Pipeline Dynamics with Flowing Contents in Abaqus/Standard

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Abstract: Increasing demand for the supply of oil and gas creates great challenges in the design of subsea pipelines. Pipelines that traverse a rough seabed terrain or lay over pipe supports may have large spans of up to several hundred metres where there is no contact between the pipeline and seabed. The behaviour of these is often investigated within Abaqus using dynamic analyses of models primarily constructed of pipe elements. Pipelines that transport multi phase flow potentially involve slugging issues. Slugging issues occur due to the variation of the content density of the pipe which can introduce changes in the loading and inertia of the pipeline giving rise to pipeline fatigue failure.

Capturing the change in inertia of the flowing contents within a pipe introduces some modelling challenges. This paper discusses a method to address this challenge by the creation of a moving tie constraint via the MPC user routine. The moving tie constraint supports the attachment of mass to the pipeline which then progresses along the pipe at a predefined velocity. This approach allows the change in weight; change in inertia and effects of fluid momentum to be correctly and conveniently captured using dynamic modelling.

Keywords: Fatigue, Pipes, Pipeline Dynamics, Mass, MPC.

1. Introduction

Abaqus is often used for modelling the structural behaviour of subsea pipelines. Modelling approaches often consider the mass of products inside the pipe as additional mass attached and integral to the pipeline. This approach is reasonable when the density of product is largely unchanging, or changes only slowly. However, when the density varies rapidly the approach can introduce approximations, especially in dynamic modelling.

The goal of the work described in this paper is to develop a modelling approach which is able to correctly predict pipeline dynamics with a variable density flowing product. The approach should capture the changing weight, inertia and momentum as the variable density product flows along the pipeline.

This paper first describes the phenomena of slugging which causes rapid variations in product density in subsea pipelines. Various Abaqus/Standard modelling approaches are then described followed by the development of a user routine that is able to more conveniently model the application. The routine is then applied to example industry applications to demonstrate its capabilities.

2. Slugging

Many subsea oil reservoirs produce a mixture of oil, gas, condensate and water which is transported in a single pipeline. The proportion of each of these products change with both the operating conditions and the life of an oil field. At high velocities products flow as a mixture. At low velocities the products flow separately, although evenly distributed along a pipe. However, at intermediate velocities and when sufficient fluid content exists (about 75%) slugging can occur where the fluid accumulates into slugs filling the diameter of the pipe and the gas forms into bubbles. For example there may be a 60m long fluid slug followed by a 20m gas bubble, followed by another fluid slug, and so on. Furthermore, the sizing of pipes tends to produce flow velocities conducent to slugging at around 8m/s. Under the appropriate conditions the slugs will occur continuously and at an average frequency of perhaps one every ten seconds.

In some cases, pipelines that are laid on the seabed span large distances (100's of meters) where there is no contact between the pipe and the ocean floor. In these instances the weight of the pipe and its product dictate the pipelines deformation and stresses. When the density of the product changes the stresses in the pipeline change at the free spans. In slug flow the density of the slug could be eight times that of the gas bubble and consequently introduces cycling of stresses and potential for fatigue. Tolerance to slug flow induced fatigue can be an important design objective at spans.

3. Modelling Approaches

There are several inbuilt options available for modelling the effects of the variable density of the flowing product within Abaqus/Standard.

Application of changing distributed loads can be used to capture the effects of the products changing weight. This can be achieved either directly via the input file with multiple load definitions or via a DLOAD user subroutine. The effects of momentum changes as fluid flows around predefined bends in the pipeline can also be included by this method (Cooper, 2009). However input complexities soon become significant with this approach. Changes in the pipelines inertia are also ignored.

The effects of varying inertia can be included by addition of mass elements to the pipeline with at least one mass element per pipeline node. The additional mass elements can then be activated and deactivated as required using model changes. Unfortunately model changes occur over the duration of a step and consequently a large number of model change steps would be required to smoothly capture the effects of a flowing product in a dynamic analysis. Losses or gains in kinetic energy with activation or deactivation of mass elements is also somewhat questionable.

