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Complex BHA Mechanics and Performance Analysis for Horizontal Wells

Mohamed Halafawi, Lazăr Avram

Drilling and Production Engineering, Petroleum-Gas University of Ploiesti, Romania

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Abstract

Increasing the complexity of wellbore and BHA establishes a demand for specified, complex, and advanced mathematical modeling for BHA mechanics and performance analysis, especially in horizontal wells applications. Recently, the applications of complex steerable BHA systems in drilling directional and horizontal wells become extensively used. Therefore, this article presents a developed model for predicting performance analysis and mechanics of complex steerable BHA systems containing PDC bit, bent housing motors, stabilizers, logging tools, wear pads, drill string components, etc. A sensitivity analysis of BHA whirl is also performed so that the BHAs' natural frequencies and lateral vibration mode shapes, the rotary speeds, and their corresponding weights on the bit can be computed and predicted. Based on field data of a long radius horizontal well which is drilled to hit 5 targets horizontally: NRQ 255 6H-1, NRQ 255 6H-2, NRQ 255 6H-3, NRQ 255 6H-4, and NRQ 255 6H-5; the complex BHA components and their mechanics are selected and optimized in order to achieve wellbore trajectory optimization and borehole stability. It was found that a slight difference of 0.006 degrees of the bit tilt led to a significant alteration in the BHA mechanics and performance, and the contact point increased from 96.6 ft to 101.2 ft. The lateral vibrations' mode shapes occur at natural frequencies 37 and 138 rpm.

Keywords: *Complex BHAs; Horizontal wellbore trajectory; Complex BHAs; Horizontal wellbore trajectory; Stress and moment analysis; BHA whirl; Lateral vibrations; Wellbore instability.*

1. Introduction

A bottom hole assembly (BHA) refers to drill collars (DC), heavyweight drill pipe (HWDP), stabilizers (STB), bits, and other accessories utilized in a drill string. The whole wellbores, whether vertical or directional, require the accurate design of the BHA to control the hole direction in order to accomplish the target objectives. DC's and STB's are the main equipment used to govern well direction. The main methods by which directional control of the hole is maintained, are the effective positioning of stabilizers within the BHA. The five basic types of BHA which may be utilized to control the direction of the well are [1]:

1. Pendulum assembly;
2. Packed bottom hole assembly
3. Rotary build assembly;
4. Steerable assembly
5. Mud motor and bent sub-assembly

In normal rotary drilling, the BHA is a part of the drill string, which is positioned above the bit for putting weight on the bit and controlling the borehole trajectory. The BHA components may be comparatively simple, consisting of only DC's and a drill pipe (DP), or more complex, consisting of two (or even three) sizes of DC's, HWDP, STB's and regular DP. If the desired directional-drilling purposes cannot be completed with one STB, two or even three STB's must be utilized in the BHA and positioned in the accurate positions relative to the bit. Using more than three STB's for well deviation control is slightly explained, but it still may be beneficial for holding the BHA off the wellbore wall in order to avoid differential sticking. For some directional-drilling applications, in order to drill complex trajectories and reach the desired targets, complex BHA is absolutely required [2].

For the BHA's in horizontal wells, BHA's for the drilling of horizontal wells are classified into three categories [3]:

a. Motor BHA's, in which a bottom hole motor is installed and the motor provides the power of turning the drill bit
b. Rotary BHA's in which the drill string is turned with a rotary table or a power swivel (top drive) at the surface
c. Steerable BHA's which have bent subs, tilt sub, offset stabilizer, and a bottom hole motor (curved or straight housing)

All three categories may have a MWD or a steering tool, which in turn requires non-magnetic drill collars. Horizontal BHA's may not have drill collars other than the non-magnetic type and HWDP. Some of the typical BHA's discussed for long, medium, and short-radius wells are [3]: 9 7/8'' angle building, 6 1/2'' angle building, 6 1/2'' short directional, and 6 1/2'' lateral reach. Generally, the BHA's mechanics and performance are affected by many parameters, including [2-3]:

- Bending stiffness and each component weight of the BHA
- Position of each element in the BHA with reference to the bit
- Local inclination, azimuth, curvature, and hole diameter
- Formation properties and drill-bit type
- WOB and bit rotational speed
- Formation tip, torque while drilling, drag during trips, and stabilizer blade wear
- Drill collar OD wear, the rugosity (hole enlargements), and mud filter cake.

Several theories and practices analyze similarly to all four kinds of BHA's mechanics, while others are very constrained to one of the types. Since the first 1D analytical model, a three-order ordinary differential equation was suggested for a multistabilizer BHA; the BHA mechanical analysis had extensively studied [4–32]. Most of these studies investigated the static mechanics of a conventional multi-stabilizer BHA and a conventional BHA with a bent housing PDM. The drill string mechanics have developed from the static to the dynamic mechanics in the latest 70+ years, and the BHA dynamics model is usually transformed into a quasi-static model for determination. Over the preceding 60+ years, the quasi-static BHA studies had advanced from 2D model [4] to 3D model [5], from the small deflection assumption [4-5] to large deflection one [6-9], from the analytical solution to numerical solution [7], and from vertical, inclined straight wellbore to deviated wellbore [10-11].

The prediction performance of the BHA is significant in increasing the efficiency of directional and horizontal drilling. Consequently, there are several theories for analyzing BHA static behavior under small deformation [12-14]. There are also some methodologies for analyzing the BHA under large deformation [6,15-17]. However, in order to improve computational efficiency, the formulations are always simplified for large deformation.

Applications of a BHA analysis in directional drilling have explained [12]. The application of a 3D directional drilling computer program was performed in order to analyze building, dropping, and holding assemblies in straight, 2-D curved, and 3-D curved (spiral) boreholes [18]. Mechanical behaviors of the BHA have presented with bent housing positive displacement motor under rotary drilling. They developed a mechanical model of the BHA with bent housing PDM based on the Timoshenko beam theory. The computed formula of bit side force (BSF) and resultant steering force (RSF) was deduced. A BHA analysis has also programmed in directional drilling by considering the effects of the axial displacement [19]. A computer program was developed for the BHA analysis in order to quantitatively predict the BHA performance in directional drilling utilizing the weighted residuals and the Newton Raphson iterations methods. A computer program is developed for prediction of the BHA performance [13]. In which, formation dip angle, hole and collar size, and stabilizer spacing are used as input parameters while the drilling predictions terms are hole curvature, hole angle, and WOB. Additionally, A program is developed in order to predict and design the BHA performance for drilling based upon techniques and algorithms which have been developed [13,20].

A new approach to selecting optimum BHA configuration for any given well trajectory was discussed [21]. They presented an analytical model for predicting the performance of steerable BHA systems containing bent housing motors, stabilizers, wear pads, etc. On the other hand, another new BHA analysis program presented for the borehole path prediction based on a sophisticated static algorithm [22]. Directional drilling behavior computations of a variety of the BHA are developed based on a newly established 3D static drill-string analysis model for arbitrarily shaped wellbores using a non-linear wall potential equation. The rotary drilling system optimizes the BHA performance in horizontal Austin Chalk wells was presented [23]. The placement of an adjustable stabilizer on the bottom of a positive displacement motor (PDM) was utilized in order to improve horizontal drilling. The Steerable system and the developed BHA configuration were reviewed and discussed.

BHA and drilling parameters design for deviation control in directional wells were presented [24]. A proper design configuration of the BHA and drilling parameters were selected for Menengai directional wells to determine the effectiveness of the various BHA design configurations in deviation control. An advanced analysis model has verified with downhole bending moment measurements [25]. An advanced engineering model and the verification of its predictions with downhole measurements were developed in order to predict bending loads and accurate wellbore curvature. Managing BHA integrity has presented with its design based on bending moment and stress analysis [26]. A new automated workflow for modeling BHA static loads was developed in order to deliver a more comprehensive solution for BHA design, to efficiently estimate the effect of various wellbore curvature at a variety of wellbore inclinations, and to realize the risk associated with the plan and deviation from the plan in the execution phase.

However, in complex BHA practical applications, only the bottom portion (almost 120–160 ft) of the BHA affects the forces at the drill bit. Utilizing more than one stabilizer into the BHA creates problems of BHA equilibrium determination more difficult due to solving more differential equations. However, many techniques and methodologies are available in order to solve these equations and obtain reasonable solutions such as analytical solutions [27-28], finite-element methods [29], finite-difference approaches [30], rotation and translation of coordinate systems [31], and transfer-matrix approaches [32]. BHAs usually are designed to a specific build, drop, or hold angle but still useful for complex practical purposes.

