PIPE DREAM BECOMES REALITY

Accurate simulation improves reliability and ensures cost-effective deployment of pipe strings in oil wells.

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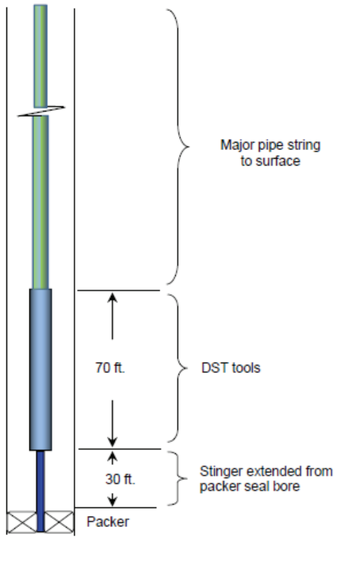
As the search for oil and gas progresses into increasingly deeper waters with exposure to higher downhole pressures and temperatures, accurate prediction of the complex stress state in oil well pipe strings is critical to ensure that operations are carried out safely and efficiently. Accurate nonlinear structural mechanics simulation makes it possible to predict the behavior of the pipe string as it undergoes complex buckling that often results from fluid injection operations. The latest simulation methods enable engineers to design pipe strings and downhole tools with the capabilities to handle the more challenging wells being drilled today.

Schlumberger, the world's leading supplier of technology solutions to the oil and gas industry worldwide, performs well tests to obtain important measurements, such as flow rate and bottomhole pressure, to characterize petroleum reservoirs. During well testing operations, fluids may be pumped under high pressure into the wellbore to stimulate the formation (rock around the borehole).

To conduct a well test, a bottomhole assembly (BHA) consisting of specialized tools and measuring instruments is conveyed downhole on the end of a pipe string and lowered into the well casing. A packer on the BHA's lower end expands within the well to isolate the interior of the pipe string from the annulus between the pipe string and casing. The packer has a smooth internal seal bore that accommodates a seal on the bottom of the BHA. This arrangement permits vertical movement of the lower end of the pipe string while maintaining a seal with the internal diameter of the packer to allow for thermal expansion and contraction of the pipe string during the well test. The lowest stiffness tubular member in the BHA is usually the stinger, whose lower end is fitted with the aforementioned seal assembly and inserted into the packer seal bore. The stinger typically extends out of the top of the packer a distance of 30 feet or more and is joined to the drill-stem test (DST) tools above, which in turn are joined to the major pipe string to the surface.

The lower end of the stinger is free to move vertically, so when the internal string pressure exceeds the pressure in the annulus, a hydraulically induced upward force is applied to the bottom of the stinger. Such conditions exist when fluid is pumped downhole and forced into the formation, such as during hydraulic fracturing or acidizing operations. The resulting pressure wave caused by firing perforating guns [1] can also apply similar upward hydraulic forces.

These upward forces on the bottom of the stinger can cause the BHA and pipe string to helically buckle inside the casing. When helical buckling occurs, as long as the elastic limit of the tubing is not exceeded, the string components will return to their initially straight condition when the pressure difference is removed. However, if the elastic limit is exceeded, permanent corkscrewing of the BHA will result. The stinger, in particular, may become jammed within the casing, preventing the retrieval of the string from the hole and resulting in the loss of expensive tubular assets. In the worst case, this can cause a safety hazard.



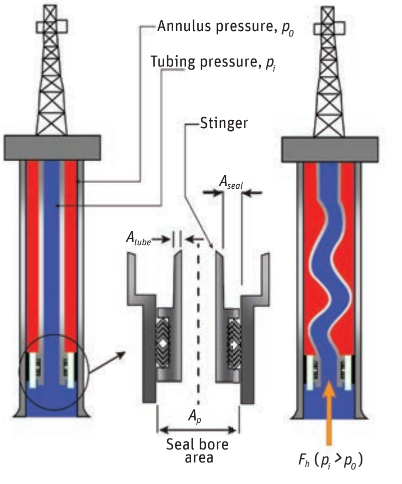
▲ Representative well test string

The latest simulation methods enable engineers to design pipe strings and downhole tools with the capabilities to handle the more challenging wells being drilled today.

