ARTICLE IN PRESS

Journal of Petroleum Science and Engineering (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

Dynamic model for longitudinal and torsional motions of a horizontal oilwell drillstring with wellbore stick-slip friction

Mejbahul Sarker[a,*], D. Geoff Rideout[b], Stephen D. Butt[c]

[a] Oil and Gas Engineering, Memorial University of Newfoundland, Canada
[b] Department of Mechanical Engineering, Memorial University of Newfoundland, Canada
[c] Department of Process Engineering, Memorial University of Newfoundland, Canada

A R T I C L E I N F O

Keywords:
Horizontal drilling
Wellbore friction
Vibration
Rate of penetration
Lumped segment approach
Finite element
Bit-rock interaction
Agitator tool
Simulation

A B S T R A C T

Horizontal oilwell drillstring failures are very costly. Vibration causes excessive wear and tear on the bottom hole assembly and reduces the life of the drill bit, and has motivated extensive research on these types of drillstring vibrations. Two key factors in simulation of motions of horizontal drillstrings are to have a model capturing coupling among various types of vibration, and an accurate but efficient treatment of the wellbore friction. In this paper, a bond graph dynamic model of a horizontal oilwell drillstring has been developed that predicts longitudinal motion, torsional motion, and coupling between longitudinal and torsional motion excited by bit-rock interaction. A lumped segment modeling approach of vertical drillstring dynamics has been extended to include dynamic wellbore friction in the 'build' and 'horizontal' sections of the drillstring. The model incorporates torsional viscous damping, longitudinal hydrodynamic damping, and buoyancy effect due to drilling fluid; an extended bit-rock interaction model that allows the drillstring to advance at the rate of penetration, a downhole mud motor, and top drive ac motor dynamics. The friction coefficient between drillstring and wellbore has been tuned with the aid of field data from a horizontal oilfield in Canada. The model predicts the expected coupling between weight on bit, bit speed, and bit-rock interaction conditions; and their effect on longitudinal and torsional motions. Finally, an experiment was conducted with a downhole axial vibration tool ("Agitator®"). A force excitation source, which simulates the Agitator® tool, in the longitudinal direction has been implemented in the horizontal section of the virtual drillstring. Simulations show a better weight transfer to the bit, with a low frequency and high amplitude force excitation giving best performance.

1. Introduction

Horizontal oilwell drilling is, necessary to maximize production from a formation and reduce environmental impact at the surface. Vibrations are always present to some degree while drilling in deviated wells but can be especially bad in difficult drilling environments (e.g. hard formations, steep angle wells). Vibration can affect weight-on-bit (WOB), rate-of-penetration (ROP), and drilling direction and can also severely damage the bottom-hole-assembly (BHA), measuring-while-drilling (MWD) tools and drill bit cutters. Field experience suggests that drillstring vibrations and related failures can account for approximately 2–10% of well costs (Jardine et al., 1994). Since horizontal drilling is one of the most expensive operations in oil exploration and development, drilling with optimum operational parameters such as WOB, top drive rotational speed, downhole mud motor speed, torque-on-bit (TOB) and bit hydraulic horsepower is required from an economic point of view. A schematic of horizontal oilwell drilling is shown in Fig. 1. MWD tools sometimes fail due to excessive vibrations. Their high cost along with cost of tripping to replace such tools, motivates the development of sophisticated drillstring vibration models to understand and prevent conditions that lead to failures. One of the key engineering challenges related to building horizontal drillstring dynamic models is the modeling of wellbore friction. While drilling horizontal wells, especially extended-reach wells, friction between the drillstring and borehole wall is the main source of decreasing ROP caused by energy lost due to poor WOB transfer. One of the first contributions to the work of understanding friction in the well has been presented in (Johancsik et al., 1984) developing a torque and drag model with basic equations for friction in deviated wellbores. It was assumed that both torque and drag are caused entirely by sliding friction forces that result from contact of the drillstring with the wellbore. Later the work was put in a standard differential form in (Sheppard et al., 1987). A larger study on friction analysis for long reach wells has been undertaken in (Aadnoy, 1998). All models

* Corresponding author.
E-mail addresses: mms426@mun.ca (M. Sarker), g.rideout@mun.ca (D.G. Rideout), sdbutt@mun.ca (S.D. Butt).

http://dx.doi.org/10.1016/j.petrol.2016.12.010
Received 13 September 2016; Received in revised form 29 November 2016; Accepted 5 December 2016
0920-4105/

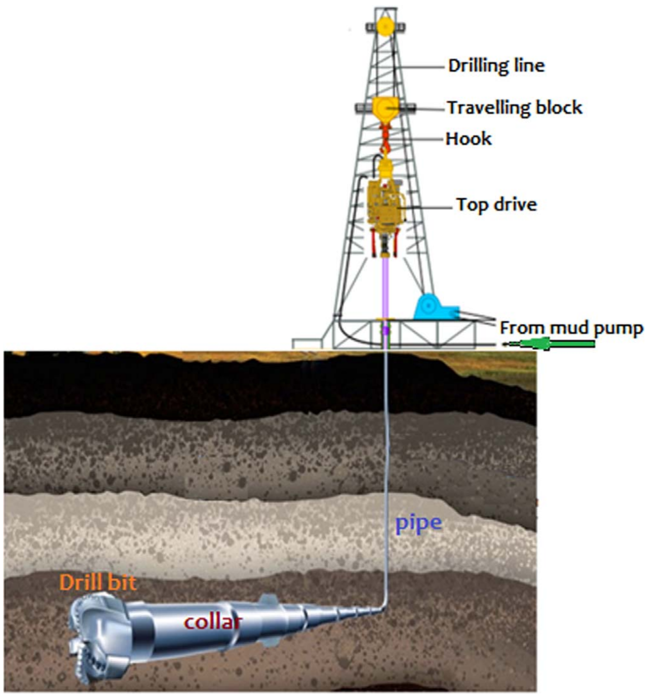

Fig. 1. Sketch of horizontal oilwell drilling system (courtesy of Schlumberger).

discussed above are soft-string models and the stick-slip phenomena in the friction model has been ignored. A computationally efficient yet predictive wellbore friction model remains an open research problem. To the best of the author's knowledge, no complete dynamic model for a horizontal oilwell drillstring has been developed.