This paper presents the main concepts that control the BHA directional and horizontal drilling behavior and mechanical performance. In order to determine the forces acting at the drill bit, to predict the direction of the predicted drill bit displacement and consequently that of the wellbore, to calculate forces and moments along with the BHA, and to assess BHA mechanical integrity, an equilibrium BHA configuration with a known composition in terms of geometric and mechanical properties must be determined as a major goal. The BHA must design not only to meet the directional and horizontal drilling objectives but also to be strong enough to avoid costly downhole failures. For the sake of summarizing, a slick BHA and direct calculations of conventional BHA will, therefore, be analyzed first, followed by a BHA with one stabilizer. Advances in straight, inclined, and curved sections of the wellbore will also be presented. Additionally, rotary, steerable, and complex BHA will be presented.

Table 1. BHA description of horizontal well under study.

Item #	Description	OD (in)	ID (in)	Stiff ID (in)	Gauge (in)	Weight (lb/ft)	Top Connection	Length (ft)	Total (ft)	Location
1	PDC	4.50	1.250		6.000	50.02	P3-1/2"REG	0.82		
2	Bit Sleeve Stabilizer	4.75	1.250	1.250	5.875	56.21	B3-1/2"IF	0.85	1.67	1.24
3	Geo-Pilot 5200	5.25	1.125	1.125	5.875	45.13	B3-1/2"IF	16.34	18.01	14.53
	Ref Housing Stabilizer				5.875					14.53
4	Geo-Pilot5200 FlexCollar	4.25	2.610	2.610		44.00	B3-1/2"IF	11.55	29.56	
	Ref Housing Stabilizer				5.256					28.47
5	5 3/4" Inline Stabilizer	4.75	1.250	2.610	5.750	56.21	B3-1/2"IF	5.61	35.17	30.74
6	4 3/4" ADR	4.75	1.250	2.206		53.70	B3-1/2"IF	25.30	60.47	

Item #	Description	OD (in)	ID (in)	Stiff ID (in)	Gauge (in)	Weight (lb/ft)	Top Connection	Length (ft)	Total (ft)	Location
7	4 3/4" GR	4.75	1.250	1.250		56.21	B3-1/2"IF	9.19	69.66	
8	4 3/4" ALD	4.75	1.250	2.696	5.750	45.50	B3-1/2"IF	14.34	84.00	73.36
	Stabilizer				5.750					73.36
9	4 3/4" CTN	4.75	1.250	1.853		50.50	B3-1/2"IF	11.09	95.09	
10	4 3/4"PWD	4.75	1.250	3.076		47.90	B3-1/2"IF	10.86	105.95	
11	4 3/4"MWD	4.75	2.815	2.815		39.18	B3-1/2"IF	17.16	123.11	
12	3X3-1/2" HWDP	3.50	2.063			25.30		92.80	215.91	
13	111X3-1/2" DP(S)	3.50	2.764			14.69		3522.40	3738.31	
14	3X3-1/2" HWDP	3.50	2.063			25.30		92.37	3830.68	
15	X-Over Sub	4.50	2.250	2.250		40.65	B4-1/2"IF	1.65	3832.33	
16	3X5" HWDP	5.00	3.000			49.30		92.74	3925.05	
17	6 1/2" Jar	6.50	2.500	3.000		96.36	B4-1/2"IF	32.35	3957.42	
18	41X5" HWDP	5.00	3.000			49.30		1257.53	5214.95	
19	5"DP	5.00	4.276			21.92		5181.00	10305.05	
								Total	10305.95	

2. Model hypothesis and mechanical properties of BHA

In order to analyze the mechanical behaviors and performance of complex BHA of a long radius horizontal well with perceded components shown in Table 1, the configuration of the BHA needs to be confirmed, assumptions and the properties of BHA's which are prevalent throughout the literature of BHA's have to be specified. The following hypotheses, general assumptions, and restrictions which are used in the analysis of the BHA are [2,16,19]:

1. Each section of the BHA and the drill string behave elastically
2. The physical and geometrical parameters are constants in each section of the BHA
3. There is no point at which the drill string lies on the lower side of the wellbore
4. The dynamic effects are ignored in the BHA
5. The BHA is modeled in 2D
6. The bit is centered in of the bottom hole plane, and no bending moment exists at the drill bit
7. Dynamic effects from drill-string and fluids are ignored
8. There is at least one stabilizer in the BHA
9. Steel has a density of 0.2832 lb/in^3
10. Steel has a modulus of elasticity of 30x10^6 lb/in^2
11. Steel has a modulus of shear of 12x10^6 lb/in^2

3. Performance analysis methodology

Figure 1 shows the methodology of the complex mechanics and performance analysis used in our study.

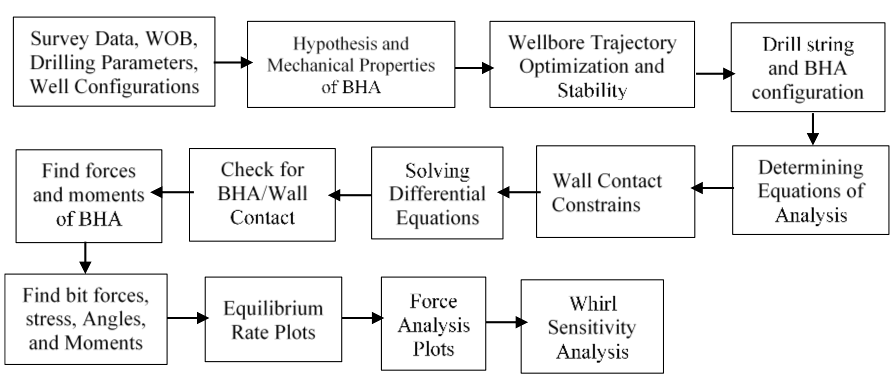

Fig.1. Model procedures flow diagram

Table 2. Direct mathematical equations and formulas for BHA mechanics

Parameter of BHA	Formula
Buoyed weight in mud	$BW_{\text{various fluid densities}} = Ws + 0.0408\,(MW_i\, d^2 - MW_e\, D^2)$ $BW_{\text{equal fluid densities}} = Ws \text{ x } BF = Ws \left[1 - \left(\frac{MW}{65.45}\right)\right] = Ws[1 - 0.01528\, MW]$
Stiffness	$I_{\text{round drill collars}} = \frac{\pi}{64}\,(D^4 - d^4)$ $I_{\text{squared drill collars}} = \frac{\pi}{64}\,(S^4/12 - d^4)$ $J = \frac{\pi}{32}\,(D^4 - d^4)$ $Sag_{6''} = \frac{5\,W\,L^4}{384\,E\,I}$; $Angle\ of\ point = \text{atan}\left(\frac{W\,L^3}{6\,E\,I}\right)$
Modulus ratio of tapered BHA	$MR = \frac{\pi}{32}\left(\frac{D^4 - d^4}{D}\right)$
Required drill collar	Required DC = 2 [Usable Hole Diameter] – Drill Bit Diameter
Wall force	$WF_{\text{doglegs}} = 2\,T\sin\left(DLS\ X\ \frac{LJ}{2}\right)$ $WF_{\text{deviated holes}} = BW \sin\,(I_{ang})$ $WF_{\text{centrifugal}} = \frac{Ws\,(H-D)\,N^2}{70471}$
Torsional Dampening–Flywheel Effect	$DV = \frac{N\,J_c\,L_c}{79058}$
Torque of a spinning BHA	t= Lc/5238 $T = 0.795\,N\,Jc$
Torsional buckling of a BHA and DP	$T = 0.795\,N\,J_p\,\left[\frac{2\,J_c}{J_c+J_p}\right]$ $BT = \left[833333\,I_c\,\left(2056\,\frac{I_c}{{L_c}^2} + P\right)\right]^{1/2}$ $Q_t = 5252\,\frac{HP}{RPM} = 7.04\frac{V\ x\ I\ x\ eff}{RPM}$ Where $HP = \frac{V\ x\ I\ x\ eff}{746}$ $Q_p = 7.04\frac{V\ x\ I\ x\ eff\ x\ mff}{N}$
Critical buckling load	$B_{crit} = f\,[BF^2\,(D^2 + d^2)(D^2 - d^2)^3]^{1/3}$ *Where f= 80 for the 1st order buckling, and f= 155 for the 2nd order buckling*
Weight on bit (WOB)	$WOB_{vertical\ hole} = BFx\ Ws_{BHA}\ x\ SF\ (0.5 - 0.9)$ $WOB_{inclined\ hole} = BFx\ Ws_{BHA}\ x\ cos\,(\beta) + 1617\,\left[\frac{BF\,(D^2 - d^2)(D^4 - d^4)sin\,(\beta)}{H - D}\right]^{1/2}$
Critical rotary speed of BHA	$F_{bit} = 3x\,\frac{N}{60} = 0.05\,N \ggg N_{CRITICAL\ BIT} = 3x\,N$ $F_{bit} = F_{long} \ggg 3x\frac{N}{60} = \frac{4212}{L} \ggg N_{CRITICAL\ LONG} = N = \frac{84240}{L}$ $F_{LONG,NoShock\ Sub} = \frac{n}{4L}\left(\frac{E}{D}\right)^{\frac{1}{2}} = \frac{4212}{L} \gg\gg\gg$ $N_{CRITTICAL\ LONG} = \frac{84240}{L} x\ n\ (match\ with\ tricone\ bit)$ $N_{CRITTICAL\ LONG} = \frac{84240}{L} x\ n\ (no\ match\ with\ tricone\ bit)$ $F_{TORS,No\ Shock\ Sub} = \frac{n}{4L}\left(\frac{G}{D}\right)^{\frac{1}{2}} = \frac{2663}{L} \gg\gg\gg$ $N_{CRITTICAL\ LONG} = \frac{53240}{L} x\ n\ (match\ with\ tricone\ bit),$ $N_{CRITTICAL\ LONG} = \frac{159780}{L} x\ n\ (no\ match\ with\ tricone\ bit)$ $F_{LONG\ With\ Shock\ Sub} = \frac{5675}{2\,\pi}\left(\frac{K}{M}\right)^{\frac{1}{2}} \ggg$ $N_{CRITTICAL\ LONG} = 62.6\,\left(\frac{k}{M}\right)^{\frac{1}{2}} (match\ with\ tricone\ bit),\ N_{CRITTICAL\ LONG} = 187.7\,\left(\frac{k}{M}\right)^{\frac{1}{2}}\ (no\ match\ with\ tricone\ bit)$
Placement of the pendulum stabilizer	Provided tables [35]

