	0.778	0.960
610	0.010	0.042	0.094	0.167	0.262	0.377	0.513	0.670	0.847	1.046
660	0.011	0.045	0.102	0.181	0.283	0.407	0.555	0.724	0.917	1.132
710	0.012	0.049	0.110	0.195	0.304	0.438	0.597	0.779	0.986	1.218
760	0.013	0.052	0.117	0.209	0.326	0.469	0.639	0.834	1.056	1.303

Table 53: LoF values, Do= 273.1 mm, t= 14.3 mm and Lspan= 7-9 m, oil line

$D_o = 273.1\ mm$ $t = 14.3mm$										
$L_{span} = 7 - 9m$										
LoF:										
ρ, v	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
60	0.002	0.008	0.019	0.033	0.052	0.075	0.103	0.134	0.170	0.209
110	0.004	0.015	0.035	0.061	0.096	0.138	0.188	0.246	0.311	0.384
160	0.006	0.022	0.050	0.089	0.140	0.201	0.273	0.357	0.452	0.558
210	0.007	0.029	0.066	0.117	0.183	0.264	0.359	0.469	0.593	0.732
260	0.009	0.036	0.082	0.145	0.227	0.326	0.444	0.580	0.735	0.907
310	0.011	0.043	0.097	0.173	0.270	0.389	0.530	0.692	0.876	1.081
360	0.013	0.050	0.113	0.201	0.314	0.452	0.615	0.804	1.017	1.256
410	0.014	0.057	0.129	0.229	0.358	0.515	0.701	0.915	1.158	1.430
460	0.016	0.064	0.144	0.257	0.401	0.578	0.786	1.027	1.300	1.604
510	0.018	0.071	0.160	0.285	0.445	0.640	0.872	1.138	1.441	1.779
560	0.020	0.078	0.176	0.313	0.488	0.703	0.957	1.250	1.582	1.953
610	0.021	0.085	0.191	0.340	0.532	0.766	1.043	1.362	1.723	2.128
660	0.023	0.092	0.207	0.368	0.575	0.829	1.128	1.473	1.865	2.302
710	0.025	0.099	0.223	0.396	0.619	0.891	1.213	1.585	2.006	2.476
760	0.027	0.106	0.239	0.424	0.663	0.954	1.299	1.696	2.147	2.651

Table 54: LoF values, Do= 273.1 mm, t= 14.3 mm and Lspan=10 m, oil line

$D_o = 273.1\ mm$ $t = 14.3mm$										
$L_{span} = 10m$										
LoF:										
ρ, v	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
60	0.004	0.015	0.034	0.060	0.094	0.135	0.184	0.241	0.305	0.376
110	0.007	0.028	0.062	0.110	0.172	0.248	0.338	0.441	0.558	0.689
160	0.010	0.040	0.090	0.160	0.251	0.361	0.491	0.642	0.812	1.003
210	0.013	0.053	0.118	0.211	0.329	0.474	0.645	0.842	1.066	1.316
260	0.016	0.065	0.147	0.261	0.407	0.587	0.798	1.043	1.320	1.629
310	0.019	0.078	0.175	0.311	0.486	0.699	0.952	1.243	1.574	1.943
360	0.023	0.090	0.203	0.361	0.564	0.812	1.106	1.444	1.828	2.256
410	0.026	0.103	0.231	0.411	0.642	0.925	1.259	1.645	2.081	2.570
460	0.029	0.115	0.259	0.461	0.721	1.038	1.413	1.845	2.335	2.883
510	0.032	0.128	0.288	0.511	0.799	1.151	1.566	2.046	2.589	3.196
560	0.035	0.140	0.316	0.562	0.877	1.263	1.720	2.246	2.843	3.510
610	0.038	0.153	0.344	0.612	0.956	1.376	1.873	2.447	3.097	3.823
660	0.041	0.165	0.372	0.662	1.034	1.489	2.027	2.647	3.350	4.136
710	0.044	0.178	0.400	0.712	1.112	1.602	2.180	2.848	3.604	4.450
760	0.048	0.191	0.429	0.762	1.191	1.715	2.334	3.048	3.858	4.763

