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Investigation of vibration effects on friction and axial force transfer of buckled rod constrained in a horizontal cylinder

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ABSTRACT

The work examines the effects of frequencies of vibrations at different amplitudes on friction force, axial force transfer, and lock-up force of buckled rod constrained in a horizontal cylinder for different media under normal and high temperature environments. Studies have shown that vibrations induced in the rod have significantly reduced friction force, improved axial force transfer and deferred the initiation of critical buckling and lock-up forces for all media in normal temperature environment. Similar trends were observed at higher temperature environments; however, vibration parameters were less effective particularly on very high temperature. Results have also shown that frequency has a particular relationship with the friction force and axial force transfer and employing higher frequency would not improve the results.

1. Introduction

Investigating buckling behavior, and lock-up conditions of a rod subjected to axial, torsion and friction forces in constrained cylinder, is of interest to the petroleum drilling industry. The rod and the constrained cylinder represent the drillstring and the horizontal wellbore in drilling operations, respectively. The concern about maintaining the flow of oil and gas has driven the industry to drill deep and horizontal wells. However, many challenges have emerged which requires the industry to go beyond the conventional methods of drilling. To reduce the effects of these challenges, new tools, techniques and technologies have been developed [1–3]. However, many drilling problems are still encountered such as buckling of drill pipes which requires intensive investigations. Some of the buckling related problems are drill pipes high drag and torque, drill pipes lock-up, and failure due to casing friction and wear.

Due to the complexity in relating friction and buckling, researchers reported simplified models and conflicting results [4]. In most studies, friction was neglected which has led to in inaccurate results. Friction has a significant influence on buckling initiation and transition as well as it influences torsion and axial compression forces [5,6]. During drilling operation, when a considerable compressive force is applied in the drill string it buckles into a sinusoidal mode. As the compressive force increases the drill string moves into helical buckling mode. The higher the compressive force, the further the drill string is pushed against the borehole wall which develops additional friction resistance and contact force. Friction resistance and contact force gradually reduces the axial force transfer to the drilling bit, and ultimately leads to lockup beyond which the drilling bit does not go further.

The drilling process competence greatly depends on the capability of the drilling mud to perform specific tasks without which the process cannot progress. Lubricants are added to the drilling mud to facilitate drilling. Drilling mud and lubricants are designed to reduce friction between drill string and wellbore wall [5,7]. However, in many cases such as deep extended reach drilling and reactive shale formations drilling, drilling fluids deteriorate which create problems such as drill string high torque and drag, mechanical and differential stick-slip oscillations, and reduction in drill pipe axial force transfer to the bit.

Vibration is a well-known technique to reduce friction between contacting bodies in many engineering systems. The effect of vibration normal to the contact surface on friction was early investigated by number of researchers [8–14]. They mainly found that friction force is higher under no vibration condition and the coefficient of friction is significantly reduced once the vibration frequency increases. Some researchers indicated that the effect of tangential vibration on the level of friction force reduction between sliding bodies is higher than that of the normal vibration [15,16]. The topic was later theoretically and experimentally investigated [17–22]. The studies indicated that the friction reduction not only depends on the vibration parameters but also the relative velocity between the contacting object as well as the contact parameters such as surface roughness and rigidity.

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In oil/gas industry, one of the main limitations of the rotary drilling is that only a fraction of the power capability of the rotary table can be realized as mechanical power output to the formation. It was, however, essential to introduce a real technology breakthrough to provide rapid separation between the drill string and the formation. In such circumstances inducing vibration in the drill pipe in the presence of lubricants improved the efficiency of the drilling operation [23–25]. Vibration decreases the friction between the drill pipe and the borehole wall and also between the drill bit and the formation thus improves axial force transfer to the bit. A common tool, axial oscillator generator tool (AGT), is used in drilling operations where drilling with motor steerable and rotary steerable system face challenges. AGT is used to reduce friction associated with low force transfer to the bit, extended reach operations, low penetration rate, helical and sinusoidal buckling. The AGT introduces hydraulic vibrations through a series of pressure pulses which create an axial oscillation in the drillstring [26,27]. Other studies have shown that the addition of axial oscillation tool improves weight on bit (WOB) by reducing friction and lowering the drilling time needed; hence positively influences drilling performance [28–31]. The experiments are carried out on such low frequency and high amplitude to imitate the vibration levels induced in the drillstring during the oil/gas drilling operations. Operating on higher frequency might introduce a strong shock in the rod that affected the borehole stability. Inducing frequencies of vibration in the rod less than 10 Hz will not provide significant effects on friction. In real field applications, only the flow rate of drilling fluids is varied. The change in flow rate usually varies from 1–3 Barrel/min, which causes a change in the frequency from 10 Hz to 20 Hz [27]. High amplitudes were used to confirm that all buckling modes and lock-up conditions are introduced. In addition, the greater the amplitude of vibration the higher actual rubbing time between the rod and the borehole.

