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Full Length Research Paper

Finite element analysis of drillstring lateral vibration

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Lateral vibration is recognized as the leading cause of drillstring and bottom hole assembly (BHA) failures, shocks and severe damages to borehole wall. This study presents a finite element model using ANSYS software to investigate the drillstring lateral vibrations in slightly deviated wells. The analysis proceeds in two stages. At first, a nonlinear static analysis is performed to determine the effective length of the string where it is free to vibrate in the lateral direction. The second stage consists in modal, harmonic and transient dynamic analyses to obtain the lateral vibration modes and natural frequencies, frequency response and time dependent response respectively. The modeling is developed in the presence of mud, friction and nonlinear contact between drillstring and wellbore wall. The effects of drilling mud, drillstring length, well inclination and WOB are considered. The model was compared with experimental and simulated results obtained from several BHA configurations, giving excellent results.

Key words: Drillstring, finite element model, lateral vibration, nonlinear contact model.

INTRODUCTION

Lateral vibration of the drillstring is known to result in fatigue failures, excessive wear, washouts and measurement while drilling (MWD) tools failures. It often results from drillcollar eccentricity, leading to centripetal forces during rotation, named as whirling. The initial eccentricity of the drillcollar can result from drillcollar sag due to gravity or high compressive loads owing to weight on bit or mass imbalance such as that created by MWD tools. Bit–formation interactions and fluctuations of the WOB are the other mechanisms that induce transverse oscillations. It is of prime importance for the drilling industry to detect and minimize the excessive lateral displacement of the drillstring while it rotates. This may reduce drilling costs by avoiding a breakdown of the drillstring components either instantaneously or by fatigue.

If drillstring excites near one of its natural frequencies, severe vibrations and impacts with the wellbore wall will appear. Such impacts create an overgauge hole and produce problems with directional control of the well. To solve the problem, one should analyze the drillstring to find its natural frequencies and modal shapes, and then by changing the drilling parameters, avoid the resonance of the drillstring. In order to optimize the drilling performance, various dynamic models have been proposed until now, employing both the analytical and numerical techniques. The analytical approach has been the basis of early analyses. Jansen (1991) derived a simple two degree of freedom lumped parameter model of the drillstring to study the whirling stability. Abbassian and Dunayevsky. (1998) presented a similar model taking into account coupling between bending and torsional vibrations. Yigit et al. (1996, 1998) modeled the drillstring based on Lagrangian formulation and the assumed mode method. One model accounts for the coupling between axial and transverse vibrations and the other between torsional and transverse vibrations.

As a result of the great complexity of the problem, recently advanced numerical methods like finite difference and finite element methods are the most widely used tools for drillstring static and dynamic analysis. In this direction, Shyu (1989) studied the coupling between axial and lateral vibrations and the whirling of drillstring using finite difference method. Besaisow and Payne. (1986) studied the excitation mechanisms and resonances that cause BHAs vibrations during drilling operations based on data gathered in a

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Table 1. Drillstring No.1 specification.

Name	Length (ft)	O. D. (in)	I. D. (in)	Aggregate length (ft)
Bit	3.25	6.25	--	3.3
Stab.	6.40	4.75	2.25	9.7
DC	30.8	4.75	2.25	40.5
Stab.	6.60	4.75	2.25	47.0
DC	529.1	4.75	2.25	576.2
HWDP	121.9	3.50	2.06	698.1

Table 2. Drillstring No.2 specification.

Name	Length (ft)	O. D. (in)	I. D. (in)	Aggregate length (ft)
Bit	3.25	6.25	--	3.3
Stab.	6.40	4.75	2.25	9.7
DC	30.8	4.75	2.25	40.5
Stab.	6.60	4.75	2.25	47.0
DC	529.1	4.75	2.25	576.2
HWDP	30.42	3.50	2.06	606

Table 3. Drillstring No.3 specification.

Name	Length (ft)	O. D. (in)	I. D. (in)	Aggregate length (ft)
Bit	3.25	6.25	--	3.3
Stab.	6.40	4.75	2.25	9.7
DC	30.8	4.75	2.25	40.5
Stab.	6.60	4.75	2.25	47.0
DC	343	4.75	2.25	390

well test. Burgess et al. (1987) used finite element method to model the lateral vibration of drillstring. They performed a static nonlinear analysis to find the location where the string above the last stabilizer touches the wellbore wall. Then, using the effective drillstring length from the bit to the touch point, they evaluated the response of the string by harmonic analysis disregarding the effects of drilling mud. Apostal et al. (1990) developed a three dimensional finite element model to investigate the harmonic response of BHA. Damping in the form of proportional, structural and viscous were included in their model. Khulief and Al-Naser. (2005) used the Lagrangian approach to formulate the finite element model of a rotating vertical drillstring.

In this paper using ANSYS software, a finite element model is presented to describe the lateral vibration of drillstring in near vertical oil wells. Initially, static analysis was performed to identify the first point above the last stabilizer where the drillcollars lie against the wellbore wall known as cut-off point. Subsequently, dynamic behavior of drillstring is exhibited by modal, harmonic and transient analyses to achieve mode shapes and natural frequencies, frequency response and time dependent response respectively. It is assumed that the wellbore is perfectly in gauge in place of bit and stabilizers and the contact between stabilizers and the wellbore is a point contact. The effect of parameters such as well inclination, WOB, drillstring length and rotary speed are considered in the presence of drilling mud and friction between drillstring and borehole wall. In order to model the contact between drillstring and borehole wall, the nonlinear beam to beam contact model with Conta176 and Targe170 elements are used.

MATERIALS AND METHODS

In this study, a drillstring of the specification adopted in Besaisow and Payne. (1986) and given in Table 1 is used for investigation. Tables 2 and 3 list the other descriptions of drillstring in Table 1 with the same BHA, merely to examine the effect of length and to compare with measured downhole data. The real data accessibility in the presence of the drilling mud was the main reason for these drillstrings selection. The geometry of the drillstring in a slightly inclined well is shown in Figure 1. Mechanical properties of the drillstring, formation and drilling mud are given in Table 4. It is assumed that the material of the drillstring is elastic, homogeneous and isotropic.

Table 4. Mechanical properties of drillstring, formation and mud.