4. Direct mathematics of BHAs mechanics

In order to simplify and implement the direct program for BHAs' mechanics analysis, direct mathematics [3] are used to determine buoyed weight in mud, stiffness, modulus ratio of tapered BHA, required drill collar, wall force, torsional dampening – flywheel effect, the torque of a spinning BHA, critical buckling load, weight on the bit in vertical and deviated holes, critical rotary speed of BHA, and placement of the pendulum stabilizer. Table 2 shows direct equations to determine these terms, and more details and explanations are provided [3].

5. Mechanics of slick BHA in an inclined hole

Mechanics analysis of a slick assembly is presented in an inclined wellbore using Lubinski's differential equations (Eqs.1&2) in order to determine EI, w, φ, Ho, and L [2]. These equations are solved by means of an iterative technique or the power-series method [36]. In order to obtain solutions independent of borehole size, DC properties, WOB, and mud density, the proposed procedure is introduced and explained [35]. Moreover, the general methodology and the solving procedures are introduced to determine whether this BHA exhibits dropping, holding, or building angle tendencies in two situations: Isotropic and anisotropic [2].

$$EI\frac{d^3Y}{dX^3}+(W-X\,w\,cos\varphi)\frac{dY}{dX}=H_o+X\,w\,sin\varphi \quad (1)$$

$$EI\frac{d^3Y}{dX^3}+W\frac{dY}{dX}=H_o+X\,w\,sin\varphi \quad (2)$$

$$h=1-\frac{tan(\gamma_f-\varphi)}{tan\,(\gamma_f-\Phi)} \quad (3)$$

$$\frac{H_o}{W}=\frac{h\,tan(\varphi-\gamma_f)}{1-h+tan^2\,(\varphi-\gamma_f)}=tan\,(\Phi-\varphi) \quad (4)$$

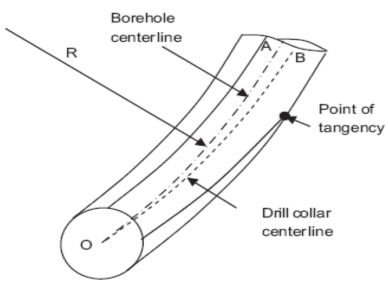

Fig. 2. Slick BHA in a curved wellbore [37]

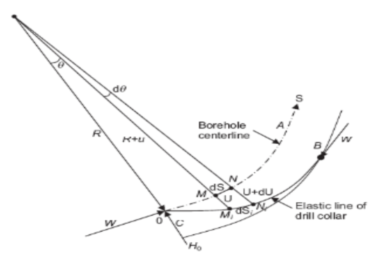

Fig. 3. S-U system of coordinates [37]

6. Mechanics of slick BHA in a curved borehole

In order to analyze BHA slick assembly performance in a curved part of the wellbore and to make the analysis independent of DC dimensions, wellbore curvature, and mud density; the differential equations (Eqs. 5 through 7) of the elastic line of DCs which are discussed in an S-U system of coordinates (Figs.2&3). Steps of mechanics and performance analysis of this BHA are performed in order to determine the side force at the bit through a sequence of calculations involved in determining the expected bit penetration direction under anisotropic drilling conditions [2].

$$EI\frac{d^3U}{dS^3}+\left(W+\frac{EI}{R^2}\right)\frac{dU}{dS}=H_o+(\frac{W}{R}+X\,w\,sin\varphi)S \quad (5)$$

$$EI\frac{d^3U}{dS^3}+W\frac{dU}{dS}=H_o+(\frac{W}{R}+X\,w\,sin\varphi)S \quad (6)$$

$$EI\frac{d^2Y}{dX^2}=EI\left(\frac{d^2U}{dS^2}+\frac{U}{R}-\frac{1}{R}\right) \quad (7)$$

7. Mechanics of a BHA with one stabilizer in an inclined hole

In order to basically understand the concepts of a stabilized BHA (Fig.4), the effective use of stabilizers was published in curved wellbore [35]. Some commonly used types of stabilizers and the selection of the proper type based on drilling data analysis from drilled wells under

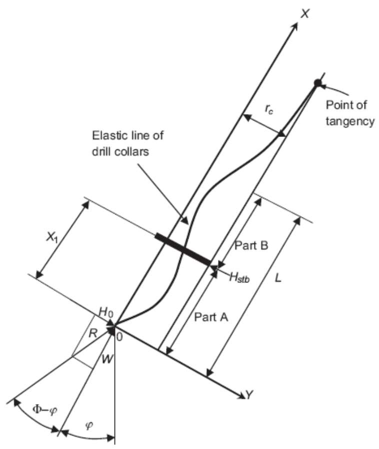

Fig. 4. BHA with one stabilizer in a straight inclined hole [2]

similar geological conditions have already been discussed. Consequently, in order to determine the equilibrium configuration of the BHA with one stabilizer, it is required to solve the following system of two differential equations (Eqs.8&9).

