Dynamics of a Completion String in a Fluid Filled Wellbore

Allan Zhong, Frederic Felten
Halliburton Company

In oil and gas well field operations, downhole completion tasks require overpull or slack off on the tubing string at the rig floor. After a completion tool is run to position, typically overpull or slack off is used to overcome locking and locating mechanisms (shear pins, collets, etc.) to release the tool (e.g. packer) so that it can be set. The mechanical manipulation of the equipment, however, can induce significant sudden movement of the completion tubing string near the tool's locking mechanism. The rapid movement of the tubing string causes large relative motion and "piston effect" forces between tool components and fluid present in the wellbore. This can potentially lead to undesirable events, such as packer element swab off where seals can be unintentionally energized and damaged by annular flow past them. Operationally, it is of great interest to know the instantaneous velocity of the tubing string at the time of tool release and the maximum allowable overpull to avoid this undesirable outcome. These questions are successfully addressed via extending an approach developed by Zhong and Gano (Dynamic Response in a Pipe String during Drop-Catch in a Wellbore by Allan Zhong and John Gano, 2008 ABAQUS USERS' Conference, Newport, Rhode Island, May 19-22, 2008) to account for additional drag from packer elements/seals and flow inside tubing.

Keywords: Dynamics, Wave, Viscosity, Pipe String, Fluid-Structure Interaction, Completion, Wellbore.

1. Introduction

Overpull or slack off on the tubing string at the rig floor, after a completion tool is run to position, to overcome locking mechanisms (shear pins, collet …), to release the tool (e.g. packer) so that it can be set. This procedure, however, can induce significant sudden movement of the completion tubing string near the locking mechanism. This process involves significant fluid structure interaction. The rapid movement of the tubing string causes large relative motion between tool components and fluid, potentially leading to undesirable events, such as packer element swab off.

Full 3D fluid structure interaction analysis of the whole tubing string would require an extremely large amount of computer memory and a very long time to run, thus is prohibitively expensive for most engineering analysis. Abaqus/Aqua, though developed primarily for application of steady current, wave, and wind loading to submerged or partially submerged structures such as offshore piping installations or risers, can be extended for the aforementioned engineering problems in the oil/gas well completion process. Abaqus/Aqua was successfully applied to the study of tubing string dynamics during slack-off process in a wellbore (Zhong, Gano, 2008). However, in that study, the wellbore size was accounted for in calculation of drag coefficients, but not for the flow in the wellbore. This limitation is due to the fact that Abaqus/Aqua was developed for structures in open sea. To assess the dynamics of completion string with sealing elements (e.g. packer elements, or seals) properly, the wellbore size must be considered. This is because downhole tools, such as packers, are equipped with rubber sealing elements and have outside diameters (OD) larger than tubing OD which can produce flow restrictions and "piston effect" forces, and thus add additional drag to the tubing string. Sufficient annular flow velocity across the sealing elements can actually energize them, where they are displaced from the packer chassis and into the annular bypass flow area around the packer assembly. When this occurs, the sealing elements can be "swabbed off" of the packer and can be damaged. Representation of drag due to fluid flow in the annular area between tubing and wellbore, and between sealing element and wellbore (flow restriction) is a major and significant extension of the approach by Zhong and Gano (Zhong, Gano, 2008).

An endeavor to answer the practical question, "what is the maximum overpull during tool release of a completion string, such that a packer element will not swab off?" has been undertaken in this study. The critical variable in this physical process is the velocity of fluid flow passing the element.

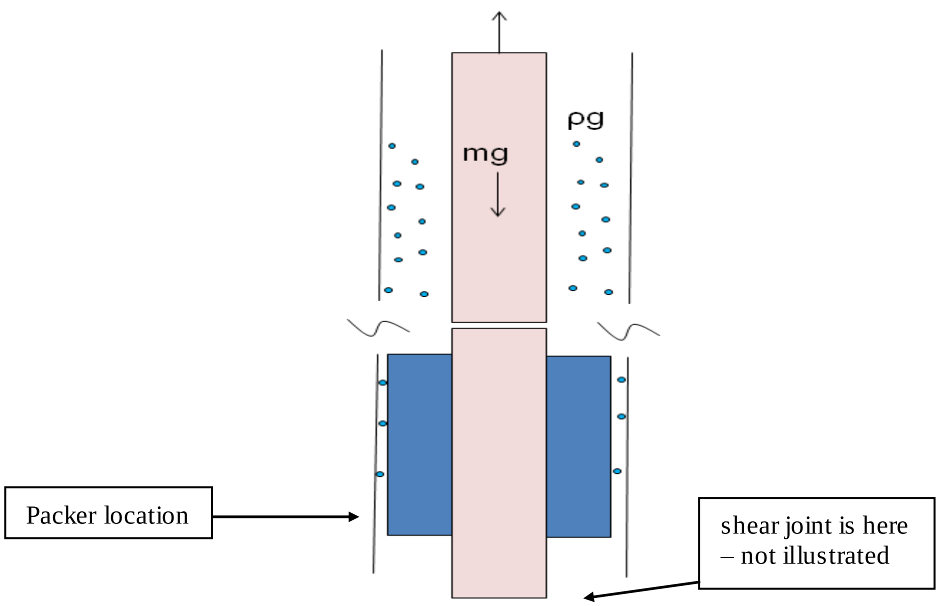


Figure 1. Illustration of the fluid problem

The completion string well bore information is presented in Section 2. The fluid related work is presented in Section 3, which includes determination of fluid friction coefficient, representation of drag due annular flow, internal flow and flow at restriction. The overall finite element analysis (FEA) model assumption and formulation is summarized in Section 4. Numerical results are presented in Section 5, which include the characteristics of dynamic response in the pipe string during tool release, as well as max flow rate at the packer elements – which determines if a swab off will occur.

