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Transient calculation of pressure waves in a well induced by tubular expansion

W. Assaad[a,*], H. R. Pasaribu[a], D. Zijsling[a], K. N. van Dalen[b], A.V. Metrikine[b]

[a] *Shell Global Solutions International BV, Kessler Park 1, Rijswijk and Postcode 2288 GS, The Netherlands*
[b] *Delft University of Technology, Stevingweg 1, Delft and Postcode 2628 CN, The Netherlands*

Abstract

Shell has developed a novel mono-diameter well concept for oil and gas wells as opposed to the traditional telescopic well design. A Mono- diameter well contains multiple casing sections with the same internal diameter. This is achieved by expansion of the casing sections concerned using an expansion cone. Since the well is drilled in stages and casings are inserted to support the open hole, an overlap section between two consecutive (expandable) casings exists which has to be expanded. When the cone enters the overlap section, the expansion force increases dramatically due to the expansion of two casings, cured cement and formation layers. When the cone finalizes the expansion of the overlap section it pops out, the expansion force vanishes and the cone accelerates upwards and it generates an empty volume to be filled by the well fluid (mud). As a result of this, fluid starts to flow through the drill pipe, around the cone and the fluid volume below the cone starts to decompress. This induces a surge pressure wave traveling upwards and a swab pressure wave in the expanded casing traveling downwards. If the pressure difference between outside and inside of the expanded casing exceeds the collapse rating of the casing, the casing will collapse which leads to the loss of the concerned well section. Repair of such a failure costs time and money, therefore this swab pressure must be well predicted to enable the installation process to be designed such that this collapse can be avoided. A model of fully coupled fluid-structure interaction between cone and the well fluid is built for calculating the swab pressure propagating downward and surge pressure propagating upward resulted from transient process occurring after cone pops out. This model has shown an effective tool for predicting the swabbing pressure in field deployments performed lately in Gulf of Mexico and according to its output the suitable cone is selected in order to avoid the casing collapse.

Keywords: fluid-structure interaction, method of characteristics, compressible, oil and gas;

1. Introduction

Shell is working on mono-diameter well. Mono-diameter well means a well with a single diameter from surface to total depth and it is accomplished by casing expansion [1]. Applying mono-diameter well technology increases the potential of lateral reach, reduces drilling related risk and trouble time, and improves in capital efficiency on drilled wells and overall field development [2]. In comparison to conventional well design, the mono-diameter well design

* Corresponding author
E-mail address: wissam.assaad@shell.com

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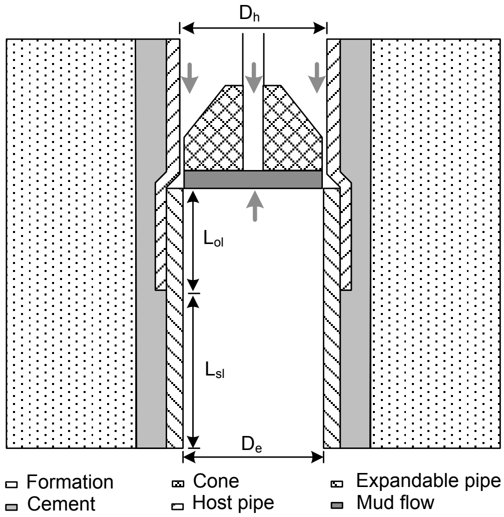

Fig. 1: Cone pop out after expansion of overlap section

has economical and environmental benefits. Main economical benefit is the increase in production rate while main environmental benefit is the reduced amount of rock cuttings [2–4].

Table 1: Swab and collapse pressures

Cone size [*inch*]	Expansion force [*tons*]	Swab pressure [*bar*]	Collapse pressure [*bar*]
10.2	215	151	150
10.0	193	140	163
9.9	167	50	170

