ABSTRACT
Recent advances in drilling and oil & gas extraction have altered the mindset among drilling engineers. One example is the recent trend to drill faster and minimize Non-Productive Time (NPT). This usually requires minimizing changes to the Bottom Hole Assembly (BHA) and improving its reliability. Directional drilling tools such as mud motors and Rotary Steerable Systems (RSS) have become a mainstay in minimizing NPT. Moreover, understanding in planning stages the tools' working envelope in downhole environment, is critical to reducing NPT. Conventional surface testing, however, have significant constraints when trying to determine the performance envelope of directional tools and BHAs.

Advances in numerical modeling enable evaluation of BHA performance under much more realistic downhole conditions. This paper discusses the advancements in the evaluation of directional drilling tools using advanced Time Domain Analysis (TDA). For example, time domain models allow exploration of the full range of BHA response under downhole conditions including the effects of formation changes. Drilling dysfunctions including stick-slip, whirl, and dynamic lateral vibrations can be realistically predicted before drilling. TDA models allow drilling engineers to explore the design space and also explore operating conditions to optimize performance and reliability of the BHAs.

This work describes a newly implemented TDA model based on rigid body dynamics (RBD) solved by finite element methods (FEM) to model drilling dysfunctions. The approach is significantly more accurate and faster compared to conventional models. Also shown is how the TDA model successfully predicted several drilling dysfunctions before drilling and reduced NPT. It is also used to analyze post drilling job cases and explain issues observed in the field.

INTRODUCTION
Oil and gas well operations are very complex, expensive and time sensitive. Successful operations require planning and making real time decisions to lower costs and improve efficiency and reliability.

Planning is a critical phase where selecting the right well design and operation parameters determine success. Static calculations help to evaluate and reveal basic issues. For more precise and complete problem evaluation, dynamic analyses are indispensable.
The present work uses a multibody beam approach to model the dynamics of long drillstrings accounting for friction, interactions, and fluid presence. The multibody beam approach allows for the efficient solution of problems involving time and intermittent contact. The drillstring, including the Bottom Hole Assembly, is modeled in the time domain accounting for lateral and torsional deformations as well as linear and rotary motions together with simplified borehole contact.

The method assumes rigid and flexible beam elements interconnected by viscoelastic connections. Beam elements are presumed to undergo large rigid body motion and small elastic deformation. Such a model is capable of solving a variety of complex field observed phenomena such as large lateral vibrations, stick-slip and whirl.

**Problem Formulation**

In drilling operations, the Bottom Hole Assembly is the lowest, most expensive and delicate portion of the drillstring extending 100 to 300 feet or more from the bit to the drill-pipe. Reducing NPT makes essential the understanding of BHA dynamics to avoid failures, delays or unnecessary operations. Better understanding the drilling dynamics can also improve drilling efficiency, optimize processes and reduce tool failures.

In the model, the BHA is discretized coarsely as rigid and flexible beam elements interconnected via viscoelastic connections. Any beam element will theoretically undergo an arbitrary rigid body motion and a small elastic deformation. Modeling identifies active contact forces such as at the BHA-wellbore and the bit-rock. This then enables the realistic evaluation of BHA dynamics, critical deformations and failure modes. The interaction is modeled with discrete contact, normally and tangentially, accounting for geometry variation. The dynamic effects of fluids on the string are reduced to buoyancy forces modeled as additional masses (Chen et Al., 1976) and frequency-dependent external damping.

**Model Formulation**

As summarized in the Problem Formulation, governing equations are based upon an isolated beam element. Considering forces and degrees of freedom, the equation of motion in a vector-dimension (Pogorelov et Al., 1998 and 2012), is established as:

$$M_b \ddot{q} + k = f_g + f_a + f_c - C_b q - D_b \dot{q}$$

Where

“q” is the generalized coordinates’ vector;
“k” is the generalized inertia forces vector;
“f_g”, “f_a”, and “f_c” are the generalized gravity, applied, and reaction forces vectors respectively;
“M_b”, “C_b”, and “D_b” are the mass, stiffness, and damping matrices of the beam respectively.

The Jacobian matrices of stiff forces are derived using implicit Park method to increase the integration step (Pogorelov et Al., 2007). Also, the Component Mode Synthesis (CMS) method in Craig-Bampton’s form (Craig et Al. 1968, Craig 2000) is used to describe beam’s flexible displacements.

