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GEODYN2: A Bottom Hole Assembly - Geological
Formation Dynamic Interaction Computer Program

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ABSTRACT

This paper describes the current development of a three-dimensional transient dynamic finite element computer program, GEODYN2, capable of simulating the behavior of a rotating bottom hole assembly (BHA) interacting with a non-uniform formation. The GEODYN2 Program facilitates a very detailed analysis/ simulation of the behavior of a BHA with a polycrystalline diamond compact (PDC) bit and various stabilizer designs. The basic drill string mechanics implemented within the program, the overall algorithm, and the more pertinent modeling features which permit this level of analysis are briefly outlined. The implementation of these features and how they allow calculation of the response behavior of a bottom hole assembly are demonstrated. Although the development and enhancement of modeling capabilities within GEODYN2 is ongoing, it is anticipated that the preliminary verification results thus far generated will further the understanding of the response behavior of BHAs.

INTRODUCTION

GEODYN2 is a BHA analysis, finite element computer program being developed under the auspices of the Sandia National Laboratories Geothermal Technology Development (GTD) Program and a consortium of industry sponsors. A major goal of this computer program development is to expand the understanding of the drill string mechanics associated with the drilling process, thereby allowing more efficient and cost effective drilling procedures to be implemented. This effort will provide

References and illustrations at end of paper.

valuable insight into two interrelated areas addressed in the GTD Program and of general interest. First, the program will be used to simulate the dynamic mechanical response of the BHA to aid in the design of "hardened" electronic and hydraulic components which may be utilized in "smart" drilling systems. Secondly, GEODYN2 will be utilized to analyze the actual drilling process itself and to ascertain how the various BHA components (the bit, drill collars, and various stabilizers) interact within the wellbore to influence the trajectory of the bit.

Prior to describing the basic mechanics and varied capabilities provided by GEODYN2, it should be recognized that this program represents the logical extension of its predecessor, GEODYN.¹⁻³ GEODYN2 not only calculates the transient dynamic response behavior of a PDC bit, but also the interaction of stabilizers and drill collar sections within a three-dimensional curved wellbore. It should be noted that the complexity of the downhole conditions and processes dealt with by GEODYN2 includes such phenomena as hole gauge, non-circular wellbore cross-sections (at the bit and stabilizer locations), formation hardness variations, and BHA startup procedures.

This paper highlights some of GEODYN2's current features and capabilities to provide insight into the mechanical representation being provided and presents some typical results to demonstrate such features.

Though static structural BHA analyses are often adequate to explain the trajectory tendencies of a BHA in the inclination angle plane, it was demonstrated by

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Millheim and Apostol⁴, utilizing an algorithm based solely on classical beam finite element theory, that a dynamic structural analysis was required to model trajectory variations in the horizontal (directional) plane. Though Millheim and Apostol developed and implemented a fairly sophisticated solution algorithm for analyzing the effect of BHA dynamics on the trajectory of a bit, several limitations were evident. Although many of the limiting features could be minimized or eliminated, it was recognized that certain quasi-friction forces which accompany bit/formation interaction and stabilizer blade/formation interaction could not be accounted for. Further, the utilization of a steady-state dynamic algorithm with such a simplified beam model idealization is not capable of analytically describing much of the complex intermittent BHA/formation contact which is known to occur.

It was also recognized that the interplay between both the bit and the stabilizer blades with the wellbore formations was of great significance and that the true characterization of the trajectory response could be obtained only by addressing these issues in a transient dynamic manner. Baird, et. al. described such an approach and aptly demonstrated that it was feasible to model a BHA by combining both beam models (for the collars and drill string) and more detailed three-dimensional models (for the bit and other complex components).