2. The Design under Investigation

Casing is 9-7/8-in. 68 lb with nominal I.D. of 8.617-in. Tubing is 5-1/2-in. 26 lb with nominal O.D. of 5.5-in. and nominal I.D. of 4.485-in. In the tubing string, a packer is located 18,444 ft from surface (rig floor). Packer O.D. is 8.350-in. and element length is approximately 11 ft long (assume packer I.D. is same as tubing). In the tubing string a short distance below the packer is the shear joint (see **Figure 1**) located at 18,570 ft from surface (rig floor). Wellbore fluid is 14.2 lb CaBr. Three shear ratings of 15k lbf, 45k lbf and 75k lb forces are evaluated, i.e. three overpulls needed.

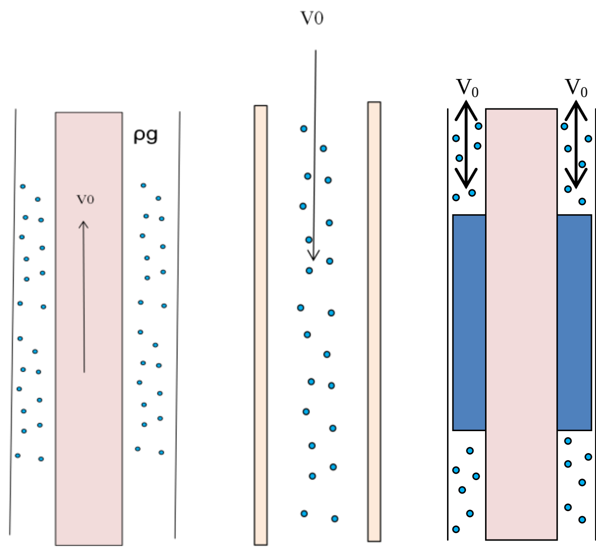


Figure 2. (a) Annular flow, (b) Internal flow, (c) Flow around Packer elements

3. Fluid Mechanics Analysis

Regarding the fluid-structure interactions, three sources contributing to the total drag force on the system have been identified:

1- The tangential drag on the OD of the tubing string due to the annular flow (**Figure 2a**),

2- The tangential drag on the ID of the tubing string due to the internal pipe flow (**Figure 2b**),

3- The drag due to the fluid flow around the packer elements. When the tubing string moves up or down, the packer elements provide substantial resistance to the flow and pipe motion (**Figure 2c**).

Tangential drag on the OD and ID of the tubing string can be determined analytically and expressions for these two components are given in sections 3.1 and 3.2, respectively. Computational fluid dynamics (CFD) modeling was used to determine the drag provided by the packer elements. Section 3.4 presents the model and results of the numerical flow simulations.

3.1 Tangential drag on OD of tubing string

The wall shear on the OD due to the annular flow must be known in order to obtain the drag force on the OD of the tubing string. An analytical expression for the wall shear is given in White (White, 2005) for axial annular Couette flow between concentric moving cylinders:

$$\tau_{Wall_{OD}} = \frac{\mu V_0}{r_o \ln(\frac{r_1}{r_o})} \tag{1}$$

Where r_0 is the tubing radius at OD, r_1 is the casing radius at ID, V_0 is the tubing speed, and μ is dynamic viscosity of the fluid. Note that the shear varies linearly with the moving pipe velocity.

The resulting drag per unit length for the tubing OD is:

$$Drag_{OD} = \left(\frac{\mu V_0}{r_o \ln(\frac{r_1}{r_o})} \right) \cdot \pi \cdot OD_{Tubing} \tag{2}$$

where $OD_{Tubing} = 2r_o$ is the tubing OD.

3.2 Tangential drag on ID of tubing string

Similarly to section 3.1, the wall shear on the ID due to the pipe flow must be known in order to obtain the drag force on the ID of the tubing string. An analytical expression for the pipe wall shear is given in White (White, 2005) for turbulent flow:

$$\tau_{Wall_{ID}} = \frac{1}{2} \rho V_0^2 \cdot \frac{0.0791}{\mathrm{Re}_{ID}^{1/4}} \tag{3}$$

Where V_0 is the fluid bulk velocity, ρ is the fluid density and Re_{ID} is the Reynolds number, based on the pipe ID, defined as:

$$\mathrm{Re}_{ID} = \frac{\rho V_0 \, ID_{Tubing}}{\mu} \tag{4}$$

Where ID_{Tubing} is the tubing ID. Note that for water or $CaBr_2$ (14.2 lb/gal and 3 cp) the internal pipe flow becomes turbulent at relatively low velocity.

