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A review of drillstring vibration modeling and suppression methods

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ABSTRACT

Drilling is one of the most costly and risky activities in oil and gas reservoir exploration and field development. A portion of this high cost is related to unwanted vibrations of the drillstring. With the advancement of "Measurement While Drilling" (MWD) tools and their real-time implementation, vibration models are still a valuable tool for pre-drilling analyses, designing the "bottomhole assembly" (BHA) and sensitivity analyses of the input parameters. In the last 70 years, a wide variety of models has been developed for design and analysis of drilling structures. Due to the complexity of downhole interactions and excitations a variety of modeling simplifications and assumptions is typically made. This paper presents a broad survey of the drillstring vibration modeling literature. The state-of-the-art of models for predicting axial, torsional and bending vibrations (uncoupled and coupled), boundary condition assumptions, equation formulation methods, and applications to vibration mitigation is reviewed. Moreover, the challenges of drillstring vibration modeling in the presence of modern drilling techniques such as deviated drilling and use of vibrating downhole tools are discussed. This survey is intended to organize and summarize the vast amount of literature in the field, and to aid engineers in both industry and academia in developing, choosing, or critically assessing the limitations of drillstring vibration models.

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1. Introduction

Drilling is an essential component of exploration and exploitation of oil and gas reservoirs in petroleum engineering, and minerals in mining engineering. Failure of drilling facilities, and in particular the drillstring, has enormous cost implications. The subject of drillstring vibration is an ongoing challenge for drillers in oil fields and drillstring vibration is assumed as the primary cause of drillstring components' premature failure, bit failure, deterioration of the well trajectory, excessive bit and stabilizer wear, lower penetration rate, reduced accuracy of "Measurement While Drilling" (MWD) tools and decreased efficiency (Bailey et al., 2008). Also, unwanted vibrations of the drillstring dissipate a portion of the energy that is intended to be delivered to the bit. Unwanted vibrations of the drillstring are said to increase the drilling cost by 10% (Jardine et al., 1994). Drilling companies are continuously working to utilize methods and technologies to identify the source of unwanted vibrations and suppress them. Although MWD tools provide downhole data and help toward real-time adjusting of the drilling parameters to avoid severe downhole vibrations, their failure due to successive lateral shocks in conjunction with their high cost has led drilling companies to develop sophisticated drillstring vibration models for "bottom-hole assembly" (BHA) design and pre-drilling analyses. Moreover, dynamic models are the first essential step toward developing control strategies for a faster and efficient drilling without premature component failures.

The complexity of the drillstring dynamic response is due to factors such as formation properties and heterogeneity, BHA imbalance, misalignment and friction. Such factors are usually unknown or not measurable in real-time. Mud damping, drillstring–wellbore contact, stochastic bit–rock interaction force and excitation sources add further complexity to the problem (Spanos et al., 2002). Models to analyze the vibration pattern of the drillstring can be formulated either in the frequency (Hakimi and Moradi, 2009) or the time domain (Yigit and Christoforou, 1998; Khulief and Al-Naser, 2005). The most common application of models is to predict the effects of adjusting the parameters of vibration generator tools, or the main drilling parameters at the surface such as rotary speed, torque, and WOB (Chin, 1994). Fidelity of the models depends on the realism of assumptions regarding drillstring geometric configuration, interacting forces, linear and non-linear excitation sources, damping effects, contact behavior with the wellbore, and boundary conditions including multiple stabilizers located along the BHA (Clayer et al., 1990). Despite the challenges in model formulation, and the compromise between model fidelity and computation speed, models are still considered to be a powerful and emerging method to compare the sensitivity of different BHAs to vibrations, and to study the propagation of near-bit vibration along the drillstring to the surface. Model predictions in conjunction with MWD tool data are considered as reliable tools to predict vibration patterns or analyze suspected vibration-related failures, and to decrease unwanted vibrations of the drillstring.

The drillstring is composed of a long, thin-walled interval (drill pipes)—which can be up to several kilometers—and a heavier, thick-walled bottom section (consisting of drill collars, heavy weight drill pipe, or both) constrained by the stabilizers inside the wellbore (BHA) with an approximate length typically up to hundreds of meters. The BHA plays the dominant role in the vibration behavior of the drillstring (Dareing, 1984a; Yaveri et al., 2010). The top of the drillstring is suspended from the hoisting system that is suspended from the derrick. The stabilizers are finned subs placed within the BHA at multiple locations to centralize the drillstring inside the wellbore, to increase the load carrying capacity of the BHA, and to control well trajectories in deviated wells. The annulus between the drillstring and the cased or uncased wellbore is filled with circulating drilling fluid, which is used to provide well control, flush and lift bit cuttings, and transmit hydraulic power to the bit. Moreover, the mud plays an important role in stabilizing the lateral vibrations of the BHA as a nonlinear damping medium. The drillstring is under interaction of several axial forces, such as WOB (to provide the axial bit load), hook load, self weight, mud hydrostatic effects (both upward and downward), torque and drag loads for non-vertical well intervals, and excitation forces (e.g. bit–formation interaction, multiple contact loads, and vibration generator tools) (Aadnoy and Kaarstad, 2006). The normal practice for drillstring design is to keep the pipe section under tension with the transition to axial compression occurring within the stiffer BHA interval. The length and material properties of the BHA, along with WOB and mud density, are controllable parameters to keep the BHA under compression (Mitchell and Miska, 2011). The rotary speed of the drillstring is typically between 50 and 200 rpm.

The vibration of the drillstring can be divided into three primary modes: axial, lateral (also referred to as transverse, or bending), and torsional modes, with different destructive natures. Bit bouncing, stick-slip and whirling are extreme examples of coupled vibration dominated by axial, torsional and lateral motions, respectively. Bit–formation interaction, multiple point drillstring–wellbore contacts, mass imbalance, and vibration generation tools are the main sources of these vibration modes. The axial vibration causes lateral vibration in the BHA, while severe downhole lateral vibration can cause axial and torsional vibrations that are detectable at the surface (Christoforou and Yigit, 2001). While lateral vibrations are very severe in vertical wells compared to torsional vibrations, axial vibrations become very important while implementing downhole axial generator tools or drilling hard formations (Schlumberger Technical Report, 2010). A typical drillstring vibrates in 3 major coupled modes: lateral–axial, lateral–torsional and axial–torsional. Rotary speed, driving torque, and curvature of the drillstring are causes of the coupling phenomenon.

Axial vibration excited by the bit–formation interaction causes bit bounce, which results in cutting tooth wear and bearing failure (Li et al., 2007). Bit bounce is the most severe manifestation of axial vibration, in which the bit loses contact with the hole bottom, usually as a result of resonance in the axial direction. Axial vibration is the most common in vertical wells while drilling hard formations and can at least be detected at the surface (Chin, 1994). Accelerated

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