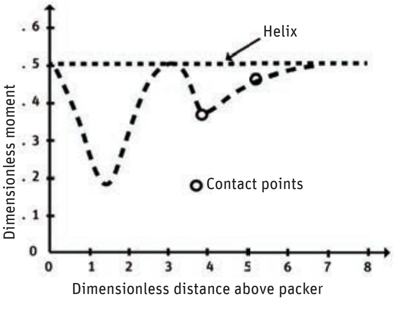
PREVIOUS DESIGN METHODS

Analytical methods have traditionally been used to predict the buckling behavior of the pipe string. First developed by Arthur Lubinski in the 1960s and refined by others in the ensuing decades, these methods not only take into account the hydraulic force acting on the bottom of the string but also the influence of internal and external tubing pressure on the lateral stability of the pipe string. Analytical methods are limited to very simple geometries and typically do not account for geometric nonlinearities, such as large deflections and complex contact between the pipe and casing, so they are unable to accurately predict complex combinations of effects found in the real world. In addition, existing analytical solutions are limited in their ability to accurately predict the post-buckled shape of the packer's stinger in the region where it exits the packer seal bore and before the string fully forms into a helix.

Prior use of finite element analysis (FEA) to study helical buckling required engineers to build large models comprising solid elements. A perfectly symmetrical and straight pipe will not buckle in a numerical simulation, so it is necessary to apply small, random lateral loads to simulate imperfection, and then incrementally increase the bottom load to induce buckling. Lateral deflection is constrained after the pipe contacts the casing wall, and equilibrium is re-established as the pipe forms into a stable helical shape. Modeling a substantial length of the well test string using solid elements and solving a sufficient number of iterative steps to explore the full load range of interest requires enormous computing resources and wall clock time.



▲ Hydraulically induced bottom force



▲ Bending moment in helically buckled pipe predicted by analytical solution

Using BEAM188 Elements for Nonlinear Simulation

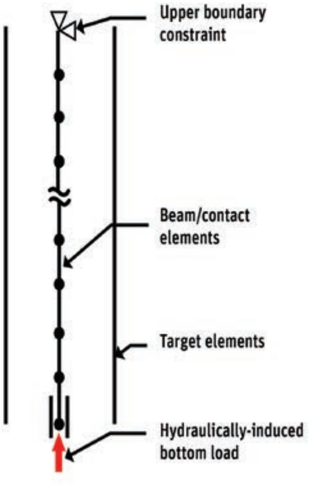
The BEAM188 element has six degrees of freedom at each node and is based on a first-order shear deformation theory that is well suited for linear and nonlinear problems with large rotations and strains. Cross sections remain plane and undistorted after deformation, but they are not required to remain perpendicular to curvature.

Once the lower end of the string buckles and the bottom load is further increased, the model remains continuously unstable as new helix coils are formed progressively higher in the string. For such a highly nonlinear problem, aggressive stabilization control is needed to maintain convergence as the solution progresses. Nonlinear stabilization using pseudo-viscous damping was used to provide the necessary control. Dampers, with appropriate damping coefficients, are attached to each node in the system. At the onset of instability, the integration increment is reduced when divergence of the solution is detected. The damping forces act in the opposite direction of the nodal displacements to enable the solver to obtain a converged solution during what would otherwise be an unstable phase of the simulation.

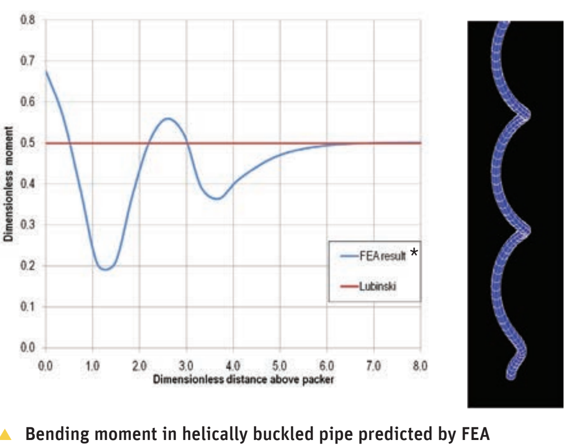
Therefore, the FEA model must be shortened considerably to avoid an impractically large number of degrees of freedom. Limiting the model length in this manner requires imposing boundary conditions, either displacements or forces, where the model is terminated. These boundary conditions are not known before the problem is solved. Applying assumed, imprecise boundary conditions can substantially reduce the accuracy of the simulation.