The GEODYN2 program incorporates much of the GEODYN development for the bit-formation interaction response characterization. These capabilities have been coupled with the structural definition of the stabilizers and an enhanced drill string representation. Additionally, the description of the three-dimensional curved wellbore into which the BHA is placed has been implemented. Though the GEODYN2 program is primarily designed to model stabilizers with beam elements, it should be noted that the program provides for exact definition of the primary contact points distributed along the stabilizer blades. This modeling capability provides for the exact representation of the interaction between the stabilizer blades and the wellbore.

GEODYN2 DESCRIPTION

The GEODYN2 program has incorporated the three-dimensional, non-linear, transient dynamic formulation inherent in GEODYN and enhanced the capabilities to permit formation interaction at points along the BHA. These include the bit, stabilizer blade regions, and drill string node points within a curved three-dimensional wellbore.

Solution Procedure

The GEODYN2 program is being developed to provide a solution to the equations of motion which drive the response phenomena associated with a BHA interacting within a three-dimensional curved wellbore. These equations (see Equation 1) are expressed in terms of a BHA system model which is assembled using two distinct subsystem idealizations with a residual flexibility, component mode synthesis (CMS) technique.⁵⁻⁷

$$[\hat{M}_{sys}]\{\ddot{q}\} + [\hat{C}_{sys}]\{\dot{q}\} + [\hat{K}_{sys}]\{q\} = \{\hat{F}_{sys}(t)\} \quad (1)$$

It should be pointed out that the nonlinearities associated with the beam model idealization (see following section for brief discussion) and the intermittent contact effects are all addressed as force terms on the right hand side of Equation 1. This approach was adopted to expedite the solution process (the stiffness terms do not vary with time) and to facilitate the calculation of a constant system equivalent dynamic stiffness matrix and its inverse.

Early in development of the program, a decision was made to model the BHA as two distinct components. These components are a lower bit-drill string section and an upper drill string section, either of which may contain stabilizers. Referring to Figure 1, the lower component for BHAs number 1 and 2 consists of the bit and five feet of drill collar, with the upper component containing the remainder of the drill collar length and stabilizers (BHA 2). The lower component for BHAs number 3, 4, and 5 contains both the bit and the near bit stabilizer with the upper subsystem containing the remainder of the BHA.

This approach has two advantages:

- (1) The use of two subsystems allows the user to develop a library of components, which may be joined within the program to study response variations. For example, an upper stabilizer spacing can be studied with two different types of bit's, or a bit may be readily studied with different types of stabilizer designs (spiral vs straight).
- (2) Because the GEODYN2 program relies on the utilization of a modally reduced bit component idealization,¹⁻³ the number of degrees of freedom upon which the eigensystem solution is performed be balanced between the two substructures, allowing the response idealization to be more accurately represented. It should be noted that the results illustrated in this paper have been obtained using a frequency response

up to approximately 2000 Hertz for the lower component and approximately 500 Hertz for the upper.

A second unique modeling aspect of GEODYN2 is the staging of the BHA system into the wellbore and the accompanying dynamic analysis under load. An analysis sequence within GEODYN2 consists of:

- (1) Placing the BHA into the wellbore without inducing drill string rotation, which requires a placement solution.
- (2) Accelerating the drill string at a constant rate from 0-RPM to the final desired rotational rate, which requires a transient dynamic solution.
- (3) Adding weight-on-bit (WOB), which also requires a transient dynamic solution.

The incorporation this staged solution sequence permits the generation of restart points to expedite solutions involving operating variations such as different RPM speeds, WOB applications, etc. This staging also facilitates the use of an artificial damping force application during placement to minimize the time spent obtaining such a solution. A more complete discussion of the forces involved in obtaining a solution will be presented in a subsequent section.

Bit-Drill String Model

The GEODYN2 program utilizes two distinct, three-dimensional finite element substructure models to characterize the structural response of the BHA being analyzed. The technique of utilizing 8-node, three-dimensional, isoparametric brick elements for modeling the body of a PDC bit in addition to three-dimensional linear beam elements to model the drill string has been preserved from GEODYN. The constraint equations relating translational brick displacements to compatible beam translational and rotational displacements at the juncture of the bit body and drill collar are required within the program.