The resulting drag per unit length for the tubing ID is:

$$Drag_{ID} = \left(\frac{1}{2} \rho V_0^2 \cdot \frac{0.0791}{\mathrm{Re}_{ID}^{1/4}} \right) \cdot \pi \cdot ID_{Tubing} \tag{5}$$

3.3 Determination of Drag coefficients in Abaqus/Aqua (Simulia, 2010)

The drag forces per unit length due to the internal and annular flow, away from the restrictions due to the packer elements, are combined to give the following:

$$Drag_{Tubing} = \left(\frac{\mu V_0}{r_0 \ln(\frac{r_1}{r_0})} \right) \cdot \pi \cdot OD_{Tubing} + \left(\frac{1}{2} \rho V_0^2 \cdot \frac{0.0791}{\mathrm{Re}_{ID}^{1/4}} \right) \cdot \pi \cdot ID_{Tubing} \tag{6}$$

Using (4), the above expression (6) can be rewritten as:

$$Drag_{Tubing} = \pi \cdot \mu \cdot V_0 \cdot \left[\frac{OD_{Tubing}}{r_0 \ln(\frac{r_1}{r_0})} + 0.03955 \cdot \mathrm{Re}_{ID}^{3/4} \right] \tag{7}$$

However, the Abaqus/Aqua model requires a drag coefficient, C_d , as defined by the following expression where V_0 is pipe–fluid relative velocity:

$$Drag_{Tubing} = \frac{1}{2} \rho \, C_d \, \pi \, OD_{tubing} V_0^2 \tag{8}$$

Obviously, equation (8) can not represent equation (7) exactly. The built-in drag should be neglected and a user subroutine should be written for drag as defined by equation (7). In this particular work, drag coefficient is determined as follows: calculate the average pipe velocity per a model considering buoyancy but neglecting drag; use the average velocity to determine overall drag on the tubing string per equation (7); match drag per equation (7) to drag per equation (8) to determine C_d .

3.4 Drag due to Packer Elements

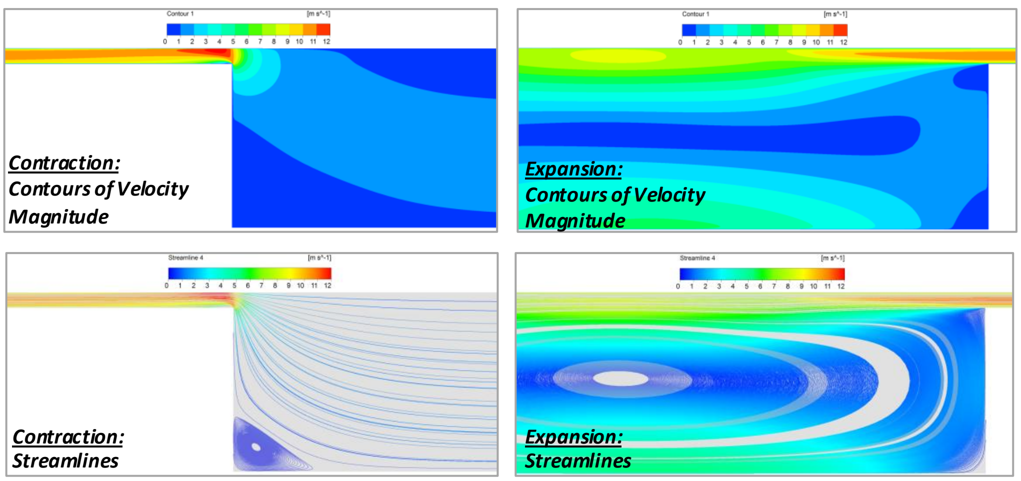
The resistance due to the flow around the packer elements could not be accurately approximated analytically, therefore, steady state CFD analyses using ANSYS FLUENT V13.0 (Fluent, 2011) were performed.

3.4.1 CFD set-up

The packer elements have been approximated by a constant diameter. The annular restrictions to the flow path have been modeled using a 2 degree sector of the full annular geometry, applying symmetry conditions. Meshing capabilities of ANSYS Workbench have been used to generate a structured mesh with an inflation layer to capture the effects of the boundary layer. A constant velocity is provided at the inlet of the numerical domain, while an averaged static pressure is imposed at the domain outlet. An incompressible fluid ($CaBr_2$) with constant properties was used for the CFD analysis. Density and viscosity were set to 14.2 lb/gal and 3 cp, respectively.

3.4.2 CFD Results

In order to predict the relationship between the flow velocity and the drag due to the packer elements, three inlet velocities were investigated: 0.3, 1.0, and 3.0 m/s. Streamlines and velocity contours for the 1m/s case are presented in **Figure 3a** and **3b**, for the front restriction and the back expansion, respectively.



(a) (b)

Figure 3. Flow behavior (a) near front restriction, (b) near back expansion

Figure 4 presents the evolution of the force on the packer elements as a function of the incoming inlet velocity. The flow resistance for the elements follows a power law relation (power exponent 1.49). The drag due to the flow restriction is accounted for in the ABAQUS code by quantifying this "drag" as a point drag as defined in the Abaqus Theory manual (Simulia, 2010), see also **Figure 5**.

4. The FEA Model

First, the complex flow field in the system is basically ignored and fluid in the well bore is assumed to be stationary. It is assumed that *the relative velocity between fluid and the pipe string in the model is due to the pipe motion*. The reasons behind this approximation are: 1) a pipe movement is small (typically less than 3 feet) and will not generate substantial flow; 2) when pipe does move, fluid would flow into the space left behind, thus reducing overall upward fluid flow speed; 3) the initial motion of the pipe string is local, most of the pipe is stationary.