Casing expansion can be performed hydraulically by applying pressure below the cone or mechanically by pulling or pushing the cone by drilling rig through drill string [5]. In this study, mechanical expansion is considered and the cone is pulled. Casing expansion is accomplished by (1) running the liner with bottom hole assembly (BHA) including cone to the targeted depth (2) anchoring the top of the liner (3) casing expansion by pulling the cone by the top drive [6]. After expansion of the single liner, the cone enters into an overlap section where a new liner is expanded against a previously expanded liner, cured cement layer and formation as depicted in Figure 1. Therefore, expansion force increases drastically during expansion of overlap section. The increase in expansion force can reach 100%. This increase is mainly related to formation strength, cement strength, expansion ratio, friction, casing dimensions and casing material. As a result of the expansion force and well depth which can reach the value of 5 kilometres, the drill pipe is stretched and the amount of stretch can reach the value of 12 meters. When expansion of the overlap section is finalized by the cone, the forces applied on the cone including friction and metal forming are released. Therefore, the potential energy in the drill string is transformed into kinetic energy and the cone pops out. As result, a volume of fluid below the cone must be filled by fluid flowing from annulus above the cone, through the drill string and expansion of the fluid volume below the cone. The last one causes the so called swab pressure below the cone. When the difference between external pressure (pressure of pore fluid) and internal pressure exceeds the collapse rating of the casing, casing collpase occurs which is a fatal loss. Since the casing is expanded plastically, the increase in casing diameter is accompanied by a decrease in casing length and wall thickness, and an increase yield stress due to hardening. The increase in OD/t_c due to casing expansion lowers the collapse rating of expanded liner according to API collapse formula [7]. In order to avoid this incident, a proper prediction must be made to take the correct actions. A model is built in house to calculate transient swab and surge pressure waves generated below and above the cone respectively when the cone pops out. The model is described in section 2.

Nomenclature

A cross-sectional area of the drill string
c speed of sound
E_v fluid bulk modulus
E_{eq} equivalent elastic modulus
F_{exp} expansion force applied on the cone
F_p force due to fluid pressure applied on the cone
F_s force due to friction between fluid and drill string
g gravitational acceleration
h_{loss} frictional head loss
K global stiffness matrix of the drill string
L length of the drill string
L_{ol} length of the overlap section
L_{sl} length of the single liner section
M global mass matrix of the drill string
OD casing outer diameter
D_h diameter of host casing
D_e diameter of expandable casing
p fluid pressure
U nodal displacement vector of the drill string
v fluid velocity
$\dot{U}$ nodal velocity vector of the drill string
$\ddot{U}$ nodal acceleration vector of the drill string
ρ fluid density
ϕ well angle
Δt time increment
t_c casing thickness
t time
z spatial coordinate

2. Cone pop out modelling

The release of metal forming and friction forces causes the cone to pop out when it finishes the expansion of overlap section. As a result, the potential energy is converted into kinetic energy. The high expansion force causes the drill string to stretch prior to the pop out. In previous work performed on surge and swab pressure generation due to running casing in or out of the well, it is stated that the swab and surge pressure are dependant on gel breaking, inertia and viscous drag of mud [8,9]. A fluid structure interaction model is built to capture the dynamics of the drill string and fluid flow towards the volume generated due to cone pop out. The fluid flow is composed into three branches: (1) flowing through drill string (2) flowing through clearance between the cone and host casing, and (3) expansion of the volume in the bottom hole.

2.1. Structural model

A discrete model is built to represent the drill string. The drill string is discretized into bar elements. Each bar element has two nodes and each node has single degree of freedom in the longitudinal direction. The stiffness and mass matrices of the drill string are built by assembling the stiffness and mass matrices of each element. The elemental mass matrix is determined according to particle mass lumping method [10]. The dynamic equation (1) is built with external forces including the expansion force, forces due to pressure and forces due to shear stresses generated by friction between well fluid and cone. The pressure and shear forces are determined from the fluid models described below. The velocity and displacement are formulated in equations (2) and (3) in terms of acceleration and velocity respectively using the trapezoidal rule. The symbols are defined in the Nomenclature.

$$M\ddot{U} + KU = F_{exp}(t) + F_p(t) + F_s(t) \tag{1}$$

$$\dot{U}_{t+\Delta t} = \dot{U}_t + \frac{\Delta t}{2}(\ddot{U}_t + \ddot{U}_{t+\Delta t}) \tag{2}$$

$$U_{t+\Delta t} = U_t + \frac{\Delta t}{2}(\dot{U}_t + \dot{U}_{t+\Delta t}) \tag{3}$$

Equations (2) and (3) are manipulated such that cone acceleration and displacement are functions of cone velocity. Finally they are substituted into Equation (1).

