Journal of Petroleum Science and Engineering 116 (2014) 36–49

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

Analysis of multi-mode nonlinear coupled axial-transverse drillstring vibration in vibration assisted rotary drilling

Ahmad Ghasemloonia*, D. Geoff Rideout[1], Stephen D. Butt[2]

Advanced Drilling Group, Faculty of Engineering, Memorial University of Newfoundland, St. John's, NL, Canada, A1B 3X5

ARTICLE INFO

Article history:
Received 5 August 2012
Accepted 18 February 2014
Available online 26 February 2014

Keywords:
drillstring model
vibration-assisted drilling
coupled nonlinear axial-transverse vibration
multi-span BHA
Bypassing PDE's
wellbore contact
multi-mode analysis

ABSTRACT

Unwanted vibration modes of a drillstring can result in inefficient drilling, and damage to the drillstring, bit, BHA components, MWD tools and mud motors. Bottom-hole assembly (BHA) configuration design, shock sub parameter tuning, and establishing drilling parameters such as rotary speed and weigh-on-bit can be improved using computer simulation of a drillstring and its vibration modes. Drilling tools are under development to apply axial vibrations for the purpose of overcoming drillstring-wellbore friction, facilitating cutting removal and improving the rate of penetration (ROP) of the bit. Predicting the effects (both desired and undesired) of such axial vibration generator tools is becoming increasingly important to industry. In this paper, the coupled nonlinear axial-transverse dynamics of the entire drillstring are modeled and lateral instabilities are qualitatively studied. The drillstring includes the pipes, a multi-span BHA with shock sub, and a force generator tool near the bit. The multi-span BHA model enables more accurate natural frequency prediction and multi-mode contact analysis of the drillstring and wellbore. The governing equations are obtained using the "Bypassing PDE's" method with the expanded Galerkin's method, which enables finding the symbolic solution of the governing equations. The effects of mud damping, driving torque, and spatially varying axial load are also included, along with nonlinearities due to geometry, axial stiffening, strain energy and Hertzian contact forces. Simulations reveal resonant frequencies and show the relative severity of the contact in each span of the BHA. The model features fast running time compared to a high-order finite element model against which it is validated.

1. Introduction

Drillstring vibration is a primary cause of premature failure of drillstring components, deterioration of the well trajectory, bit and stabilizer wear, lower penetration rate, deteriorating accuracy of measurement while drilling (MWD) systems and decreased efficiency. Bottom-hole assembly (BHA) design and control strategies to reduce unwanted drillstring vibration require enhanced dynamic models that can reveal the modal characteristics and dynamic time response of the entire drillstring. This study is motivated by two factors: (1) the need to extend existing models to include more realistic effects such as multiple-span BHA's and nonlinearities and (2) the increasing trend towards downhole tools that generate intentional axial vibration.

Several recent classes of drilling tools apply axial vibration to the drillstring for the purpose of reducing drillstring-wellbore friction (Barton et al., 2011), enhancing penetration mechanism (Manko et al., 2003; Babatunde et al., 2011) and facilitating cutting removal. Vibration drilling may transmit power to the bit more efficiently than rotary drilling. Vibration tools improve drilling performance by various means, and collectively for the purpose of this investigation their use is called "vibration assisted rotary drilling" (VARD).

Introduction of vibration in rotary drilling must be done carefully. The implementation of a VARD force above the bit excites the drillstring axially, and as a result of coupling effects, the lateral mode will also be excited. Therefore, the vibration behavior of the drillstring under the effect of axial force generators such as jars, agitators, and higher-frequency tools for ROP enhancement in rotary drilling must be predicted with accurate models. The model should incorporate drilling parameters such as weight-on-bit (WOB), rotary speed, and torque; should be able to predict natural frequencies for realistic BHA configurations, capture coupled axial and lateral vibrations, incorporate VARD tools, and manage the

* Corresponding author. Tel.: +1 709 8642573; fax: +1 709 8648975.
E-mail addresses: a.ghasemloonia@mun.ca (A. Ghasemloonia), g.rideout@mun.ca (D. Geoff Rideout), sdbutt@mun.ca (S.D. Butt).
[1] Tel.: +1 709 8643746; fax: +1 709 8648975.
[2] Tel.: +1 709 8648955; fax: +1 709 8648975.

http://dx.doi.org/10.1016/j.petrol.2014.02.014
0920-4105

trade-off between accuracy and computation time. To complement high-order finite element models that may require extremely long simulation times, the authors have developed an analytical model from which a symbolic set of partial differential equations is generated, and then solved symbolically. The model presented in this paper runs very quickly on a desktop personal computer, and allows rapid sensitivity studies of things such as the effect of shock sub stiffness, and VARD tool force amplitude and frequency, on vibration along the entire drillstring. The effects of mud damping, driving torque, and spatially varying axial load are also included, along with nonlinearities due to geometry, axial stiffening, strain energy and Hertzian contact forces.

The models are developed for vertical wellbores. Although the application of horizontal and directional drilling is increasing in low permeability formations, each deviated wellbore begins with a vertical section (vertical pilot well) which might be through a difficult formation. Deviation from vertical to horizontal can take up to 2000 ft. The model which is developed in this study is useful for analysis and design of either vertical well drillstrings, or for the drillstrings of vertical sections of horizontal and deviated wells. The following section reviews relevant literature about importance of various vibration modes and physical phenomena associated with the drillstring; modeling of wellbore contact, and methods for equation derivation and solution. Section 3 derives governing equations, including eigenfrequencies and eigenfunctions of a multi-span BHA which are implemented using a Lagrangian approach. Section 4 provides numerical simulation results showing the ability of the model to predict axial and lateral response of a drillstring with a VARD force generator. The new model described in this paper is validated with a high-order finite element model. Sections 5 and 6 give discussion, conclusions and future research directions.

