Dynamic Response in a Pipe String during Drop-Catch in a Wellbore

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***Abstract**: In field operations, during rapid deceleration of pipe (simulated by drop-catch process) or slack-off stop process, significant dynamic effects can occur. The dynamic event can amplify the load on the pipe string, and the amplified load can break a weak thread. It is necessary to understand the mechanics of this dynamic event, and thus, provide guidelines or directions for safe design and operation of the pipe string. An analysis procedure using FEA, which involves fluid-pipe interaction, has been established for this study. It shows that fluid viscosity is a very important parameter in determining whether a given pipe string with a weak thread will be safe or not under a given operating procedure.*

***Keywords:** Dynamics, Fluid Structure Interaction, Pipe string, Wave, FEA, Viscosity*

1. Background

When operating on a pipe string in the field, an operator may decelerate a fast moving pipe in too short a time. For a very long pipe string, the dynamic effect in this process is significant, and load on a thread can be much larger than the pipe weight (in fluid) below the thread, i.e. the load is amplified. When a weak thread, e.g. 60% thread, is near the top of the string, the thread may fail in this process. This failure due to rapid deceleration at a weak thread has been a thorny issue to design engineers for some time. It is necessary to understand the mechanics of this dynamic event, and thus, provide guidelines or directions for safe design and operation of the pipe string. Here, a drop-catch process is used to simulate the fast deceleration process. The drop-catch process is designed to allow the pipe to drop freely, and then, to catch it to achieve the rapid deceleration effect in a simple way.

Questions of practical importance include: 1) for given environment (well bore size, drill-in fluid) and operation condition (e.g. pipe is dropped 1 ft before being caught), how long the pipe string can be below a weak thread 2) Is the drop height important? (i.e., Is the pipe velocity important?) 3) How does the fluid in the wellbore affect the operation? 4) Is the size of the wellbore an important parameter?

The rapid deceleration of a pipe string in a wellbore is a complex process, which involves wave propagation in the pipe and interaction between pipe string and fluid. Currently, there is limited fluid-structure interaction analysis capability in commercial FEA codes. To use this limited capability, some assumptions and simplifications have to be made. How to make proper assumptions and simplifications is an essential part of this study.

The pipe string wellbore information is presented in Section 2. The FEA models, which include the procedure to lump fluid mass into pipe and the determination of fluid friction coefficient, are discussed in detail in Section 3. Numerical results, which include the characteristics of dynamic response in the pipe string during a drop-catch process (simulated rapid deceleration), effect of fluid viscosity, and effect of drop height are presented in Section 4.

2. The design under investigation

Well bore size is 8.5-in. At the top of the string is a 90-ft long, 5 ½-in. 24.7lb/ft drill pipe. Attached below the drill pipe is a 4500-ft long, 7-in.OD (.0305-in. thick) base pipe with 7.4-in.-OD screen 28.12lb/ft. The screen has 3½-in. 9.2lb/ft inner wash pipe (not considered in the model). The screen basically covers the whole 4500-ft base pipe. Fluid viscosity is in the range of 100 to 300 centipoises, density 1.13sg. There is fluid in the pipe due to the screen and perforation, but the pipe bottom is plugged. The weak thread is at the joint of the dill pipe and base pipe; the minimum yield strength of the thread is 164,000 lbs. In this work, it is assumed that the pipe string falls ~ 0.5, 1, 2 ft before it is caught (**Figure 1**).