Rather than activation and deactivation, the additional mass elements can be transported along the pipeline. Transport of mass captures all desired effects of changing weight; inertia and momentum. The most convenient inbuilt manner to transport the mass elements is to attach their nodes to the pipeline using slideline contact. Slideline contact is typically used to model the contact of a cylindrical body within (or outside) another cylindrical body, such as a pipeline within a borehole. The additional mass elements can be considered as cylindrical bodies contacting the interior of the pipeline. Unfortunately there are two disadvantages of this approach; firstly slideline contact does not support zero clearance (or a tied option). Consequently some clearance must exist and the contact status must be continually resolved which is undesirable especially in a dynamic analysis. Secondly, controlling the movement, or speed, of the mass elements along the pipeline requires extra boundary conditions on the masses which are cumbersome; especially for non-straight pipelines. The boundary conditions can also conflict with the master-slave relationships of the slidelines and require introduction of springs (either on the masses or pipes) to avoid overconstraint.

4. Moving Tie Constraint

The Abaqus MPC user routine interface allows implementation of quite arbitrary multiple point constraints where the degrees of freedom of one node (the dependent node) are replaced by a function of degrees of freedom of other nodes (independent nodes). This interface was used to create a constraint which conveniently moves mass along a pipeline. The user routine constrains the nodes of additional mass elements to the axis of the pipeline and simultaneously transports those nodes along the pipeline at a predefined speed. This can be described as a moving tie constraint.

The nodes on the masses are the dependent nodes. The nodes on pipeline are the independent nodes and are assumed to define a continual path along the whole pipeline. Although typically all pipeline nodes are defined as the independent nodes, the position of each dependent node is tracked and the constraint equations are continually updated to constrain the dependent node only to the two independent nodes of the closet segment of the path.

Constraints in axial and lateral pipeline directions are treated differently as discussed in the following sections.

4.1 Lateral Constraint

The current version of the routine constrains the lateral position of the dependent node to a straight line between the independent nodes of the closest path segment. This constraint is straight forward to impose and is consistent with the linear displacement field used in the formulation of the linear (**PIPE31**) elements typically employed for the pipeline analysis. That is; the dependent nodes move along the axes of the **PIPE31** elements. However this linear constraint does result in sharp corners in the path at bends the pipeline. Such sharp corners can generate spurious vibrations in the loading of the pipeline and necessitates a fine mesh in some areas.

Work is currently underway to increase the order of lateral constraint to cubic using nodal rotations as well as displacements to define the path. This should eliminate the sharp corners in the path and reduce the spurious vibrations. Initial curvature in the path could also be included by utilising initial nodal normals. However, introduction of dependency on rotations suggests that moments (as well as forces) should be transmitted to the independent nodes. This would be consistent with the formulation and use of cubic (**PIPE33**) elements but is inconsistent with linear elements. Further investigation is required on this topic to determine if moment transmission is appropriate for a cubic constraint.

4.2 Axial Constraint

Three options have been implemented for constraint of the dependent node in the local axial directions of the pipeline:

- Pipeline attached defined speed: The dependent nodes progress along the pipeline at a speed dictated by a predefined field and the length of the path segments. Any applied or inertial forces on the dependent nodes in the axial pipeline directions are transmitted to the pipeline. For example, in a riser (vertical pipe) the weight of the fluid is carried by the pipe.
- Ground attached defined speed: The dependent nodes progress along the pipeline at a speed dictated by a predefined field and the length of the path segments. Any applied or inertial forces on the dependent nodes in the axial pipeline directions are transmitted to ground. For example, in a riser the weight of the fluid is not carried by the pipe but is reacted to ground.
- Axially free: No constraints are applied in the pipeline axial direction and the dependent nodes can slide freely along the pipe.

The difference between the first and second options relate to the treatment of the axial forces. In practice, for fluid flow, the axial forces are a result of pressure differences along the pipeline. Detailed inclusion of this effect is beyond the scope of the current work and hence the above approximations are provided.

In all cases instantaneous axial directions are used for application of the constraints. Depending on the application, the path length can be based on either the instantaneous lengths of the segments or the initial lengths.