2. Literature review

Drillstring vibration is not simply independent axial, torsional and lateral vibration. A typical drillstring vibrates in 3 major coupled modes: lateral-axial, lateral-torsional and axial-torsional. Bit bouncing, stick-slip and whirling are extreme examples of coupled vibration dominated by axial, torsional and lateral motions respectively. Among these coupled modes, the coupled transverse mode is a major cause of drillstring failures (Chin, 1994; Sotomayor et al., 1997; Spanos et al., 2002; Ghasemloonia et al., 2012, 2013) and wellbore washout which happens at low frequencies. The deteriorating effect of the orthogonal lateral modes could be explained through the wave speed phenomenon. Bending waves are not propagated to the surface via the drillstring as are torsional and longitudinal waves, due to the difference in the wave speed for different types of modes. The propagation speed for axial and torsional motions is quite high compared to the lateral motion (Chin, 1994). Therefore, there could be severe bending vibrations deep in the hole, which the surface measuring tools do not detect. BHA–wellbore contact is the main excitation source for lateral vibration. In the case of VARD drilling, axial vibration plays an important role since the high frequency VARD force directly excites the axial modes and lateral instabilities may exist due to axial excitation (Berlioz et al., 1996). Therefore, in order to precisely model the VARD drillstring, two orthogonal coupled transverse modes along with the axial mode will be considered in this study. In non-VARD applications, bit-rock interaction will lead to axial vibrations near the bit, which could excite axial modes. Natural frequencies in these directions are also influenced by the driving torque (Yigit and Christoforou, 1996, 1998; Gulyaev et al., 2009; Liao et al., 2011; Ghasemloonia et al., 2012, 2013). The torque couples the two orthogonal lateral modes and must be kept in the equations, although it adds complexity. Since the rotation speed of the drillstring is small (50–150 rpm in practice), the gyroscopic effect may be negligible (Chen and Geradin, 1995; Yigit and Christoforou, 1996; Heisig and Neubert, 2000; Hakimi and Moradi, 2009; Ghasemloonia et al., 2012, 2013). Current literature reports no studies of the effect of VARD force generators on the nonlinear coupled axial-transverse vibration of the drillstring, either in the frequency or the time domain. The model described herein has the important benefits of providing accurate natural frequencies, generating time domain response, and capturing wellbore contact with greater fidelity than simpler single-span BHA models.

Determining natural frequencies is important because, from an operational standpoint, vibration severity can be reduced if rotation speed is kept away from these frequencies (Dareing, 1984a; Gulyaev et al., 2007). In the last decades, several studies have been conducted to investigate the lateral natural frequencies of the drillstring or BHA. Approaches and simplifications include simple non-rotating beam models (Dareing, 1984a, 1984b), and single-span BHA's (differential quadrature method of Hakimi and Moradi, 2009; transfer matrix method of Chen and Geradin, 1995; undamped finite element model of Khulief and Al-Naser, 2005 with no wall contact). While Gulyaev et al. (2007) included two orthogonal lateral modes and mud internal flow, they neglected the contact, axial mode and damping effect. Lateral natural frequencies based on buckling analysis for different BHA lengths from Gulyaev et al. (2009) were much lower than values measured in the field (Khulief et al., 2008), suggesting the need for extended models. The effect of fluid damping, added fluid mass, stabilizer clearance and the friction coefficient on the critical rotary frequencies was investigated by Jansen (1991), but the effects of torque, gravity and axial-lateral coupling were neglected and the implementation of these terms was suggested for future studies.

In the present paper, the axial and orthogonal lateral resonance frequencies of a drillstring, assuming a multi-span BHA, will be calculated. The first four modes will be retained for the two orthogonal lateral directions and one axial direction (12 generalized coordinate systems in Lagrange's equations). After implementing the solution method, the FFT analysis will be applied on each generalized coordinate system to extract the first four natural frequencies in each direction. Considering a multi-span BHA will give results that are more accurate than those from a single span BHA model. Moreover, the resonance frequencies which are extracted from the developed nonlinear model are more precise compared to the ones which are derived from idealized linear model. In fact, instabilities may occur at rotary speeds which may not be considered critical from an uncoupled linear analysis (Yigit et al., 1998).

In addition to natural frequencies, the axial or lateral time responses of the drillstring or BHA are desirable. FEM and modal analysis are two major methods used to predict the time response of the drillstring. Yigit and Christoforou (1996) investigated the axial-transverse behavior of the non-rotating BHA and verified nonlinear axial-lateral coupling due to nonlinear strain. Mud damping, rotation and the other orthogonal lateral modes were not considered in their model. They implemented a force mode in their one-mode approximation assumed mode method to accelerate the convergence rate. Since the axial load in the BHA was assumed constant in their study, one static axial deformation mode was added to the assumed mode approximation. Spanos et al. (1997) addressed the effect of contact and added fluid mass generating the deformed shape of the BHA in the lateral modes, based on natural mode analysis. Based on the transfer function of the BHA lateral vibration in the single orthogonal plane, frequency and mud density-dependent damping was proposed. Torque, axial force and axial displacement were not included.