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Coupling Axial Vibration With Hook Load/Bit Force And The Effect Of Shock Absorber

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Abstract

Drill string vibrations reduce drilling efficiency. Often vibrations cause drill string dysfunctionalities such as early failure of drill string components and bit damage. This as a result costs the industry unnecessary expenditure. Axial vibration causes drill string to lift off bottom, and hence reduces rate of penetration (ROP). By controlling vibrations intensity level, one can improve drilling efficiency and mitigate dysfunctionalities. These can be controlled by using appropriate drilling parameters and vibration control tools. Mathematical model based simulation results from the considered system and parameters show that:

- In absence of shock sub, axially induced dynamic force fluctuates weight on bit (WOB), ROP and Hook load significantly.
- On the other hand, the presence of the shock sub reduces these drilling parameters along with the amplitude and the acceleration level of drill string vibration.

This illustrates the impact of axial vibration and the performance of shock sub.

1 Introduction

Due to formation and drill string interaction, the impact force generates an impulse shock wave. This generates a movement in drill string, and this is called vibration. This is a repeated cyclic motion of drill string. The lower vibration level does not cause any significant effect. On the other hand, the higher vibration level over time can cause a number of serious problems. Drill string vibrations and high shock loads are a significant factor contributing to poor drilling performance, and create both visible and invisible nonproductive time.

Drill string vibrations have a random nature. Among others, the two primarily excitation forces usually induce vibrations are due to bit/formation and drill string/borehole interactions. As a result of interactions, the primary mode of vibrations may occur in drill string are axial, torsional and lateral and bending vibration. There are also many other sources excite drill string vibrations. These includes bits, motors, stabilizers and drill string imbalance. To detect harmful downhole vibrations events, on needs to install real-time vibration detection system as part of the drilling unit. Based on the severity of the vibration levels, in the industry, there are several ways of vibration control and remedial action methods. However, still the control/suppression methods are not yet standardized [1].

Axial vibration results in bit bouncing, which repeatedly lifts off bottom and impact on formation. Axial vibration typically occurs when the well is near vertical hole, and drilling with tricone bits. In addition, drilling out shoe track, and drilling in hard formations [2].

Axial vibration can be identified at surface as top drive vibrate axially and fluctuating downhole WOB measurement. This dynamic effect can result in drill bit and bottom hole assembly (BHA) component failure and reduces ROP as well. Shock absorber tools developed in the industry can control axial vibration [2].

During drilling, drill string experiences several loading, such as frictional, bending, and fluid flow viscous force can be mentioned. These loads are coupled with torque and drag models. In addition, the dynamic drill string vibration force also influences hook load/bit force. Among the mentioned drill string mode of vibrations, coupling axial vibration force with hook load/bit force and studying the effect of shock sub are the main focus of this paper.

2 Theory

2.1 Force in drill string-Hook load

Figure 1 illustrates a drill string discretized into small segments. The segments are loaded at the top and the bottom loaded with axial loads and torque. In addition to these loads, thermal, hydrostatic and fluid flow forces are also responsible for the change in length and hook load. The axial load transfer in drilling string during tripping is given as the sum of loads in the axial direction. As illustrated on **Figure 1**, the force at the top of the small element ‘’*ds”* is given as (Johancsik et al, 1989): [3]

$$F_{i+1} = F_i \pm \mu\left(\sqrt{\left(\beta w_s \sin\theta ds - F_e d\theta\right)^2 + \left(F_e \sin\theta d\varphi\right)^2}\right) + \beta w_s \cos\theta ds + F_{fl} \qquad 1$$

Where, $d\theta$ =change inclination, $d\varphi$ =change azimuth, β is buoyancy factor, w_s is weight per unit length, μ is coefficient of friction, Fi is force at the bottom and F_{i+1} is force at the top of the string segment. F_{fl} is the fluid flow effect on drill string.