The major enhancements to the characterization of the Bit-Drill String Model involve both the formulation of an equivalent nonlinear force vector for the beam elements and the coupling of the two distinct substructure components being combined to model the BHA. The nonlinear force vector has been implemented to represent large displacement geometry effects associated with the placement of the BHA within a curved wellbore. This force vector has been derived from the nonlinear terms of the strain energy function which are generated for the large displacement form of the linear beam element⁸ implemented in both GEODYN and GEODYN2.

Substructure Assembly

The assembly of the two BHA substructures is facilitated by utilization of a residual flexibility component mode synthesis (CMS) technique⁵⁻⁷. Although GEODYN2 permits the upper substructure to be modeled as either a physical finite element model or a modally reduced equivalent model, all results reported were obtained using a modally reduced equivalent model.

Briefly, component mode synthesis is a technique of dynamic substructuring and reduction often used for large finite element models. In the CMS technique, the assumed vectors (displacements and forces) include both static and dynamic displacement shapes, with the substructures partitioned to reflect both interface and remaining degrees of freedom. Since a modal reduction of each substructure has been performed, a truncated set of the resulting eigenvectors is used as the dynamic displacement shapes and each substructure will contain the number of mode shapes kept plus the six physical interface degrees of freedom. To model the response, the dynamic displacement shapes are augmented with static displacement shapes, and these shapes are used to define a reduction transformation. The equations of motion for the two subsystems are combined to form the system equations (Equation 1) by invoking physical interface displacement and force compatibility. The static displacement shapes associated with the residual flexibility (which characterizes flexibility not associated with kept eigensystem modes) attachment modes at the interface degrees of freedom have been calculated using inertia relief loading.

Stabilizer Model

To understand how the stabilizers are dealt with in GEODYN2, consider the generation of the BHAs thus far analyzed (see Figure 1) which incorporate the standard four straight bladed stabilizer configuration illustrated in Figure 2. This stabilizer configuration has been modeled using the GEODYN2 representation schematically illustrated in Figure 3. As illustrated, the body of the stabilizer is represented by either standard linear beam elements or non-linear beam elements. The four blades of the stabilizer are each characterized by a set of individual blade "cutters", which describe the primary contact points of the blade and permit the transfer of the formation interaction forces from the point of contact to the respective beam node point.

The blade "cutters" themselves are, massless, structureless, rigid bodies connected directly to the corresponding beam nodes. The stabilizer modeling algorithm is sufficiently general and flexible in nature to permit a user to model a variable

number of different blades on one body, to allow each blade to possess a finite width (if desired) and to permit the representation of fairly arbitrary shapes for each blade (e.g. straight or spiral blades). It should be stressed that the capabilities of the blade "cutter" mechanism will be qualified relative to its ability to accurately depict laboratory derived response behavior in much the same manner as that performed for bit "ghost cutters"⁹.

Bit Cutter Model

The bit cutters are modeled in GEODYN2 through the same "ghost cutter" mechanism previously incorporated into GEODYN, see Baird, Apostol et.al.³ In this approach, the ghost cutters are established as massless rigid body elements which are constrained to move in accordance with the bit body motion and which are designed to simulate the impact interaction between a real PDC bit's studs, gauge cutters and wear buttons with the formation.

Formation Model

The GEODYN2 downhole formation model in the bit region mimics that incorporated in GEODYN. In this representation, a combination of discrete points is used to define the surface contours of the formation. A bottom surface, a sidewall surface and an inclined surface lying between the bottom and sidewall are modeled in the code. Figure 4 illustrates the application of this scheme in representing the downhole formation model for a typical bit region; the grid intersections are the discrete points mentioned above.