Table 55: LoF values, Do= 323.9 mm, t= 15.9 mm and Lspan= 6-7 m, oil line

$D_o = 323.9\ mm$ $t = 15.9mm$										
$L_{span} = 6 - 7m$										
LoF:										
ρ, v	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
60	0.001	0.004	0.009	0.015	0.024	0.035	0.047	0.062	0.078	0.096
110	0.002	0.007	0.016	0.028	0.044	0.064	0.086	0.113	0.143	0.176
160	0.003	0.010	0.023	0.041	0.064	0.092	0.126	0.164	0.208	0.257
210	0.003	0.013	0.030	0.054	0.084	0.121	0.165	0.216	0.273	0.337
260	0.004	0.017	0.038	0.067	0.104	0.150	0.204	0.267	0.338	0.417
310	0.005	0.020	0.045	0.080	0.124	0.179	0.244	0.318	0.403	0.497
360	0.006	0.023	0.052	0.092	0.144	0.208	0.283	0.369	0.468	0.577
410	0.007	0.026	0.059	0.105	0.164	0.237	0.322	0.421	0.533	0.657
460	0.007	0.030	0.066	0.118	0.184	0.266	0.361	0.472	0.597	0.738
510	0.008	0.033	0.074	0.131	0.204	0.294	0.401	0.523	0.662	0.818
560	0.009	0.036	0.081	0.144	0.225	0.323	0.440	0.575	0.727	0.898
610	0.010	0.039	0.088	0.157	0.245	0.352	0.479	0.626	0.792	0.978
660	0.011	0.042	0.095	0.169	0.265	0.381	0.519	0.677	0.857	1.058
710	0.011	0.046	0.102	0.182	0.285	0.410	0.558	0.729	0.922	1.139
760	0.012	0.049	0.110	0.195	0.305	0.439	0.597	0.780	0.987	1.219

Table 56: LoF values, Do= 323.9 mm, t= 15.9 mm and Lspan= 8-10 m, oil line

$D_o = 323.9\ mm$ $t = 15.9mm$ $L_{span} = 8 - 10\ m$ LoF:										
ρ, v	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
60	0.002	0.008	0.018	0.032	0.050	0.072	0.098	0.128	0.162	0.200
110	0.004	0.015	0.033	0.059	0.091	0.132	0.179	0.234	0.296	0.366
160	0.005	0.021	0.048	0.085	0.133	0.192	0.261	0.341	0.431	0.532
210	0.007	0.028	0.063	0.112	0.175	0.251	0.342	0.447	0.566	0.698
260	0.009	0.035	0.078	0.138	0.216	0.311	0.424	0.553	0.700	0.865
310	0.010	0.041	0.093	0.165	0.258	0.371	0.505	0.660	0.835	1.031
360	0.012	0.048	0.108	0.192	0.299	0.431	0.587	0.766	0.970	1.197
410	0.014	0.055	0.123	0.218	0.341	0.491	0.668	0.873	1.104	1.363
460	0.015	0.061	0.138	0.245	0.382	0.551	0.750	0.979	1.239	1.530
510	0.017	0.068	0.153	0.271	0.424	0.611	0.831	1.085	1.374	1.696
560	0.019	0.074	0.168	0.298	0.466	0.670	0.912	1.192	1.508	1.862
610	0.020	0.081	0.183	0.325	0.507	0.730	0.994	1.298	1.643	2.028
660	0.022	0.088	0.198	0.351	0.549	0.790	1.075	1.405	1.778	2.195
710	0.024	0.094	0.212	0.378	0.590	0.850	1.157	1.511	1.912	2.361
760	0.025	0.101	0.227	0.404	0.632	0.910	1.238	1.617	2.047	2.527