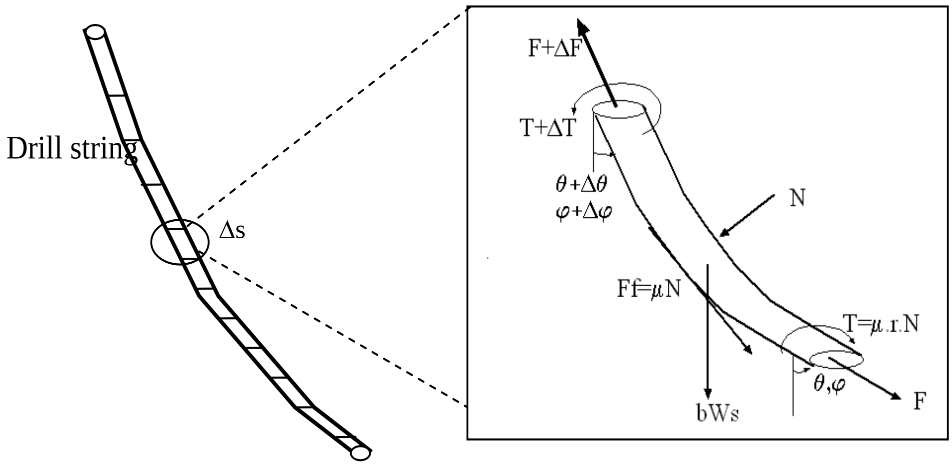

Figure 1: Segmented drill string and loads

Maidla and Wojtanowicz' (1987, a) [4] also derived the effect of viscous pressure for each pipe element. The hydrodynamic viscous drag force shown in Eq. 1 is given as:

$$F_{fl} = \frac{\pi}{4}\sum_{i=1}^{n}\left(\frac{\Delta P}{ds}\right)\Delta s_i d_i^2 \qquad 2$$

Where, ΔP is pressure loss pressure loss, *d* is outer diameter of the drill string.

Special case: Assuming a near vertical well, the possibility of the friction force and dogleg effect will disappear and equation 1 will be reduced to:

$$F_{i+1} = F_i + \int_{o}^{L}\beta w_s ds + F_{fl} \qquad 3$$

The force at the top is the sum of all string elements and would be equal to HL. The Fi(i=0) = WOB, which has negative sign since it is compressive load. The vibration uncoupled hook load is given as Eq. 4:

$$HL = WOB + \sum_{i=1}^{n}\beta w_s \Delta s + F_{fl} \qquad 4$$

Where β is the buoyancy factor:

$$\beta = 1 - \frac{\rho_{fluid}}{\rho_{string}} \qquad 5$$

Where, ρ_{fluid} is the density of fluid and ρ_{string} is the density of string.

2.2 Drill string axial vibration and dynamic load

It is common practice to model vibration behavior of drill string by using linear spring-mass system. The linear spring mass model is analogy to an electrical system comprising of capacitor, inductor and resistor. Just as *Fdx* is the amount of work done by a driving force *F*, in a displacement, *dx*. So *Vdq* is the amount of work done by the driving voltage, *V*, when a charge *dq* moves in a circuit. The energy absorbed at a resonance in the mechanical system is also similar to the analogy in the electrical system. Several authors have analyzed axial vibration using mass spring dashpot system analogy [5, 6]. In this paper, we considered **Figure 2a** setup that has been analyzed by reference [6].

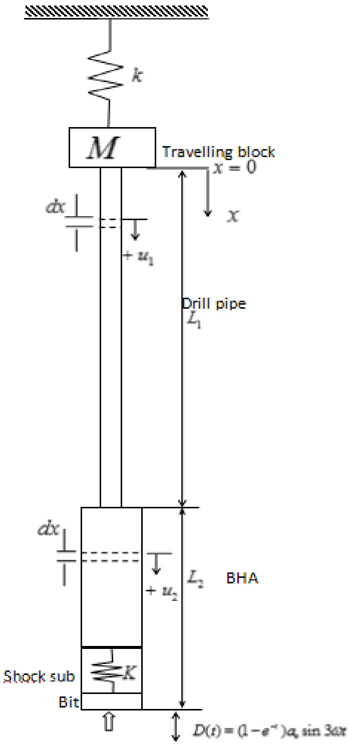

Figure 2a: Drill string mass-spring [6]