Drillstring	Modulus of elasticity (lb/ft^2)	4.32×10^9
	Density (slug/ft^3)	15.18
	Poisson ratio	0.25
Formation	Modulus of elasticity (lb/ft^2)	4×10^8
mud	Density (slug/ft^3)	1.52
	Viscosity (slug/ft.s)	2.1×10^{-4}

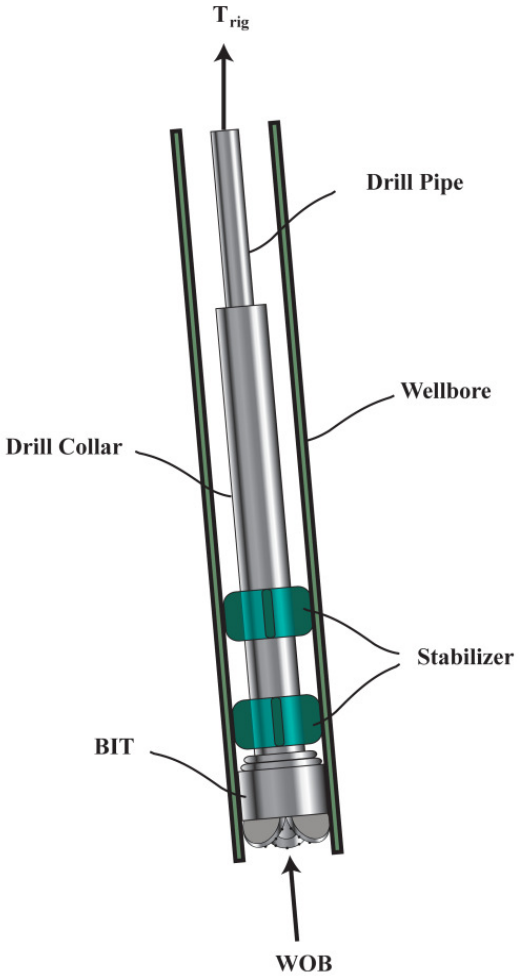


Figure 1. Geometry of the drillstring.

Drillstring and wellbore modeling

In this research, the drillstring and the well formation are modeled by Beam188 element which is a linear 2-node beam element in three dimensions (3-D) and has six degrees of freedom at each node, including translations in the x, y, and z directions and rotations about the x, y, and z directions. It is suitable to model slender beam structure, large deformation and finite strain. This element is based on Timoshenko beam which is a first order shear deformation theory. It can be used with any beam cross-section defined via Sectype and Secdata commands. Beam188 ignores any real constant data and can receive properties such as density and damping in material properties section. The meshed model of drillstring and borehole formation is shown in Figure 2. To simulate the formation around the wellbore, a hollow cylinder with the internal radius equal to external radius of bit and 3 feet thick is used.

The Contact effect between drillstring and wellbore wall is the most important factor which causes the nonlinearity and complexity in drillstring vibrational equations. To make a model for beam to beam Contact effect, Conta176 and Targe170 elements were used. Conta176 represents contact and sliding between 3-D line segments (Targe170) and a deformable line segment defined by this element. Internal contact where a beam or a pipe slides inside another hollow beam or pipe is one of its applications utilized here. The contact element coincides with the external surface of the drillstring while the target coincides with borehole wall as shown in Figure 3. Contact is detected when two circular beams touch or overlap each other. The non-penetration condition for beams with a circular cross section and internal contact can be defined as:

$$g = |r_t - r_c| - d \le 0 \quad (1)$$

Where r_c and r_t are the radii of the cross sections of the beams on the contact and target sides, respectively; and d is the minimal distance between the two beams which also determines the contact normal direction. Contact occurs for negative values of g .

According to the coulomb friction model which is allowed by this contact pair, the static and dynamic coefficients of friction for sticking and sliding cases are assumed equal to 0.3 and 0.2, respectively. These values are confirmed through experiments by research and development center in National Iranian Oil Company.

Boundary conditions

Drillstring boundary conditions are defined as:

1. At the stabilizers position, radial deflection is constrained while axial translation and rotation about drillstring axis are found.
2. At the place of bit, drillstring can rotate about longitudinal axis of drillstring and support axial and radial forces.
3. At the location of rotary table, radial displacement is constrained while rotation around drillstring axis is released.

Dynamic effects of mud

When a structural component vibrates in a viscous fluid, the

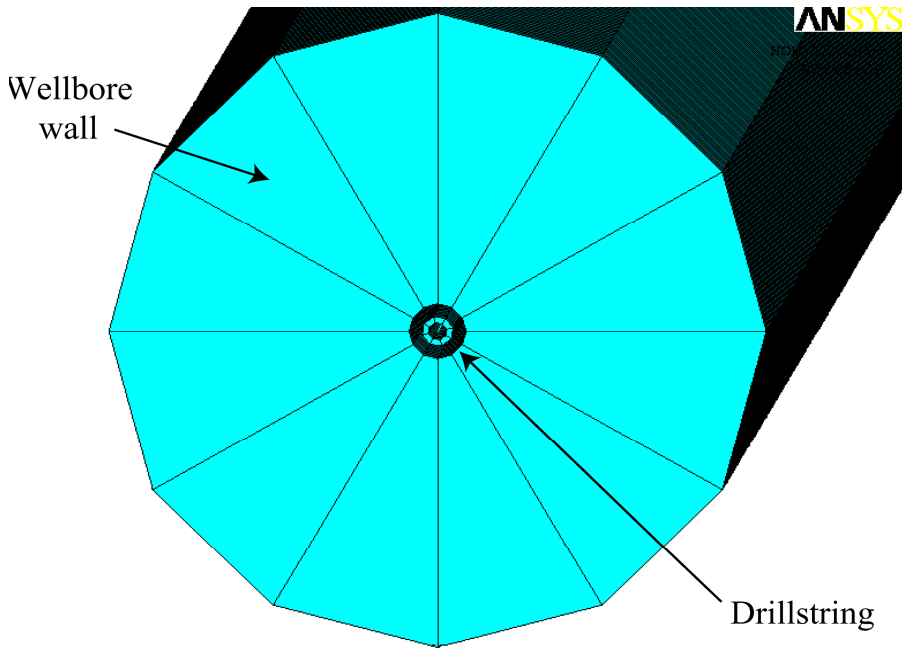


Figure 2. Meshed model of drillstring and wellbore formation.