Table 57: LoF values, Do= 323.9 mm, t= 15.9 mm and Lspan= 11-13 m, oil line

$D_o = 323.9\ mm$ $t = 15.9mm$										
$L_{span} = 11 - 13\ m$										
LoF:										
ρ, v	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
60	0.004	0.015	0.033	0.058	0.091	0.131	0.178	0.232	0.294	0.363
110	0.007	0.027	0.060	0.106	0.166	0.239	0.326	0.426	0.539	0.665
160	0.010	0.039	0.087	0.155	0.242	0.348	0.474	0.619	0.784	0.968
210	0.013	0.051	0.114	0.203	0.317	0.457	0.622	0.813	1.029	1.270
260	0.016	0.063	0.142	0.252	0.393	0.566	0.770	1.006	1.274	1.572
310	0.019	0.075	0.169	0.300	0.469	0.675	0.919	1.200	1.519	1.875
360	0.022	0.087	0.196	0.348	0.544	0.784	1.067	1.393	1.763	2.177
410	0.025	0.099	0.223	0.397	0.620	0.893	1.215	1.587	2.008	2.479
460	0.028	0.111	0.250	0.445	0.695	1.001	1.363	1.780	2.253	2.782
510	0.031	0.123	0.278	0.493	0.771	1.110	1.511	1.974	2.498	3.084
560	0.034	0.135	0.305	0.542	0.847	1.219	1.659	2.167	2.743	3.387
610	0.037	0.148	0.332	0.590	0.922	1.328	1.808	2.361	2.988	3.689
660	0.040	0.160	0.359	0.639	0.998	1.437	1.956	2.554	3.233	3.991
710	0.043	0.172	0.386	0.687	1.073	1.546	2.104	2.748	3.478	4.294
760	0.046	0.184	0.414	0.735	1.149	1.655	2.252	2.941	3.723	4.596

Table 58: LoF values, Do= 323.9 mm, t= 15.9 mm and Lspan= 14 m, oil line

$D_o = 323.9\ mm$ $t = 15.9mm$										
$L_{span} = 14\ m$										
LoF:										
ρ, v	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
60	0.014993	0.05997	0.134933	0.23988	0.374813	0.53973	0.734633	0.95952	1.214393	1.49925
110	0.027486	0.109945	0.247376	0.43978	0.687156	0.989505	1.346827	1.75912	2.226387	2.748626
160	0.03998	0.15992	0.35982	0.63968	0.9995	1.43928	1.95902	2.558721	3.238381	3.998001
210	0.052474	0.209895	0.472264	0.83958	1.311844	1.889055	2.571214	3.358321	4.250375	5.247376
260	0.064968	0.25987	0.584708	1.03948	1.624188	2.338831	3.183408	4.157921	5.262369	6.496752
310	0.077461	0.309845	0.697151	1.23938	1.936532	2.788606	3.795602	4.957521	6.274363	7.746127
360	0.089955	0.35982	0.809595	1.43928	2.248876	3.238381	4.407796	5.757121	7.286357	8.995502
410	0.102449	0.409795	0.922039	1.63918	2.561219	3.688156	5.01999	6.556722	8.298351	10.24488
460	0.114943	0.45977	1.034483	1.83908	2.873563	4.137931	5.632184	7.356322	9.310345	11.49425
510	0.127436	0.509745	1.146927	2.038981	3.185907	4.587706	6.244378	8.155922	10.32234	12.74363
560	0.13993	0.55972	1.25937	2.238881	3.498251	5.037481	6.856572	8.955522	11.33433	13.993
610	0.152424	0.609695	1.371814	2.438781	3.810595	5.487256	7.468766	9.755122	12.34633	15.24238
660	0.164918	0.65967	1.484258	2.638681	4.122939	5.937031	8.08096	10.55472	13.35832	16.49175
710	0.177411	0.709645	1.596702	2.838581	4.435282	6.386807	8.693153	11.35432	14.37031	17.74113
760	0.189905	0.75962	1.709145	3.038481	4.747626	6.836582	9.305347	12.15392	15.38231	18.9905

Table 59: LoF values, Do= 496.4 mm, t= 19.1 mm and Lspan= 6-8m, oil line

$D_o = 406.4\ mm$ $t = 19.1\ mm$										
$L_{span} = 6 - 8\ m$										
LoF:										
ρ, v	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
60	0.001	0.003	0.007	0.013	0.021	0.030	0.041	0.053	0.067	0.083
110	0.002	0.006	0.014	0.024	0.038	0.055	0.074	0.097	0.123	0.152
160	0.002	0.009	0.020	0.035	0.055	0.080	0.108	0.141	0.179	0.221
210	0.003	0.012	0.026	0.046	0.072	0.104	0.142	0.186	0.235	0.290
260	0.004	0.014	0.032	0.057	0.090	0.129	0.176	0.230	0.291	0.359
310	0.004	0.017	0.039	0.068	0.107	0.154	0.210	0.274	0.347	0.428
360	0.005	0.020	0.045	0.080	0.124	0.179	0.244	0.318	0.403	0.497
410	0.006	0.023	0.051	0.091	0.142	0.204	0.277	0.362	0.458	0.566
460	0.006	0.025	0.057	0.102	0.159	0.229	0.311	0.406	0.514	0.635
510	0.007	0.028	0.063	0.113	0.176	0.253	0.345	0.451	0.570	0.704
560	0.008	0.031	0.070	0.124	0.193	0.278	0.379	0.495	0.626	0.773
610	0.008	0.034	0.076	0.135	0.211	0.303	0.413	0.539	0.682	0.842
660	0.009	0.036	0.082	0.146	0.228	0.328	0.446	0.583	0.738	0.911
710	0.010	0.039	0.088	0.157	0.245	0.353	0.480	0.627	0.794	0.980
760	0.010	0.042	0.094	0.168	0.262	0.378	0.514	0.672	0.850	1.049