Modeling and solution of these differential equations are presented so as to estimate the side force at the bit and stabilizer, the direction of the tilt angle, the influence of changing the position of the stabilizer, distance to the point of tangency, radial clearance at the point of tangency, distance to the stabilizer, radial clearance at the stabilizer and BHA tendency whether build, hold, or drop if a stabilizer is placed [2].

$$\mathrm{EI}\frac{\mathrm{d^3Y_A}}{\mathrm{dX_A^3}} + \mathrm{W}\frac{\mathrm{dY_A}}{\mathrm{dX_A}} = \mathrm{H_o} + \mathrm{X_A}\,\mathrm{w}\sin\varphi \qquad (8)$$

$$\boldsymbol{E}\mathrm{I}\frac{\mathrm{d^3Y_B}}{\mathrm{dX_B^3}} + \mathrm{W}\frac{\mathrm{dY_B}}{\mathrm{dX_B}} = \mathrm{H_o} - \mathrm{H_{stb}} + \mathrm{X_B}\,\mathrm{w}\sin\varphi \qquad (9)$$

8. Mechanics of a BHA with one stabilizer in a curved wellbore

The solution to the problem of obtaining the performance equilibrium configuration of the BHA with one stabilizer and illustrating its practical application and consequently the side force at the bit, the tilt angle, and the side force at the stabilizer in a curved wellbore can be determined in a manner similar to that for an inclined well. Once again, it is necessary to solve a system of two differential equations with the proper boundary conditions like those of the preceded case. The solution of this system results in the following equation [2,37]:

$$(\mathrm{sinl_1})(\mathrm{C_{2b}} - \mathrm{C_{2a}}) + (\mathrm{cosl_1})(\mathrm{C_{3a}} - \mathrm{C_{3b}}) + \mathrm{h_o} - \mathrm{h} = 0 \qquad (10)$$

where: $C_{2a} = 1 - \frac{1}{r_d}$; $C_{2b} = \cos l + (h + l)\sin l$; $C_{3b} = sinl - (h - l)cosl$;

$$C_{3a} = \frac{\pm c_{stb} + \left(1 - \frac{1}{r}\right)(1 - cosl_1) - h_0 l_1 - 0.5\, l_1^2}{\sin l_1};\; h = \frac{1 - c \pm c_{stb} + 0.5\,(l^2 - l_1^2) - \cos(l - l_1) - l\sin(l - l_1)}{l_1 - l + \sin(l - l_1)};$$

$$h = \frac{1 - \frac{1}{r_d} \pm c_{stb} + 0.5 l_1^2 - \cos(l - l_1) - (h + l)\sin(l - l_1)}{l_1};$$

In order to determine the expected directional tendency of a BHA with one stabilizer in a curved wellbore, the data of hole diameter, hole curvature, hole inclination angle at the bit, OD and ID of DCs, WOB, mud weight, distance from the bit to the stabilizer, and stabilizer clearance are utilized. The methodology, which includes the determination of the phases of solution for each section of the inclined hole, is provided [2].

Although the above-mentioned ideas are very helpful in acquiring a good knowledge of the basic values engaged in deviation control, their practical usefulness in the field is restricted because most BHAs are compositionally quite complicated.

9. Rotary steerable BHA

Steerable systems are composed of motors and bent housing with an angle varying from 0 to 3 degrees. They are utilized for drilling highly deviated and horizontal wells with both sliding and rotating modes. An analytical model presented in order to predict the performance of the steerable BHA system [21]. This model is based on expressing the total potential energy (U) (Eq. 11) which is the sum of the total amount of bending strain energy (Ubent), the effective axial component of weight and initial curvature (Uwc), variation due to lateral component weight (UL), and effect of reaction force from the formation (Ur). A BHA simulation modeling of a steerable configuration was implemented based on Lubinski and Williamson's equations

[20]. The performance of a conventional steerable BHA has predicted using Weighted Residuals Method and Newton-Raphson iteration in order to estimate the nonlinear effects of the BHA deformation [19]. Additionally, the performance of a complex BHA with an unstabilized steerable motor and the bent sub was predicted based on a sophisticated static algorithm so that the BHA integrity with its design can be managed based on bending moment and stress analysis [22]. Moreover, a new automated workflow is presented for modeling BHA static loads [26]. This new technique allows evaluating the impact of various borehole curvature magnitude for various inclinations, to understand risks accompanied by the plan and its deviation, and to mitigate or minimize failures. A case example of the rotary steerable BHA was used to explain the new technique of workflow automation. In Austin Chalk wells, the rotary steerable BHA configuration is used in order to optimize the BHA performance in horizontal drilling [23]. It's managed to control inclination while drilling, reduce trips, extent the horizontal section, decease mud additives, increasing the lifetime of MWD tools, and reduce costs of field trial testing. A generic algorithm [16] has also developed for modeling the steerable motor systems and the rotary steerable systems utilizing the 4th order nonlinear differential equations' solution of Lubinski's equations (Eq. 13).

$$U = U_{Bent} + U_{wc} + U_L + U_r \tag{11}$$

$$y = y + \frac{1}{K^2}\left[c_o'(1-\cos Kx) + f_o(Kx - sinKx) - \frac{q}{2}(Kx)^2 + Ktan\alpha_o\, sinKx\right] \tag{12}$$

$$x(z) = P_1 + P_2\,\cos\left(\sqrt{\frac{W}{EI}}\,Z\right) + P_3\,\sin\left(\sqrt{\frac{W}{EI}}\,Z\right) + \frac{H'}{W}\,z + \frac{q\,\sin\alpha}{2\,W}\,z^2 \tag{13}$$

$$Where \quad K = \sqrt{\frac{C}{EI}}\ , c_o' = c_O + q\ , \quad q = \frac{1}{K^2}\frac{Q\sin\beta}{EI}\ , f_o = \frac{1}{K}\frac{F_o}{EI}$$

10. Complex BHA

More differential equations are used for complicated BHA practical applications to solve BHA equilibrium issues created by the use of more than one stabilizer in the BHA. In addition, many techniques and approaches are provided to define and solve complicated BHAs equations and to achieve appropriate solutions. These techniques include:

- Analytical solutions [27-28] categorized into three categories [37-38]: differential equation techniques: this is based on the mechanical evaluation of BHA, to determine differential equations and definite circumstances, and finally to solve differential equations using analytical, semi-analytical or numerical techniques [38]; the most commonly used technique include analytical technique [4], finite difference technique [30], beam-column technique [40] and weighted residual technique [11]. The benefit of these techniques is the quick calculation and simple use.
- Finite-element technique [29,37-38] is a very helpful technique of numerical analysis, particularly appropriate for solving mathematical and mechanical problems with uneven fields and complicated limitations, and commonly used in static and dynamic evaluation [37].
- Energy technique: it is used only in two-dimensional tiny static deformation evaluation of tubular strings in petroleum and gas wells, and it is not convenient when handling BHA and borehole wall contact problems [38].
- Finite-difference approaches [30].
- Rotation and translation of coordinate systems [31].
- And transfer-matrix approaches [32].

BHAs are generally intended for a particular angle of build, drop, or hold, but are still helpful for complicated practical reasons. These models and techniques are continually enhanced and commonly used in the real drilling process to predict well trajectory. Currently, analyzing the mechanical behavior of the complex BHA is still a very helpful way. Although extensive studies of BHA's mechanical behavior have been investigated, the complex mechanics of a horizontal BHA with components shown in Table 1 are rarely studied, and the current method has ignored the influence of certain parameters and terms of differential equations to simplify the study of

BHA's mechanics and performance. Therefore, a new mechanical model was suggested for the complicated BHA with multi-stabilizers based on the preceding techniques and principles. On average, BSF and RSF were explored the impact of rotational speed, WOB, wellbore path, structural characteristics, and BHA. Finally, to demonstrate the performance optimization of the BHA model, the field case study was introduced.