This paper is organized as follows. Section 2 develops, implements and validates a stick-slip friction model that will allow the simulation to accurately capture an important source of energy loss during drilling and tripping. In Section 3, dynamic normal forces for the friction submodel are calculated based on a modification of an existing static treatment. A lumped-segment drillstring model, with coupled axial and torsional vibratory motions, is presented in Section 4, followed by a bit-rock interaction model in Section 5 that allows the drillstring and bit to advance in the borehole. Field data is used in Section 6 to tune the friction factor. Given that the authors and their industry partners are motivated to predict the vibrations on and induced by downhole tools, Section 7 summarizes an experimental program by which an axially-vibrating tool (Agitator®) was characterized for use in the simulation. In Section 8, the complete horizontal drillstring model is used to show the effect of downhole tool output on WOB, ROP, and vibration levels at multiple locations. The model is a potentially valuable tool in the design of drillstrings with optimized top drive speeds, stabilizer and downhole tool locations, mud motor speeds, and trajectories. The model development was facilitated by the bond graph approach, an overview of which is given in Appx. A.

2. Modeling of stick-slip friction phenomena

The stick-slip nature of friction is very common when the relative velocity between sliding surfaces approaches zero and the surfaces become 'stuck', requiring a force larger than the sliding friction force to break the surface loose. The most basic friction models contain Coulomb friction and linear viscous damping which describe the friction forces well for steady state velocities. When velocity crosses zero most models present numerical problems. To overcome these problems during simulations, Karnopp (1985) proposed a friction model to set the friction force equal to the external forces acting on the object, for a small neighborhood around zero velocity, outside of which friction is function of velocity. The model has the advantage of generating ordinary differential equations but can still experience numerical instabilities in the stick phase. A switch model proposed in (Leine, 2000) consists of three different sets of ordinary differential equations for the stick, slip and the transition phases. At each time step the state vector is inspected to determine whether the system is in the slip mode, in the stick mode or the transition mode. The corresponding time derivative of the state vector is then chosen. A region of small velocity is defined for the stick band and the system is considered to be in the slip mode if the relative velocity lies outside this narrow stick band. In one state the velocity is prescribed and the force is determined, and in other state, the force is prescribed and the velocity is determined. Such causal inversions create formulation and computational problems, and these problems can be quite prohibitive if many switches are part of the model.

A modification of the Karnopp's model is presented by Margolis (2004) that allows the stick-slip friction element to be self-contained, which is represented as a combination of dissipative and elastic elements in a bond graph. The elements require a velocity input from the attached system and output the friction force similarly to Karnopp's model. The difference can be identified during the 'stuck' phase where the friction force continues to be calculated internally to the element and does not require any information from the attached system. The model is self-contained because the tests of the 'stuck' and 'unstuck' states have no dependence on the overall systems to which the friction generated elements are attached.

The stick-slip friction model proposed in this paper takes a similar modeling approach to Margolis. A bond graph C-element (compliance with some logical modification of build-in codes) simulates the stick-slip phenomena. The output of the C-element is the friction force. The input velocity, which is the relative motion between the contact surfaces, allows determination of the 'stuck' and 'unstuck' states. The necessary logical information is shown in Figs. 2 and 3. In the 'stick' phase, the friction force is generated by the small but finite deformation of a high stiff spring-damper system which represents deformation of contact surface asperities. When the force exerted by the spring-damper on the system mass becomes equal to the maximum static friction force and the relative motion is still in the stick band, then the spring state (deflection) is set at a constant value in order to create a constant static friction force output. During the 'slip' phase the output from the C-element is simply the kinetic friction force. The model from Figs. 2 and 3 are simulated in 20Sim® bond graph software using the proposed self-contained friction model. The bond graph model of the mass-surface system is shown in Fig. 4. As described in Appx. A, elements bonded to the 1-junction have a common generalized flow (velocity) and their generalized efforts (forces) sum to zero. Therefore,

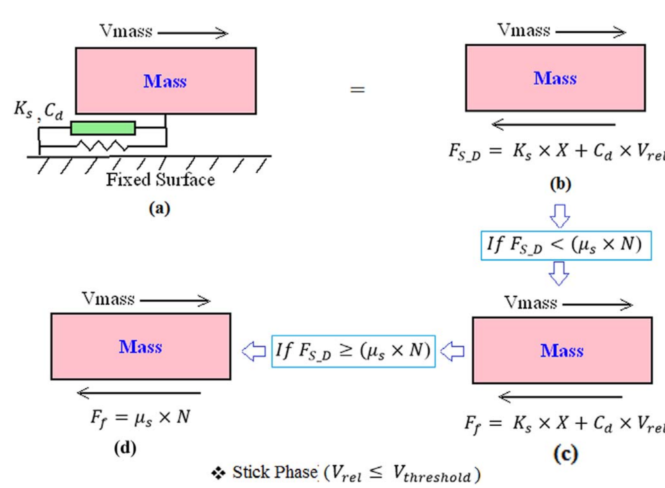

Fig. 2. Physical schematic of stick-phase.