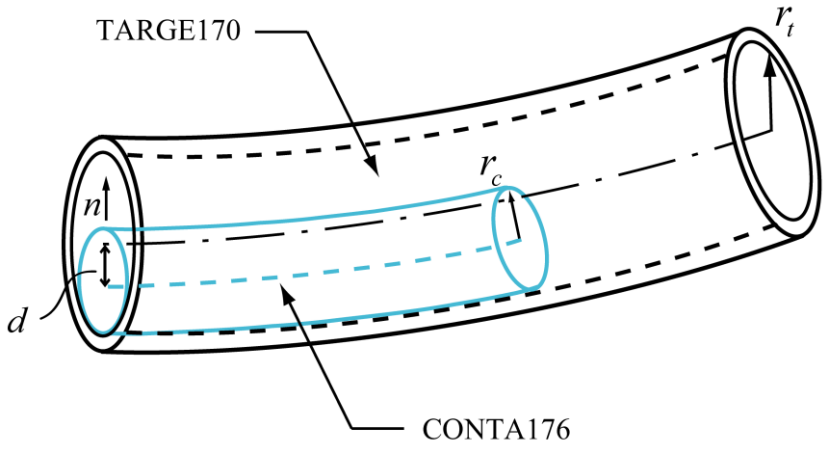


Figure 3. Beam to beam contact and target elements.

presence of the fluid gives rise to a reaction force which can be interpreted as an added mass and a damping contribution to the dynamic response of the component. Added mass due to a force in phase with the acceleration and damping due to fluid drag force known to be dependent on fluid properties in particular, density and viscosity (Chen et al., 1976).

As presented in detail in Appendix A, the value of 20.32 $slug / ft^3$ is regarded as the equivalent density of the drillstring when the mud is present in the well. In this direction, the added mass is divided upon the drillstring volume to yield the added density. Additionally, the value of 0.03 for damping ratio is attained, neglecting damping, associated with internal friction in the solid material and losses at the support location. Although some differences exist between downhole condition and theoretical basis for the approximation of the mud effects, but no better source is known for the added mass coefficient.

FINITE ELEMENT ANALYSES RESULTS

Static analysis results

As previously mentioned, the effective length of drillstring plays an important role in dynamic analysis. In static analysis, by simulation of drillstring in near vertical well, the “cut-off” point where the effective BHA terminates is identified. This point is located above the second stabilizer. Then, by using Upgeom command in ANSYS software, the static equilibrium state is imported in

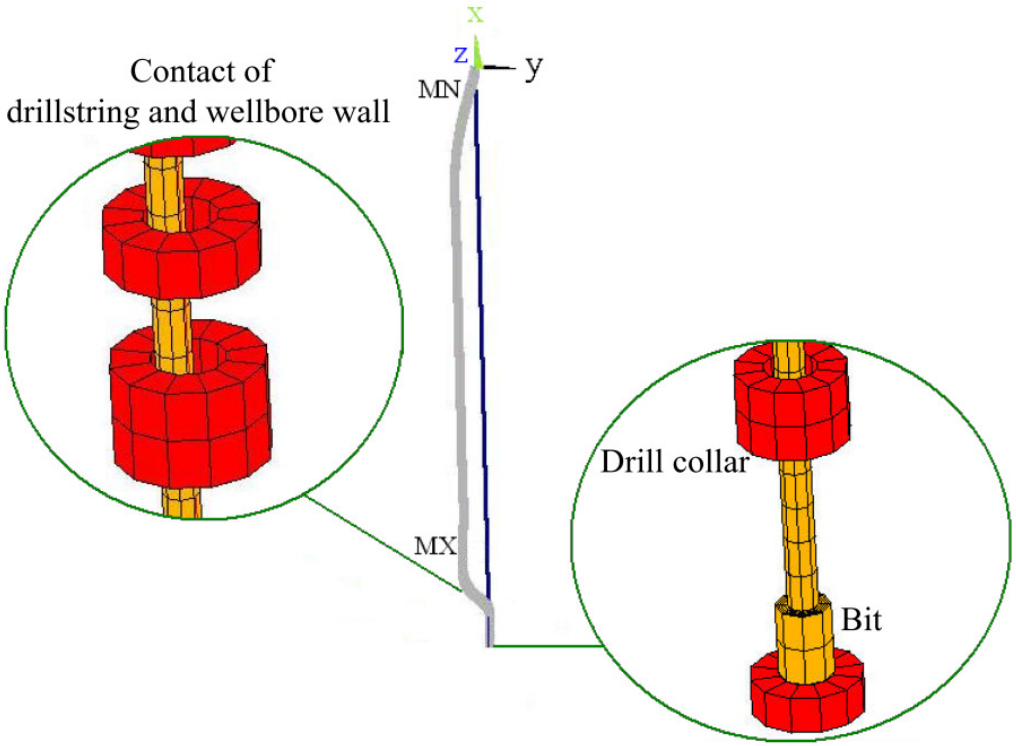


Figure 4. Static deformation of drillstring No. 1

subsequent dynamic analyses. This command updates the model geometry according to the displacement results of static analysis and creates a revised geometry at the deformed configuration for the other analyses.

Static deformation of drillstring described in Table 1 with 1 degree deviation from vertical and 15 klb WOB, indicated in Figure 4 where most of its length rests on the borehole wall. Neglecting the effect of mud, it reveals that "cut off" point is 114 feet from the bit which is in agreement with 113 feet reported by Burgess et al. (1987). The "cut-off" point moves upwards and will be 120 feet from the bit if the mud buoyancy effect is regarded. For this purpose, the buoyancy correction coefficient must be multiplied in drillsring density according to Hyon (1991).This value equals 0.809 for the $1.52\, slug/ft^3$ mud density.

Modal analysis results

The objective of modal analysis is to specify lateral natural modes and frequencies of the drillstring. If external excitations exert at such frequencies, the resonance happens and the amplitude of lateral vibration increases exceedingly, drillstring strikes wellbore wall and creates large shocks. To prevent happening of this destructive phenomenon, the frequency of external loads must be far from natural frequencies.

Modal analysis reveals that the effective length of drillstring affects the lateral natural mode shapes. Mode shapes of three main frequencies for drillstring No.1 are attained and shown in Figure 5a disregarding the mud effects. The mode shape curves tend to zero, 114 feet from the bit at "cut-off" point as revealed from Figure 5b. Lateral natural frequencies of drillstrings in Table 1 through 3 with mud effects are given in Table 6 (in 1 degree deviated well and 8 klb tensile force on the first node on the rotary table place).