Table 60: LoF values, Do= 496.4 mm, t= 19.1 mm and Lspan= 9-11 m, oil line

$D_o = 406.4\ mm$ $t = 19.1\ mm$										
$L_{span} = 9m - 11m$										
LoF:										
ρ, v	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
60	0.002	0.007	0.016	0.029	0.045	0.064	0.087	0.114	0.144	0.178
110	0.003	0.013	0.029	0.052	0.082	0.118	0.160	0.209	0.265	0.327
160	0.005	0.019	0.043	0.076	0.119	0.171	0.233	0.304	0.385	0.476
210	0.006	0.025	0.056	0.100	0.156	0.225	0.306	0.400	0.506	0.624
260	0.008	0.031	0.070	0.124	0.193	0.278	0.379	0.495	0.626	0.773
310	0.009	0.037	0.083	0.147	0.230	0.332	0.452	0.590	0.746	0.922
360	0.011	0.043	0.096	0.171	0.268	0.385	0.524	0.685	0.867	1.070
410	0.012	0.049	0.110	0.195	0.305	0.439	0.597	0.780	0.987	1.219
460	0.014	0.055	0.123	0.219	0.342	0.492	0.670	0.875	1.108	1.367
510	0.015	0.061	0.136	0.243	0.379	0.546	0.743	0.970	1.228	1.516
560	0.017	0.067	0.150	0.266	0.416	0.599	0.816	1.065	1.348	1.665
610	0.018	0.073	0.163	0.290	0.453	0.653	0.889	1.161	1.469	1.813
660	0.020	0.078	0.177	0.314	0.490	0.706	0.961	1.256	1.589	1.962
710	0.021	0.084	0.190	0.338	0.528	0.760	1.034	1.351	1.710	2.111
760	0.023	0.090	0.203	0.361	0.565	0.813	1.107	1.446	1.830	2.259

Table 61: LoF values, Do= 496.4 mm, t= 19.1 mm and Lspan= 12-14 m, oil line

$D_o = 406.4\ mm$ $t = 19.1\ mm$										
$L_{span} = 12m - 14m$										
LoF:										
ρ, v	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
60	0.003	0.013	0.030	0.053	0.082	0.119	0.162	0.211	0.267	0.330
110	0.006	0.024	0.054	0.097	0.151	0.218	0.296	0.387	0.490	0.605
160	0.009	0.035	0.079	0.141	0.220	0.317	0.431	0.563	0.712	0.880
210	0.012	0.046	0.104	0.185	0.289	0.416	0.566	0.739	0.935	1.154
260	0.014	0.057	0.129	0.229	0.357	0.515	0.700	0.915	1.158	1.429
310	0.017	0.068	0.153	0.273	0.426	0.614	0.835	1.091	1.380	1.704
360	0.020	0.079	0.178	0.317	0.495	0.712	0.970	1.267	1.603	1.979
410	0.023	0.090	0.203	0.361	0.563	0.811	1.104	1.443	1.826	2.254
460	0.025	0.101	0.228	0.405	0.632	0.910	1.239	1.618	2.048	2.529
510	0.028	0.112	0.252	0.449	0.701	1.009	1.374	1.794	2.271	2.804
560	0.031	0.123	0.277	0.493	0.770	1.108	1.509	1.970	2.494	3.079
610	0.034	0.134	0.302	0.537	0.838	1.207	1.643	2.146	2.716	3.353
660	0.036	0.145	0.327	0.581	0.907	1.306	1.778	2.322	2.939	3.628
710	0.039	0.156	0.351	0.625	0.976	1.405	1.913	2.498	3.162	3.903
760	0.042	0.167	0.376	0.668	1.045	1.504	2.047	2.674	3.384	4.178

