ARTICLE IN PRESS

Journal of Petroleum Science and Engineering xxx (2017) 1–10

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

Torsional vibrations with bit off bottom: Modeling, characterization and field data validation

Ulf Jakob F. Aarsnes [a,b,*], Roman J. Shor [c]

[a] International Research Institute of Stavanger (IRIS), Oslo, Norway
[b] DrillWell - Drilling and Well Centre for Improved Recovery, Stavanger, Norway
[c] University of Calgary, Department of Chemical and Petroleum Engineering, Calgary, Canada

ABSTRACT

A distributed model of a drill string is presented, with Coulomb stiction as a distributed source term, to investigate the effect of borehole inclination and borehole friction on the incidence of torsional vibrations along a drill-string. To isolate the effect of this distributed friction, only cases where the bit is off bottom and with no axial movement are considered, and consequently a purely torsional model is used. The model is used to study the stick slip limit cycle, as caused by distributed Coulomb friction, and the limit-cycle period and amplitude dependence on the friction parameters is derived. This enables the qualitative limit-cycle behavior to be characterized as inertia or stick dominated, and examples of this characterization is validated with the field data. For comparison, high frequency field data from two deviated wells from surface and downhole sensors are considered. Time-series are isolated where angular rotation is restarted after a connection, with the bit off bottom and before axial motion is re-initiated, to make the data consistent with the model assumptions. A close match is obtained between recorded and modeled downhole data, however, in some cases either the initial torsional strain in the drillstring is not known or axial motion is initiated, which violates model assumptions, causing a mismatch.

1. Introduction

Exploration and production of oil and gas in the deep subsurface, where hydrocarbon reservoirs are found at depths between 2000 and 36,000 feet (Stokka et al., 2016), requires that a narrow borehole, between 4 and 24 inches in diameter, be drilled using a slender drill-string through a varied downhole environment and along an often snaking wellpath. Drill string vibrations, and their negative consequences on Rate of Penetration (ROP) and equipment, are a well known phenomenon when drilling for hydrocarbons. In particular, the torsional oscillations known as stick slip, which are considered to be some of the most prevalent vibrations, are to be avoided. These stick-slip oscillations are characterized by a series of stopping – "sticking" – and releasing – "slipping" – events of the bit.

Significant literature exists which seeks to explain the incidence of stick slip through various implementations of bit-rock interaction and various complexities of drill-string dynamic models. The most used models abstract the drill-string as a lumped mass, representing the bottom hole assembly (BHA) inertia, and a torsional spring, representing the drill-string stiffness (Bailey and Finnie, 1960; Dashevskiy et al., 2011). Stick-slip is then introduced by making the model unstable through imposing a bit-rock interaction as a *velocity weakening* frictional force (Stribeck-like effect) (Brett, 1992; Pastusek et al., 2013; Kapitaniak et al., 2015), or through the regenerative effect (Richard et al., 2004, 2007; Germay et al., 2009b). These models may be confounded by introducing higher complexity dynamics at the bit-rock interaction or through higher order models along the drill-string (Leine et al., 2002; Nandakumar and Wiercigroch, 2013; Liu et al., 2013), but still assume that stick slip is due to the velocity-weakening effect (actual or apparent (Besselink et al., 2016; Germay et al., 2009b)) of the frictional force at the bit. All these models have been used to demonstrate the occurrence of the limit cycle which exhibits itself as stick-slip and many have been used to verify various types of stick-slip mitigation controllers, including simple tuned PID controllers (Kyllingstad and Nessjøen, 2009; Runia et al., 2013), impedance matching controllers (Dwars, 2015), H-infinity controllers (Yilmaz et al., 2013; Vromen et al., 2015), sliding mode controllers (Navarro-Lopez et al., 2007), and others.

A key factor in common with the above referenced literature is that the bit-rock interaction is used to explain the cause of stick slip. A consequence of this is that the models are unable to explain the occurrence of stick-slip with the bit off bottom (where there is no bit-rock interaction). Off-bottom stick slip is a well known phenomenon from the field, and when mentioned in literature is hypothesized to be caused by a negative difference between static and dynamic *along-string*

* Corresponding author. International Research Institute of Stavanger (IRIS), Forskningsparken AS, Gaustadalléen 21, 0349 Oslo, Norway.
E-mail address: ujfa@iris.no (U.J.F. Aarsnes).

https://doi.org/10.1016/j.petrol.2017.11.024
Received 1 August 2017; Received in revised form 31 October 2017; Accepted 9 November 2017
Available online xxxx
0920-4105/

Please cite this article in press as: Aarsnes, U.J.F., Shor, R.J., Torsional vibrations with bit off bottom: Modeling, characterization and field data validation, Journal of Petroleum Science and Engineering (2017), https://doi.org/10.1016/j.petrol.2017.11.024

Coulomb-type friction, see Brett et al. (1989); Halsey et al. (1986); Zhao et al. (2016), (see e.g. Beer et al. (1972) for a description of Coulomb friction). This is an important phenomena as it indicates that non-linear frictional forces along the drill-string (and not just the bit rock interaction), in deviated or horizontal wells, plays a significant role in the torsional oscillatory behavior of drill-strings. Hence, models which only incorporate the bit rock interaction as the cause of torsional stick slip fail to explain off-bottom stick slip vibrations, as observed in field data after connections and in back-reaming operations. This potential cause of stick-slip, have not received nearly the same analysis or attention in the literature, in particular in the context of occurrence, characterization and avoidance.