Although, theoretical analyses and experimental investigations provided some insight into the effects of vibration on improving the drilling efficiency, until now the mechanism of reduction of the friction force under influence of vibration is still not yet fully identified. In this work, through the means of experimental investigations carried out with the use of an in-house designed experimental setup, the authors undertook the task of explaining the buckling behavior of a drill pipe/rod in a wellbore/constrained cylinder and identifying the vibrations levels required for reducing of friction forces and improving axial force transfer to the drill bit. Such investigations are essential for oil/gas industry as they provide solutions for very common problems such as drill string failure and lockup.

2. Buckling theories

The analysis of drill strings is important for oil and gas industries. Buckling of drill strings causes problems during drilling operations which lead to reduction of axial force transfer to the drill bit, drill string failure and lockup. The axial force required to initiate buckling is different at various sections of the drill pipe. Fig. 1 presents a schematic of the geometry of vertical, curved and horizontal sections of a drill string moving downward in a borehole.

Numerous studies were dedicated to identify the sinusoidal and helical critical buckling forces for horizontal, inclined and vertical drill strings/pipes [32–38], just to name few. In a horizontal section when the axial force exceeds the critical force in Eq. (1) the drill pipe exhibit a sinusoidal buckling [39].

$$F_{cr} = 2\sqrt{\frac{EI\beta w}{\Delta r}} \tag{1}$$

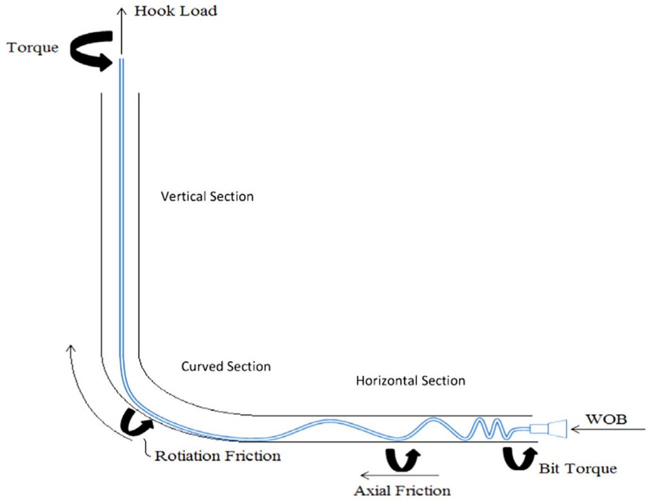

Fig. 1. Schematic of a drillstring moving in a borehole with the geometry of vertical, curved and horizontal sections.

For an inclined section the critical sinusoidal buckling force could be written as follows

$$F_{cr} = 2\sqrt{\frac{EI\beta w\ \sin(\alpha)}{\Delta r}} \tag{2}$$

For a vertical section the critical sinusoidal buckling force is

$$F_{cr} = 2.55\left(\frac{EI(\beta w)^2}{\Delta r}\right)^{1/3} \tag{3}$$

However, the effect of sinusoidal buckling on the axial force transfer is limited. It is known that when the compressive force increases and exceeds a critical force, helical buckling occurs. In a horizontal and inclined borehole the helical buckling force is presented in the following form [39].

$$F_{cr}^{h} = 2\sqrt{2}\sqrt{\frac{EI\beta w}{\Delta r}} \tag{4}$$

In a vertical wellbore the helical buckling is about 2.18 time the sinusoidal buckling and can be written as follows

$$F_{hel} = 2.18\, F_{cr} \tag{5}$$

where

w: unit weight of drill pipe (N/m).
Δr: radial clearance between drill pipe and wellbore wall (m).
I: area moment of inertia (m^4).
E: modulus of elasticity ($\mathrm{N/m}^2$).
β: buoyancy factor.
α: inclination angle (rad).

3. Axial force transfer along the drill pipes in a horizontal well

Friction and excessive lateral wall contact forces are introduced due to the contact between the buckled drill pipe and the borehole wall which reduces the force transmitted along the drill pipe to the bit. The drill pipe is pushed inside the horizontal section due to the heavy weight of the drill pipes in the vertical and build-up sections which provide sufficient drive to push it. The axial friction force in the horizontal section is a function of the weight of drill pipes. The pipes push the borehole wall at number of contacts during the sinusoidal mode; however, the friction force becomes significant at helical mode. Fig. 2 shows a schematic of drill pipe buckled in a horizontal section. In case where there is no buckling or sinusoidal buckling Eq. (6) could be used to relate the compressive force, at any point along the drill string,