Table 62: LoF values, Do= 508 mm, t= 20.6 mm and Lspan= 8-9m, oil line

$D_o = 508mm$ $t = 20.6mm$										
$L_{span} = 8m - 9m$										
LoF:										
ρ, v	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
60	0.001	0.003	0.007	0.012	0.019	0.027	0.036	0.048	0.060	0.074
110	0.001	0.005	0.012	0.022	0.034	0.049	0.067	0.087	0.111	0.136
160	0.002	0.008	0.018	0.032	0.050	0.071	0.097	0.127	0.161	0.198
210	0.003	0.010	0.023	0.042	0.065	0.094	0.128	0.167	0.211	0.260
260	0.003	0.013	0.029	0.052	0.081	0.116	0.158	0.206	0.261	0.323
310	0.004	0.015	0.035	0.062	0.096	0.138	0.188	0.246	0.311	0.385
360	0.004	0.018	0.040	0.071	0.112	0.161	0.219	0.286	0.362	0.447
410	0.005	0.020	0.046	0.081	0.127	0.183	0.249	0.325	0.412	0.509
460	0.006	0.023	0.051	0.091	0.143	0.205	0.280	0.365	0.462	0.571
510	0.006	0.025	0.057	0.101	0.158	0.228	0.310	0.405	0.512	0.633
560	0.007	0.028	0.063	0.111	0.174	0.250	0.340	0.445	0.563	0.695
610	0.008	0.030	0.068	0.121	0.189	0.272	0.371	0.484	0.613	0.757
660	0.008	0.033	0.074	0.131	0.205	0.295	0.401	0.524	0.663	0.819
710	0.009	0.035	0.079	0.141	0.220	0.317	0.432	0.564	0.713	0.881
760	0.009	0.038	0.085	0.151	0.236	0.339	0.462	0.603	0.764	0.943

Table 63: LoF values, Do= 508 mm, t= 20.6 mm and Lspan= 10-13 m, oil line

$D_o = 508mm$ $t = 20.6mm$										
$L_{span} = 10 - 13m$										
LoF:										
ρ, v	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
60	**0.002**	**0.007**	**0.015**	**0.027**	**0.043**	**0.062**	**0.084**	**0.110**	**0.139**	**0.172**
110	**0.003**	**0.013**	**0.028**	**0.050**	**0.079**	**0.113**	**0.154**	**0.201**	**0.255**	**0.315**
160	**0.005**	**0.018**	**0.041**	**0.073**	**0.114**	**0.165**	**0.224**	**0.293**	**0.371**	**0.458**
210	**0.006**	**0.024**	**0.054**	**0.096**	**0.150**	**0.216**	**0.294**	**0.384**	**0.486**	**0.601**
260	**0.007**	**0.030**	**0.067**	**0.119**	**0.186**	**0.268**	**0.364**	**0.476**	**0.602**	**0.744**
310	**0.009**	**0.035**	**0.080**	**0.142**	**0.222**	**0.319**	**0.434**	**0.567**	**0.718**	**0.887**
360	**0.010**	**0.041**	**0.093**	**0.165**	**0.257**	**0.371**	**0.504**	**0.659**	**0.834**	**1.030**
410	**0.012**	**0.047**	**0.106**	**0.188**	**0.293**	**0.422**	**0.575**	**0.750**	**0.950**	**1.173**
460	**0.013**	**0.053**	**0.118**	**0.210**	**0.329**	**0.474**	**0.645**	**0.842**	**1.066**	**1.316**
510	**0.015**	**0.058**	**0.131**	**0.233**	**0.365**	**0.525**	**0.715**	**0.933**	**1.181**	**1.459**
560	**0.016**	**0.064**	**0.144**	**0.256**	**0.400**	**0.577**	**0.785**	**1.025**	**1.297**	**1.602**
610	**0.017**	**0.070**	**0.157**	**0.279**	**0.436**	**0.628**	**0.855**	**1.116**	**1.413**	**1.745**
660	**0.019**	**0.075**	**0.170**	**0.302**	**0.472**	**0.679**	**0.925**	**1.208**	**1.529**	**1.887**
710	**0.020**	**0.081**	**0.183**	**0.325**	**0.508**	**0.731**	**0.995**	**1.300**	**1.645**	**2.030**
760	**0.022**	**0.087**	**0.196**	**0.348**	**0.543**	**0.782**	**1.065**	**1.391**	**1.761**	**2.173**