2.2. Fluid model

The fluid is represented in three domains: (1) fluid in drill string, (2) in annulus and (3) in bottom hole. The continuity and momentum equations are built for each domain.

2.2.1. Continuity equation for unsteady flow

The continuity equation for unsteady and compressible flow is built according to [11,12]:

$$\frac{\partial\rho}{\partial t} + v\frac{\partial\rho}{\partial z} + \rho\frac{\partial v}{\partial z} + \frac{\rho}{A}\Big(\frac{\partial A}{\partial t} + v\frac{\partial A}{\partial z}\Big) = 0 \tag{4}$$

The density and cross-sectional area depend on z and t via the pressure. After applying the chain rule, the continuity equation becomes:

$$\Big(\frac{1}{\rho}\frac{\partial\rho}{\partial p} + \frac{1}{A}\frac{\partial A}{\partial p}\Big)\Big(\frac{\partial p}{\partial t} + v\frac{\partial p}{\partial z}\Big) + \frac{\partial v}{\partial z} = 0 \tag{5}$$

but fluid bulk modulus is defined as:

$$\frac{1}{E_v} = \frac{1}{\rho}\frac{\partial\rho}{\partial p} \tag{6}$$

using Equation (6) and elastic stress strain relations of a pressure vessel due to internal and external pressure [12], the equivalent elastic modulus of the system is determined as described in Equation (7).

$$\frac{1}{\rho}\frac{\partial\rho}{\partial p} + \frac{1}{A}\frac{\partial A}{\partial p} = \frac{1}{E_{eq}} \tag{7}$$

2.2.2. Momentum equation for unsteady flow

The momentum equation is formulated according to [9,11]:

$$\rho\Big(\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial z}\Big) + \frac{\partial p}{\partial z} - \rho g sin(\phi) + h_{loss} = 0 \tag{8}$$

where h_{loss} is composed of friction and interruption of flow smoothness. The last is caused by expansion or contraction in fluid flow area [11].

2.3. Method of charactersitics

The partial differential equations (PDE) contain two unknowns $p(z,t)$ and $v(z,t)$. A linear combination of two PDE is performed by multiplying Equation (5) by $\rho\gamma c^2$ and adding it to Equation (8). Considering $\gamma = \pm\frac{1}{c}$, assuming $v \ll c$ and using the relation $\frac{dv}{dt} = \frac{\partial v}{\partial t} \pm c\frac{\partial v}{\partial z}$ two ordinary differential equations (ODE) are obtained.

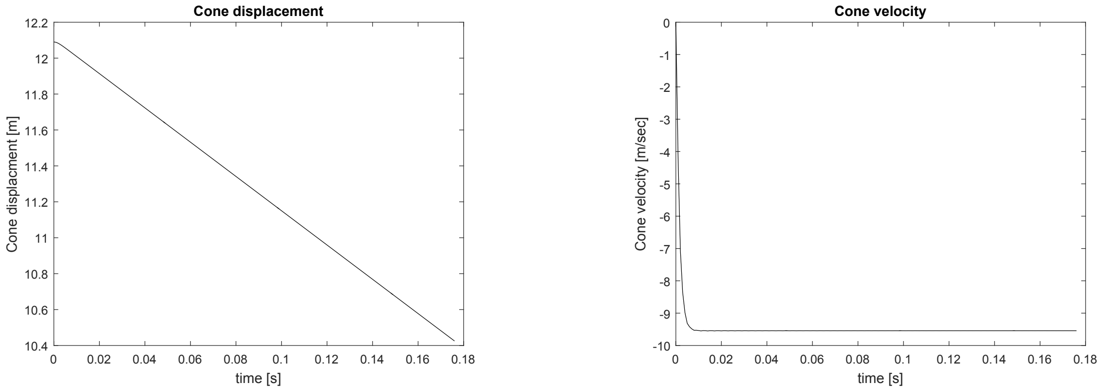

Fig. 2: Displacement and velocity of cone after pop out

2.4. Boundary and interface conditions

They include the following:

- The degree of freedom of the node at top of drill string is constrained. This assumption is valid because the length from the cone to the bottom of the well is smaller than the length from the cone to top of the well.
- A fully reflective boundary condition is applied at the bottom of the fluid volume below the cone.
- At the top of the fluid column in the annulus a zero pressure is applied because it is assumed that it is open to the atmospheric pressure.
- At the top of the fluid column in the drill string a zero pressure is applied because it is assumed that it is opened to the atmospheric pressure. But in reality, a pressure can be applied.
- At interaction, the pressures in fluid regions are applied on the cone.