The interaction between the pipe and the fluid in the well bore is through the drag and friction only. The key parameter is the friction coefficient, or tangential drag coefficient per Abaqus terminology. The estimation of the friction coefficient and point drag at the packer element is described in Section 3.

In addition to the assumptions and approximations made above, it is further assumed that the pipe string can be represented by a 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) Well bore size was considered in drag calculation.
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 tool release process:
    1. Hold tubing string at the top by tubing total weight in fluid.
    2. Fix the bottom; overpull the string at top to 15kips, 45kips or 75kips (the force is converted to Newton in the models).
    3. When overpull reaches the designated value, fix top, and let the bottom go.
    4. Investigate the dynamics of the tubing string **in fluid.**

The tool release process is analyzed via (implicit) linear dynamic elasticity. Materials of the pipes are assumed to be linear elastic. The steel properties used are as follows: $E = 210GPa$, $\gamma = 0.3$, $\rho = 7800\,kg/m^3$. Fluid density is 1701.53kg/m^3. The packer element is not explicitly represented in the model but treated as a geometric discontinuity that forms a flow restriction. The drag it induces is represented by two point drag at the top and bottom of the packer element. Since the wave speed in the tubing string is approximately 5188m/s – the pipe string length is 5660m – thus, the wave period is ~ 2 seconds. The simulation is carried out for 4 seconds. Numerically, a relatively large half-step residual must be allowed for the simulation to begin.

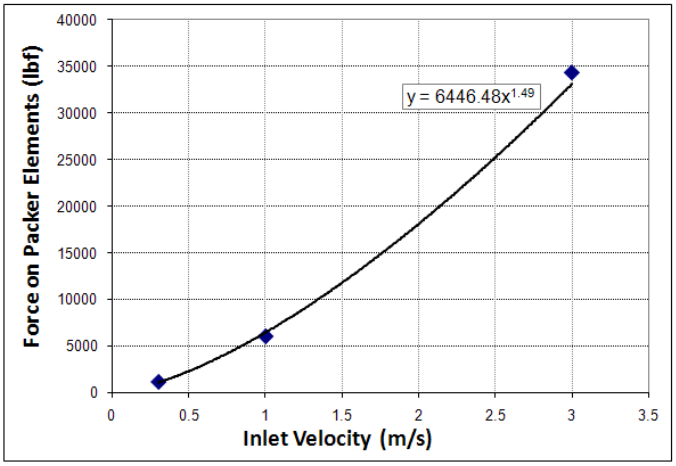


Figure 4. Force on packer elements

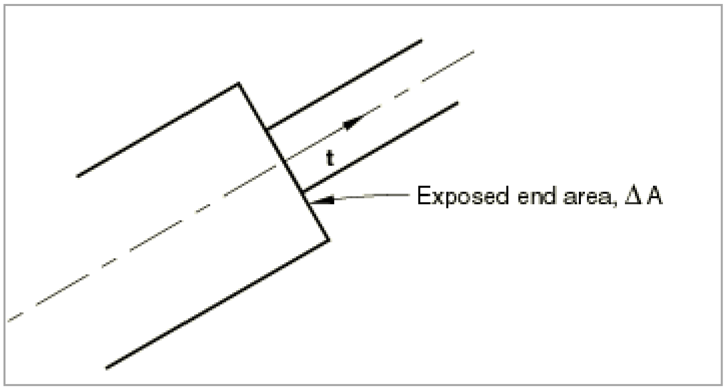


Figure 5. Change in section in an immersed beam (Simulia, 2010)

Note: for convenience of dynamic analysis, SI unit is used in FEA.

5. Dynamics of Tubing String during Tool Release

Per the description in Section 2, the force at the rig floor equals the weight of the tubing string in the fluid before overpull. At this time, the force at the shear joint (the lock) is assumed to be zero. As overpull is applied, the force at the rig floor equals the weight in fluid plus overpull. The force at the shear joint is equal to overpull. The whole tubing string is stretched and stores a tremendous amount of elastic energy.

5.1 Dynamics of the String

For the first case, when the shear joint is sheared at 15,000lb load, the shear joint becomes a free end. Accelerating initially, it moves upward reaching a peak velocity of 0.33m/s and then reaches a "steady state" velocity of about 0.3m/s. The upward motion will turn downward when the wave reflected from rig floor reaches the shear joint after 2.2 seconds, a little longer than 2 seconds, due to fluid damping. The shear joint will overshoot in the downward direction before reaching "steady state" velocity of ~ 0.23m/s (see **Figure 6**). During this process, the element (126 ft (38.4m)) above the shear joint, will have a slightly delayed upward motion as well (**Figure 7**). It has a maximum upward displacement of 2.12 feet (0.646m) (see **Figure 8**).

The force at the rig floor changes with time as well (**Figure 9**). Before the wave from the shear joint reaches the rig floor, the force there remains constant and equals the tubing string weight in fluid plus overpull. When the wave reaches the rig floor, the force will have a sudden drop because the whole string is moving upward. As in the other quantities discussed earlier, the force will overshoot in the reverse direction, and then settle down to a "steady state" value.

The element velocity in the fluid is compared to a case where drag is neglected as shown in **Figure 7**. Element velocity is appreciably larger without drag so it is very important to include drag properly in this type of analysis. The overall characteristics of the dynamics match general field experience.

