Fluid Structure Interaction Analysis of Two-Phase Flow in an M-shaped Jumper

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Introduction

Subsea production systems require different types of pipelines to transport fluids between components. A typical pipeline in performing this function is a jumper which usually connects a tree with a manifold. Rigid jumpers are standard shaped pipes that can withstand high static and dynamic loads due to internal pressure, temperature and external fluid effects. This is basically a fluid structure interaction (FSI) problem in which internal or external flow interacts with the structure creating stresses and pressures that deforms the pipe, and consequently alters the flow of the fluid. This interaction phenomenon is important when designing a piping system since it is understood that this has effects on fatigue life of the jumper.

According to some statistics in topside facilities, up to 21% of failures is caused by neglecting this hidden vibration issue (Swindell). Subsea industry is currently putting a lot of effort in investigating vibration-induced fatigue cases to prevent costly and complex repair procedures.

Research has revealed that slug flow has a tendency to generate fatigue damage due to the transient pressures caused by motion of liquid slugs. Taitel and Dukler came with a method to determine the slug frequency of two-phase flow in horizontal pipes, in which they defined the slug frequency based on the characteristics at the inlet (Sim et al., 2010). Other studies have set a resonance case where the slug frequency approaches to the structural natural frequency, which usually drives to a high response of the pipe and potential risk of failure. Similarly, bends are key regions in forming slugs and experiencing large transient pressures which can induce high levels of vibrations (Aravind et al., 2011).

Flow Induced Vibration is one of the important phenomena that contribute to failure of jumpers. A computational study was developed to analyze vibrations caused by slug flow in a
rigid M-shaped jumper and to estimate effects on its fatigue life. Results will show a correlation between flow conditions and pipe characteristics. In this FSI problem, coupling the Finite Element Analysis (FEA) model with the Computational Fluid Dynamics (CFD) model is the best alternative to determine if the vibrations levels lead to failure of the jumper.

**Jumper Analysis**

The objective of this paper is to study the internal fluid effects on the stress distribution and fatigue life of a rigid M-shaped jumper when 50% water and 50% air flows through it. The initial velocity of the two-phase flow is 10 ft/s. Numerical simulations were performed to obtain stresses and pressure fluctuations exerted on the wall of the pipe. The purpose is to find regions of large displacements and have a curve of stress versus time that engineers can use to determine the fatigue life of the structure. Before performing a numerical analysis, a screening method was implemented to determine the likelihood of failure of the jumper due to flow induced turbulence.

**Multiphase Flow**

Subsea production systems are nowadays inclined to extract oil without previous separation from other components such as water and gas. Multiphase flow differs from single phase flow in its motion and structure response due to the usual unsteady behavior. It is a challenge for engineers to predict how multiphase flow will behave and how it will vary with time and space. They must to consider fluid properties of each phase plus the interaction between phases.

Analytical solutions are usually performed for single phase flow using basics from fluid dynamics, but two-phase flow is more difficult to predict due to many factors such as density, viscosity, volume fraction, surface tension, initial velocity, flow pattern, liquid holdup and pipe geometry.
The flow pattern dictates the behavior and characteristics of the flow. Volume fraction is one of the major factors in determining the flow pattern formed at a particular location in a pipe, and it is defined as the volume of a pipe segment occupied by liquid over the volume of the pipe segment. This parameter is considered to determine the frequency in slug flows.

**Slug Flow**

This is an unsteady intermittent flow in which chunks of liquid travel along the pipe separated by long gas bubbles known as Taylor bubbles, and it is undesirable since it can create large pressure fluctuations, cause flooding in tanks, and accelerate corrosion. There are three types of multiphase surges: terrain generated slugs, operationally induced surges, and hydrodynamic slugs (Bai and Qiang, 2010)

The hydrodynamic slug is the only form of multiphase surge that a jumper is likely to experience due to its geometry and operation condition. This hydrodynamic slugging happens when an unsteady state is created as a result of the instability at the interface between air and water. As shown in Fig. 1, a stratified flow is initialized with both fluids having the same entrance velocity. As the two-phase flow travels along the pipe, the liquid starts slowing down because of the higher shear stress at the wall. When velocity difference is too high, the hydrodynamic air force exceeds the surface tension at the interface, which lifts the interface in the form of a wave. This wave can reach to the top of the pipe, and subsequently the gas is blocked by the liquid (slug). The liquid slug is then pushed by the gas that entrains small bubbles (turbulence) into the slug. The amount of turbulence and the growth rate of the slug will determine the pressure drop and size of the slug in the jumper. Slug velocity, frequency and volume fraction of liquid are the design parameters in a jumper with multiphase flow.