5. Sleeper Span Slug Flow

Figure 1 shows an example of a finite element model of a pipeline laid on the ocean floor and across a concrete sleeper. The section of pipeline is 300m long; has a diameter of approximately 0.4m and is modelled with typically 1m `PIPE31` elements (a finer mesh is used in the sleeper contact region). The sleeper, shown as a cylindrical body, is 0.5m high. The model is shown after the laying operation which takes several analysis steps to perform starting with a straight pipeline. Due to the pipelines length the view is shown looking almost along the axis of the pipeline. Figure 1a shows the stress distribution along the pipe and Figure 1b the contact pressure.

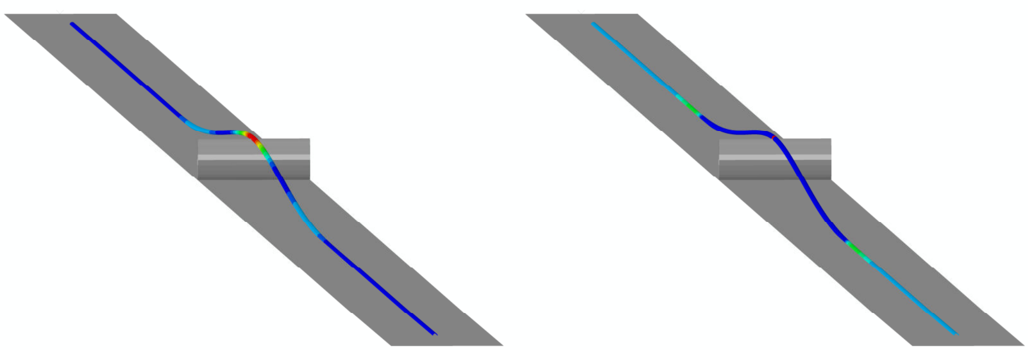

Figure 1. Pipeline and Sleeper Model, (a) Von Mises Stress, (b) Contact Pressure.

The products transported through subsea pipelines can be quite hot and create significant thermal expansion and an associated increase in the length of the pipeline. Restraint of this increase in length can result in large uncontrolled lateral buckles in the pipeline causing damage. To relieve the thermal expansion sleepers are placed at regular intervals along the pipeline and act as imperfections to initiate buckling at multiple locations; the multiple small buckles along the pipeline being less damaging than a single large buckle.

A significant free span can be seen either side of the sleeper. In this example the distance between sleeper and the point of first contact with the seabed is approximately 60m.

Figure 2 shows a view of the side of the pipeline with the pipeline full of gas. The vertical (only) displacement is scaled 50 times so that it is visible against the length of the span . Von Mises stresses in the top fibre of the pipe are show on the contour.

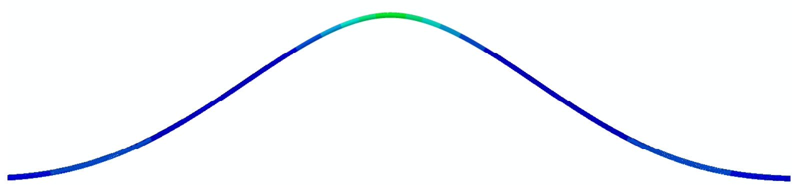

Figure 2. Pipeline Side View and Stresses.

5.1 Single Slug

The mass of a 60m oil slug was added to the pipe using mass elements with a uniform 0.1m separation. These where constrained to the pipeline using the user MPC's and given a speed of 8m/s (left to right). A dynamic implicit analysis was performed over a 60s time period.

Figure 3 shows snapshots of the pipeline at four different slug transition times; without slug; slug to the left of sleeper (32s); slug centrally over the sleeper (35s) and slug to the right (38s). The mass elements can be seen in black attached to the pipeline.

The pipeline tends to see-saw back and forth on the sleeper as the slug moves along the pipe. When the slug is to the left of the sleeper the extra weight depresses the left side and the right side lifts. The reverse occurs as the slug moves to the right. No sliding of the pipe on the sleeper is apparent. Note that the vertical deformation is scaled by 50 and hence it appears that the pipe pivots on a knife edge, when actually it pivots on the cylindrical sleeper.