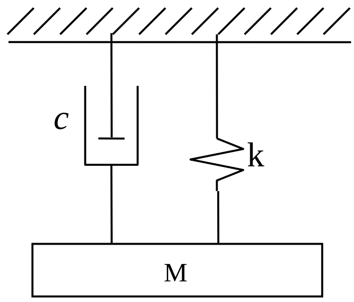

Figure 2b: Illustration of Spring-Mass-Dashpot

Figure 2b shows the spring mass system to describe the drill string dynamics. Assume that the system is under forced oscillation, the Newton law reads:

$$m\frac{\partial^2 z}{\partial t^2} = F' - c\frac{\partial z}{dt} - kz \qquad 6$$

As shown in Eq. (6), drilling string axial dynamic load is determined by many influence factors such as elastic modulus, cross-sectional area, line weight (m), spring constant (*k*) linear damping coefficient (*c*) and so on.

Kreisle et. al. [6] have presented equation motions for the drilling string (Eq.7a) and for bottom hole assembly (Eq.7b) are given as:

$$\frac{\partial^2 u_1(x,t)}{\partial t^2}+\frac{c_1}{\rho_1 A_1}\frac{\partial u_1(x,t)}{dt}=a_1^2\frac{\partial^2 u_1(x,t)}{\partial x^2} \tag{7a}$$

$$\frac{\partial^2 u_2(x,t)}{\partial t^2}+\frac{c_2}{\rho_2 A_2}\frac{\partial u_2(x,t)}{dt}=a_2^2\frac{\partial^2 u_2(x,t)}{\partial x^2} \tag{7b}$$

Where, $a_{1,2}=\sqrt{E/\rho}$. The parameters are defined in **Table 1**. The differential equations have been solved by using residual theory and Laplace transformation. The vibration induced force, which is to be coupled is given as [6]:

$$F_e = EA\left.\frac{\partial u}{\partial x}\right|_{x=L_1+L_2} \tag{8}$$

2.3 Coupling drill string vibration force with Hook load and WOB

The primary objective of this paper is to couple axial vibration induced forces with hook load and bit force. Due to the nature of axial force, which causes bit bouncing, the axial vibration force will fluctuate the weight on bit and hence the hook load the top of the string. Therefore, since we do not have experimental measured data, we present two coupling scenarios. However, the coupling scenarios need to be verified by experimental data.

The first coupling scenario assumes that the dynamic vibration force impact is reflected on the bit force (WOB). The coupled hook load is given in terms of the uncoupled hook load as:

$$HL(coupled) = HL(uncoupled) + E_{BHA}A_{BHA}\left.\frac{\partial u_2}{\partial x}\right|_{x=L_1+L_2} \tag{9}$$

HL (uncoupled) is the hook load given as Eq. 3 or Eq. 4.

$$WOB(coupled) = WOB(uncoupled) + E_{BHA}A_{BHA}\left.\frac{\partial u_2}{\partial y}\right|_{x=L_1+L_2} \tag{10}$$

The second scenario assumes that the dynamic force impact on hook load at a given time is due to the vibration force at the weight on bit and at the surface. The coupled hook load is given as:

$$HL(coupled) = HL(uncoupled) + E_{BHA}A_{BHS}\left.\frac{\partial u_2}{\partial x}\right|_{y=L_1+L_2} + E_{BHA}A_{BHA}\left.\frac{\partial u_1}{\partial x}\right|_{x=0} \tag{11}$$

3 Simulation examples

This section presents the simulation sensitivity study and the axial vibration effect on amplitude, acceleration and bit force. The example is based on scenario-1coupling.

3.1 Simulation setup

Figure 2a drill string setup is used for the simulation study. The well is vertical and **Table 1** shows the simulation parameters. The effect of fluid flow is not included in this simulation. However, the drilling fluid viscous effect is included with the damping coefficient of drill string and drill collar in the measured values [5].