Harmonic analysis results

Harmonic analysis is performed to achieve the frequency response of the drillstring. The result of this analysis is depicted for the lateral displacements versus frequency of the axial load tolerated at the first node in the place of rotary table as the excitation node. The onset of resonance phenomenon is identified by appearance of spikes on harmonic plot. It can be used to interpret which points in the BHA are subject to large banding stresses. For drillstring No.1, regarding the added mass and damping due to drilling mud, the influences of deviation angle and WOB on harmonic response for a single point between two stabilizers where MWD tool located there, are considered. Also, the effect of drillstring length for two different points (one point between two stabilizers and the other above the second stabilizer) are illustrated.

For drillstring No.1 located in 1 degree deviated well at

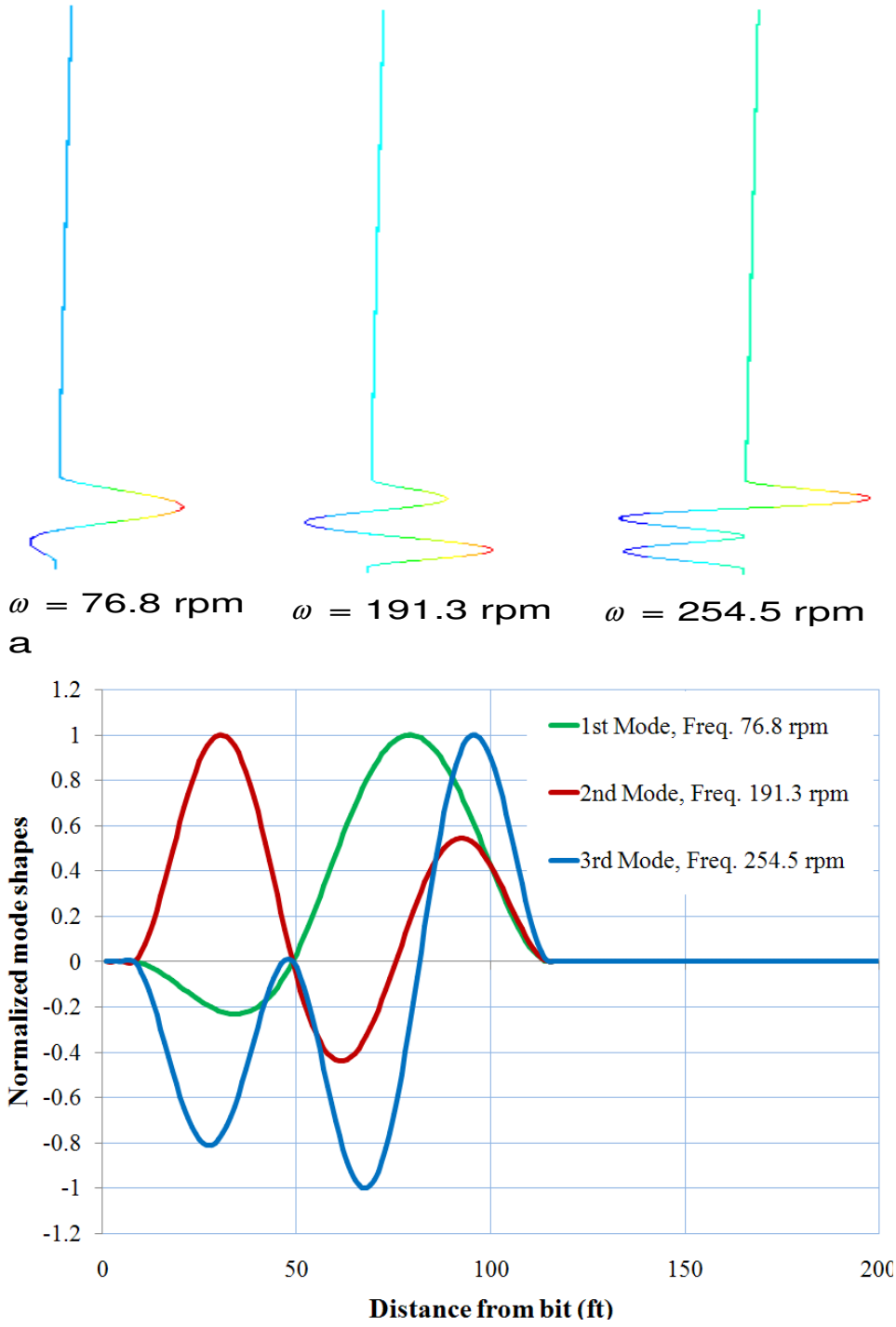


Figure 5. First three mode shapes and natural frequencies of drillstring No.1 (a) finite element mode shapes (b) cut-off point position.

the presence of mud, it was evident that 15 klb WOB is equivalent to 8 klb tensile force on the place of rotary table. The harmonic responses for 25 and 75 feet from the bit in the presence of mud are shown in Figures 6a and b and compared with results in the absence of mud. Obviously, the added mass will decrease the drillstring natural frequencies and damping lessens its amplitude.

Figures 7a and b represent the harmonic analysis results for drillstrings No.1 through 3 in one point between two stabilizers and the other above the second stabilizer