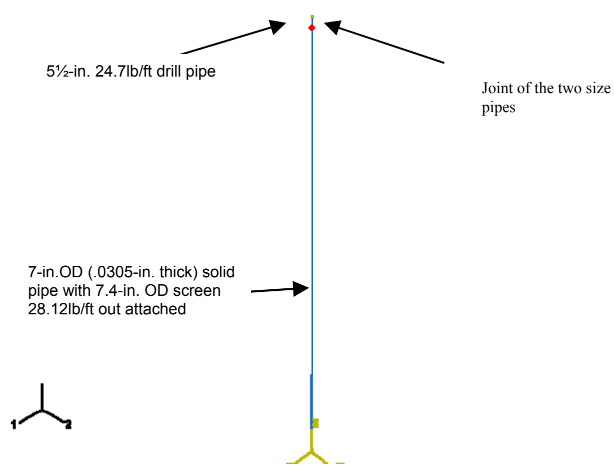

Figure 1. **The pipe string**

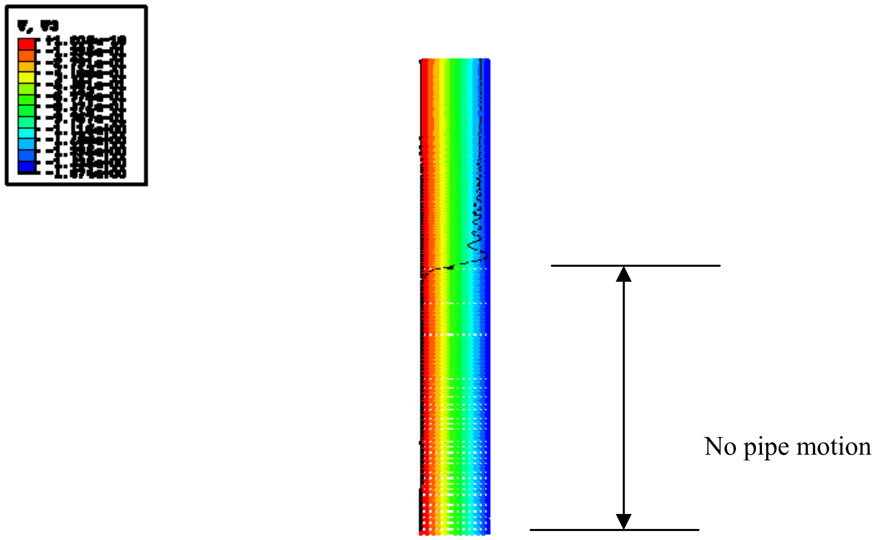

Figure 2. Velocity profile in the pipe string right before the top is caught (0.1732 second after the pipe is dropped).

3. The FEA model

The real flow of fluid in the system is very complex due to the existence of the screen. Also, the detailed structure of the pipe string is very complex. Some appropriate simplifications have to be made in order to conduct a meaningful analysis.

First, the complex flow field in the system is basically ignored, and fluid in the well bore is assumed to be stationary. The reasons behind this approximation: 1) a pipe drops in small distance (typically less than 3 feet), which will not generate a lot of flow; 2) when pipe does move, fluid would flow into the basepipe via the screen, thus reducing overall upward flow speed; 3) initially, the motion of the pipe string is local, most part of the pipe is stationary (see **Figure 2** for example). *With this approximation, the relative speed between fluid and the pipe string in the model is due to the pipe motion.*

As described in Section 2, there is fluid in the pipe, but the string is plugged at the bottom. This means that the mass of the fluid inside the pipe will contribute to dynamics of the pipe motion, but it will not contribute to the pipe fluid weight. To achieve this effect, *fluid mass for fluid inside the pipe is lumped into the pipe mass.* The details of this calculation are described in Section 3.1.

The interaction between the pipe and the fluid in the well bore is through the drag and friction. The key parameter is the friction coefficient, or tangential drag coefficient per Abaqus terminology. The estimation of the friction coefficient is described in Section 3.2. The overall FEA model formulation is described in Section 3.3.

3.1 Approximation of a pipe string in a wellbore

Abaqus/Aqua deals only with closed end pipe without fluid in the pipe. One way to include the fluid in the plugged pipe is to lump fluid mass into the pipe.

Due to the perforation on the screen, we lump fluid mass and screen mass into the 7-in. OD base pipe. Equivalent density for the 4500-ft fluid/pipe/screen assembly is calculated as following: 1) 7-in. OD (0.305-in. thick pipe) has a linear density of 21.55lb/ft; 2) The fluid linear density is15.72 lb/ft ; 3) The equivalent density is 2.019 times steel density, or in SI units, 15752 kg/m3. For the 90-foot drill pipe, effective density is 10719.53kg/m^3

3.2 Fluid/Pipe friction

The interaction between the pipe string and the pipe is mainly through fluid friction (**Table 1**). The fluid friction coefficient is dependent on fluid viscosity, fluid density, and relative motion between the fluid and the pipe. With the assumption made so far, the fluid-friction coefficient is a very important parameter in the current model. The fluid friction coefficient is defined typically for steady-state flow in or around a pipe (Grovier and Aziz., 1972), (Sabrersky and Acosta, 1964). Considering the steady-state flow in the annular area between pipes, see **Figure 3** for illustration:

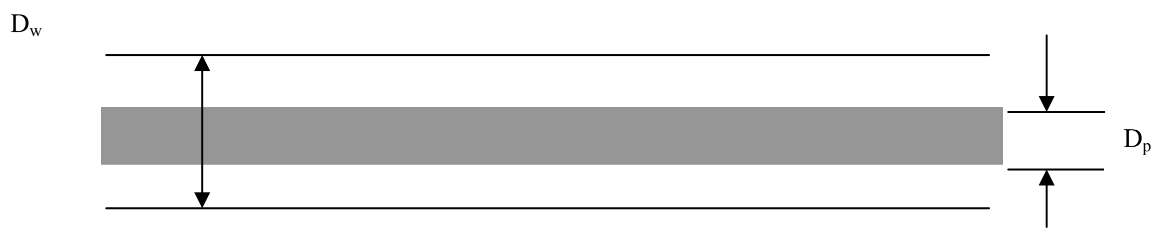

Figure 3: Illustration of a pipe string in a well

Assuming the pressure drop along the annular area is ΔP in a length of ΔL, per equilibrium condition in a steady-state flow, shear stress on the pipe

$$\tau = \frac{\Delta P \pi (D_w^2 - D_p^2)/4}{\pi D_p \Delta L} \qquad (1)$$

The pressure drop is related to flow velocity via the following equation (Grovier and Aziz., 1972)

$$\frac{\Delta P}{\Delta L} = \frac{2 f \rho V^2}{D_w - D_p} \qquad (2)$$

where ΔP is pressure drop in distance ΔL, f is friction coefficient, V is the average fluid velocity in the annular area, and $D_w - D_p$ is the hydraulic diameter. From Equations 1 and 2, one has

$$\tau = \frac{1}{2D_p}(D_w + D_p) f \rho V^2 \qquad (3)$$

So, the force on the pipe per unit length is ($\tau \pi D_p \cdot 1$)

$$F = \frac{1}{2}\pi(D_p + D_w) f \rho V^2 \qquad (4)$$

The friction coefficient, f, is dependent of Reynolds's number Re

$$f = \frac{16}{\mathrm{Re}} \qquad (5)$$

$$\mathrm{Re} = \frac{\rho V (D_w - D_p)}{\mu} \qquad (6)$$

where ρ is fluid density, V is the flow speed, and μ is the fluid viscosity. Rearrange Equations 4, 5, to make the formula in the same form as that shown in (ABAQUAS, 2003), then

$$f_{eff} = \frac{D_w + D_p}{D_p} \frac{16}{\mathrm{Re}} \qquad (7)$$

and

$$F = \frac{1}{2} \rho f_{eff} \pi D_p V^2 \qquad (8)$$

So we can use Equations 6 and 7 to estimate fluid friction coefficient in Equation 8 in the ABAQUS manual. It should be noted that there is a different definition of friction coefficient, which leads to a formula different from that shown in Equation 5, see (Sabrersky and Acosta, 1964), but the final equation relating force and velocity are equivalent. Following Equations 6 and 7, fluid skin-friction coefficients used in the analyses in this study are determined as follow:

Table 1: Friction coefficient

	Friction coefficient @ 200cp viscosity	Friction coefficient @ 300cp viscosity	Assumed friction coefficient
5.5-in. pipe	0.31616	0.4742	0.7
7-in. pipe	0.5486	0.8229	0.7

As shown in Equations 6, 7, friction coefficient is related to relative velocity between the pipe and fluid, so it is changing during the pipe-dropping process. An average relative velocity of 0.3m/s is assumed in estimating the friction coefficients. Strictly speaking, Equations 7 and 8 apply to pipe in steady-state flow only. So, these equations only approximate the physical relations in the pipe drop-catch process.

3.3 Model formulation

Note: for convenience of dynamic analysis, SI units are used in FEA model

In addition to the assumptions and approximations made above, it is further assumed that the pipe string can be represented by the beam element in FEA. The cross sections of the pipes in the pipe string are accounted for. In summary:
1) Pipes are modeled as beams with proper cross-section profiles.
2) Interaction between pipe and fluid is approximated by (buoyancy, drag) fluid force acting on pipes via Abaqus/Standard, Abaqus/Aqua
3) Wellbore size was considered in estimation of the fluid/pipe-skin friction
4) Material damping of steel pipe is assumed to be very small. Environmental damping to the pipe string due to fluid is accounted for from fluid loading
5) Simulation of the drop-catch process:
   a) Pipe string is first hung statically to account for stretching due to pipe weight with top 3.3 foot (1 meter) of the string above fluid
   b) Drop: Pipe string falls into fluid by 0.5-, 1- or 2-ft per prescription
   c) Catch: Top of the pipe string is constrained (velocity is reduced to zero in 0.01 seconds)