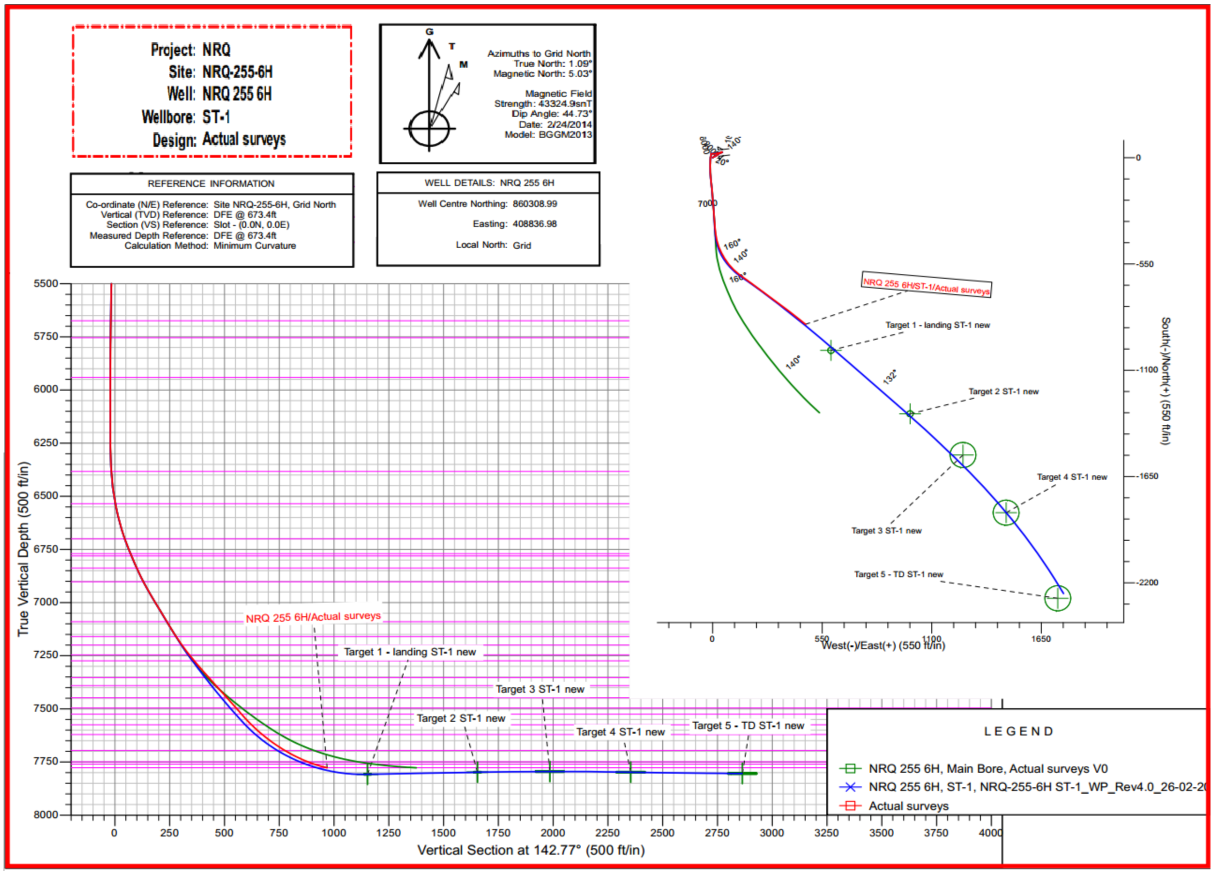

Fig.5. Final horizontal well trajectory- the planned versus the reality [41]

11. Horizontal Well data

A long radius horizontal well is drilled to 6200 ft. vertically with 12 1/4" hole and directed to pass through 5 targets: NRQ 255 6H-1, NRQ 255 6H-2, NRQ 255 6H-3, NRQ 255 6H-4, and NRQ 255 6H-5 horizontally. The actual total measured depth and vertical depth of the well are 10021and 7786.4, respectively. After drilling 12 1/4" borehole vertical to 6200 ft., building section with 39.83 degrees inclination along 177.83 degrees azimuth at 7192 ft. with 4 dogleg angle was implemented, then a hold section with the same to 7404 ft. was kept. Building curve section in 8 1/2'' hole was continued with 5.5 dog leg angle to the landing point at 8519 ft. MD, 7773.4 ft. TVD with 88 degrees inclination along 132 degrees azimuth. However, during drilling 8.5” wellbore, the drill string was stuck due to wellbore instability. After that, the hole was sidetracked at 7315ft and drilled until hitting the 5 targets. The complex BHA components utilized in drilling the well are shown in Table 1. Three wellbore trajectories of the well are shown in Fig.5: The plan and the actual two trajectories before and after sidetracking. More details of this well are presented and provided [40-41].

Table 3. Stress and moment analysis during drilling the horizontal section of 6" hole with 0.246 degree bit angle (Contact 96.6 ft)

Component	Distance From Bit (ft)	OD (in)	Stiffness ID (in)	Bending Moment (ft-lb)	Bending Stress (psia)	Endurance Stress (psia)	Stress Ratio (%)
[Bit] PDC	0.00	4.50	1.2500	0	14.70	40014.70	0.04
[Bit] PDC	0.50	4.50	1.2500	-17	37.53	40014.70	0.09
[Bit] PDC	0.80	4.50	1.2500	-22	44.23	40014.70	0.11
[Stabilizer] Bit Sleeve Stabilizer	1.00	4.75	1.2500	-22	40.10	40014.70	0.10
[Stabilizer] Bit Sleeve Stabilizer	1.20	4.75	1.2500	-20	38.09	40014.70	0.10
[Rotary Steerable] Geo-Pilot 5200	1.70	1.949	1.1250	-157	194.75	40014.70	0.49
[Rotary Steerable] Geo-Pilot 5200	3.20	1.949	1.1250	-627	11665.87	40014.70	29.15
[Rotary Steerable] Geo-Pilot 5200	3.50	5.25	4.7500	-717	13337.52	40014.70	33.33
[Rotary Steerable] Geo-Pilot 5200	5.40	5.25	4.7500	-917	2361.45	40014.70	5.90
[Rotary Steerable] Geo-Pilot 5200	6.20	5.25	4.7500	-937	2414.35	40014.70	6.03
[Rotary Steerable] Geo-Pilot 5200	7.30	5.25	4.7500	-906	2333.48	40014.70	5.83
[Rotary Steerable] Geo-Pilot 5200	10.00	5.25	4.7500	-535	1385.29	40014.70	3.46
[Rotary Steerable] Geo-Pilot 5200	15.80	3.18	2.1250	1048	4991.92	40014.70	12.48
[Rotary Steerable] Geo-Pilot 5200	15.90	4.75	2.1250	1045	4975.73	40014.70	12.43
[Rotary Steerable] Geo-Pilot 5200 Flex Collar	18.00	4.25	3.2500	1478	2173.81	30014.70	5.43
[Rotary Steerable] Geo-Pilot 5200 Flex Collar	19.90	4.25	2.6100	1479	2759.75	30014.70	9.19
[Rotary Steerable] Geo-Pilot 5200 Flex Collar	20.00	4.25	2.6100	1348	2516.70	30014.70	8.38
[Rotary Steerable] Geo-Pilot 5200 Flex Collar	29.50	4.75	2.6100	2058	2597.24	30014.70	8.65
[Stabilizer] 5 3/4" Inline Stabilizer (ILS)	30.00	4.75	1.2500	2362	2721.92	40014.70	6.80
[Stabilizer] 5 3/4" Inline Stabilizer (ILS)	30.70	4.75	1.2500	2818	3244.37	40014.70	8.11
[MWD] 4 3/4" ALD	40.00	4.75	2.2060	-543	664.24	30014.70	2.21
[MWD] 4 3/4" ALD	42.60	4.75	2.2060	-820	995.80	30014.70	3.32
[MWD] 4 3/4" ALD	43.50	4.75	2.2060	-839	1018.57	30014.70	3.39
[MWD] 4 3/4" ALD	50.00	4.75	2.2060	147	189.96	30014.70	0.63
[MWD] 4 3/4" ALD	50.50	4.75	2.2060	74	102.63	30014.70	0.34
[MWD] 4 3/4" ALD	57.30	4.75	2.2060	-886	1074.92	30014.70	3.58
[MWD] 4 3/4" ALD	60.00	4.75	2.2060	-703	855.72	30014.70	2.85
[MWD] 4 3/4" ALD	69.70	4.75	2.6959	3537	4515.93	30014.70	15.05
[MWD] 4 3/4" ALD	70.00	4.75	2.6959	3557	4541.08	30014.70	15.13
[MWD] 4 3/4" ALD	71.60	4.75	2.6959	3711	4736.82	30014.70	15.78
[MWD] 4 3/4" ALD	80.00	4.75	2.6959	866	1116.27	30014.70	3.72
[MWD] 4 3/4" CNT	90.00	4.75	2.6959	-626	810.94	30014.70	2.70

Table 4. Force, deflection, and moment analysis of the horizontal BHA for bit and stabilizer during drilling the horizontal section of 6" hole with 0.246 degree bit angle (Contact 96.6 ft)

Description	Distance from bit (ft)	Side force (lbf)	Deflection (in)	Slope (deg.)	Shear force (lbf)	Moment (lb-ft)
Bit	0	-2	0	0.246	-45	0
Stab	1.24	-323	0.062	0.235	-307	-20
Stab	14.53	-429	0.063	-0.107	25	988
Stab	30.74	-1220	0.125	0.143	-552	2842
Contact	49.90	-472	0.625	0.005	-162	162
Contact	51.30	-193	0.625	-0.005	-289	-19
Stab	73.36	-756	0.125	0.036	-579	3972

Table 5. Force, deflection, and moment analyses of the horizontal BHA for bit and stabilizer during drilling the horizontal section of 6" hole with 0.240 degree bit angle (Contact 101.2 ft)