The free span decreases to a minimum of 27m and increases to a maximum of 72m with the see-saw action. This continual change in span raises concerns for the pipe to seabed contact behaviour. In areas where the contact is repeatedly opening and closing local changes to the seabed shape may occur further affecting the span.

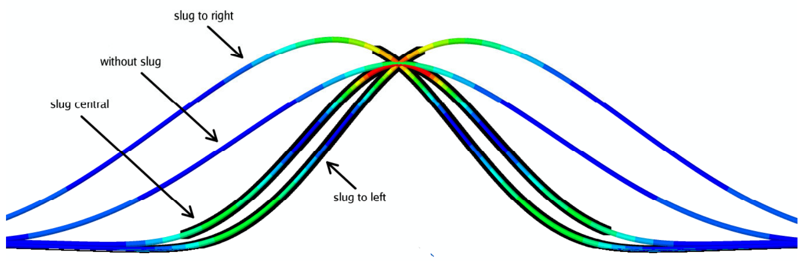

Figure 3. Snapshots at Four Slug Positions.

Figure 4 shows the stress history in the pipe at the position central to the sleeper which is the most severely stressed location. The increase in stress caused by the passing slug is clearly visible.

The stress history is slightly asymmetric around the time when the slug is centrally over the sleeper. This asymmetry is produced by the dynamic effects which are relatively small in this example. A static analysis produces a response which is symmetric.

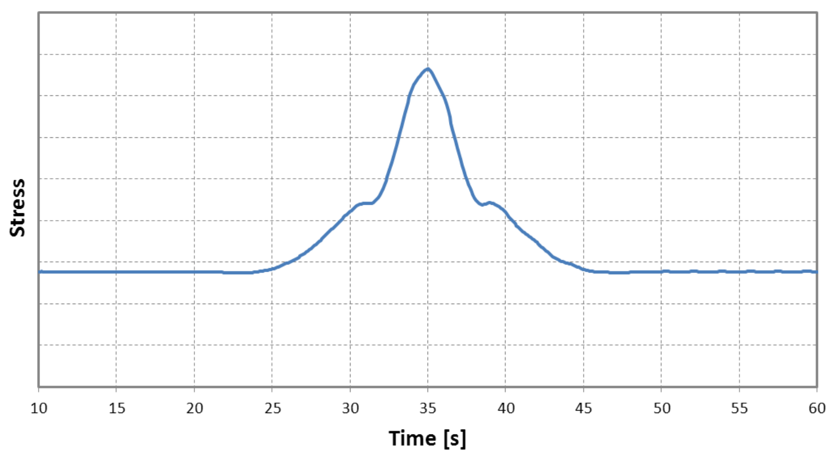

Figure 4. Stress History of Pipeline at Sleeper, One Slug.

5.2 Multiple Slugs

The single slug was replaced by a series of four evenly spaced slugs to investigate the behaviour under continuous slugging conditions. Figure 5 shows the stress history in the pipe at the location central to the sleeper.

The large peaks coincide with each of the slugs being centrally over the sleeper. The smaller peaks occur when the bubble is over the sleeper and slugs equal distance either side of the sleeper. This double peaked response is interesting and critical in calculating the stress range.

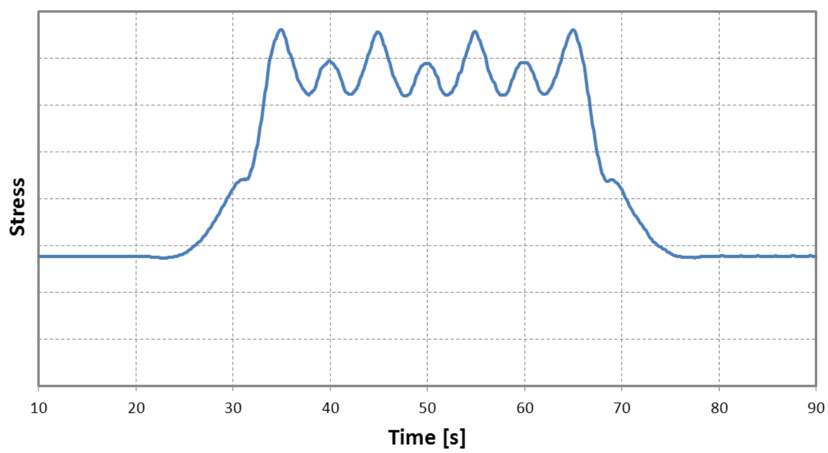

Figure 5. Stress History of Pipeline at Sleeper, Multiple Slugs.