**CFD Model Verification**
A laminar flow through a straight pipe example (from Applied Fluid Mechanics by Robert Mott, 6th edition) was simulated in Star CCM+ to identify features and advantages of this CFD engineering software, and validate the results obtained with the analytical solution.

The problem consists of glycerin flowing at an average velocity of 3.6 m/s in a 150 mm diameter pipe. The density and dynamic viscosity (μ) of glycerin at 25 °C are 1258 kg/m³ and 9.60x10⁻¹ Pa-s respectively, which corresponds to a Reynolds number of 708 (laminar). The length of the pipe is 8 m.

To calculate the local velocity for laminar flow, the following equation is used (Mott, 2006):

\[ U = 2v \left[ 1 - \left( \frac{r}{r_o} \right)^2 \right] \]

The maximum velocity occurs at the centerline of the pipe with a value of \(2v\) (7.2 m/s). Comparing this value with the computational velocity in Star CCM+, there is less than 1 percent error.

Also, the pressure drop through the pipe can be calculated using the Hagen–Poiseuille equation. This gives a theoretical value of 13221.9 Pa. The simulation results in only 0.14 % difference with respect to the analytical pressure drop.

**Jumper Description**

A rigid M-shaped jumper is the configuration that will be studied and its dimensions are shown in Fig. 2. The rigid jumper is made of carbon steel grade 65. Properties and cross section characteristics are listed on table 1.

**Modal Analysis**

A modal analysis was carried out using the Finite Element Method (FEM) to determine the natural frequencies when structure vibrates freely.
One of the cases of this study is a model of the first two bends of the jumper and its fundamental natural frequency whose value is 1.079 Hz, was extracted from Abaqus. For the boundary conditions, both ends have neither rotation nor translation. The jumper model was meshed using linear elastic stress hexahedral elements (8-node brick) for a total of 9960 elements.

This study will focus on simulating a mechanical resonance case such that slug frequency is set to match the first natural frequency of the system, which amplifies the response and therefore increases the risk of structural failure. The first modes generate higher amplitudes of vibration and therefore experience higher dynamic responses. Table 2 shows the frequencies for the first four modes. The mode shape of the fundamental natural frequency of the jumper is shown in Fig. 3 with the highest displacement at the middle section.

**Two-Way Coupling Analysis**

By coupling the CFD solver with the FEA solver, the deformation of the jumper resulting from the fluid pressures can be determined and then fatigue life calculation is derived from stress vs. time graph.

For two-way coupling, Star CCM+ imports the pressure fluctuations into Abaqus, then Abaqus calculates the displacements to export them to Star CCM+, and cycle starts again. Both programs run simultaneously and exchange data each time step.

The Reynolds-Averaged Navier-Stokes (RANS) was the turbulent model selected since it is less computational demanding and well approximated. For the CFD program, the jumper was meshed using polyhedral elements that are extruded along the length of the pipe. There are a total of 640159 cells.
The following physics models were specified for both simulation and co-simulation: three dimensional, implicit unsteady, Eulerian multiphase, Volume of Fluid (VOF), segregated flow, $k-\omega$ turbulence, all $y+$ treatment, gravity, and cell quality remediation.

**Results**

**Two-bend simulation**

A simulation with a time step of 0.004 seconds and a $k-\omega$ under-relaxation factor of 0.2 was carried out to keep a balance between accuracy and computational time. There are a total of 295000 cells.

The flow starts running upwards, then stabilizes in a horizontal section and finally falls towards the vertical pipe of the outlet.

The two-phase flow was initialized as stratified flow (50% water-50% air) even though it is not one of the flow patterns in vertical pipes. As the two-phase flow accelerates, the air increases its velocity instantaneously due to the difference in density. Water, in the other hand, tends to lean towards the air region because of the gravity. Water compresses the column of air against the wall, and again the air accelerates. The hydrodynamic force of air creates surface tension at the interface and then vertical waves are generated as shown in point A of Fig. 4. The kinetic energy of the air is too high preventing water to exert a significant force on the wall of the bend. Once both fluids reach to the horizontal section, a stratified flow is formed with a thick interface (point B). From this point, the flow repeats the same patterns as described for the one-bend case.

High turbulence is induced after the bend due to the high kinetic energy of the flow and a bubble of about 2 diameters is developed (point C). Air is then mixed with water forming irregular bubbles of gas that carries droplets of water with them. Small bubbles start merging
each other until an elongated shape with a thin film of water wetting the wall is formed as shown in point E. This Taylor bubble blocks the path of the water and then the slug generates a pressure that makes small bubbles coalescing into the slug. Point F represents a cross section of the slug, which goes from the tail of the gas at point E to the outlet. When the gravity force exceeds the buoyancy effect of the air, the intermittent flow is interrupted and water passes through and churn flow will be developed at the third bend of the jumper.

