Modeling and Measuring Dynamic Well Intervention Stack Stress
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Abstract
This paper reports the field results obtained from application of a system that provides both pre-job modeling capabilities and real-time monitoring of maximum stress levels in the entire intervention stack, from the wellhead to the injector assembly. In addition, the paper documents the dynamic movement capabilities recently incorporated in the model and validation of the model calculations.

Introduction
Reference 2 discusses an intervention riser safety system which has become known as the μ (Zeta) Safety System. This paper documents further development and testing that has been done with this system. The system is composed of two basic components:

1. μ model – a numerical dynamic simulation model which models the stresses in an intervention stack.
2. μ gauge – a lubricator spool, instrumented with fiber-optic strain gauges, is placed in the intervention stack. It measures axial force, internal pressure, and bending moments in the spool.

The initial coiled tubing (CT) field application of this safety system was performed to satisfy several primary objectives, including:

- Validation of modeled calculations versus field data measured by independent devices
- Sensitivity of the field stress measurements provided by the system
- Confirmation that system design and calibration is sufficiently robust for routine field applications

The ability to accurately model dynamic movement of two independent structures was driven by increased utilization of floating structures (TLPs and Spars) being deployed in deepwater projects. The tethered topside structure typically exhibits some amount of horizontal displacement in a figure-eight pattern as a result of wave motion, with the wellhead exhibiting a similar displacement pattern but with differing frequency and amplitude. The intervention stack may experience increased stress levels when each end of the rigid lubricator/riser assembly is attached to these two independently-moving bodies. A dynamic modeling capability incorporated in this model addresses these field conditions.

In addition, offshore intervention stacks are becoming taller to accommodate offshore floating structure size, and often pass through multiple deck surfaces that constrain lateral stack movement. This can create a condition whereby conventional safety limits are exceeded. While contrary intuitive, removal of lateral stack constraints may actually increase the safety of a given stack. Another finding is that the maximum stack stress may occur in situations where no CT hanging weight is applied to the stack.

The pre-job modeling capabilities of the system are used to optimize intervention rig-up design and to determine the probability of exceeding pre-set safety limits during the operation. During the field operation, real-time stress values provided by the system enable informed decisions, rather than a judgment call, to be made if maximum stress levels are approaching unsafe limits.

Failure Modes
There are two ways an intervention stack can fail.

Buckling
Buckling occurs due to instability in the structure. A long slender column will fail when a compressive “buckling load” is applied to the column. The classical method of calculating this buckling load is known as an Euler buckling calculation. There are several models in the industry that use Euler buckling calculations to try to determine if an intervention stack design is within safe operating limits. There are several problems with this calculation technique which may cause it to be non-conservative:

- A K factor is required for the Euler equation, which is selected based upon the end conditions of the column. Real world intervention stacks often have more complicated end conditions than those provided for with theoretical Euler buckling. Often the K factor is
misapplied. Fortunately, this error is usually on the side of caution.

- The Euler models apply to a straight, constant diameter, weightless column. An intervention stack has large BOPs, small lubricator, larger valves, all of which are far from weightless! The buckling loads given by the Euler model are non-conservative when compared to the real buckling loads.

- These Euler models cannot handle the complex loading conditions and supports found in a typical intervention stack. Side loads such as coiled tubing reel back tension, bending moments applied by off-center loads, guy wire or chain supports attached at various locations along the stack, and the bending and dynamics of moving wellheads and platforms (SPARs and TLPs) cannot be considered in these models.

With all of these shortcomings, why don’t we hear of more failures due to catastrophic buckling? The authors have studied many different intervention stacks and found that even though accurate modeling had not been performed, most stacks had buckling loads far higher than any expected working loads. Tall stacks (100 ft or more in height) which use 4 1/16” or 5 1/8” lubricator would buckle if they weren’t supported along their length. But these stacks are usually on offshore platforms and pass though several decks at which lateral supports are provided.

**Bending**

Bending or yielding of a stack component is considered a “failure” in engineering terms, but often does not result in a catastrophic event such as the collapse of the stack or a release of well pressure. Thus, bending failures are often not counted as failures. They may be counted as a “near miss”, if they are counted at all. Yet this type of failure is much more common than a buckling failure.