The drop-catch process is analyzed as a dynamic process using (implicit) linear dynamic elasticity. In real analysis, one has to perform two analyzes for each case: First, run an analysis for hang and drop to determine the velocity (v_0) at the top of the pipe string when it dropped the prescribed height and the time needed (t_0); in the second analysis, time period for the drop is prescribed as t_0, at the start of catch step, the velocity at the top is reduced from v_0 to 0 in 0.01 seconds and held there. It is noted that numerically, one has to allow a relatively large half-step residual for the catch process. To improve accuracy of the numerical calculation, one may split the catch period into the catch and catch-hold. Materials of the pipes are assumed to be linear elastic. The steel properties used are as follows:

$$E = 210GPa\ , \gamma = 0.3\ ,\ \rho = 7800kg/m^3\ .$$

Fluid density is 1130kg/m^3.

4. Analysis results

4.1 Basic dynamic characteristics of a drop-catch process

The deformation in the pipe string during drop is quite complex. In the following, the example results shown are for the pipe string drop by 1 ft under assumed 0.7 friction coefficient.

First, when the top of the string is released, the top of the string springs back at a relatively high speed in a very short time (see **Figure 4**), and then, the speed is reduced gradually (due to elasticity and fluid friction) until the top is constrained to zero velocity; i.e. catch. The velocity at the joint (i.e. weak thread) is oscillating after the top is caught due to wave propagation and wave interaction (see **Figure 5**) Secondly, sometime after the top of the string is dropped, part of the pipe string is still motionless, because the wave generated at the top has not reached there. In the example considered, more than half length of the string is still motionless after 0.1723 second(as shown in **Figure 2**).

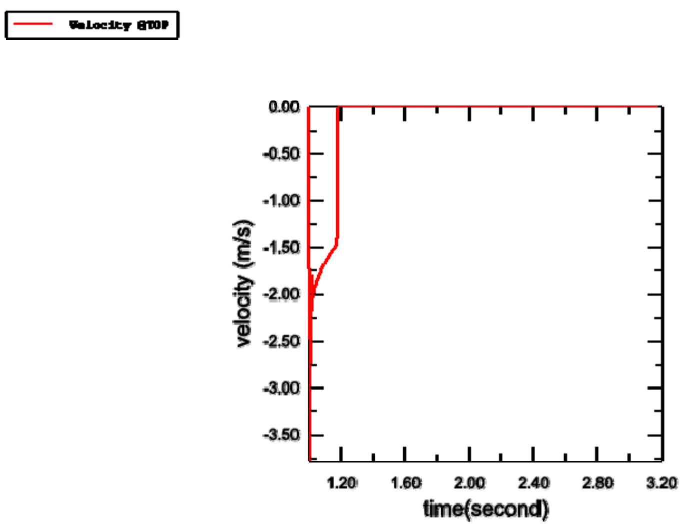

Figure 4. The velocity change at the top of the string during drop-catch.

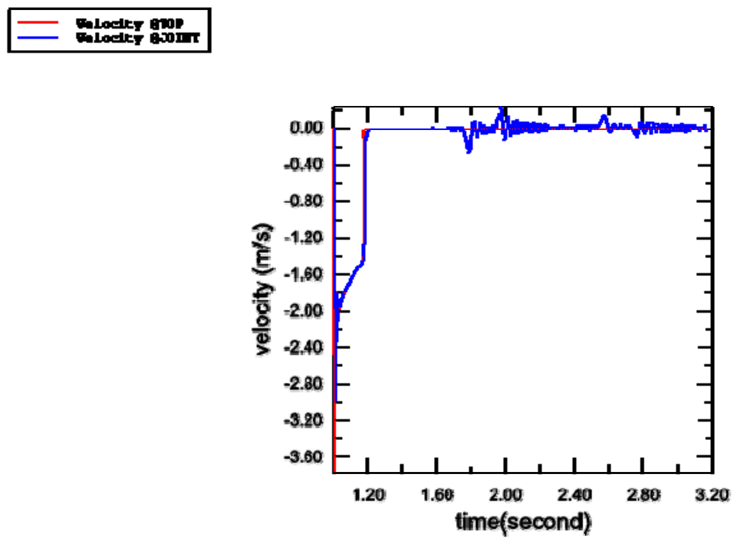

Figure 5. Comparison of the velocity at the top and the joint of the string.