The slug period was determined by tracking and recording the time the slug takes to travel downwards until another slug appears at the same location. The period between slugs is 0.96 s which corresponds to a frequency of 1.0417 Hz. This is considered as a resonance case since the fundamental natural frequency (1.079 Hz) matches with the slug frequency.

**Jumper Simulation**

For the jumper, the flow follows the predicted patterns from the two-bend simulation. A slightly change is the vertical section after the fourth bend in which the two-phase flow travels upwards. The water being denser blocks the air and this starts pushing the slug upwards as shown in plane D Fig. 6, where the fraction of water is about 65 % after 22.5 seconds of flow according to the time history of the simulation. Once it reaches the fifth bend, water is discharged at the horizontal section and air finds a clear path to keep running freely.

A churn flow is developed shortly after the bend to make a transition to an uneven stratified flow with 80-85 % of water at the bottom layer and a mixture of 50 % at the top. The two-phase flow hits the wall of the bend and air merges at the last section with low pressure and escapes easily at the outlet.

The slug frequency can be predicted by taking the difference in time between two peaks when a discernible pattern is observed. However, the periods between peaks for plane D ranges
from 0.92 to 2.2 seconds (Fig. 7), which corresponds to a frequency range from 0.444 Hz to 1.087 Hz. The average frequency is about 0.7 Hz, which is to a certain degree close to the structural natural frequency.

Pressure fluctuations are higher for the first four bends with the 3rd and 4rd having the greater response with a maximum pressure of 6.9 psi. This agrees with the locations and time periods of the slugs which exert high forces on the bends. After 12-13 seconds, the two-phase flow reaches steady state.

**Stresses and Displacements**

From the structural analysis, stresses and displacements were computed in Abaqus for the 20 seconds in the two-bend co-simulation. The two-phase flow causes the pipe to displace 0.0725 inches at the second bend. This occurs after 8.28 seconds and its deformed shape can be clearly seen from the top view in Fig. 9.

For the two-bend case, the maximum von Mises stress is 400 psi and occurs at the fixed end on the outlet region. This stress is below the yield strength of carbon steel, which is 40000 psi.

Dynamic stresses are fluctuating with time and location. A critical point is at the bends where the two-phase flow hits the wall and significant vibrations might be generated. An element at the second bend was selected to plot the von Mises stress vs. time (Fig. 10). According to the results, a steady state is achieved around 6 seconds and the stress varies from 20 psi to 34 psi with the passage of slugs. From this data, the response frequency is about 0.167 Hz for this resonance case.

Having the response frequency of the system, a fatigue analysis can be performed to check if the response is high enough to generate significant vibrations.
Conclusions

This study analyzed the internal air-water two-phase flow behavior in an M-shaped jumper and described a numerical method that solves this fluid structure interaction problem efficiently. The instability of two-phase flow, specifically slug flow, can induce significant levels of vibration and reduce the fatigue life of the jumper. Designing a methodology that predicts the effects of slugs has been a challenge for engineers due to the complexity behavior of slug flow.

The two-way coupling, which couples the FEA solver (Abaqus) and the CFD solver (Star CCM+), is a technique that simulates the effects of the pressure fluctuations from the two-phase flow in the structure. This is optimum for slug flows which might generate large amplitude deformations such that the structure of the flow is altered. Once the pressure fluctuations are exported from Star CCM+, Abaqus determines the stresses and displacements, and those displacements are exported to Star CCM+.

The two-phase flow was initialized as stratified with a volume fraction of 50% water and 50% air. It was found that slugs are randomly developed in vertical sections of the jumper.

For vibrational analysis, the structural natural frequency of the jumper should be fall out of the range of the slug frequency to avoid a resonance case. It was found that the slug frequency estimated for the two bend case of the jumper matches with the structural natural frequency, which generates a discernible pattern in the response frequency.
References


Figures and Tables

Figure 1. Formation of a hydrodynamic slug

Figure 2. Dimensions of the M-shaped Jumper
**Figure 3.** Mode-1 shape for jumper model – isometric view

**Figure 4.** Volume fraction of water after 7.4 seconds for two-bend simulation
Figure 5. Tracking of a slug in vertical section of two-bend model
Figure 6. Contour of volume fraction of water after 22.5 seconds for the second half of the jumper

Figure 7. Time history of volume fraction of water for plane D and E
Figure 8. Time history of the pressure fluctuations for the first four bends of the jumper.
Figure 10. Stress oscillations with time of the two-bend model.

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Table 1. Carbon Steel properties and cross section parameters.

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Table 2. Structural natural frequencies for 1st modes of jumper.