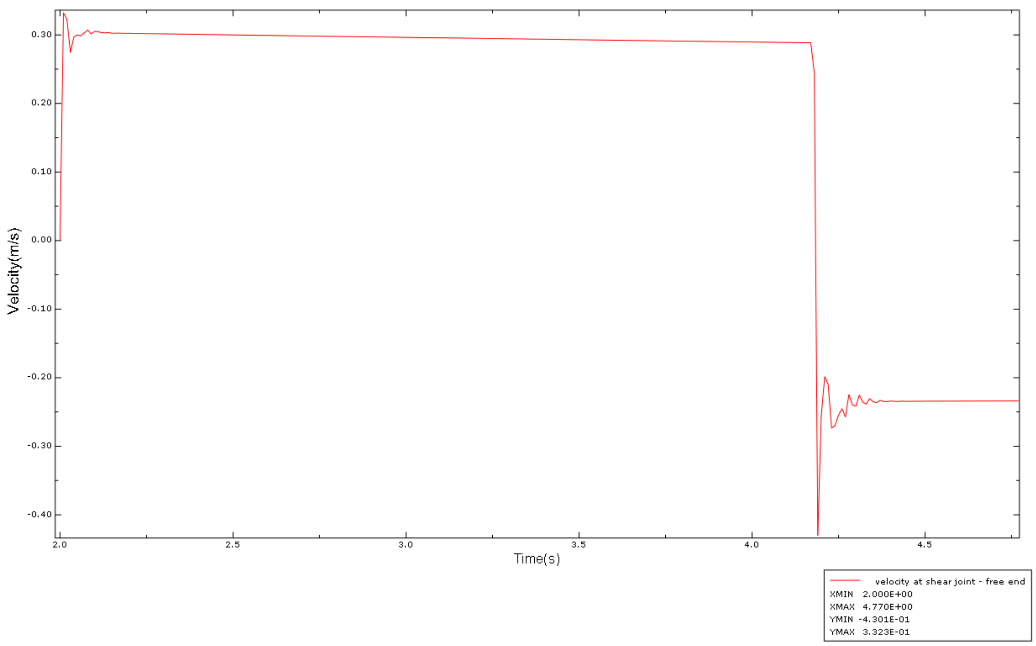


Figure 6. Shear Joint Velocity History

5.2 Effect of Overpull on String Dynamics

It is expected that as the overpull is increased, the force at the rig floor will decrease more than the element velocity and displacement will increase.

Element velocity at different overpull magnitudes is shown in **Figure 10**. The dynamic characteristics remain the same at increasing overpull. The maximum element velocity is nearly proportional to the overpull magnitude (see **Figure 11**). This is significant in practical applications for confidence in the results obtained for the three overpulls for other overpull values. Element displacement at different overpull magnitudes is shown in **Figure 12**. It is 0.645m (2.12ft) at 15kips, 1.79m (5.87ft) at 45kips, and 3.18m (10.43ft) at 75kips.

The rig floor force change with time for different overpull is shown in **Figure 13**. The higher the overpull, the larger the rig floor force will drop. It is foreseeable that when overpull is too large, the tubing string can be in compression at the rig floor!

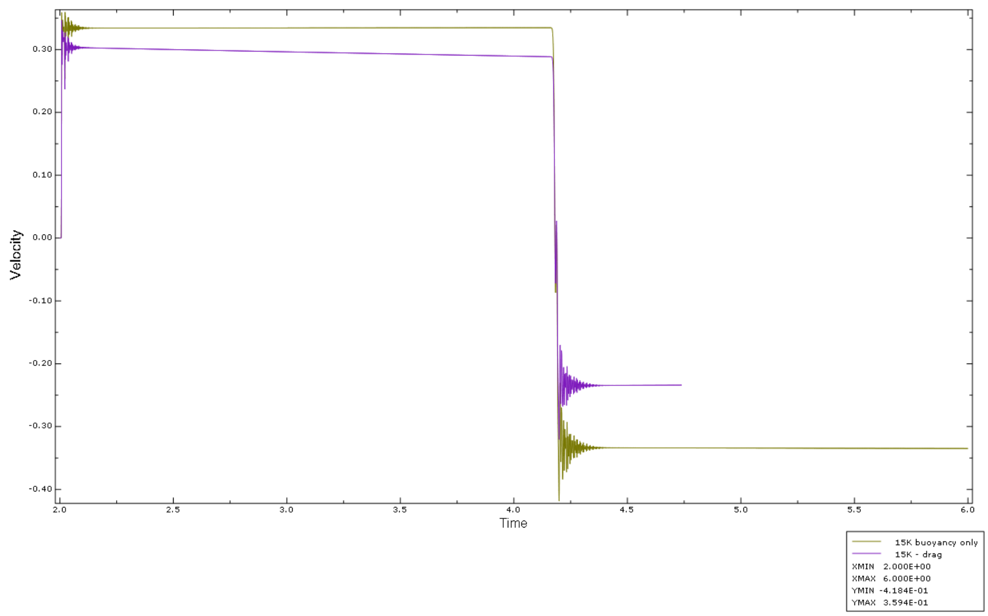


Figure 7. Element Velocity due to shearing of shear joint, with and without drag in the model

5.3 Flow Rate at Sealing Element and Swab Off

The flow rate at the element is calculated per max element velocity. The dimension of the wellbore size is very important. The flow rate is determined per annular flow profile (White, 2005) equations (9) to (11) which has max velocity at element – assumed fluid moving with the element, and zero velocity at wellbore ID.