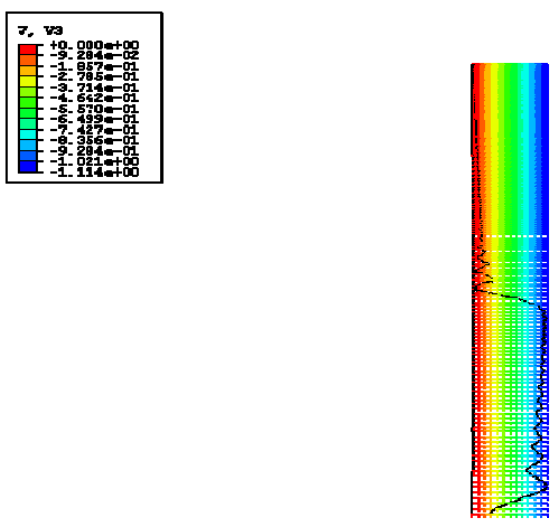

Figure 6. Wave propagation in the pipe string

The peak of the wave (generated at the top of the string due to drop) reaches the bottom in about 0.4 seconds, see **Figure 6**. This time is much longer than what it takes for the dilatation wave to reach the bottom (0.23seconds, using L/$\sqrt{\dfrac{E(1-\gamma)}{\rho(1+\gamma)(1-2\gamma)}}$). This reduction in wave-propagation speed is due to the environmental damping to the pipe string, which is not easily estimated. *Note: see appendix for further discussion*.

The time it takes for the wave to reach the bottom, 0.4 seconds for the current geometry and material, is an important parameter in determining the effect of the pipe-string length and drop length. As a matter of fact, the force at the joint reaches peak when the 1st wave reflected from the bottom of the string reaches the top, i.e. 0.8 second, see **Figure 7**. The compression observed in Figure 7 is due to spring back overshoot; it will become neutral until the top of the string is constrained.

This result is valid if the top is caught within 0.8 seconds after it is dropped; otherwise, the qualitative feature of the dynamics in the string changes (see Section 4.3). Interestingly, the period of 0.8 seconds remain approximately constant when the viscosity in the fluid is between 200cp to 300cp (see section 4.2).

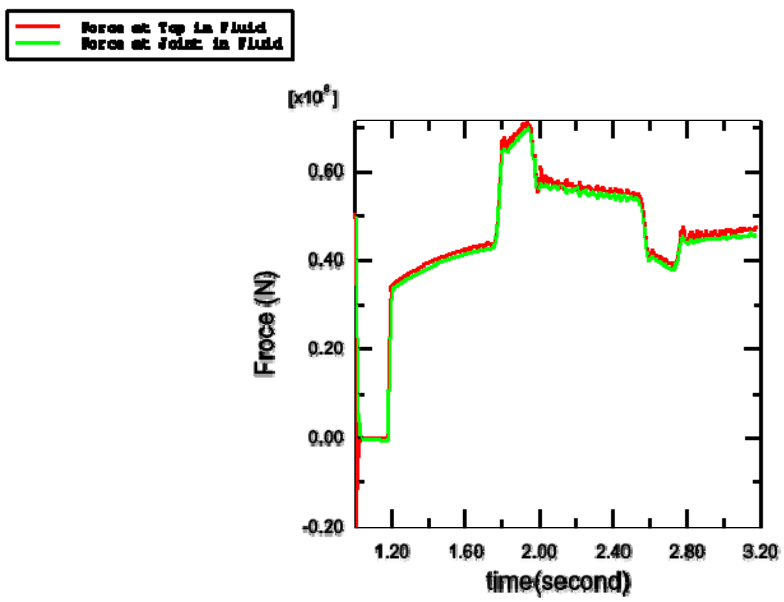

Figure 7. Variation of force at the top and joint of the string with time.

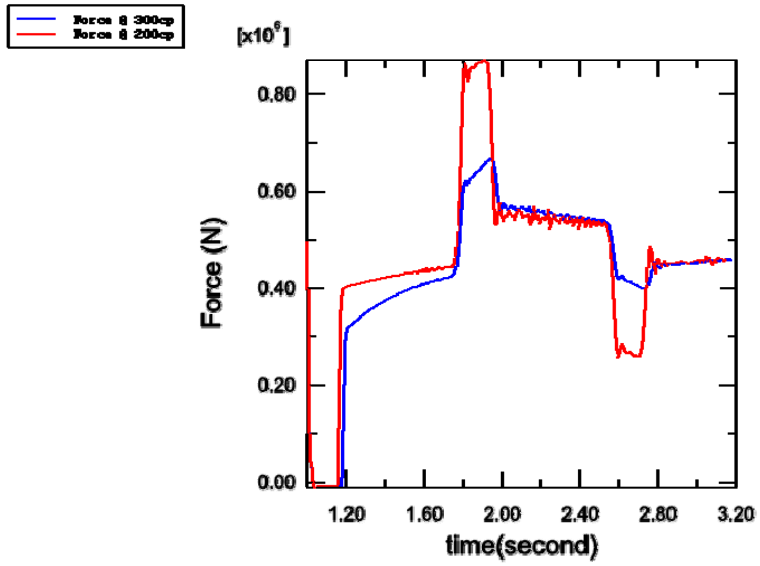

Figure 8. Comparison of force at the joint when $\mu = 0.2$ (200cp) and $\mu = 0.3$ (300cp).