**Static Case Study**

A static analysis solves for the static state of equilibrium. It could accounts for all effects and interactions but provides no time or motion information. In fact, it does not solve intermediate time equilibrium steps. However, static results can provide information about locations of most stressed tools and high local contact sections.

Following is a static solution using the multibody model for a 475’ drillstring within a borehole. The effect of hole size is examined by considering both 8-1/2” and 9-1/2” hole sizes. The trajectory of the well changes from an initially vertical segment to a horizontal extended reach, as shown in Figure 1. The dogleg chart given by Figure 2, presents the change of inclination and azimuth of the borehole. The BHA as shown in Figure 3, consists mainly of bit, RSS, stabilizers, and drill-collars.
Simulation of a 20,000lbf applied Weight-On-Bit (WOB) results in the BHA deformations presented in Figure 4 and Figure 5. The largest deviation occurring in the vertical plane is not surprising because of the higher clearance. The highest stresses (8,500/24,000psi at 8-1/2" and 9-1/2" hole size, respectively) and contact pressures (45/165psi at 8-1/2" hole size) are recorded at the near bit stabilizer (Figure 6 and Figure 7). Such considerable stresses and contact pressures explain the stabilizer wear observed in the field, as shown in Figure 8.

**Dynamic Case Study**

The above static analysis clearly provides a snapshot of the BHA's situation. Adding time dependency to the analysis provides a clearer and more complete and valuable insight into actual BHA dynamics while planning as well as understanding field scenarios.

Critical speed analysis for a combination of RPM and WOB is a common method for determining a preliminary safe operating window. The method utilizes a free vibration linear dynamic analysis and assumes the drillstring lays on the borehole centerline. While a useful tool for planning and operational guidance, the critical speed analysis has significant limitations including the inability to model the borehole interaction and predict drilling dysfunctions.

Solving time domain governing equations for BHA dynamics present a variety of challenges but the most significant of these is the numerical
complexity and computational time cost. Following is an explanation of the current approach to overcoming such challenges.

As an example of solving complex time domain equations, the BHA, trajectory, and borehole of concern are the same used in the previous static example: drillstring operating at 180 RPM and 20,000lbf WOB. Figure 9, Figure 10, and Figure 11 present the BHA time deviation in the vertical plane, Von-Mises stresses, and contact pressures for both 8-1/2” and 9-1/2” hole sizes at three locations (bit, near-bit-stabilizer, and RSS shaft), respectively. One significant result is identification that the RSS shaft is subjected to high displacements and stresses. The transient mode, while ramping up the string rotation, noticeably affects the RSS dynamics.

TDA clearly shows stresses and contact pressures almost three times those indicated by the steady state analysis. This demonstrates a serious shortcoming of both static and steady state analyses: they would not have predicted stresses and pressures that could lead to tool failure. In the study, the TDA confirms two important additional details: 1) the higher the BHA/borehole clearance the higher its vibration and stresses, and 2) the near bit stabilizer, as designed, secures and decreases bit vibrations which reduce hole enlargement.

Furthermore, the effect of borehole oversize and ovality is studied. Without sufficient caliper logs, the hole oversize and pattern are studied as hole imperfection and oversize oriented along the two Y and Z principal directions. This permits the evaluation of the BHA vibrations and the resulting wear and failure. A polar presentation of various BHA locations and several borehole configurations demonstrates vibration data. Figure 12, Figure 13, and Figure 14 show the motion of bit, near-bit-stabilizer and RSS shaft, respectively.
The figures show that borehole oversize, especially when oriented, greatly affects BHA vibrations. In fact, vibration amplitudes are much higher when the oversize hole’s largest dimension is in the horizontal orientation (Z-Stretched hole). Figure 8 shows how this may lead to stabilizer wear and tool failures observed in the field.

**SUMMARY**

A multibody beam approach to developing solutions for modeling the dynamics of long drillstrings in extended deviated wells, has been examined. The approach accounts for a variety of variables including friction, string-borehole interaction and effects of fluid.

Comparing static and time domain case studies, the latter method permits effective solutions for vibrations and interactions to better plan and accurately predict and explain field challenges and logs. Time domain studies of hole oversize and orientation show significant effect on the overall dynamics of the BHA as well as its plausible wear or failure.

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**REFERENCES**