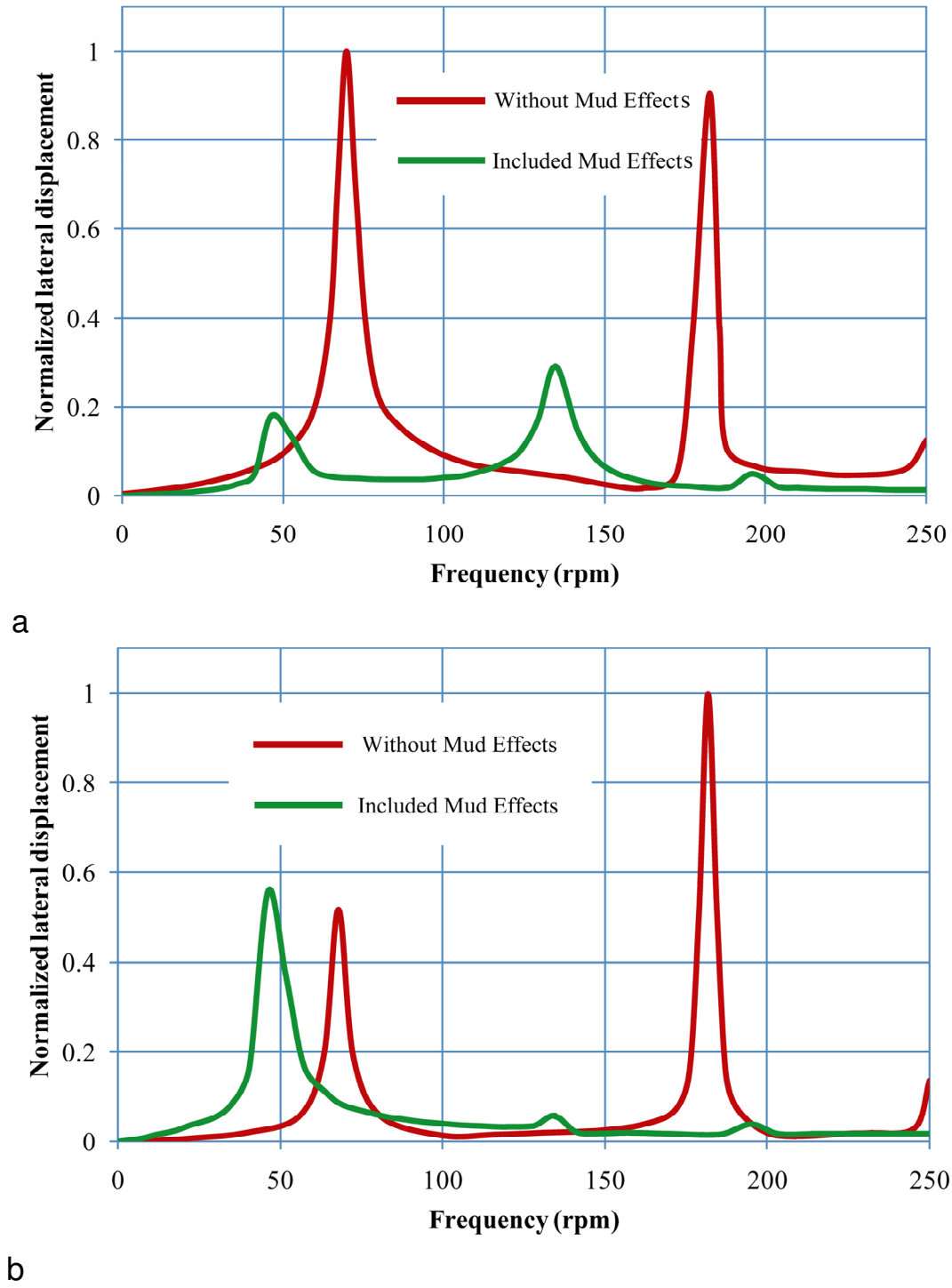
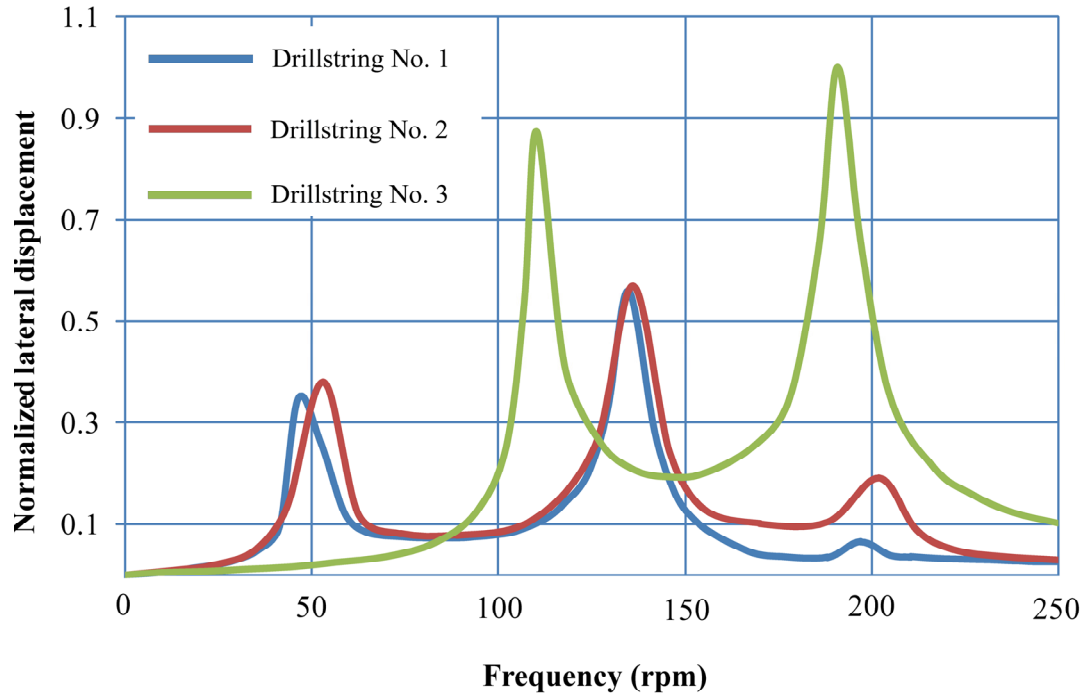