The GEODYN2 code permits the user to interactively input data to define the formation surfaces and permits arbitrary specification and variation of both surface geometry and material properties. To facilitate actual penetration of the formation by "ghost cutters", a linear spring is incorporated to model penetration resistance. A friction force is also computed and applied to the cutter. This friction force is a function of both the penetration resistance and the absolute velocity of the cutter relative to the formation surface. The GEODYN2 code utilizes the interaction between cutters and formation to describe transient, non-linear responses necessary for solution.

GEODYN2 implements the piecewise application of the sidewall surface model at the bit as a mechanism for defining surface geometry and formation properties in a region surrounding each stabilizer defined by the user. As in the case of the bit, this preserves the ability to specify arbitrary variation of surface geometry and formation properties around each stabilizer.

The remainder of the wellbore surface, which encloses the majority of the collars

and drill pipe, is assumed to be represented by a homogeneous formation distributed around a three-dimensional curved circular cylinder whose diameter can vary as a function of measured depth.

Solution Algorithm

The GEODYN2 program utilizes essentially the same transient, dynamic solution algorithm (a modified Newton-Raphson procedure in concert with a Newmark-Beta numerical integration technique) developed during Phase 1 implementation.³ This algorithm has, however, been modified and extended to recognize the transient dynamic response of a system comprised of two distinct BHA substructures. For each substructure the individual physical degrees of freedom associated with a given node point, in addition to the physical locations of all ghost cutter and blade cutter geometry node points are interrogated to characterize the intermittent formation interaction response within the wellbore.

General Features

The GEODYN2 program incorporates the wellbore geometry via the reduction of the measured survey data (inclination, azimuth, and depth) utilizing the "Radius of Curvature Method". This information is coupled with the diameter survey information (hole diameter versus depth) to construct a continuous wellbore centerline and diameter profile. The detailed discrete point formation models utilized for the bit and stabilizer locations utilize the centerline and diameter profiles as starting points for the interactive description of their final topology and material property characterization.

In addition to the formation interaction forces (the penetration of a geometric sub-node point ["cutter"] or a beam node point, and the frictional forces due to the velocity and penetration components) several other force components are worthy of note. Certain of these forces act at all times during the solution process with others being considered only during a given stage (placement, etc.). First, consider the forces acting on the BHA during the placement stage. During placement, the BHA is initially assumed to be centered along a Z-axis oriented up-hole normal to a plane characterizing the inclination and azimuth direction survey data at the bit's placement measured depth. The BHA is straight at this point. Assuming that the wellbore is curved, it is necessary to compute both an elastic strain energy force component $\{F_{UO}\}$ and a non-linear string energy force $\{F_{NLB}\}$ associated with the displacement set necessary to push the BHA to the centerline of the wellbore. Gravitational forces $\{F_{grav}\}$ are also computed. With knowledge of the wellbore centerline locations, buoyancy forces, $\{F_{buoy}\}$ based on a hydrostatic pressure

cross-sectional area differences, are computed. At the initiation of the placement process these driving forces are balanced by an initial placement force $\{F_0\}$ to maintain equilibrium. During the placement stage $\{F_0\}$ is slowly reduced to permit the formation interaction forces and dynamic forces to equilibrate the driving forces. Since a zero WOB condition is being sought, an additional force is ramped on at the uppermost node point in the z-direction to balance any z-axis force imbalance. Finally, an artificial damping force is utilized only during placement to impede motion and expedite the solution.

Following the placement stage, additional forces are brought into play. These forces, which are based on the angular velocity, include inertial bit body forces, drill string non-linear torque forces, and fluid drag forces.

GEODYN2: VERIFICATION-DEMONSTRATION RESULTS

The BHA's shown in Figure 1 have been utilized to verify the GEODYN2 program. Portions of the calculated response are provided to demonstrate many of the capabilities inherent in GEODYN2. The bit utilized in all the BHAs is the Smith 8 3/4 inch PDC bit reported in a previous paper². A conical bottom formation mesh profile using a uniform material idealization and being 0.10 inches overgauge has been implemented in the verification runs. All stabilizer blades have been modeled as 2 feet in length and have been characterized by a blade cutter at each end. A 6.50 inch OD, 2.25 inch ID drill collar has been utilized to model the drill string beam sections. The wellbore diameter has been modeled as 8.80 inches with the wellbore itself being inclined 30 degrees. The pertinent input control parameters utilized in the verification runs are summarized in Table 1.