Analyses of this type allow slug flow induced fatigue to be determined. Of course from a design validation perspective a series of simulations need to be conducted covering a wide range of potential slugging conditions.

6. Jumper Spool Slug Flow

Figure 6 shows an example finite element model of a jumper spool. Jumper spools are used to connect subsea wellheads to other equipment. The length of the spool is approximately 30m and is only supported at its ends.

The figure shows the spool loaded by self weight and gas. Von Mises stresses in the top fibre of the pipe are show on the contour.

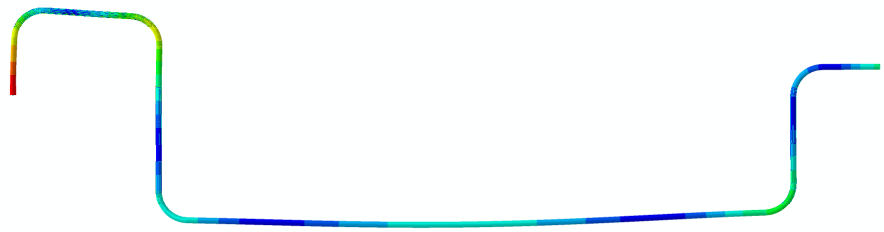

Figure 6. Spool and Stresses.

The mass of four evenly spaced slugs was constrained to the pipe using user MPC's and given a speed of 8m/s. The slugs were 60m in length with a 20m separation and consisted of 0.1m spaced mass elements. Analyses were conducted for a duration of 60s.

Figure 7 shows snapshots from a static analysis with slugs at four different transition times; without slug; slug on the left half of spool (9.8s); slug centred on spool (14s) and slug to right half of the spool (17.2s). The displacements are scaled 200 times so the deformation is clearly visible.

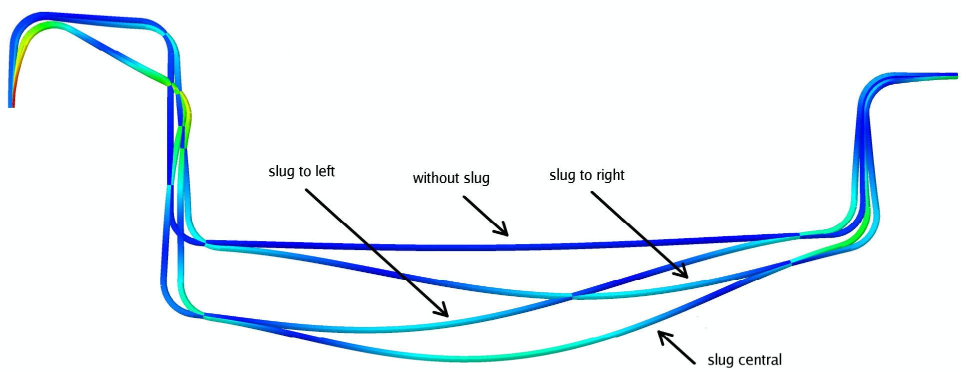

Figure 7. Snapshots at Four Slug Positions.

Figure 8 shows the stress history at the most highly stressed element in the model (left support) for static and dynamic analyses.