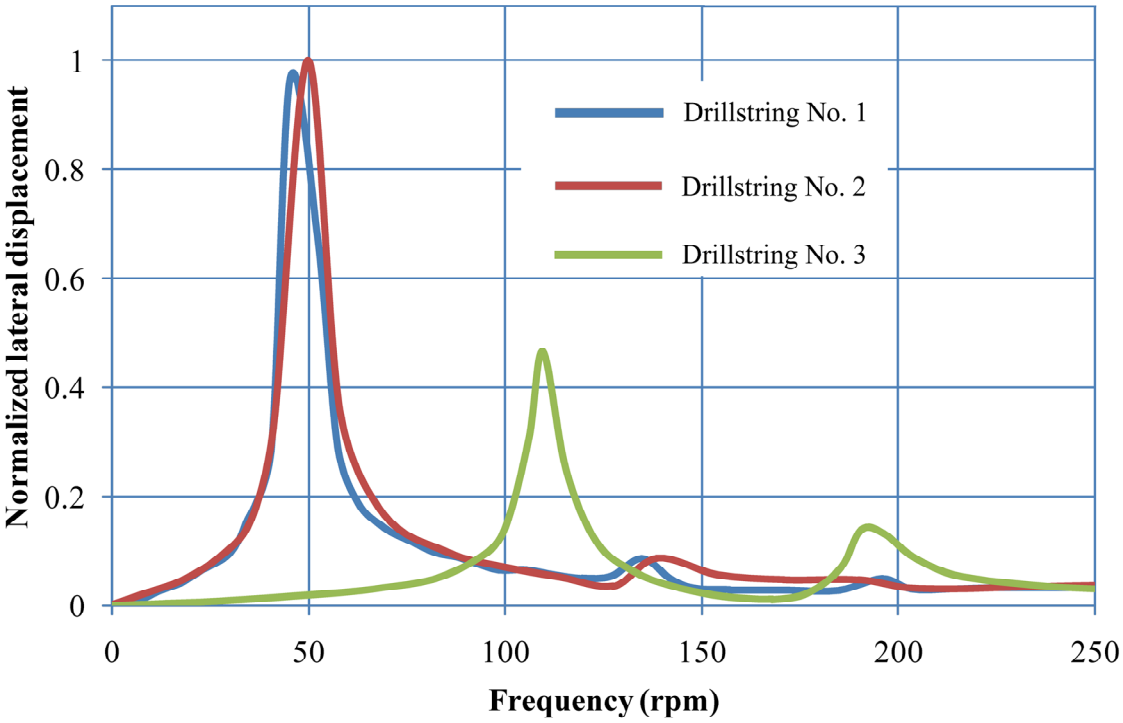
Figure 6. Effect of mud on natural frequencies of drillstring No. 1 (a) 25 feet from the bit (b) 75 feet from the bit.

respectively. It is assumed the tensile force on the first node is constant and equal to 8 klb. These clearly show as the total length of drillstring increases, the natural bending frequencies decrease.

Figure 8 displays the effect of varying the WOB and hence the effect of the neutral point on the first three bending frequencies for drillstring No.1. The cut-off point moves downwards and resonant frequencies shift upwards as the WOB increases (as would be expected from the shorter component). In Figure 9, the influence of



a



b

Figure 7. Effect of length on harmonic response drillstring in point (a) 25 feet from the bit (b) 75 feet from the bit

the inclination angle on the resonant frequencies is demonstrated. It shows that the more the wellbore inclination, the less the effective length and the higher the resonant frequencies.

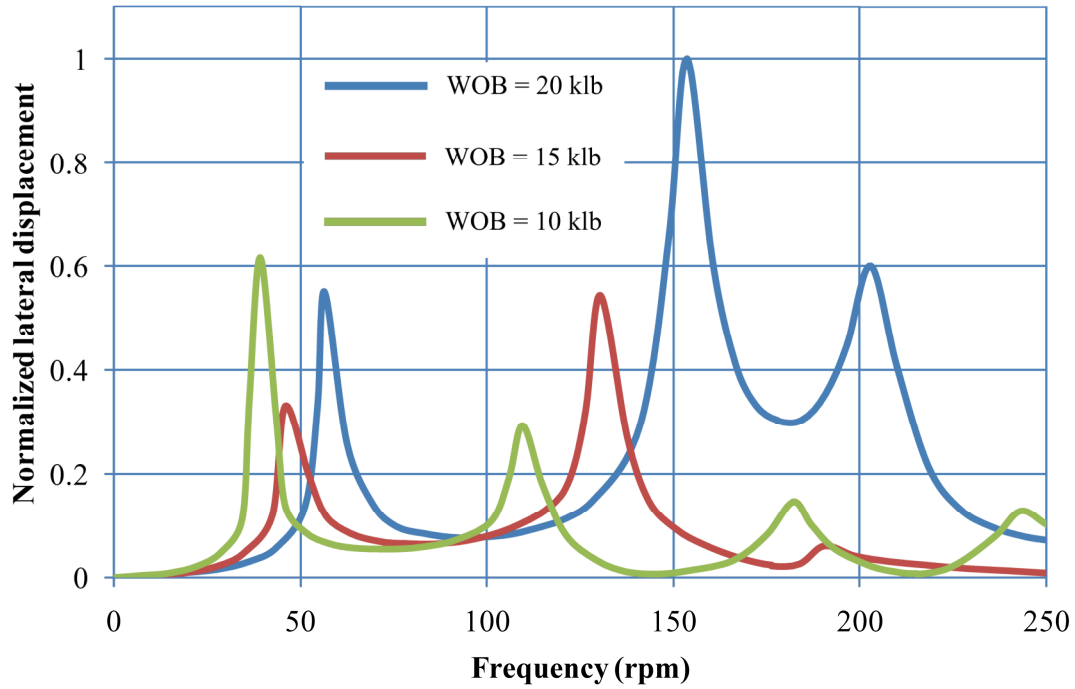


Figure 8. Effect of WOB on harmonic response of drillstring No. 1.