It should be remembered in viewing these results that rock removal at the formation/bit interface surfaces is not accounted for in GEODYN2. It should also be noted that the results illustrated were derived during the initial phases of verification and that developmental efforts and enhancements are currently in progress.

Illustrative Results

The following discussion will describe results obtained during the verification-demonstration phase of the GEODYN2 program development. In light of the limited length of this paper, only the response behavior associated with BHAs number 2 and 4 (a dropping and holding assembly respectively) will be reviewed. It should be noted, however, that many of the general observations cited are appropriate for the other BHAs considered.

As described in the preceding sections the actual execution of a GEODYN2 run is performed in three distinct operational stages (placement, rotary speed ramping, and WOB application). These different stages of operational response provide convenient reference points at which to assess the overall capabilities of the program and to characterize the behavioral response of the two BHAs being considered. The placement process occurs during the initial 2.5 seconds of execution with the artificial damping force being removed during the last 0.5 seconds of this period.

Figure 5 illustrates the motion response of the center point (apex point) of the BHA 2 bit face in the inclination direction (high or build side/low or drop side) during placement. Initially this point, and all others, experience a downward translation accompanying the gradual reduction in the placement force $\{F_0\}$ as a direct consequence of gravity effects $\{F_{grav}\}$. Due to the close proximity of the bit to the borehole in addition to the conical profile of the bit bottom surface, formation interaction occurs after only a short period of time and the bit bounces off the low side of the hole. The subsequent response contrasts with that observed at a drill collar beam node point located approximately 177 feet upstring, and illustrated in Figure 6. It should be noted that the radial clearance between the bit and the formation is approximately 0.05 inches while that between the drill collar and the wellbore surface is 1.15 inches. Displacements greater than 1.15 inches on Figure 6 represent penetration of the drill collar into the formation. It should also be kept in mind that the upper BHA substructure has many bending modes which respond at very low frequencies (several less than 1 Hertz) while the bit substructure will respond at a much higher frequency. These points are made because the response observed for the drill collar node point is very much like that expected while that for the bit differs from that preconceived. The combined effect of the wellbore proximity and frequency response of the bit clearly account for the very transient response observed at the bit face. Although not readily discernable in Figure 5, the overall motion of the bit is toward the low side of the hole. This observation is supported by motions, both translational and rotational, observed at other node points.

Prior to making any comparisons to BHA 4, refer to Figure 7 which illustrates BHA 2's integrated bit body/formation interaction side force in the inclination direction. This figure clearly demonstrates the significance of the transient motion response. A static analysis performed on essentially the same BHA (beam node idealization) predicted that a dropping force of approximately 620 pounds is expected. The GEODYN2 analysis predicts that transient

loads between 100 and 150 times greater may be expected. A close look at both the transient load magnitudes and the average placement bit side force magnitude illustrated in Figure 7, however, suggests that the bit inclination force also acts toward the low side of the hole (dropping).

Although a direct comparison between the two different BHA's is impossible, a review of the bit side force response for BHA 4 (holding assembly) illustrated in Figure 8 provides some insight into how varied the overall response behavior was. The first variation evident upon direct comparison of Figures 7 and 8 is the marked difference in the magnitudes of the interactive force magnitudes. The pattern in Figure 8 is quite balanced with peak magnitudes approximately 4 times lower than those observed in Figure 7. It should also be noted that the motion (side force magnitude and direction differences) is somewhat less chaotic. Although not herein illustrated, the observed motion response for BHA 4 did not feature nearly as much transient variation as that illustrated for BHA 2. Typically, the greater the tendency of the BHA to cause a deviation in the wellbore trajectory (i.e. BHA 3 vs. BHA 5), the more transient the response observed.