Parameters	Value
Modulus of elasticity drill pipe/collar, E (psi)	$3x10^7$
Density of drilling fluid (sg.)	1.5
Mass density of drill pipe/collars (lb./sec^2)/(in.^{4})	$0.730x10^{-3}$
Length of drill pipe, L1 (in.)	9400
Length of collar, L2(in.)	600
Cross section drill pipe, A1 (in.^{2})	5.87
Cross section collars, A2(in.^{2})	29.6
Damping coeff. drill pipe,c_1 (lb./in.)/(in./sec)	0.00888
Damping coeff. Collar, c_2 (lb./in.)/(in./sec)	0.01331
Amplitude of forcing function, a_o, (in.)	1
Spring rate cables and derrick, k (lb./in.)	$6.5x10^4$
Mass of travelling block etc., M(lb./sec^2)/(in.)	38.9
Spring constant at shock sub, K (lb./in.)	20000, 40000
Weight on bit (Vibration uncoupled), (kN)	150

Table 1: Simulation parameters

3.2 Effect of shock sub and RPM on vibration amplitude

Figure 3a and **Figure 3b** show the effect of RPM and shock absorber on the vibration amplitude of drill string. As shown, the presence of shock absorber reduces the amplitude level by about 70%. The vibration amplitude increases as rotational speed per min (RPM) increases up to 126RPM and then decreases afterwards. At about 126RPM, the shock sub reduces the vibration amplitude by about 55% as compared with shock sub free BHA.

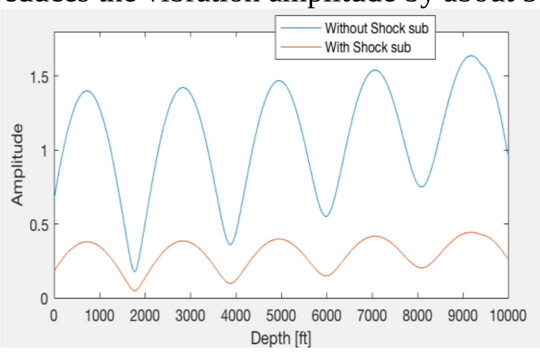

Figure 3a: Amplitude with and without shock sub

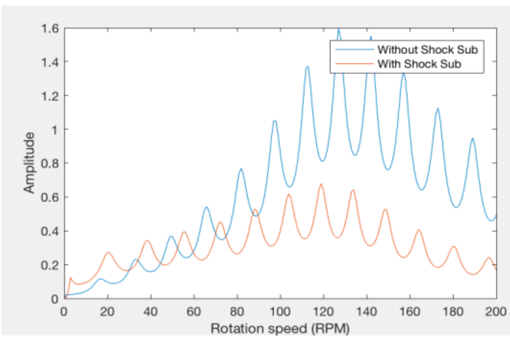

Figure 3b: Amplitude as a function of RPM with and without shock sub

3.3 Effect of axial vibration on bit force

Vibration induced in the axial direction causes drill string bouncing up and down. This dynamic force has impact on the weight on bit and hence on hook load. The simulation results presented here are to analyze the effect of shock absorber in damping the dynamic force level. Vibration uncoupled static weight on bit (bit force) is assumed to be 150kN in magnitude and the rotation speed of the drill string was 126RPM. **Figure 4a** and **Figure 4b** display the simulation results comparing with and without shock sub.

As shown on **Figure 4a**, in the absence of shock sub, the dynamic vibration force fluctuates the weight on bit by +/-100%. This generates a huge impact force and results in ROP reduction and also the impact may cause a premature drill bit cutters failure.

On the other hand, in the presence of shock sub having the 40000lb/in. spring constant, the bit force oscillation due to axial vibration is by +/-25%. Replacing the spring constant by 20000lb/in., the bit force fluctuation reduced to +/-14%.

Similarly, the dynamic load impact on bit force will be reflected on the hook load as well. The simulation results illustrate the performance of the shock absorber reducing the intensity level of axial vibration effect. In addition, the spring constant is the key factor for the performance.

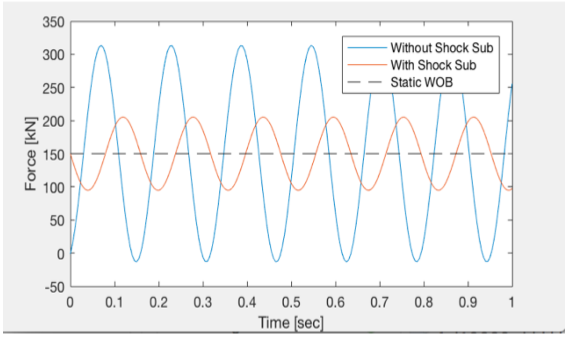

Figure 4a: Bit force for 40000lb/in spring constant at shock sub.