For the static analysis the slugs apply additional weight loading to the structure. For the dynamic analysis the slugs also apply additional loading due to their change in momentum as they traverse the bends in the pipe. This loading is the primary cause of the difference is stresses in two results shown in Figure 8

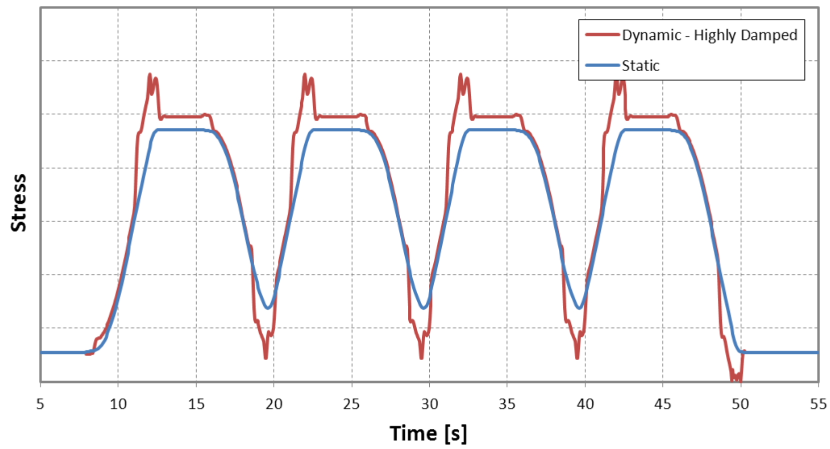

Figure 8. Stress History of Most Highly Loaded Location, Static and Dynamic.

The dynamic analysis results in Figure 8 were generated with high damping and essentially show little vibration of the spool. Figure 9 shows further dynamic results with lower damping factors and vibration of the spool is clearly evident.

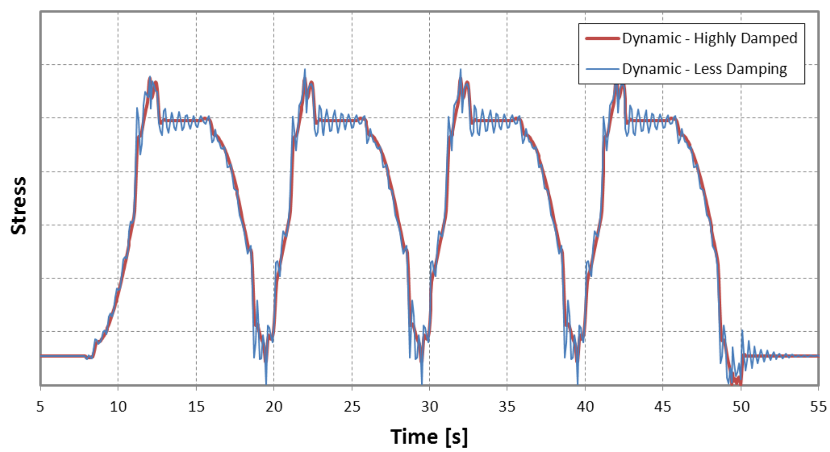

Figure 9. Stress History, Dynamic, High and Reduced Damping.

The dynamic analyses demonstrate some sensitive to time increment sizes and some care in selection of stepping parameters is beneficial in obtaining accurate (and noise free) results. Investigation into this topic is continuing although it is clear that relationships exist between ideal time step sizes and the spacing of the mass elements. Some randomness in the mass element sizes and spacings may also be a better choice than the uniformly sized and spaced elements used here.

7. Conclusion

Slugging is a phenomenon that occurs naturally in the flow of some subsea oil and gas pipelines. This results in significant and cyclic changes to the density of the flowing products. In regions where pipelines span the cyclic variability in density can cause significant cyclic stresses which can result in fatigue of the pipe.

Structural modelling of the pipeline with slugging is non-trivial in Abaqus especially where dynamic behaviour is important. This paper has described the creation of a user MPC routine that allows additional mass elements to be attached to the pipeline and transported along it at a predefined speed. The capability is best described as a moving tie constraint and allows convenient modelling of slugging. The effects of changing pipeline weight; inertia and momentum are correctly captured.

The moving tie constraint was applied to typical industry applications to demonstrate its capabilities.

8. References

1. Cooper, P., "Fatigue Design or Flowline Systems with Slug Flow", Proceedings of the ASME 2009 28th International Conference of Ocean, Offshore and Arctic Engineering, OMAE2009, 2009.