The next stage of the solution procedure involves increasing the drill string rotation from 0-RPM to the final rotational speed (in these runs, 120-RPM). This stage of solution occurs between 2.5 seconds and 4.5 seconds. Figures 9 and 10 respectively illustrate the rotational displacement about the upstring z coordinate axis and the formation torsional drag force about the same axis experienced at the rear edge of the middle stabilizer in BHA 4. Two very interesting response features are evident in these Figures. First, a rotational displacement of the drill string occurs during the placement stage, with the point illustrated rotating roughly 0.22 radians in the positive z sense. Although no rotation is applied during placement, the drill string is free to respond torsionally and it is currently felt that this rotation occurs because the PDC studs on the bit are not symmetrically positioned. As contact with the formation is made, torsional modes therefore are excited. This induced response coupled with the fact that only one blade cutter is utilized to represent the stabilizer blade width, results in a stabilizer rotation with a second blade coming into contact with the wellbore during placement. The second response behavior to observe is the drastic variation in rotational displacement which accompanies the initiation of rotation at 2.5 seconds. The swing at approximately 3.3 seconds is dramatic. The corresponding stabilizer torsional drag force, illustrated in Figure 10, closely parallels the rotational displacement motion but is characterized by many transient response interactions with the wellbore.

Figures 11 and 12 have been provided to demonstrate the response behavior associated with BHA 2 during RPM-ramping. The point illustrated corresponds to the rear edge of the upstring stabilizer. Such differences in rotational response behavior occurred in nearly every BHA analysis at the stabilizer locations.

The final stage of the solution procedure simulates the application of WOB, herein approximated by a force applied at the uppermost BHA node point. Figure 13 illustrates the external WOB force-time history response utilized in the runs performed. Figure 14 illustrates the z-axis displacement-time history response experienced by the center point of the bit in BHA 4. The upward motion experienced during the early stages of the solution occurs as a consequence of the fact that a large upward directed buoyancy force is active at the bit. As the balancing forces and the subsequent WOB force is applied the bit face moves down and comes into contact with the bottom formation surface. This Figure, however, clearly demonstrates that the bit is continually bouncing up and down even during the constant WOB phase (after 8.5 seconds). The corresponding formation-bit force response in the z-direction is illustrated in Figure 15. A positive force magnitude indicates the formation force is acting upwards on the bit. This Figure quite vividly illustrates the difference in magnitude between the transient contact forces and the constant 10,000 pound external WOB application after 8.5 seconds. As might be expected, the z-axis formation-bit force response for BHA 2 illustrated in Figure 16 is even more transient in nature.

Summary

This paper describes many of the more pertinent modeling procedures and analytical techniques utilized in the GEODYN2 program. It is hoped that this background information will provide some insight into the basic level of dynamic analysis capabilities provided by GEODYN2. To demonstrate certain of these capabilities, aspects of the response behavior accompanying the placement, RPM ramping and WOB application stages of verification runs on BHA 2 and BHA 4 have been provided. These results suggest that the overall BHA response behavior is very transient in nature and that the magnitudes of both the transient forces and motions experienced is very significant.

Although still in development, GEODYN2 provides the capability to analyze BHA response behavior characterizing realistic drilling environments for a fairly modest investment in computer time. The runs described in this paper each took about one hour of CRAY-1S computer time.

Additional reports on GEODYN qualification, enhancements and analyses will be forthcoming.