4.2 Effect of fluid viscosity

Similar dynamic response was obtained for the pipe string when it was in the fluid with viscosity of 200cp and 300cp, with a drop of 1 foot. Now, let us take a look at the effect of fluid viscosity, which in turn, changes fluid-friction coefficient.

The velocity in the pipe string is lower when viscosity is higher, as expected. However, the time the force at the joint reaches peak is about the same (see **Figure 8**), which means that the wave period in the string is about the same when fluid viscosity changed from 200cp to 300cp, but the peak value changed significantly from 196,000lbs to 149,000lbs. So, when the fluid viscosity is high, the weak thread is safe (164000 lbs minimum yield), when the viscosity is low, it is not safe. The reason that the force at the joint peaks at the wave period (0.8 seconds for 200 ~ 300cp fluid) is that the whole pipe is moving downward; thus, the downward inertia force reaches peak value

4.3 Effect of drop height

Now, let us look at the effect of drop height for fixed viscosity (300cp). The drop height of practical value is chosen — 0.5-ft, 1-ft and 2-ft.

The direct consequence of catching the pipe after different lengths of drop is the change of velocity at the top of the pipe string; the longer the drop, the slower the velocity (**Figure 9**), when the drop height is not too large; i.e., the time to catch the pipe after the drop is less than 0.8 seconds, consequently, the lower the peak force (**Figure 10**). Contrary to intuition, the longer drop leads to a lower peak force at the joint, mainly due to viscosity effect. However, if the drop height is larger than a certain value (dependent of viscosity, for 300cp, the height is about 3-ft), then, the qualitative trend described will change. If the drop height is longer than 3-ft, the pipe string reaches a steady-state motion (see **Figures 11, 12**). The reason for the quick increase of velocity magnitude (around 1.8 seconds in Figure 11) is due to the fact that wave reflected at the bottom of the string reaches the top.

Furthermore, when the long drop of pipe in the 300-cp fluid is compared to the 1-ft drop in the same fluid, it turns out that the long drop has a slightly higher peak force at the joint (**Figure 12**) despite the fact that that the velocity at the top is 1.4m/s for the 1-foot drop, and 1.18m/s for the long drop. This is because for the 'long drop' case, the whole string is moving at the velocity before it is caught, while for the 1-ft drop case, only a small portion of the string moves near 1.4m/s. The 'long drop' case has higher downward inertia force.