Table 64: LoF values, Do= 508 mm, t= 20.6 mm and Lspan= 14 m, oil line

$D_o = 508mm$ $t = 20.6mm$										
$L_{span} = 14\ m$										
LoF:										
ρ, v	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
60	**0.003**	**0.013**	**0.029**	**0.052**	**0.081**	**0.116**	**0.158**	**0.207**	**0.262**	**0.323**
110	**0.006**	**0.024**	**0.053**	**0.095**	**0.148**	**0.213**	**0.290**	**0.379**	**0.480**	**0.592**
160	**0.009**	**0.034**	**0.078**	**0.138**	**0.215**	**0.310**	**0.422**	**0.551**	**0.698**	**0.861**
210	**0.011**	**0.045**	**0.102**	**0.181**	**0.283**	**0.407**	**0.554**	**0.723**	**0.916**	**1.130**
260	**0.014**	**0.056**	**0.126**	**0.224**	**0.350**	**0.504**	**0.686**	**0.896**	**1.134**	**1.399**
310	**0.017**	**0.067**	**0.150**	**0.267**	**0.417**	**0.601**	**0.818**	**1.068**	**1.352**	**1.669**
360	**0.019**	**0.078**	**0.174**	**0.310**	**0.484**	**0.698**	**0.949**	**1.240**	**1.570**	**1.938**
410	**0.022**	**0.088**	**0.199**	**0.353**	**0.552**	**0.794**	**1.081**	**1.412**	**1.788**	**2.207**
460	**0.025**	**0.099**	**0.223**	**0.396**	**0.619**	**0.891**	**1.213**	**1.585**	**2.005**	**2.476**
510	**0.027**	**0.110**	**0.247**	**0.439**	**0.686**	**0.988**	**1.345**	**1.757**	**2.223**	**2.745**
560	**0.030**	**0.121**	**0.271**	**0.482**	**0.754**	**1.085**	**1.477**	**1.929**	**2.441**	**3.014**
610	**0.033**	**0.131**	**0.295**	**0.525**	**0.821**	**1.182**	**1.609**	**2.101**	**2.659**	**3.283**
660	**0.036**	**0.142**	**0.320**	**0.568**	**0.888**	**1.279**	**1.741**	**2.274**	**2.877**	**3.552**
710	**0.038**	**0.153**	**0.344**	**0.611**	**0.955**	**1.376**	**1.873**	**2.446**	**3.095**	**3.822**
760	**0.041**	**0.164**	**0.368**	**0.655**	**1.023**	**1.473**	**2.004**	**2.618**	**3.313**	**4.091**

Table 65: LoF values, Do= 609.6mm, t= 25.4 mm and Lspan= 14 m, oil line

$D_o = 609.6mm$ $t = 25.4\ mm$										
$L_{span} = 8 - 9m$										
LoF:										
ρ, v	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
60	**0.001**	**0.002**	**0.005**	**0.009**	**0.015**	**0.021**	**0.029**	**0.038**	**0.048**	**0.059**
110	**0.001**	**0.004**	**0.010**	**0.017**	**0.027**	**0.039**	**0.053**	**0.069**	**0.087**	**0.108**
160	**0.002**	**0.006**	**0.014**	**0.025**	**0.039**	**0.056**	**0.077**	**0.100**	**0.127**	**0.157**
210	**0.002**	**0.008**	**0.019**	**0.033**	**0.051**	**0.074**	**0.101**	**0.132**	**0.167**	**0.206**
260	**0.003**	**0.010**	**0.023**	**0.041**	**0.064**	**0.092**	**0.125**	**0.163**	**0.206**	**0.255**
310	**0.003**	**0.012**	**0.027**	**0.049**	**0.076**	**0.109**	**0.149**	**0.194**	**0.246**	**0.304**
360	**0.004**	**0.014**	**0.032**	**0.056**	**0.088**	**0.127**	**0.173**	**0.226**	**0.286**	**0.353**
410	**0.004**	**0.016**	**0.036**	**0.064**	**0.100**	**0.145**	**0.197**	**0.257**	**0.325**	**0.402**
460	**0.005**	**0.018**	**0.041**	**0.072**	**0.113**	**0.162**	**0.221**	**0.288**	**0.365**	**0.451**
510	**0.005**	**0.020**	**0.045**	**0.080**	**0.125**	**0.180**	**0.245**	**0.320**	**0.405**	**0.500**
560	**0.005**	**0.022**	**0.049**	**0.088**	**0.137**	**0.197**	**0.269**	**0.351**	**0.444**	**0.549**
610	**0.006**	**0.024**	**0.054**	**0.096**	**0.149**	**0.215**	**0.293**	**0.382**	**0.484**	**0.597**
660	**0.006**	**0.026**	**0.058**	**0.103**	**0.162**	**0.233**	**0.317**	**0.414**	**0.524**	**0.646**
710	**0.007**	**0.028**	**0.063**	**0.111**	**0.174**	**0.250**	**0.341**	**0.445**	**0.563**	**0.695**
760	**0.007**	**0.030**	**0.067**	**0.119**	**0.186**	**0.268**	**0.365**	**0.476**	**0.603**	**0.744**