Description	From Bit (ft)	Side Force (lbf)	Deflection (in)	Slope (deg.)	Shear Force (lbf)	Moment (ft-lb)
Bit	0.00	173	0.00	0.240	131	0.00
Stab	1.24	-628	0.063	0.242	-437	198
Stab	14.53	-62	0.063	-0.184	297	-377
Stab	30.74	-1905	0.125	0.412	-1003	5846
Stab	73.36	-1273	0.125	-0.220	-731	6368

Table 6. Stress and moment analysis during drilling the horizontal section of 6" hole with 0.240 degree bit angle (Contact 101.2 ft)

Component	Distance From Bit (ft)	OD (in)	Stiffness ID (in)	Bending Moment (ft-lb)	Bending Stress (psia)	Endurance Stress (psia)	Stress Ratio (%)
[Bit] PDC	0.00	4.5000	1.2500	0	14.70	40014.70	0.04
[Bit] PDC	0.50	4.5000	1.2500	71	110.32	40014.70	0.28
[Bit] PDC	0.80	4.5000	1.2500	119	174.66	40014.70	0.44
[Stabilizer] Bit Sleeve Stabilizer	1.10	4.7500	1.2500	172	211.26	40014.70	0.53
[Stabilizer] Bit Sleeve Stabilizer	1.20	4.7500	1.2500	190	232.64	40014.70	0.58
[Stabilizer] Bit Sleeve Stabilizer	1.30	4.7500	1.2500	172	211.39	40014.70	0.53
[Rotary Steerable] Geo-Pilot 5200	3.20	1.9490	1.1250	-664	12354.04	40014.70	30.87
[Rotary Steerable] Geo-Pilot 5200	3.50	1.9490	1.1250	-793	14745.71	40014.70	36.85
[Rotary Steerable] Geo-Pilot 5200	5.40	5.2500	4.7500	-1235	3177.29	40014.70	7.94
[Rotary Steerable] Geo-Pilot 5200	7.20	5.2500	4.7500	-1456	3742.54	40014.70	9.35
[Rotary Steerable] Geo-Pilot 5200	8.40	5.2500	4.7500	-1496	3845.85	40014.70	9.61
[Rotary Steerable] Geo-Pilot 5200	9.20	5.2500	4.7500	-1476	3792.67	40014.70	9.48
[Rotary Steerable] Geo-Pilot 5200	10.00	5.2500	4.7500	-1417	3641.96	40014.70	9.10
[Rotary Steerable] Geo-Pilot 5200	15.90	3.1800	2.1250	57	282.92	40014.70	0.71
[Rotary Steerable] Geo-Pilot 5200	18.00	4.7500	3.2500	1082	1595.50	40014.70	3.99
[Rotary Steerable] Geo-Pilot 5200 Flex Collar	18.90	4.2500	2.6100	1353	2526.39	30014.70	8.42
[Rotary Steerable] Geo-Pilot 5200 Flex Collar	20.00	4.2500	2.6100	1520	2836.66	30014.70	9.45
[Rotary Steerable] Geo-Pilot 5200 Flex Collar	27.70	4.2500	2.6100	3574	6648.91	30014.70	22.15
[Rotary Steerable] Geo-Pilot 5200 Flex Collar	29.50	4.7500	2.6100	4769	5998.84	30014.70	19.99
[Stabilizer] 5 3/4" Inline Stabilizer (ILS)	30.00	4.7500	1.2500	5193	5965.68	40014.70	14.91
[Stabilizer] 5 3/4" Inline Stabilizer (ILS)	30.70	4.7500	1.2500	5814	6677.73	40014.70	16.69
[MWD] 4 3/4" ALD	40.00	4.7500	2.2060	-1852	2229.60	30014.70	7.43
[MWD] 4 3/4" ALD	50.00	4.7500	2.2060	-5483	6573.79	30014.70	21.90
[MWD] 4 3/4" ALD	51.30	4.7500	2.2060	-5534	6634.44	30014.70	22.10
[MWD] 4 3/4" ALD	60.00	4.7500	2.2060	-3342	4012.90	30014.70	13.37
[MWD] 4 3/4" ALD	69.70	4.7500	2.6959	4566	5824.64	30014.70	19.41
[MWD] 4 3/4" ALD	70.00	4.7500	2.6959	4699	5994.77	30014.70	19.97
[MWD] 4 3/4" ALD	71.60	4.7500	2.6959	5456	6958.08	30014.70	23.18
[MWD] 4 3/4" ALD	80.00	4.7500	2.6959	2151	2751.89	30014.70	9.17
[MWD] 4 3/4" CNT	90.00	4.7500	2.6959	-1210	1555.10	30014.70	5.18
[MWD] 4 3/4" PWD	100.00	4.7500	2.6959	-391	512.60	30014.17	1.71

Table 7. Whirl Sensitivity of BHA

Source	Sensitivity Variable	Tangent (ft)	Frq1 (rpm)	Frq2 (rpm)	Frq3 (rpm)	Frq4 (rpm)	Frq5 (rpm)	Frq6 (rpm)	Frq7 (rpm)	Frq8 (rpm)
BHA	5.00	96.70	37	138						
BHA	10.00	96.60		131						
BHA	20.00	96.50		117						
Bit	5.00	96.70	7	28	75	109				
Bit	10.00	96.60		26	73	107				
Bit	20.00	96.50		23	69	103	147			
Stab @1.240ft	5.00	96.70	12	46	125					
Stab @1.240 ft	10.00	96.60		44	122					
Stab @1.240 ft	20.00	96.50		39	116					
Stab @14.530 ft	5.00	96.70	12	46	125					
Stab @14.530 ft	10.00	96.60		44	122					
Stab @14.530 ft	20.00	96.50		39	116					
Stab @30.737 ft	5.00	96.70	12	46	125					
Stab @30.737 ft	10.00	96.60		44	122					
Stab @30.737 ft	20.00	96.50		39	116					
Stab @73.355 ft	5.00	96.70	12	46	125					
Stab @73.355 ft	10.00	96.60		44	122					
Stab @73.355 ft	20.00	96.50		39	116					

12. Horizontal Well Analysis and Discussion

Complex BHA mechanics and performance analysis of the BHA are performed for an actual horizontal well that passes through five targets with 90 degrees: NRQ 255 6H-1, NRQ 255 6H-2, NRQ 255 6H-3, NRQ 255 6H-4, and NRQ 255 6H-5 as shown in Tables 3 through 7 and Figs. 5 through 8. After selecting the optimum wellbore trajectory, which achieving the well-bore stability for this well as shown in Fig. (5), the BHA components illustrated in Table (1), which are used to drill the 6'' horizontal borehole section, are studied and analyzed in order to complete wellbore stability and optimization study. During drilling 6'' borehole horizontally with the selected drilling and BHA parameters of 90 deg. inclination angle, -0.82°/100 ft build rate, 0.246 degree bit angle, 9 ppg mud weight and 10000 lb weight on bit; a contact with wall of the well is mainly occurred at 96.6 ft from the bit. Stresses, Forces, deflection, and moment analyses of the horizontal BHA for bit and stabilizer with showing the location of wall contact are shown in Tables 3 & 4, and Fig.6. It is clear that a slightly tangent of the BHA with the borehole wall is also happened at distance nearly 49.9 ft and 51.3 ft from the bit as appeared in the profile of BHA in Fig.6. However; side forces, shear forces, bending moments, defections, Endurance and bending stresses are slight increased till -0.6 deg. maximum de-flection, 2818 lb-ft maximum bending moment at 5 3/4" Inline Stabilizer, -1220 psi maximum side force, and -552 psi as a maximum shear force (Fig.6). Although there are two contact points beside the contact point of location 96.6 ft from the bit, forces and moments resulting from this contacting are slightly considerable. On the other hand, changing the bit tilt from 0.246 to 0.240 degrees and keeping the preceded parameters as the same is resulted in a significant alteration in the BHA mechanics and performance. Firstly, the main contact point is shifted from 96.6 ft to 101.2 ft, that means it is increased. Additionally, the contacting area with the wall of the wellbore is increased to include a larger zone with higher stresses, forces, and moments in BHA as shown in BHA profile in Fig.7 and Tables 5&6. A higher deflection of 2.1 deg. as a maximum is also resulted. Side forces, shear forces, bending stress, endurance stress, and bending moments are obviously increased as shown in Fig.7 and Tables 5&6. The maximum values are 2.1 degree, -1003 psi, -1905 psi, 6368 lb-ft, 36.85 for BHA deflection, shear force, side force, moment, and stress ratio respectively at stabilizer.