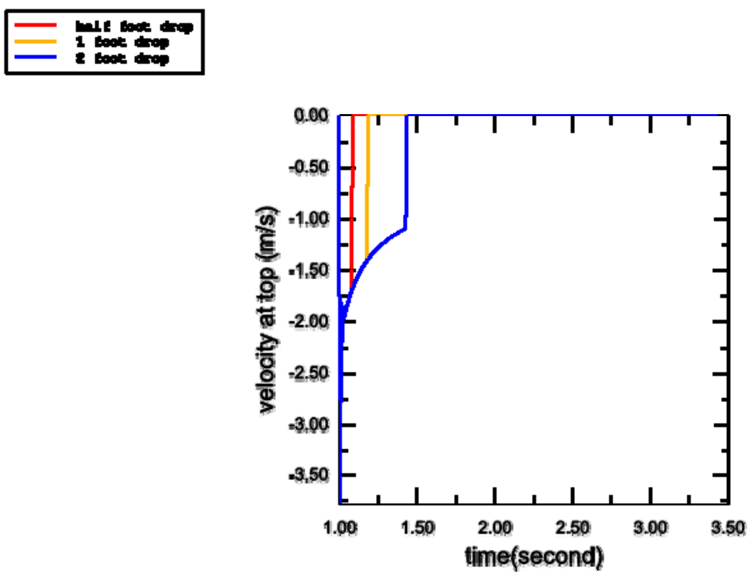

Figure 9. Velocity at the top after 0.5, 1 and 2ft drop and catch

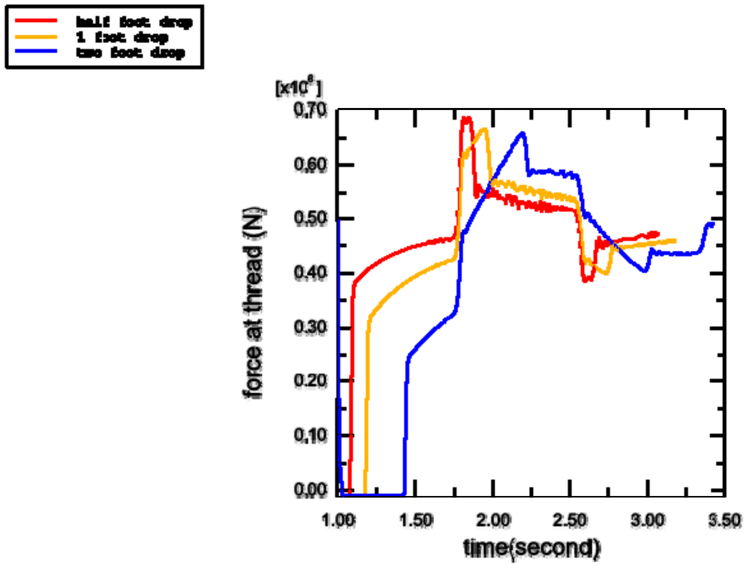

Figure 10. Force at the joint after 0.5, 1, and 2-ft drop and catch

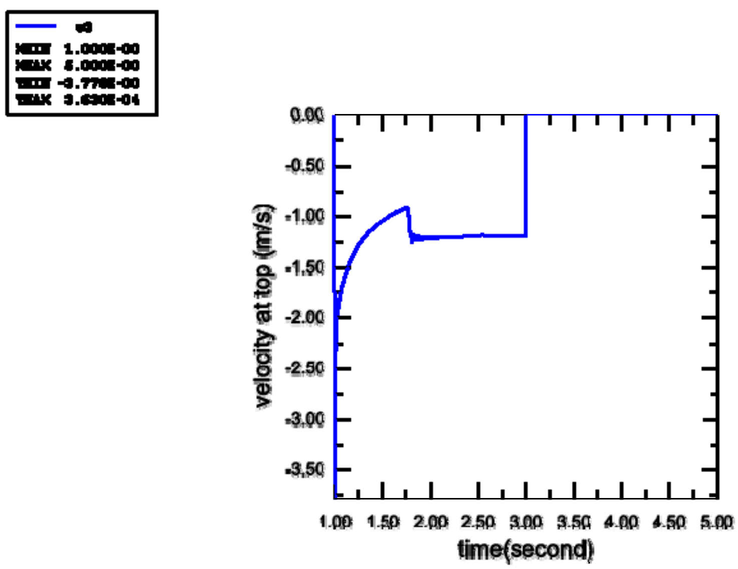

Figure 11. Velocity at the top drops continuously until the reflected wave reaches the top (1.8 seconds or so)

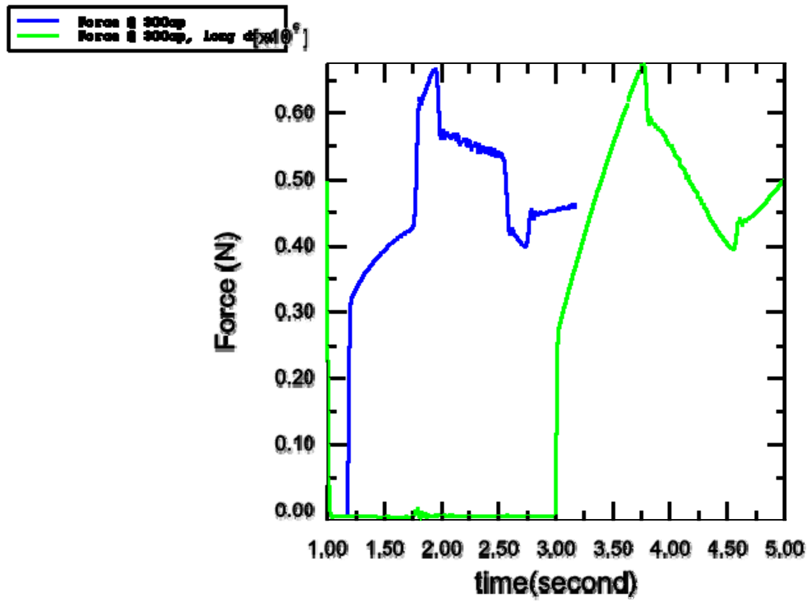

Figure 12. The peak force in the pipe string is more or less constant when the pipe is caught after 0.8 seconds