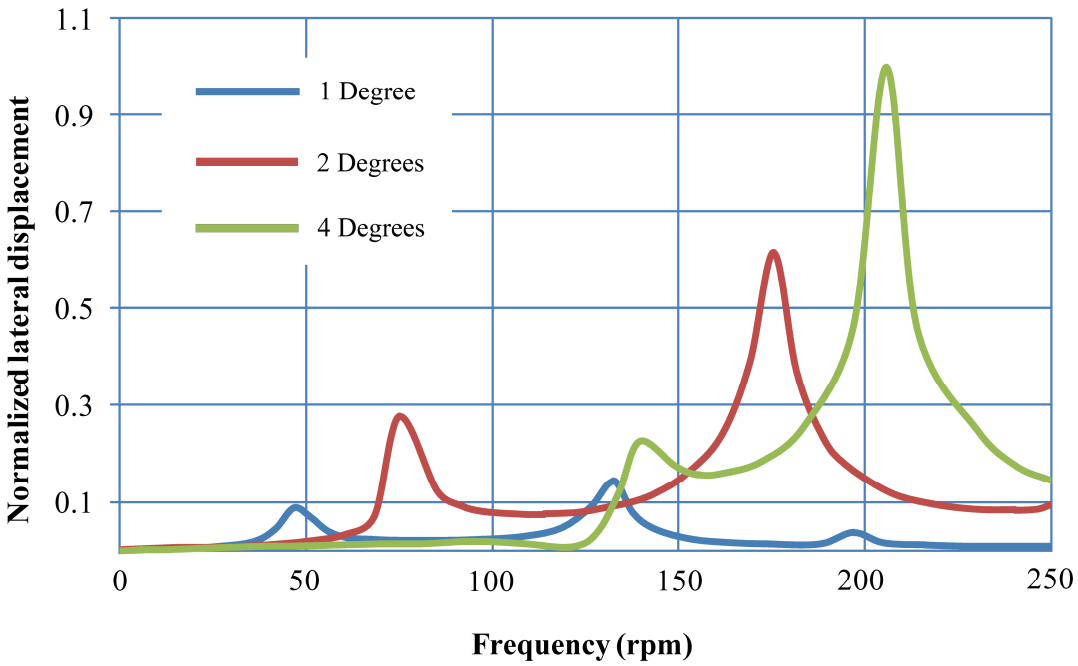


Figure 9. Effect of hole angle harmonic response of drillstring No. 1

Transient analysis results

In this analysis, time dependent response of dynamic behavior of drillstring detailed in Table 1, situated in a 1 degree inclined well with 15 klb WOB was obtained. Lateral deflection for two different points as a function of time was plotted at 95 and 135 rpm rotary speeds. The rock/bit interaction is another source of excitation used

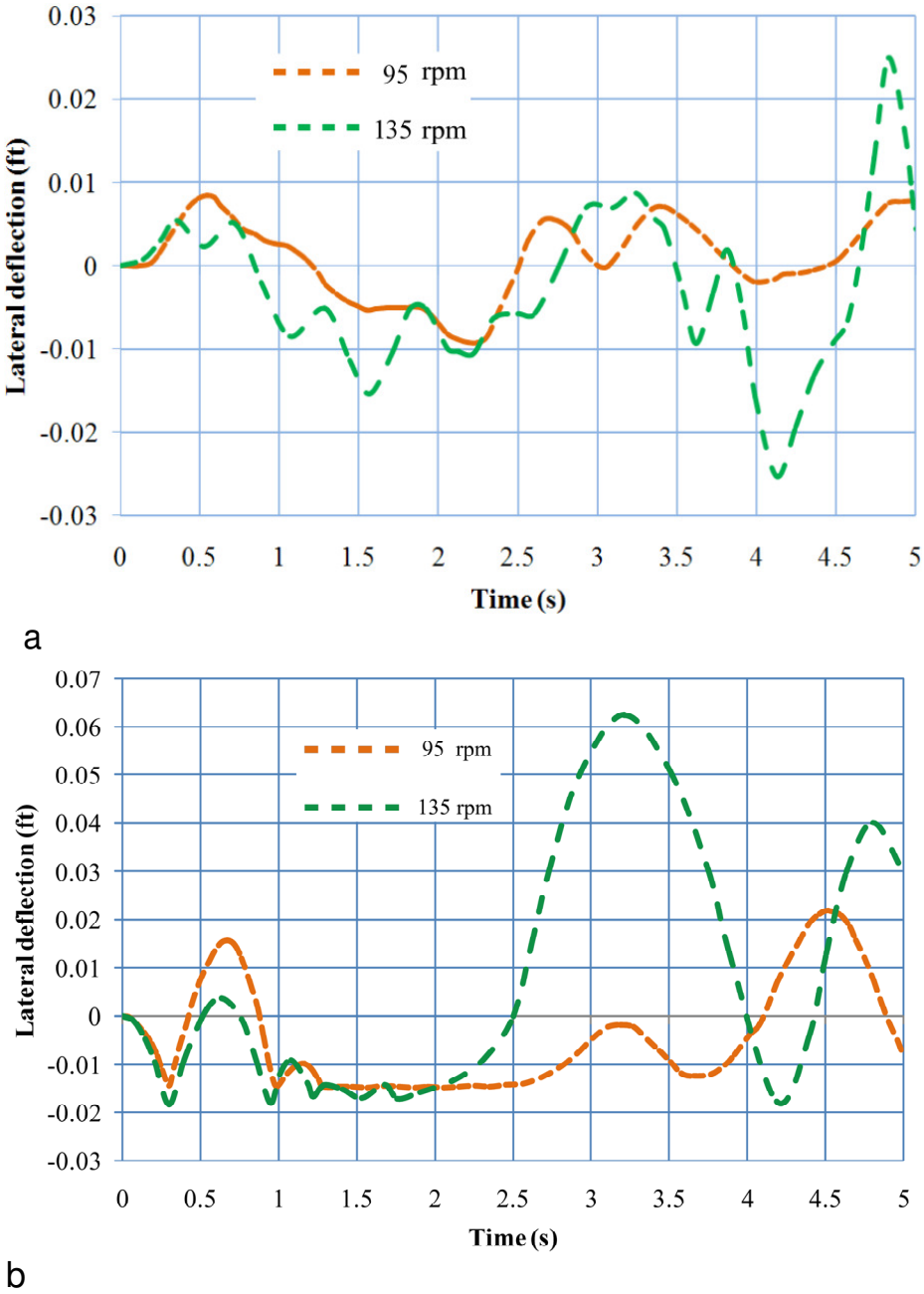


Figure 10. Time dependent behavior of drillstring No.1 at 95 and 135 rpm rotary speeds at (a) 25 ft (b) 250 ft from the bit.

here. To model three-cone bit and hard rock interaction, an axial excitation with amplitude of 0.1 inch and a frequency of 3ω rpm ($0.1\sin 3\omega t$) is necessary to apply on the bit. Notice that mass imbalance or bent pipe due to static deformation causes excitation primarily in the lateral direction that is on the order of frequency $1\times\omega$ (Besaisow and Payne, 1986). Lateral deflections for 25 and 250 feet from the bit during the first 5 s are shown in Figures 10a and b respectively. Because the angular velocity of 95 rpm is not close to any critical frequencies, the lateral displacements remain in low level, especially at the point located between two stabilizers.