NOMENCLATURE

$\{\hat{M}_{sys}\}$	= The assembled (CMS) BHA mass matrix
$\{\hat{C}_{sys}\}$	= The assembled (CMS) BHA damping matrix
$\{\hat{K}_{sys}\}$	= The assembled (CMS) BHA stiffness matrix
$\{\ddot{q}\}$	= The assembled (CMS) BHA acceleration vector
$\{\dot{q}\}$	= The assembled (CMS) BHA velocity vector
$\{q\}$	= The assembled (CMS) BHA displacement vector
$\{\hat{F}_{sys}(t)\}$	= The assembled (CMS) vector of forces acting on the BHA at time (t)
dof	= Degrees of freedom
$\{U_o\}$	= The physical displacements set relating the underformed node point positions to the centerline of the curved wellbore
$\{F_{uo}\}$	= $[K] \{U_o\}$ = The elastic strain energy force vector in the physical dof system
$[K]$	= The subsystem stiffness matrix
$\{F_{NLB}\}$	= The non-linear beam strain energy force vector in the physical dof system
$\{F_{grav}\}$	= The gravitational force vector in the physical dof system
$\{F_{BUOY}\}$	= The buoyancy force vector in the physical dof system
$\{F_o\}$	= The initial placement force vector in the physical dof system

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TABLE 1
Operating Parameters for Verification Runs

- Rotational Speed is 120 RPM
- Time Step Size is 1 millisecond
- Placement Process Elapsed Time is 2.5 Seconds With An External Damping of 95 percent of Critical
- RPM Ramping Startup Process Elapsed Time is 2 Seconds At Constant Angular Acceleration
- Externally Applied Vertical Load Rate of 2500 lb/sec was Utilized Up to 10,000 lb. Then Held Constant
- Number Modes Utilized
26 For Lower (Bit) BHA Substructure
100 For Upper BHA Substructure
- Mud Weight of 10 ppg Used
- Bit Face Was Located At Measured Depth of 1000 Feet
- Wellbore Inclination Is 30 Degrees (Constant)
- No Azimuth Variation
- Formation Grid Spacing

Bottom	$\Delta x = 0.25$ Inches
	$\Delta y = 0.25$ Inches
Side Incline	$\Delta s = 0.25$ Inches
	$\Delta \theta = 5$ Degrees
Bit Sidewall	$\Delta z = 0.5$ Inches
	$\Delta \theta = 10$ Degrees
Stabilizer Sidewall	$\Delta z = 3$ Inches
	$\Delta \theta = 10$ Degrees
- Conical Bottom Bit Profile

Cone Origin Height Is 0.44785 Inches
Bottom Flat Height Is -0.7694 Inches
Cone Diameter Is 4.84 Inches
Bottom Flat Diameter Is 7.0195 Inches
Incline Angle Is 52.5104°

DROPPING

(BHA 1)

DROPPING

(BHA 2)

BUILDING

(BHA 3)

HOLDING

(BHA 4)

BUILD OR DROP

(BHA 5)

Fig. 1 Demonstration BHA Configurations

Fig. 2 Standard Four Straight Blade Stabilizer Configuration

Fig. 3 A Stabilizer Idealization

Fig. 6 Drill Collar Inclination Displacement
Response for BHA 2

Fig. 4 Representation of a Typical Downhole
Surface Geometry

Fig. 7 Bit Side Force Inclination Response
for BHA 2

Fig. 5 Bit Apex Point Inclination Dis-
placement Response for BHA 2

Fig. 8 Bit Side Force Inclination Response
for BHA 4

Fig. 9 Rotational Displacement at Rear Edge of Middle Stabilizer for BHA 4

Fig. 12 Formation Torsional Drag Force at Rear Edge of Upstring Stabilizer for BHA 2

Fig. 10 Formation Torsional Drag Force at Rear Edge of Middle Stabilizer for BHA 4

Fig. 13 Weight on Bit Force for BHA 2

Fig. 11 Rotational Displacement at Rear

Fig. 14 Bit Displacement Z-direction

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Fig. 15 Formation-Bit Force Z-direction
Response for BHA 4

Fig. 16 Formation-Bit Force Z-direction
Response for BHA 2

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