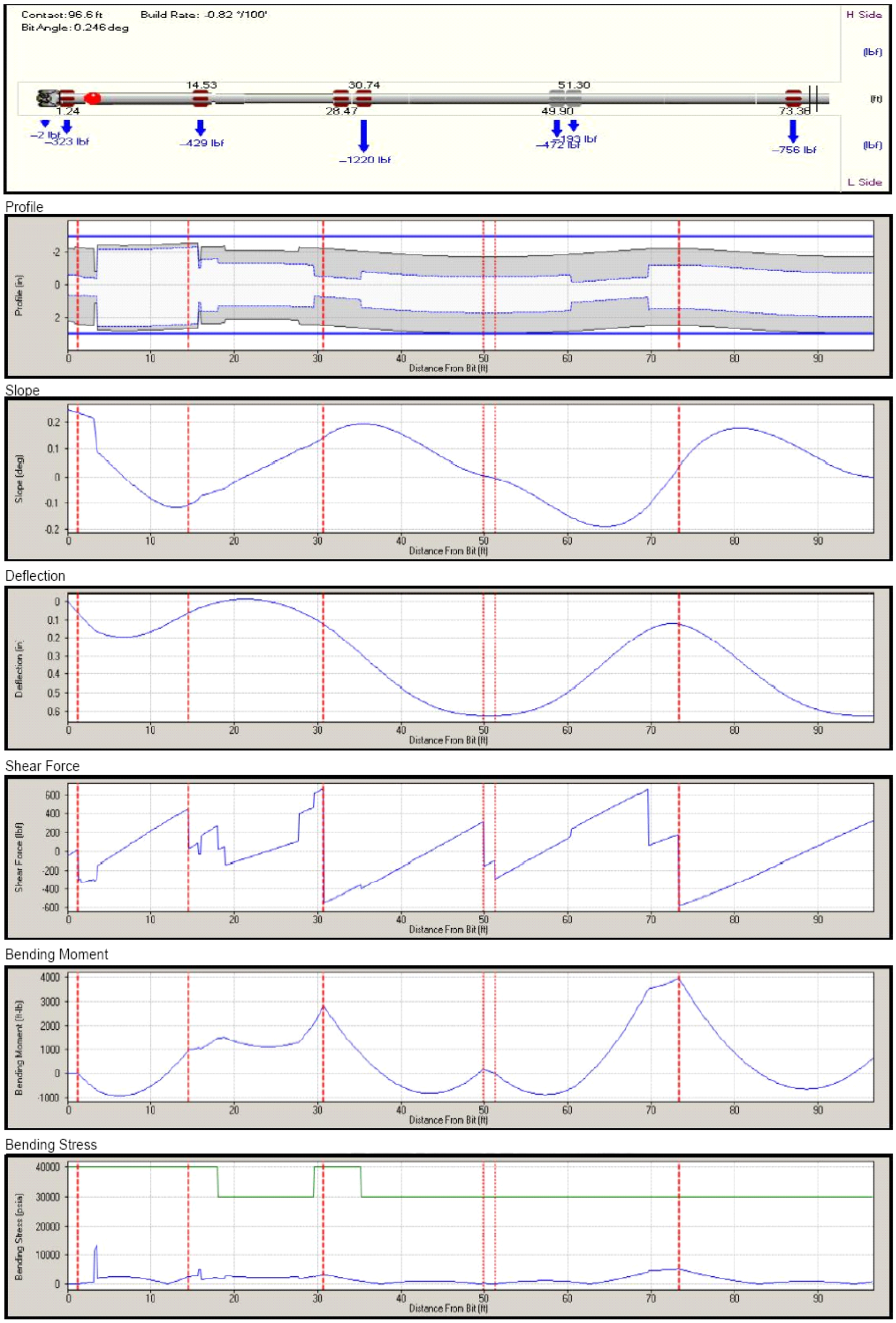

Fig.6. BHA configuration, mechanics and performance analysis during drilling the horizontal section of 6" hole with 0.246 degree bit angle

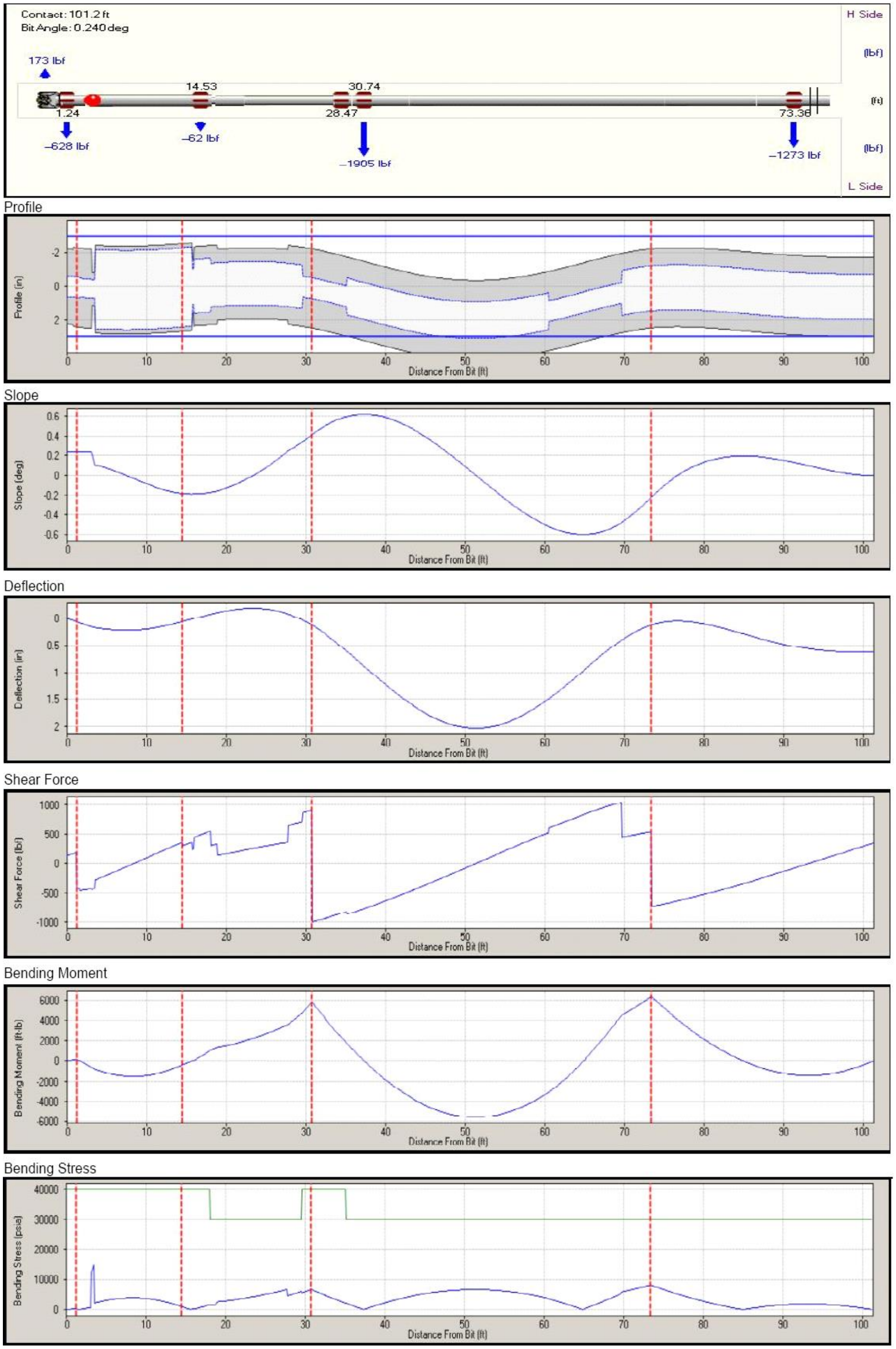

Fig.7. BHA configuration, mechanics and performance analysis during drilling the horizontal section of 6" hole with 0.246 degree bit angle