Table 66: LoF values, Do= 609 mm, t= 25.4 mm and Lspan= 14 m, oil line

$D_o = 609.6mm$ $t = 25.4\ mm$										
$L_{span} = 10 - 14m$										
LoF:										
ρ, v	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
60	0.001	0.006	0.013	0.023	0.036	0.052	0.071	0.093	0.118	0.146
110	0.003	0.011	0.024	0.043	0.067	0.096	0.131	0.171	0.217	0.267
160	0.004	0.016	0.035	0.062	0.097	0.140	0.191	0.249	0.315	0.389
210	0.005	0.020	0.046	0.082	0.128	0.184	0.250	0.327	0.413	0.510
260	0.006	0.025	0.057	0.101	0.158	0.227	0.310	0.404	0.512	0.632
310	0.008	0.030	0.068	0.121	0.188	0.271	0.369	0.482	0.610	0.753
360	0.009	0.035	0.079	0.140	0.219	0.315	0.429	0.560	0.709	0.875
410	0.010	0.040	0.090	0.159	0.249	0.359	0.488	0.638	0.807	0.996
460	0.011	0.045	0.101	0.179	0.279	0.402	0.548	0.715	0.906	1.118
510	0.012	0.050	0.112	0.198	0.310	0.446	0.607	0.793	1.004	1.239
560	0.014	0.054	0.122	0.218	0.340	0.490	0.667	0.871	1.102	1.361
610	0.015	0.059	0.133	0.237	0.371	0.534	0.726	0.949	1.201	1.482
660	0.016	0.064	0.144	0.257	0.401	0.577	0.786	1.027	1.299	1.604
710	0.017	0.069	0.155	0.276	0.431	0.621	0.845	1.104	1.398	1.725
760	0.018	0.074	0.166	0.296	0.462	0.665	0.905	1.182	1.496	1.847

Chapter 5 Discussion

The thesis conducted a Screening checks for a generic spool alignment using the methodology outlined in the EI guidelines by Calculating LoF values. There were also done some sensitivity analysis on the spools to see how parameters influenced the LoF due to FIV.

Whereas most of subsea facilities' integrity issues are dealt with during the design stage, flow induced vibrations is more of a forgotten problem or pushed further down the agenda. Nevertheless, the failure of this kind is considered dangerous, and the outcome is a complex and costly repair.

Specific benefits of introducing a FIV assessment in design phase would include:

- Enhanced integrity of the piping system.
- Safety improvements.
- Eliminate incidents of hydrocarbon release.
- Enhanced reliability and availability of assets.
- Meeting the existing legislation as well as guidelines for best practices in the industry.
- An enhanced design approach for installing new systems.
- Reduced incidents of shutdowns and lowered cost of maintenance.
- Allows for installations beyond existing conditions of operations and those in an existing plant.