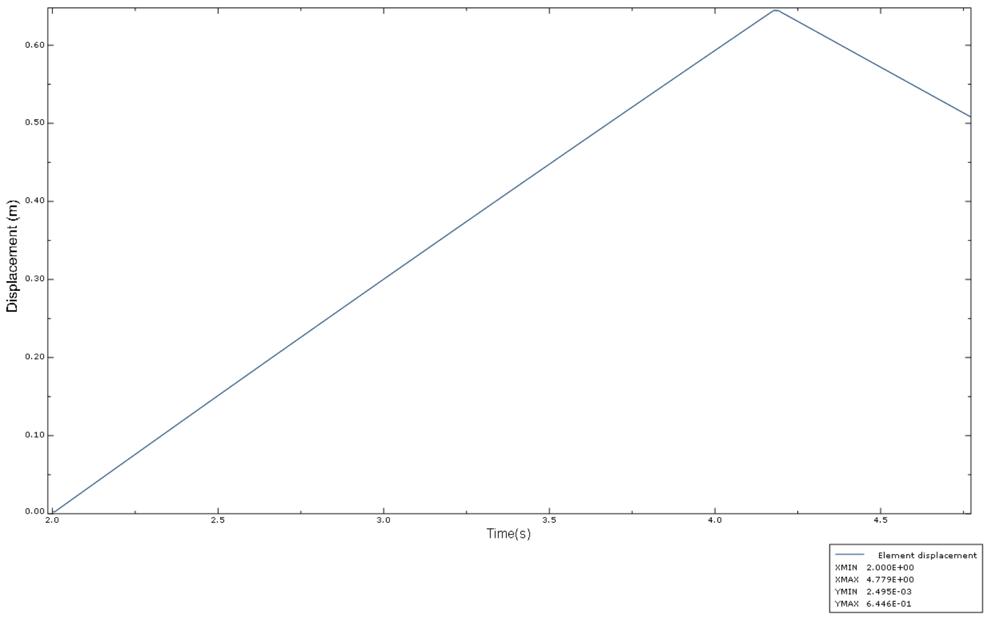


Figure 8. Element displacement due to wave propagation

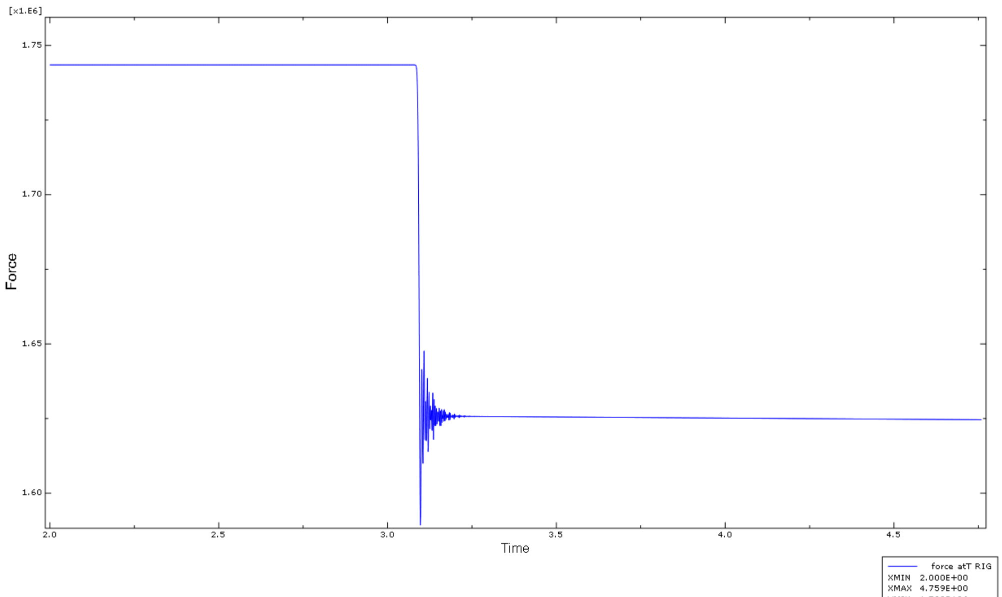


Figure 9. Force history at rig floor

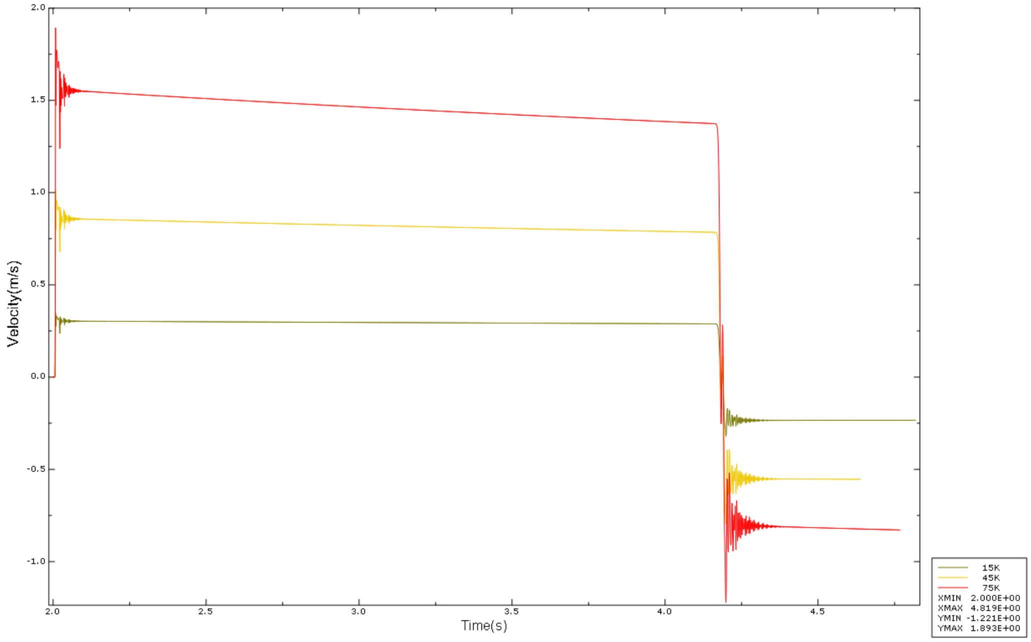


Figure 10. Effect of overpull magnitude on element velocity

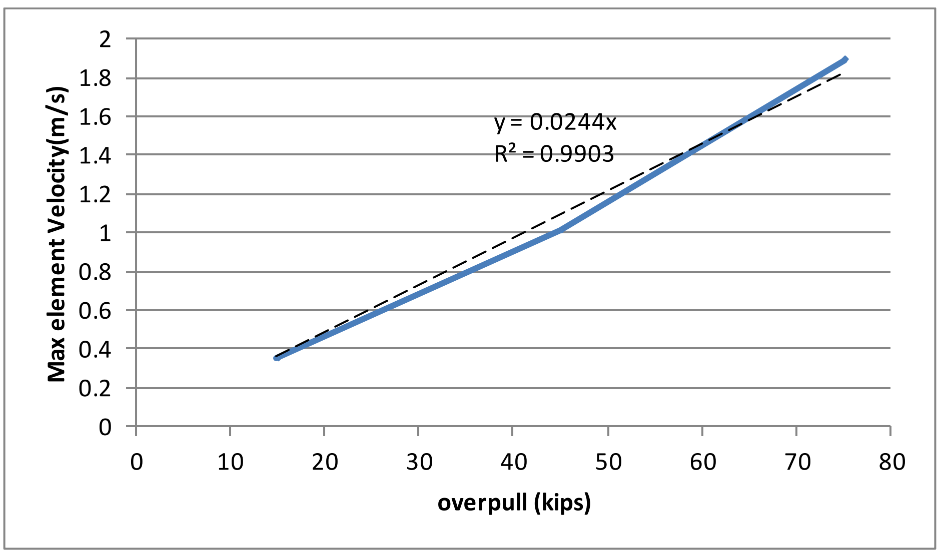


Figure 11. Relation between max element velocity and overpull magnitude

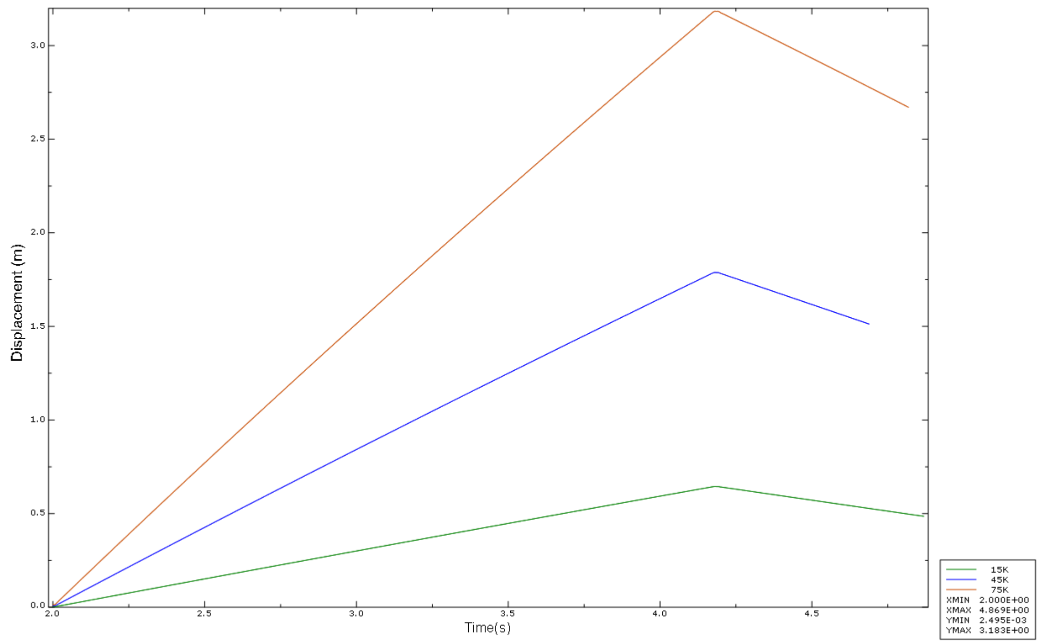


Figure 12. Effect of overpull magnitude on element displacement

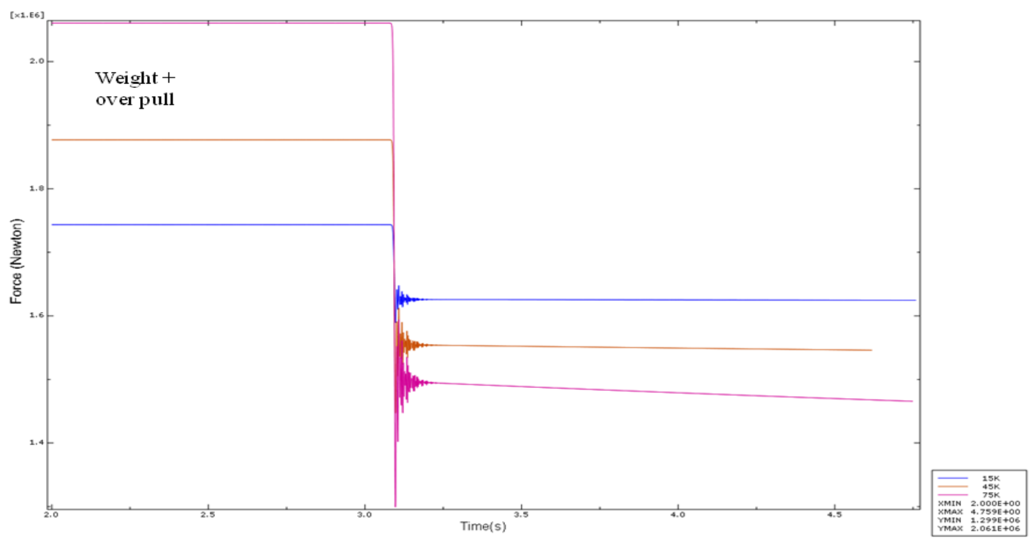


Figure 13. Effect of overpull magnitude on rig floor force

$$V = \frac{V_{\max} \ln(\frac{r_1}{r})}{\ln(\frac{r_1}{r_0})} \tag{9}$$

$$\overline{V} = \frac{V_{\max}}{r_1 - r_0} \int_{r_0}^{r_1} \frac{\ln(\frac{r_1}{r})}{\ln(\frac{r_1}{r_0})} dr \tag{10}$$

$$Q = \pi(r_1^2 - r_0^2)\overline{V} \tag{11}$$

The max flow rates of flow passing packer elements for different overpull are listed in **Table 1**. These flow rates can be used to determine occurrence of packer element swab off.

Table 1. Flow rate at element under different overpull

overpull (kips)	15	45	75
element max velocity (m/s)	0.35	1.01	1.89
equivalent flow rate (barrel per minute, bpm)	1.36	3.95	7.36

Typically, the critical flow rate that leads to swab off for a given element design in a given size of casing or wellbore is determined from flow tests. ***Assuming*** that the critical flow rate in this application is 7 bpm, then the maximum overpull that can be applied to the tubing is 72.7 kips without causing element swab off during the tool unlocking process (shear joint shearing).