A similar scheme is depicted for identical points at 135 rpm rotary speed. In view of the fact that this angular velocity is close enough to the second resonant frequency, the lateral displacements rise up seriously relative to the previous case, until at 250 ft from the bit, impacts with the wellbore wall. From time histories of two lateral displacements in y and z directions, orbital trajectories of various locations on the BHA have been

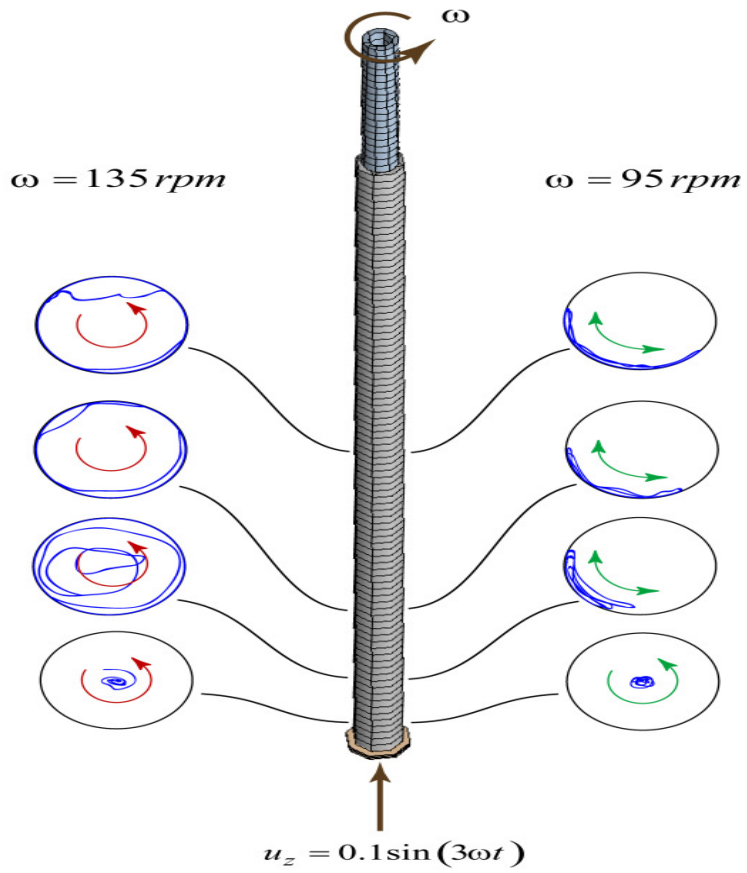


Figure 11. Orbital trajectories at 25, 75,150 and 300 ft from the bit in the BHA.

Table 5. Comparison of three main frequencies of drillstring No. 1 with Burgess et al. (1987) without mud effect.

	Effective length (ft)	1st Natural frequency (Hz)	2nd Natural frequency (Hz)	3rd Natural frequency (Hz)
Ansys model	114	1.23	3.14	4.19
Burgess et al. (1987)	113	1.25	3.15	Not reported

obtained and drawn in Figure 11; while rotary speeds stay 95 and 135 rpm (second natural frequency of drillstring No.1). At critical rotary speed, the drillstring undergoes large lateral displacement and the whirling motion typically propagates quickly throughout the BHA.

DISCUSSION

The computational model proposed in this research, is capable of accurately predicting the drillstring natural bending frequencies in comparison with other formulations and experimental data. As follows in Table 5 for no mud effects, results are satisfactory when compared with Burgess et al. (1987). Furthermore, a comparison between experimental data reported by Besaisow and Payne. (1986) and ANSYS outcomes was carried out as given in Table 7, giving excellent results. The harmonic plot for effect of length clearly shows that the rotary speed which is not critical at a given depth may become critical as drilling progresses into deeper sections.

The inversed analytic relation of natural frequencies with the length square for a beam confirms soundness of the results trend. By transient analysis, the drillstring rotational behavior over a period of time is examined. The drillstring which is rotating in a critical rotary speed deviates from the well center considerably, strike the wellbore wall and whirling motion propagates throughout the BHA located above the second stabilizer. Although

Table 6. Main natural frequencies of three drillstrings included mud effect.

	1st Natural frequency (Hz)	2nd Natural frequency (Hz)	3rd Natural frequency (Hz)
Drillstring No. 1	0.78	2.25	3.28
Drillstring No. 2	0.88	2.27	3.37
Drillstring No. 3	1.84	3.21	6.03

Table 7. Comparison of ANSYS results and measured data.

	Natural frequency from ANSYS (Hz)	Empirical results from Besaisow et al. (1986) (Hz)
Drillstring No. 1	3.28	3-4
Drillstring No. 2	3.37	3.33
Drillstring No. 3	3.21	3.36

the described analysis techniques were developed specifically for drillstrings applied here, these guidelines are generally applicable to other types of dynamic downhole assembly analysis.

Conclusions

A finite element dynamic model of the vibrational characteristics of rotating drillstring was developed using ANSYS software. It can be invaluable in the prevention of vibration induced damage to sensitive BHA components. The model identifies the critical rotary speeds at which severe drillstring vibration can occur. For field application, with respect to height of peaks and defining dangerous and nondangerous regions, the model can be used to determine safe operation ranges of rotary speed or to change BHA configurations to minimize failure risk.

As a rule of thumb, it can be inferred that the more the mass and the longer the drillstring, or less the WOB, or the more vertical the hole, the lower the lateral resonant frequencies. In comparison with the experimental data, high accuracy of the model presented here in predicting the natural bending frequencies, makes it a good candidate for use in the modeling of drillstring vibration problems by drilling engineers.

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APPENDIX

Appendix A

The effect of mud including added mass and damping can be written, as in Chen et al. (1987):

$$M_{adjusted} = M_{string} + C_M \times M_{disp} \quad \text{(A1)}$$

$$\zeta = \frac{1}{2}\left(\frac{M_{disp}}{C_M M_{disp} + M_{string}} \right) H \quad \text{(A2)}$$

M_{disp} is the mass of displaced mud and C_M is the coefficient that depends on two parameters which are S and β where:

$$S = \frac{\rho \omega D^2}{4\mu} \quad , \quad \beta = \frac{D}{d} \quad \text{(A.3)}$$

Where

ρ : mud density in $slug / ft^3$

μ : dynamic viscosity in $slug / ft.s$

ω : circular frequency of rotation in rad / s

d : external diameter of drillcollar in ft

D : diameter of the wellbore in ft

Values of C_M and H as a function of β for selected value of S depicted in [14] reveal that C_M and H will be 3.7 and 0.5, if S and β are equal to 2930 and 1.32 respectively at 100 rpm circular frequency. Thus, the equivalent density of drillstring and damping ratio will be 20.32 $slug / ft^3$ and 0.03. It should be noted, because of the low value of 1.32 for diameters ratio, the change in S due to change in ω have little influence on C_M and H values. Hence, assuming the mean circular frequency (ω) is reasonable and is let to be 100 rpm for dynamic mud effect calculations.