Until this \( \zeta \) model was completed, there were no commercially available models (to the authors’ knowledge) which determined the stresses in an intervention stack due to pressure, bending, axial load and dynamic forces. A long intervention stack may have relatively low combined stresses when it is static, but when it begins to sway dynamically due to reel back tension surge, wellhead movement and/or platform movement, the stresses can increase very rapidly. One method of avoiding bending of the stack is to use a flexible component at some point in the stack such as a titanium lubricator section. However, without a good modeling tool it is difficult to determine when and where in the stack such a flexible component is needed.

**Dynamic 3D Finite-Element \( \zeta \) Model**

A 3D nonlinear finite-element model, originally written to model BHA bending in wellbores, was modified to model well intervention stack structures. The resulting model, known as the \( \zeta \) (Zeta) model, calculates the dynamic response of the structure and the Von Mises stresses throughout the structure. The static version of this model has been documented in references 1 and 2. This static model was converted into a dynamic model by adding a finite-difference time step iteration.

The fundamental equation for the dynamics calculation written in matrix form is:

\[
MA_i + BV_i + KU_i = R_i \quad (1)
\]

Various forward difference schemes for calculating the velocity and acceleration were tried. The following calculation provided the most satisfactory results.

\[
V_i = \frac{(3U_i - 4U_{i-1} + U_{i-2})}{2dt} \quad (2)
\]

\[
A_i = \frac{2U_i - 5U_{i-1} + 4U_{i-2} - U_{i-3}}{dt^2} \quad (3)
\]

Substituting these equations into equation (1) and rearranging yields:

\[
\begin{bmatrix} K_{dyn} + K \end{bmatrix} U_i = R_i + R_{dyn} \quad (4)
\]

Where:

\[
K_{dyn} = \frac{2M}{dt^2} + \frac{3B}{2dt} \quad (5)
\]

\[
R_{dyn} = \frac{M}{dt^2} \left[ 5U_{i-1} - 4U_{i-2} + U_{i-3} \right] + \frac{B}{2dt} \left[ 4U_{i-1} - U_{i-2} \right] \quad (6)
\]

Thus the basic finite-element \( K \) and \( R \) matrices are modified to include the dynamic components as is shown in equation (4) for each time step. Another version of these equations was developed to allow for varying time step lengths. The length of each time step depends upon the processing speed of the computer and the number of iterations required to converge. The speed of the average new PC today is sufficient enough to run most stack simulations in real-time. The presence of guy wires in the stack simulation will cause the number of iterations to increase.

The \( \zeta \) model allows modeling of a complex structure with unlimited supports, guy wires (or chains), and applied loads and applied moments to be defined by the user. The loading in the guy wires varies as the guy wires are stretched, and the load disappears if the guy wire goes slack. The user can force the stack to have specific displacements in cases where misalignment occurs. Wellhead and platform movements are defined using sinusoidal, periodic motion and can provide a simple figure eight movement pattern or a more complex movement pattern. The wellhead and platform can move independently of each other. All of these capabilities add complexity to the dynamic model.

**Validation of the \( \zeta \) Model**

For any numerical simulation model, it is necessary to validate that the model results are correct. Extensive validation testing was performed for the \( \zeta \) model. Some of that validation testing is summarized below.
One proof of validity for a model of this type is the calculation of buckling loads. In contrast to the Euler buckling equation discussed above, the \( \zeta \) model doesn’t utilize any buckling equations. Instead, the finite element analysis (FEA) becomes unstable when the stack becomes unstable. Thus, a simple vertical pipe with simple loading can be modeled for validation purposes, and the results should compare well with the Euler buckling calculation.

Another simulation was performed using 7 1/16” lubricator, with no supports at the rig floors. Thus the structure was only supported at the wellhead and at the top of the injector. This scenario had a much lower bending stress, and a high buckling load.

Conclusions from this study:

- The lubricator should not be restrained at any of the rig floors.
- No crane or support structure is needed.

These conclusions were much different than expected. The resulting structure is less complex, less time consuming to install, easier to operate, and thus less expensive than the original anticipated stack design.

Example – 5,000 ft Subsea Riser

Recent improvements to the \( \zeta \) model have made it capable of modeling very long “stacks” which include a subsea riser. Wind and/or water current loading can be applied along the length of the stack. Figure 4 shows the upper portion of such a model. The current loading varies in direction by 45° through the 5,000 ft of water depth. The boat is moving in a figure eight pattern which is 20 ft in the north/south direction and 10 ft in the east/west direction. This simulation allows the vertical force with which the boat is holding the lubricator to be varied. Ideally, this could be done without a compensation system holding the injector.