Where the piping system is vulnerable to flow-induced vibration various approaches can be used to lessen or eradicate the problem. The main objective is to eradicate the vibration of various piping natural frequencies and the flow-induced excitation frequency match. One approach is through an increase of the piping diameter which has a negative effect on the weight and the system cost. Moreover, a configuration of the piping system is an alternative solution. By using shorter span, the system will be stiffer, and the LoF value will be low. This is essentially ideal since it eliminates the need for operational parameter changes including those involving the piping systems and the cost of the system. For example, in topside system using a three-support system in place of two can mitigate or at least reduce the problem. On the other hand, having all U-bolts piping supports where necessary as well as clamps having full circumferential bands creates a rigid system while increasing the natural frequency of the modes across the system. (Harper, 2016) The reason for doing these thing like shortening the span, increasing the diameter, and adding additional support is to get the natural frequency increased beyond the excitation frequency. Additional support like the one used in top side systems are quite challenge and are often not feasible. Nevertheless, one should be careful when using these approaches to allow for certain flexibility critical for permitting thermal movements in any piping. Less flexibility in a stiff piping system may provide high natural frequency and reduce the likelihood of flow-induced vibration although such may increase thermal stresses and reaction loads beyond stipulated limits.

Besides, another approach to reducing flow-induced vibration is to increase the piping wall thickness essentially in a small-bore piping system. From the sensitivity analysis it shows that an increase in wall thickness will decrease the LoF values. (Swindell & Hill, Guidelines for the avoidance of vibration-induced fatigue failure in subsea systems, 2018)

Chapter 6 Conclusion and Recommendations

FIV for subsea production systems (SPS) development has gained significance in design and piping system and components in the recent past because it increases production flow rates, the need for low weight and size, and the enacting of the subsea processing installation. Nonetheless, the science behind the approach is not entirely clear and certain gaps require research to streamline this method. This thesis offers an outline of the FIV prediction and analysis approaches including screening and illustrating the likely sources of acoustic and vibratory noise within the SPS and evaluating the likely excitation frequency range and source strengths essential to envisage the mechanical response related to flow-induced excitation. Screening methods are demonstrated for two mechanism using the EI Guidelines for avoiding vibration-induced fatigue failure in subsea systems. Sensitive analysis was also done for FIT were multiple inputs were evaluated to see how they influenced LoF Score. For the O&G industry screening methods used are, however, costly, time-consuming, and conservative in most instances in verifying risk and providing design changes to lessen the risk. Thus, the likelihood of influencing the budget and schedule of the project is high. In most instances, the mechanical response evaluations suggest that screening can overate the level of risk. Presently, clear FIV standards for subsea installations are unavailable and various standards from other industries are often applied. (Swindell & Hill, Guidelines for the avoidance of vibration-induced fatigue failure in subsea systems, 2018)

Summary of the major limitations

- The screening and assessment approaches are conservative. This is evident in the guidelines where a safety factor of 10 is recommended.
- There are currently no standards for subsea and validation of methodologies.
- Lack of industry practical analysis models in the current academic arena.

Moreover, the high cost associated with the engineering analysis it is often ideal to conduct these evaluations earlier. Though, the preliminary design must be finalized first before the detailed analysis is conducted. Thus, a better approach is needed to alleviate the exposure to FIV of the piping systems. What I have done

Cooperation in the field involving academia, solution providers, and oil companies can offer a clear foundation for the FIV assessments in the future. It will create a sense of a shared vision for solutions providers and organizations that cost-effectively provide products without facing integrity issues. During challenges, solution providers would seek to help operators cut costs, reduce risk and enhance investment certainty. In future developments the FIV can be a challenge because of potential HPHT environments resulting from high flow velocities and models of prediction would need to be developed to mirror future developments in HPHT. (Gharaibah, Barri, & Tungen, 2016)

Presently, topside screening methodology can be utilized although detailed evaluation approaches are necessary. Topside experience can be useful for limiting vibration during design and before deployment conduct key measurements including impact testing where ideal.

Various recommendations should be considered in developing FIV prediction approaches, they include;

- Having improved dynamic forces prediction for various pipe sizes from slug and multiphase to model the mechanical response and eventually the weariness. Results of experiments can be utilized to authenticate CFD models directly.
- O&G companies should invest in research to better understand the issue of FIV. This is especially important when more and more field are gas field which has higher FIV potential due to higher speed.

- Seek correction element for multiphase FIT having various testing approaches for example in single-phase speed of flow and different bend configurations. For example, Norton and Bull's design can be used for comparison.

- Having ideal monitoring systems may eliminate the problem in the short run, however, such an approach is costly for installations in the subsea and limit the increase of scientific knowledge concerning the phenomenon. For vibration dampers such is true because they have been used for topside but not in the subsea. The use of ROV for monitoring can be more ideal solutions than fitting the spools and subsea structure with costly monitoring devices.

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