5. Conclusions and Remarks

With the assumptions made, it is shown that for the given pipe string during a rapid deceleration process – the drop-catch process:

1) The safe operation of the given pipe string is dependent on drill-in fluid viscosity, 2) The time period of wave propagation, which is a very important parameter in the rapid deceleration process, is ~ 0.8 second for the given pipe string when fluid viscosity is between 200cp to 300cp.The system is sub-critically damped due to fluid structure interaction. Time period for the wave to travel back to top is almost doubled (0.8second vs. 0.46 second) from no damping (in air) to highly damped (in fluid). The damping ratio is estimated to be around 0.814 (see Appendix) When a pipe string is caught within this time period after its drop, the dynamic response of the string shows a trend – the shorter the drop height, the larger the peak force at the joint; when the string is caught in a time longer than the time period (> 3ft drop in a 300cp fluid), the peak force at the joint will be a constant and close to the value achieved in 1-ft drop dynamics). 3) The force at the joint reaches peak value 0.8 seconds after it is dropped, and then, caught. Other factors that may influence the potential failure of a weak thread include: pipe dimension, strength of the weak thread, and location of the thread.

Based on the dynamics of pipe rapid deceleration process, one can take a few measures to avoid potential failure of a weak thread: 1) increase drill-in fluid viscosity; or 2), reduce pipe weight (i.e.

length of pipe) below the weak thread. The length of pipe string below a weak thread is determined by thread strength and fluid viscosity; 3) enhance the thread rating.

In this analysis, the wellbore size is not important for reasons given in Section 3. When wellbore size is considered, the fluid in the wellbore is pushed up (very little for the cases considered) due to the fall of pipe string. For given pipe string, the smaller the wellbore, the higher the upward velocity of the fluid. The higher the upward motion of the fluid, the higher the upward fluid force is applied on the pipe string, and thus, it reduces tensile force in the pipe string. Current analysis (without fluid upward motion) predicts a slightly higher peak force at the thread than in a real situation (under the assumptions).

The pipe dynamic response in a slack-off and stop process should be similar to that in a 'drop-catch' process, except that the pipe string velocity is imposed by operator during the slack-off, and the velocity in the pipe string can be much higher than in 'drop-catch'. One should not slack-off the pipe string too fast to prevent the dynamic amplification of pipe weight during deceleration, which might break the string at the weakest link.

6. Acknowledgements

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8. Appendix: Effect of damping on wave propagation period.

The system under consideration is a system with infinite degree of freedom. The effect of damping on the change of wave period is not easily determined or estimated. Here, a 1-degree-of-freedom system is used to illustrate the effect of damping.

Let us represent a circular rod (E, ρ) with cross section area A, length L by a spring (m, K),

$m = AL\rho$, $k = \dfrac{EA}{L}$. So, the dynamics of the rod with damping can be approximated by

$$m\ddot{x} + c\dot{x} + kx = 0$$

The period of the longitudinal vibration of rod is

$$T = \frac{1}{\omega\sqrt{(1-\xi^2)}} = \sqrt{\frac{m}{k(1-\xi^2)}} = \frac{1}{\sqrt{(1-\xi^2)}}\frac{L}{\sqrt{E/\rho}} = \frac{1}{\sqrt{(1-\xi^2)}}T_0$$

So, the period increases with the increase of the damping. Here,

$\xi = c/2\sqrt{km}$ is the damping ratio;

$T_0 = \dfrac{1}{\omega} = \sqrt{\dfrac{m}{k}} = \dfrac{L}{\sqrt{E/\rho}}$ is the period for a system without damping.

If the pipe string is dropped in air, there is no environmental damping; then, the time for the wave to get back to the top (accounting for Poisson's ratio) is 0.4647 seconds.

For the pipe in air caught 0.17232 seconds after free drop, it takes about 0.6370 seconds (0.17232 + 2T) for the force at the joint to reach peak value after the drop, per the 1-d system model. The prediction per Abaqus/Aqua was 0.64364 seconds (see Figure A1). The 1-D estimation was quite accurate. It is noted that when there is no damping, the velocity at the joint oscillates at much larger amplitude in higher frequency.

Using the time period of 0.8seconds for the damped system (per Abaqus/Aqua) and 0.4647 seconds (per 1-D model) for the undamped system, one can estimate the damping ratio of the system as:

$$\zeta = \sqrt{1-(\frac{T_{air}}{T_{fluid}})^2} = 0.814$$

Thus, the system is highly damped.