The effect of the distributed, along-string, Coulomb friction, becomes an increasingly prominent feature of torsional drill string dynamics in wellbores with high-inclination laterals. The nonlinear nature of the Coulomb friction can excite a wide range of frequencies where higher order modes become essential for representing the dynamics of the system, in particular for long wells. Hence, lumped approximations of the drill string (where the drill string is approximated as a point mass as in e.g. Germay et al. (2009b)) easily fall short, and it is desirable to develop a distributed model representation of the torsional dynamics, along the lines of (Aarsnes and Aamo, 2016; Germay et al., 2009a; Aarsnes and van de Wouw, 2018). Specifically, a distributed model where also the distributed nature of the Coulomb friction is represented.

1.1. Contribution and approach

The approach taken in the present work is to use a distributed model of the drill string with the Coulomb friction given as a distributed source term implemented as an inclusion. The distributed nature of the model enables it to capture the full range of possible dynamics regardless of well length and survey. At the same time, the relative mathematical simplicity of the formulation, a 1-D wave equation with a source term, enables us to derive simple yet accurate relations for the expected period, amplitude and behavior of the stick-slip limit cycle. These relations can in turn be used to estimate the dynamic and static friction factors which have important applications for directional drilling (Skyles et al., 2012; Cheng and Polak, 2007).

To validate the model we compare the response of the model to field data from rotational startups, off bottom and without any axial movement, after a connection. This allows us to *isolate* the effect of the angular motion of the drill string against *only* the Coulomb friction of the well bore. That is, without any bit rock interaction or coupling with the axial dynamics.

A significant attraction with this approach is that, having isolated the effect of the torsional Coulomb friction in this way, it can be quantified in a rigorous manner, and then in a future work combining with axial motion and existing results on bit-rock interaction, for simulating the full coupled on-bottom dynamics.

The main contributions of the paper are the following:

- The robust and effective numerical representation of a torsional drill string model with distributed Coulomb friction given as a source term and modeled as an inclusion explicit in the Riemann invariants of the wave equation.
- The successful comparison of this relative simple dynamic formulation against field data.
- The derivation of the period of stick slip oscillations in terms of drill string parameters and angular top-drive velocity, and the further classification of the type of oscillation as inertia or stick dominated.

2. Model

In this section we derive the model that will be used to recreate and analyze the torsional vibrations when the bit is off–bottom. To facilitate its relative simplicity, the formulation requires certain approximations, the main assumptions used are the following.

- As the bit is assumed to be off bottom, no bit-rock interaction is modeled.
- The torsional motion of the drill string is the dominating dynamic. No lateral or axial motion is assumed.
- The transition from static to dynamic Coulomb friction is modeled as a jump, i.e., the Stribeck curve is assumed negligible.
- The effects of along-string cuttings distribution on the friction is assumed to be homogeneous.
- The effect of the pressure differential, inside and outside the drill string, on the bending moment is not represented and is assumed to be negligible.

2.1. Torsional dynamics of the drill string

We use a distributed model, similar to Aarsnes and Aamo (2016); Aarsnes and van de Wouw (2018); Germay et al. (2009a), except that in this case we consider only the torsional dynamics. That is, for the angular motion, we denote the angular velocity and torque as $\omega(t,x), \tau(t,x)$, respectively, with $(t,x) \in [0,\infty)$. See Table 1 for units, and Fig. 1 for a schematic indicating locations. The torque is found from shear strain, given as twist per unit length, and letting ϕ denote the angular displacement in the string s.t. $\frac{\partial\phi(t,x)}{\partial t} = \omega(t,x)$, we have $\tau(t,x) = JG(\phi(t,x) - \phi(t,x+dx))/dx$, see Fig. 2. Here J is the polar moment for inertia and G is the shear modulus. Hence the equations for the angular motion are given by

$$\frac{\partial\tau(t,x)}{\partial t} + JG\frac{\partial\omega(t,x)}{\partial x} = 0 \quad (1)$$

Table 1
Nomenclature.

Symbol	Unit	Description
$A(x)$	m^2	Drill string cross-sectional area
c_t	m/s	Torsional wave velocity
f_{rat}	–	Static to dynamic Coulomb friction coefficient
$\mathscr{F}$	N	Friction, Coulomb component
F_c, F_d	N^2	Static and dynamic Coulomb friction torque per meter
F_N	N/m	Normal force per meter
G	Pa	Shear modulus
J	m^4	Polar moment of inertia
J_p, J_c	m^4	Pipe and collar polar moment of inertia
J_{TD}	kgm^2	Top-drive inertia
k_t	1/s	Viscous friction coefficient
L_p, L_c	m	Pipe and collar lengths
r_o	m	Drill string effective outer radius
S	N	Friction source term
$\mathscr{S}$	rad/s^2	Riemann formulation source term
t	s	Time (independent variable)
t_{bu}, t_{fp}	s	Drill string fundamental and build-up period
t_p	s	Oscillation period
W_b	N/m	Buoyed weight per meter
x	m	Axial position (independent variable)
$\overline{Z}$	–	Relative impedance
α	rad/s	Riemann invariant, downward
β	rad/s	Riemann invariant, upward
μ	–	Static friction coefficient
ρ	kg/m^3	Drill string density
σ_e	N	Tension profile
τ	Nm	Torque profile
τ_m	Nm	Motor torque
$\overline{\tau}$	Nm	Maximum static torque profile
ϕ	rad	Angular displacement profile
ω	rad/s	Angular velocity profile
ω_{bit}	rad/s	Angular velocity, bit
ω_c	rad/s	Coulomb friction threshold velocity
ω_{SP}	rad/s	Top-drive velocity set-point
ω_{TD}	rad/s	Top-drive velocity