5.4 Sensitivity of flow rate prediction to model assumptions

To simplify the dynamic analysis, various assumptions could be made. The simplest way to perform the dynamic analysis is to ignore fluid all together. A better approach would be to account for buoyancy while assuming the fluid has no viscosity or neglecting the viscous effect. A more reasonable approach would be to account for drag as accurately as possible, such as the approach proposed in this paper. The highest fidelity model would be full 3D fluid structure interaction accounting for the complex fluid dynamics, which is prohibitively time consuming and expensive. Here a comparison is made between the first three approaches (see **Table 2**) – in air, in fluid but neglecting drag, and in fluid accounting for drag. All three approaches actually yield similar characteristics of string dynamics, but the amplitude of dynamic responses can be dramatically different.

Obviously, the “in air” model is not a suitable model for this purpose. The “buoyancy only” model accounts for major impact from fluid but is still too conservative. It over-predicted flow rate by 20%. The proposed approach, to account for drag due to fluid flow in an annular area and at flow restriction, can properly predict completion string dynamics efficiently, providing a quantitative estimation of dynamic effects.

It is believed that the proposed approach captures the dominant factors that influence completion string dynamics. It is noted that the model prediction can be verified by comparing predicted force at the rig floor to that recorded on the rig scale.

Table 2: comparison of different model predictions

	overpull (kips)	15	45	75
In fluid with drag	element max velocity (m/s)	0.35	1.01	1.89
	equivalent flow rate (bpm)	*1.36*	*3.95*	*7.36*
In fluid without drag	Element max velocity	0.42	1.26	2.06
	Equivalent flow rate buoyancy only (bpm)	*1.63*	*4.88*	*8.02*
In air	Element max velocity	3.8	4.5	5.5
	Equivalent Flow rate in air (bpm)	*14.4*	*17.5*	*21.4*

6. Summary and Concluding Remarks

An extension of Abaqus/Aqua to an internal flow problem is proposed and applied to the study of dynamics of completion tubing strings in fluid filled wells. The predictions from the model correlate with general field experience.

The proposed approach captured dominant factors that influence completion string dynamics during tool release, specifically the drag due to flow in an annular area and at restrictions. Despite the fact that there is no fluid in the model, the annular flow profile is accounted for in the flow rate determination. The proposed model provides an effective and efficient method for the study of dynamics of a completion string or any other tool string in wellbores.

7. References

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4. Zhong, A. and Gano, J. (2008), Dynamic Response in a Pipe String during Drop-Catch in a Wellbore, 2008 ABAQUS USERS' Conference, Newport, Rhode Island, May 19-22, 2008.

8. Acknowledgements

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