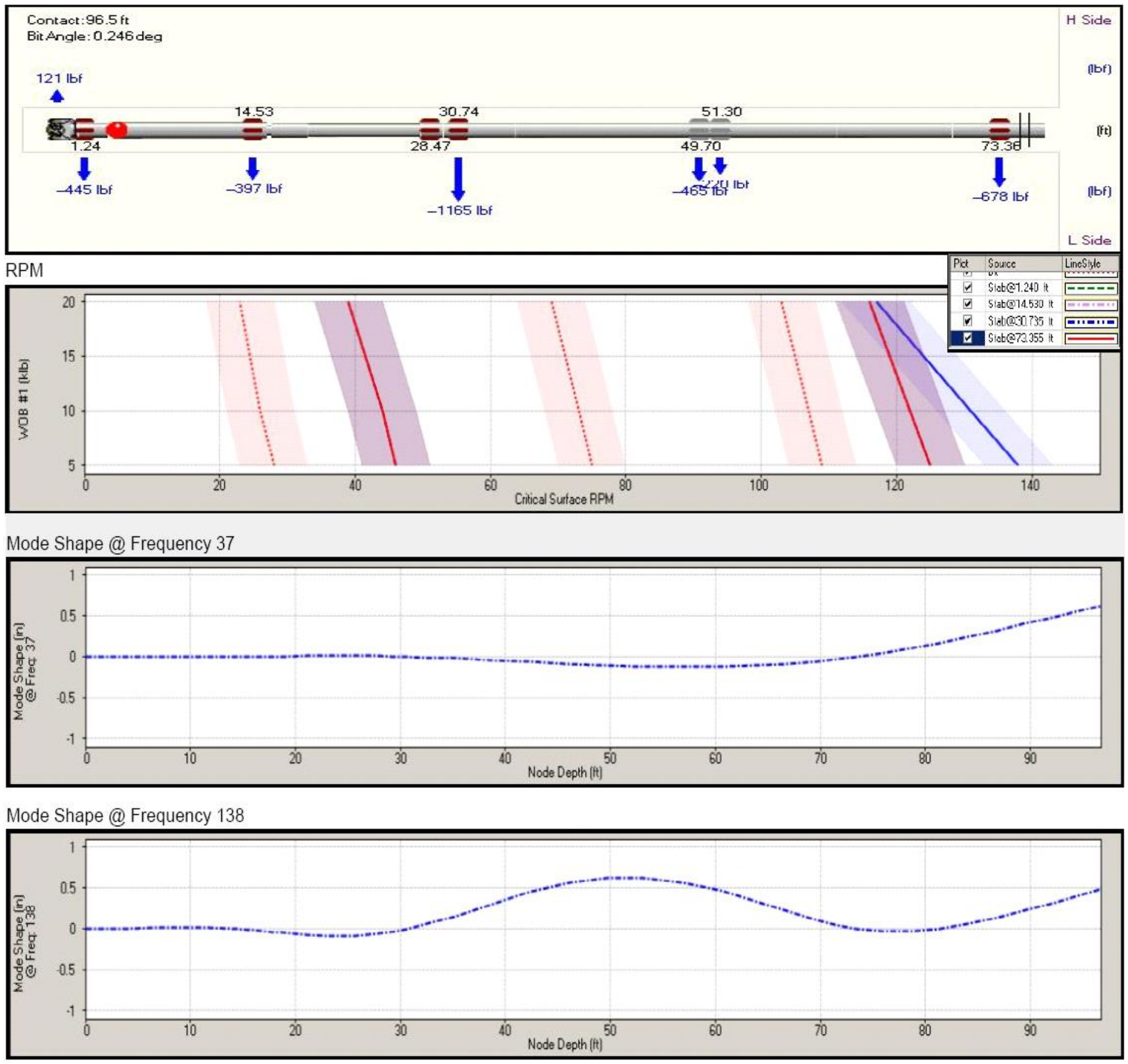

Fig.8. Whirl Sensitivity of BHA

In order to avoid BHA failure problems and wellbore instability resulting from vibrations, a sensitivity analysis of BHA whirl, is performed so that the critical rotary speeds and their corresponding weights on the bit can be predicted. Changing the WOB from 5000 lb to 20000 lb with 5000 lb interval needs a higher surface RPM and leads to shifting the contact point away from the bit (Fig. 8). Based on formation properties, BHA component orientation and imbalance, BHA contact points, Displacement analysis, and all previous BHA mechanics and performance analysis, BHAs' natural frequencies and lateral vibration mode shapes are computed (Table 7 & Fig. 8). These fundamental frequencies are at which the BHA tends to move and vibrate. Additionally, if the BHA is excited at one of its fundamental frequencies, resonance will appear, and large amplitude oscillations may generate. For BHA, the natural frequencies encountered are 37, and 138 rpm and the mode shapes' amplitude oscillations versus node depth are shown in Fig. 8. Table 7 shows the sensitivity of various BHAs' options to vibrations and their corresponding frequencies. Changing the bit or stabilizer location with alteration of tangent points leads to changing the fundamental frequencies. This vibration modelling and whirl sensitivity analysis will improve the future development wells and their stability.

13. Conclusions

Based on the results and analysis, the complex mechanics of the BHA and performance can be predicted and analyzed for horizontal wells. Additionally, stress and moment analyses are highly considered to predict the contact points of the BHA. The bit tilt has significantly impacted on the BHA mechanics' analysis. The wellbore trajectory optimization is a key factor of BHA performance analysis. A vibration model and sensitivity of bit whirl to compute the natural frequencies have a significant effect in keeping wellbore stability.

Nomenclatures

5238	*speed of a torsional wave in steel, fps*
B_{crit}	*Critical buckling load*
BF	*Buoancy factor*
BT	*resistance to buckling of the tube, lb-ft*
C	*compression, assumed constant (weight on bit in Section 1)*
co	*curvature of the elastic line at origin of coordinates*
d	*Inside diameter of tube, in*
D	*Outside diameter of tube, in*
DLS	*Dogleg severity of the dogleg, deg./ft*
E	*Young's modulus*
eff	*electrical efficiency of a big motor (0.92), hp/hp*
EI	*the bending stiffness of the drill collars*
G	*shear modulus, psf*
h	*the drilling anisotropy index*
H	*hole diameter, in*
H'	*the normalized side force acting on the left hand side of the segment*
H0	*the bit side force*
HP	*The horsepower of an electric motor*
I	*moment of inertia, in4*
I	*amperes consumed, amps*
I_{ang}	*Inclination of the hole, deg.*
J_c	*polar moment of intertia, in4*
J_p	*polar moment of inertia of the drillpipe, in4*
K	*spring constant of shock sub, lb/ft*
k	*spring constant of shock sub, lb/ft*
L	*the distance from the bit to the point of tangency*
L_c	*length of BHA, ft*
L_c	*length of the tube, ft*
L_c	*length of component, ft*
L_J	*Joint length of one drillpipe, ft*
M	*mass of BHA, lb*
m_{ff}	*mechanical efficiency of the rotary system*
MW_e	*Fluid density outside the tube, ppg*
MW_i	*Fluid density inside the tube,ppg*
n	*1,3,5, (gives higher harmonic frequencies)*
N	*rotary speed, rpm*
P	*axial load (compression is –ve, and tension is +ve), lb*
P1,P2, P3	*three variables called segment profiles*
Q	*weight per unit length in fluid*
Q_t	*torque output of a motor, lb-ft*
q	*unit weight of the drillstring*
Qp	*drillpipe torque by the rotary system, lb-ft*
R	*the axial component of the resultant force at the bit*
RPM	*rotational speed of the motor, rpm*
S	*the shearing force at any arbitrary cross section*
S-U system of coordinates	*S-coordinate is defined to coincide with the center of the borehole, and the abscissa, U, is chosen to be perpendicular to S. The function U(S) represents the radial deflection of the centroidal axis of the elastic line of drill collars and*

	is considered to be a positive deflection if directed to the right of the bore- hole center line
T	*tension in the drillpipe at the dogleg, lb*
t	*time torque is applied to the bit, seconds*
T	*torque transmitted to the drill bit, lb-ft*
V	*voltage across a motor, volts*
w	*the unit weight in fluid*
W	*the weight on bit*
W	*weight on bit*
w	*weight per foot of the BHA, ppf*
WF	*Wall force on a single tool joint, lb*
y_o	*deflection of the elastic line at the origin of coordinates*
α	*inclination angle*
β	*hole inclination angle, degrees*
γ_f	*the formation dip angle*
Φ	*the resultant force direction angle*
φ	*the same as the hole inclination angle*

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To whom correspondence should be addressed: Mohamed Halafawi, Drilling and Production Engineering, Petroleum-Gas University of Ploiesti, Romania, E-mail: halafawi@upg-ploiesti.ro