An alternative approach is to use 3-D beam elements to model a long section of the pipe string in combination with a concentric contact surface to represent the casing constraint. A line element model can be made long enough to represent a significant portion of the pipe string while keeping the model size manageable. However, traditional beam elements based on classical Euler–Bernoulli theory do not work well in this type of model because of inherent restrictions. One of these restrictions is the requirement for the beam cross sections to remain perpendicular to curvature, which prevents the helix from developing after the initial buckling load has been reached.

It is important to more accurately predict buckling and the resulting stress state in the well test string.

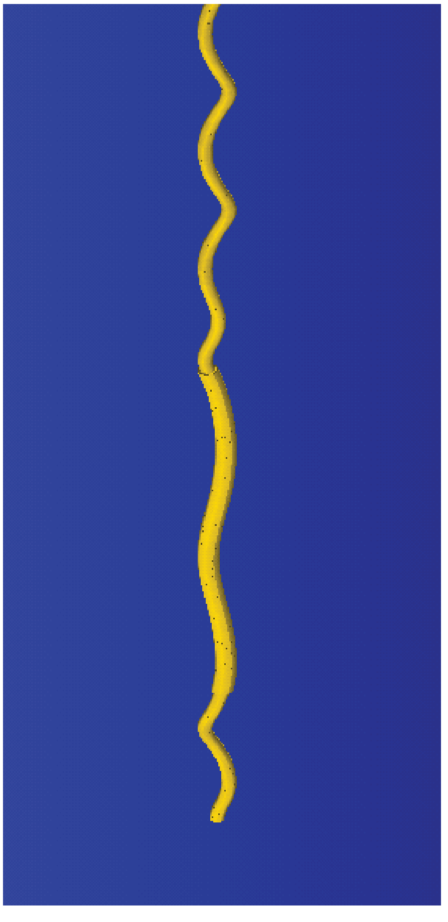


Schematic of finite element method



Bending moment in helically buckled pipe predicted by FEA
*For 3.5-inch continuous string in 9.625-inch casing

The higher accuracy of this FEA method makes it possible to design BHAs that ensure safe operation in deeper wells, which can help satisfy the world's need for oil and gas.



Shape of helically bucked well test string from simulation

The approach provides a more accurate method of simulating helical buckling in a well test string sealed in a packer.

NEW SIMULATION APPROACH

Schlumberger has developed a new approach employing ANSYS Mechanical BEAM188 elements. The team models a sufficiently long portion of the well test string so that the upper boundary condition remains above a sufficiently long portion of the fully developed helix such that the upper boundary condition does not affect the region of interest near the packer. The model is solved as a large deflection, nonlinear buckling problem along a load path that progresses from initial instability and casing contact, to formation of a fully formed helix, and finally to a bottom load magnitude that corresponds to field conditions of practical interest.

To compare the FEA approach with the analytical solution, Schlumberger engineers ran FEA cases for uniform strings of varying diameters constrained by different-sized casings. Unlike analytical solutions, the FEA simulation fully accounts for geometric nonlinearity. Next, the models were enhanced to represent a realistic BHA having regions with different diameters and flexural stiffness. Such an analysis is not practical using a simplified analytical solution.

The new FEA approach provides a more accurate method of simulating helical buckling in a well test string sealed in a packer. For the case of a uniform stinger, there is excellent agreement between established analytical solutions and FEA within the fully developed helix. In the region between the packer and fully developed helix, FEA predicts higher bending stresses than existing analytical solutions. Furthermore, the bending stress in the stinger just above the packer was found to vary somewhat depending upon problem geometry, indicating the influence of geometric nonlinearity on the solution. The discrepancy in the region before the helix is fully developed is attributed to simplifying assumptions inherent in the derivation of the analytical solutions. A nonlinear finite element solution is not restricted to these simplifications. The higher accuracy of the new FEA method will make it possible to design BHAs that ensure safe operation in deeper wells, which can help satisfy the world's need for oil and gas.

Footnote

[1] Perforating gun: downhole device containing explosive charges used to perforate sections of the casing below the packer to allow oil and gas to enter the lower portion of the wellbore