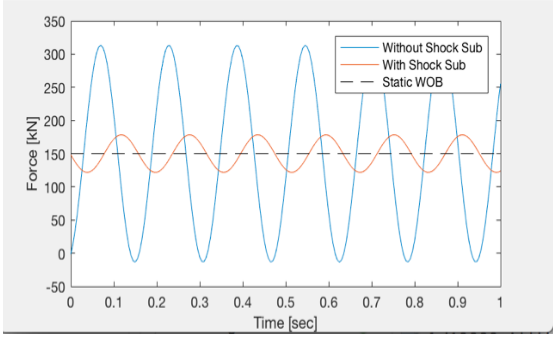

Figure 4b: Bit force for 20000lb/in spring constant at shock sub.

3.4 Effect of axial vibration on acceleration

The acceleration of drill string is defined as the second time derivative of displacement. In the industry, acceleration is used to analyses the risk level of drill string. **Figure 5a** and **Figure 5b** show the drill string acceleration in the absence and presence of shock absorber. As shown, the shock absorber reduced the acceleration by 71 % and 82%, respectively.

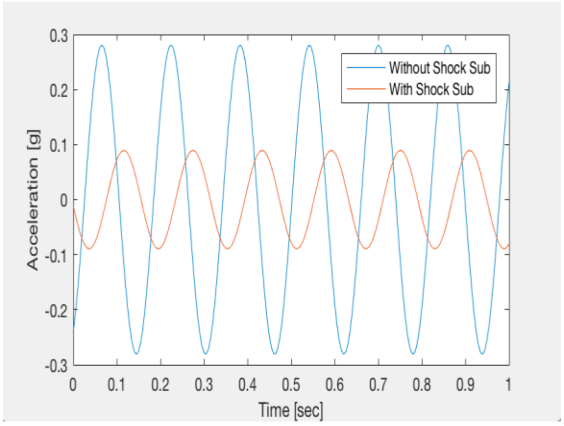

Figure 5a: Axial acceleration for 40000lb/in. spring constant at shock sub.

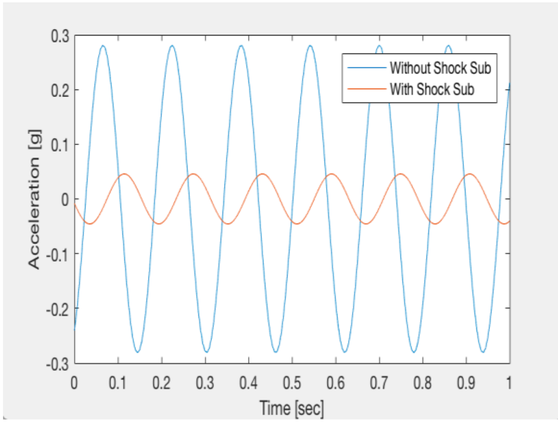

Figure 5b: Axial acceleration for 20000lb/in. spring constant at shock sub

4 Summary

During planning and operational phases, it is important to use appropriate and optimized parameters for safe and efficient operations. Drill string mechanics such as torque, drag and string elongation analysis are very important.

Due to bit-rock interaction, a shock wave generated in drill string causes drill string vibration. As a result, dynamically induced vibration force influences torque, hook load and reduces drilling efficiency. Vibrations measurement and prediction may help to control/mitigate drill string dysfunctionalities such as buckling, twist off, bit and drill string component failures.

In this paper, mathematical model based axial vibration force is coupled with hook load/weight on bit and its impact is analyzed on the considered simulation setup. Several sensitivity studies have been performed. The selected simulation results show that:

- In absence of shock sub, axially induced dynamic force fluctuates the WOB, ROP and Hook load significantly.
- On the other hand, the presence of the shock sub reduces these parameters along with the amplitude and the acceleration level of drill string vibration.

The results illustrate the impact of axial vibration and the performance of shock sub.

Future work

In the future, experimental setup will be designed and the presented coupling scenarios will be tested.

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