3. Results

A case is selected from our deployments in Gulf of Mexico and analyzed by the model. The related parameters are tabulated in Table 1. The cone displacement, velocity, acceleration, flow rates to fill the volume generated by the cone pop out, swab pressure below the cone and surge pressure above the cone are depicted in Figures 2, 3 and 4 respectively. The data is plotted with respect to time and the maximum time is equivalent to the time for the pressure wave to travel downward and before reaching the bottom of the well. The pressure wave passes through two sections one is an overlap section while the other is a single liner section. The collapse rating of the overlap section is almost double the collapse rating of a single liner. The important section is the single liner section which has the tendency to collapse when the difference between outer and internal pressure exceeds the collpase rating of the expanded single liner. Therefore, the swab pressure must be predicted at this section in order to take the proper actions before the deployment.

4. Conclusion

The model for transient swab pressure wave calculation is a successful tool which is built in house. It helps the company to predict the swab pressure before deployments and to take the proper actions such as choosing a smaller cone in order to avoid failure. In addition, this model provides the company with better understanding to find mitigation solutions.

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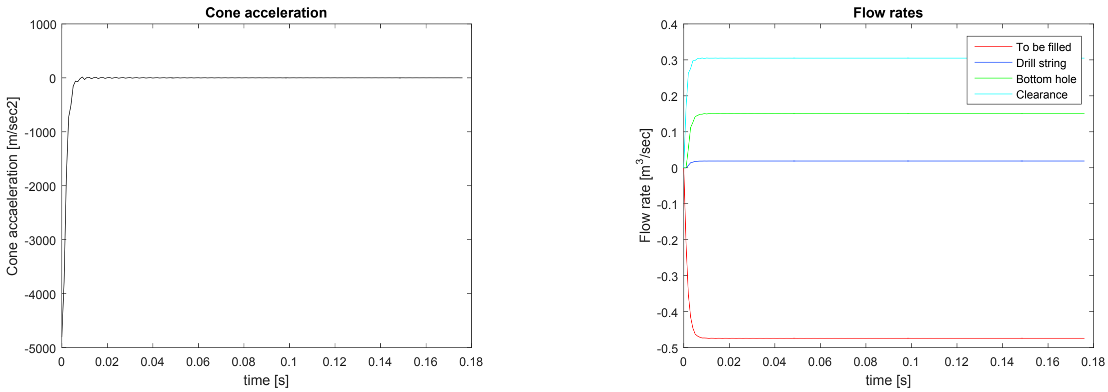

Fig. 3: Acceleration of cone and flow rates after cone pop out

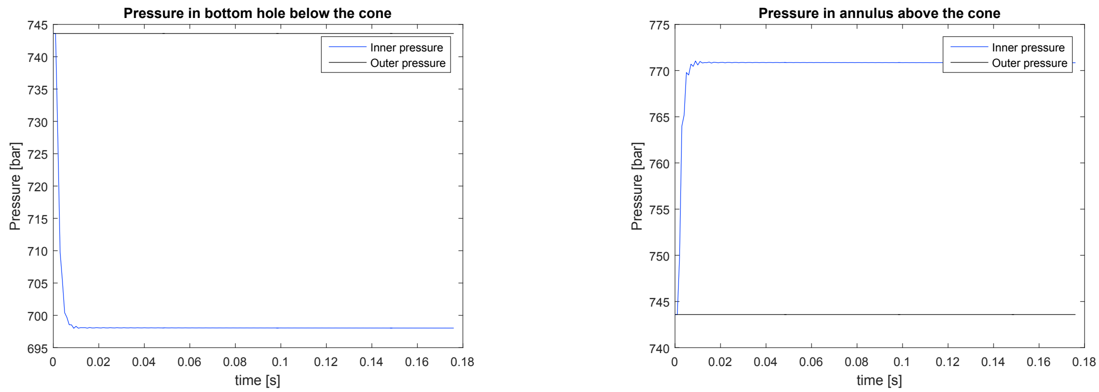

Fig. 4: Pressure below the cone and pressure above cone after pop out

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