Initial results indicate that the change in vertical force at surface transfers quickly to the subsea wellhead. If the force is released below some threshold value, the riser will buckle above the wellhead.

Field Results with the \( \zeta \) Safety System

The \( \zeta \) Safety System, described in reference 1, has been exercised in real-time mode during well intervention field operations to ensure the system is robust and to further validate its measurements (Figure 2). The system provided accurate data with no operational difficulties during multiple days of operation. It was also confirmed that the calibration of the \( \zeta \) Gauge was very stable.

The fiber optic strain gauges utilized in the \( \zeta \) Safety System were expected to provide measurements of stress level changes in the well intervention stack, and a quick review of the measurements from an actual field job confirm this. Figure 5 contains a plot of the measured axial force (in this case coiled tubing weight) and bending moment recorded by the \( \zeta \) system. The “Z” bending moment is the loading applied in the left/right directions, as if you were in the coiled tubing unit control cabin and looking directly at the wellhead. The “Y” bending moment is the loading applied in the plane connecting the coiled tubing unit and wellhead (perpendicular to the Z bending moment direction).

Note the sinusoidal nature of the Z bending moment, with a frequency of approximately 20 minutes. This bending moment in the Z axis is actually the fleet angle of the coiled tubing as it is spooled off the reel, from one side to the other...
and back again. This small change in the direction of the reel-back-tension force being applied to the intervention stack was measured by the $\zeta$ system.

The Y bending moment that was recorded by $\zeta$ provides further evidence of the system’s ability to measure small changes in stack stress. During the run-in-hole period for the operation (from approximately 45 minutes until 175 minutes on the time scale), the Y bending moment measurement had 3,000 ft lbs of oscillation imparted to it (illustrated by the sharp, vertical spikes on this line). This oscillation is shown in more detail in Figure 6, which is a plot of 5 minutes of the same moment data seen in Figure 5. This oscillation is a result of the normal surging action on the coiled tubing reel. This surging action imparted a small, but constantly changing load on the top of the intervention stack.

The $\zeta$ system’s ability to measure both of these small changes in stack loading provides insight into the ability of the system. Stack stress levels can be impacted by changing surface, downhole and floating offshore platform/wellhead movement. One can easily envision how these real-time Zeta measurements could be used to determine when operations should be suspended if safe stack stress limits are approached. Alternatively, the real-time measurements from the $\zeta$ system could be used to direct the adjustment of a gimbal table device, and to confirm that stack stress levels were within acceptable limits following table adjustment.

Conclusions
• An accurate intervention stack model has been developed which calculates both potential modes of stack failure, bending and buckling.
• This model has shown that some intervention stack support systems are significantly over-designed, adding unnecessary time, complexity and cost to the intervention.
• It has also shown that in cases with wellhead and platform movement, supporting the stack along its length may actually do more harm than good.
• The gauge developed as part of this safety system has been field tested and proven to be easy to install and operate, while producing accurate monitoring of the stack stress.

Nomenclature
- A Acceleration matrix
- B Damping matrix
- $dt$ Time step (sec)
- K Stiffness matrix
- $i$ Time step index
- $K_{dyn}$ Dynamic stiffness matrix
- M Mass matrix
- R Matrix of applied forces
- $R_{dyn}$ Dynamic matrix of applied forces
- U Displacement matrix
- V Velocity matrix

References

Acknowledgements
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<table>
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<tr>
<th>End Condition</th>
<th>Euler K Factor</th>
<th>Euler $P_{cr}$</th>
<th>$\zeta P_{cr}$</th>
<th>Diff. w/o Gravity</th>
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Table 1 - Critical Buckling Load Modeling Comparisons

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<tr>
<th>End Conditions</th>
<th>Analytical Frequency w/ Gravity</th>
<th>$\zeta$ Frequency w/ Gravity</th>
<th>Diff. w/ Gravity</th>
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<td></td>
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<td>Hinge - Hinge</td>
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Table 2 - Vibration Natural Frequency Validation
Figure 1 - Displacement vs Time for Finite-Difference Scheme

Figure 2 - Safety System Field Test
Figure 3 - $\zeta$ Model for the BP Holstein Platform
Figure 4 - Analysis of 5,000 ft Subsea Riser
Figure 5 - Field Test Measurements from $\zeta$ Gauge

Figure 6 - Bending Moments Over 5 Minutes