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(54) Title: PATH TRACKING FOR DIRECTIONAL DRILLING AS APPLIED TO ATTITUDE HOLD AND TRAJECTORY FOLLOWING

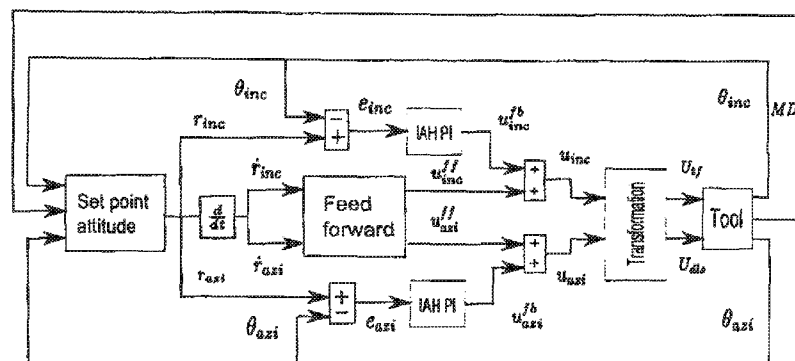


FIG. 1

(57) Abstract: A method for directional control of a drilling system, having steps of using an inclination and azimuth hold system to develop a path to be followed by the drilling system, wherein the inclination and azimuth hold system calculates an inclination angle of a tool face and an azimuth angle of the tool, generating a set point attitude to establish the path to be followed by the drilling system and controlling the drilling system to drill along the path obtained by the inclination and azimuth hold system.



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## PATH TRACKING FOR DIRECTIONAL DRILLING AS APPLIED TO ATTITUDE HOLD AND TRAJECTORY FOLLOWING

### FIELD OF THE INVENTION

[0002] Aspects relate to directional drilling for wellbores. More specifically, aspects relate to directional drilling where control of the drilling procedure is used to develop path tracking for both path following and attitude hold applications.

### BACKGROUND INFORMATION

[0003] Directional drilling is an important aspect of discovery of petroleum products in geotechnical formations. Directional drilling naturally gives rise to the requirement to autonomously control the attitude and trajectory of wells being drilled. Drivers may be used to control the drilling in order to maximize economic return of the drilling. Practical drivers for this include drivers that reduce well tortuosity due to target attitude overshoot as well as well collision avoidance. Conventional systems have proposed applications that enable sliding mode control to minimize errors in position and attitude. Other conventional technologies have approached path planning and trajectory following as an optimal control problem where researchers have tackled the problem using generic algorithms.

[0004] It is also the case that it is required to follow a predefined well plan as closely as possible, where the well plan has been optimally constructed off-line to minimize the measured depth of drilling given a set of target coordinates and drilling constraints, however conventional technologies have significant difficulties in achieving this result. There is a need to provide for directional drilling methods and apparatus such that control of the drilling procedure is used to develop path tracking for both path following and attitude hold applications.

### BRIEF DESCRIPTION OF THE DRAWINGS

[0005] FIG. 1 is an architectural layout drawing of a general path tracking controller.

[0006] FIG. 2 is a side view of a geometry for a preview point evaluation, in a trajectory following application.

[0007] FIG. 3 is a side view of a geometry for a preview point evaluation, in an attitude hold application.

[0008] FIG. 4 is a series of three response plots from an attitude hold simulation, wherein a first plot shows a noisy  $V_{rop}$  input into the model, a second plot shows the dogleg severity or curvature output from the attitude controller and a third plot illustrates the true vertical displacement response.

[0009] FIG. 5 is an attitude hold azimuth and inclination response.

[0010] FIG. 6 is a graph of a trajectory following response using an aspect described.

[0011] FIG. 7 is a trajectory following tool face response in a zoomed view using an aspect described.

[0012] FIG. 8 is a trajectory following  $V_{rop}$ , SR and TVD response.

[0013] FIG. 9 is a series of trajectory following attitude sensor signals.

## DETAILED DESCRIPTION

[0014] In one aspect, a driver is described to provide for drilling control for exploration of geotechnical features. In the illustrated examples that follow, the methodologies may be conducted such that they may be contained on a computer readable medium, for example, or may be installed in a computer readable medium such as a hard disk for control of drilling functions. In some aspects, simulations may be run to allow an operator to preview the actions to be chosen. In other aspects, direct control of the drilling apparatus may be accomplished by the methodologies and apparatus described. In one example embodiment, a model is used, derived from kinematic considerations. In this simplified model, lateral and torsional dynamics of the drill string and the bottom hole assembly, (hereinafter called "BHA") are ignored. In this specific example embodiment provided:

$$\dot{\theta}_{inc} = V_{rop}(U_{dis}\cos U_{tf} - V_{dr}) \quad \text{Equation 1}$$

$$\dot{\theta}_{azi} = \frac{V_{rop}}{\sin \theta_{inc}}(U_{dis}\sin U_{tf} - V_{tr}) \quad \text{Equation 2}$$

where:

$\theta_{inc}$  is the inclination angle

$U_{tf}$  is the tool face angle control input

$U_{dis}$  is the 'dog leg severity' or curvature

$V_{dr}$  is the drop rate disturbance ( $V_{dr} = \alpha \sin \theta_{inc}$ )

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$V_{tr}$  is the turn rate bias disturbance

$V_{rop}$  is the rate of penetration and is an uncontrolled parameter

[0015] In one example embodiment, transformations may be used, as presented in equations 3 and 4:

$$U_{tr} = \text{ATAN2}(u_{azi}, u_{inc}) \quad \text{Equation 3}$$

$$U_{dis} = K_{dis} * \text{sqrt}((u_{azi})^2 + (u_{inc})^2) \quad \text{Equation 4}$$

[0016] Ignoring the disturbances, the plant model simplifies to Equations 5 and 6 as disclosed below.

$$\Theta_{inc} = V_{rop} K_{dis} U_{inc} \quad \text{Equation 5}$$

$$\Theta_{azi} = V_{rop} / \sin \Theta_{inc} K_{dis} U_{azi} \quad \text{Equation 6}$$

[0017] The following two equations illustrate two PI ("proportional-integral") controllers for the inclination and azimuth hold control loop:

$$\mu_{inc}^{fb} = K_{pi} \Theta_{inc} + K_{ii} \int_0^t e(inc) dt \quad \text{Equation 7}$$

$$\mu_{azi}^{fb} = K_{pia} \Theta_{azi} + K_{iia} \int_0^t e(azi) dt \quad \text{Equation 8}$$

[0018] In the above,  $e_{inc} = r_{inc} - \theta_{inc}$  are the inclination and azimuth errors respectively. PI gains, for example, may be obtained through a method known as pole placement. The robustness of aspects of the control system to measure feedback delays, input quantization delay and parametric uncertainty of  $V_{rop}$  and  $K_{dis}$  may be determined through a small gain theorem, as a non-limiting embodiment.

[0019] Referring to FIG. 1, an architecture for a general path tracking controller is illustrated. The illustrated embodiment has an inner loop and an outer-loop trajectory following controller. The inner loop controller is illustrated as modified by adding feed-forward terms to  $U_{inc}$  and  $U_{azi}$  as follows:

$$\mu_{inc} = \mu_{inc}^{ff} + \mu_{inc}^{fb} \quad \mu_{azi} = \mu_{azi}^{ff} + \mu_{azi}^{fb} \quad \text{Equation 9}$$

[0020] The feed forward terms are generated from an inversion of Equations 5 and 6 with  $r_{inc}$  and  $r_{azi}$  evaluated using numerical differentiation. The feed forward terms are used to reduce the initial response overshoot that would otherwise occur due to the unknown  $V_{dr}$  and  $V_{tr}$  disturbances requiring the IAH integral action to build up before the steady state error approached zero. In an alternative embodiment, the method may shift the dominant closed loop poles to speed up the response, but at the expense of stability. The feed forward, therefore, has the effect of speeding up the attitude response without destabilizing the overall controller action and the feedback action compensates for the un-model dynamics in the feed forward model inversion and uncertainty in the parameters used for the feedback control design.

[0021] In addition, with reference to FIG. 1, it can be seen that the described IAH tracks an attitude demand set point derived from the outer loop such that the tool is made recursively to track back from the tool position to the target position and attitude along a correction path. Both the attitude hold and trajectory following algorithms use the architecture shown in FIG. 1, the only difference between the two applications therefore being the internal content of the setpoint generator block shown in FIG. 1.

[0022] For both trajectory following and attitude hold, the setpoint attitude is evaluated at a higher update rate and then the sample is held recursively over each drilling cycle as the demand to be passed to the IAH. The trajectory following and attitude hold algorithm functionality will be split such that the attitude generator will be implemented on the surface while the IAH will be implemented autonomously downhole. The tool attitude is fed back from downhole to the surface and the measured depth, MD, is also fed back from a surface measurement. For both applications, the update rates for the algorithms described are in the order of 10 seconds for the feedback measurements and controllers, while drilling cycle periods on the order of multiples of minutes, as a non-limiting embodiment.

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[0023] The trajectory following algorithm requires a method to fit a setpoint attitude providing a correction path from the tool to the stored path position and attitude over a number of recursion cycles. The correction path is constructed by providing a demand attitude, defined as the attitude of the vector joining the tool position (point A) and a point at some preview position along the plant path, point O, from the closest point of the tool to the stored path, point C', as shown schematically in FIG. 2. This error vector is then taken as the setpoint attitude both for feed forward and feedback control of the tool attitude.

[0024] From the global coordinates of points A and O, the attitude in terms of azimuth and inclination are evaluated using the following Cartesian to spherical coordinate transformations:

$$\theta_{azi} = \text{atan} \left( \frac{\Delta z}{\Delta y} \right)$$

$$\theta_{inc} = \text{atan} \left( \frac{\rho}{\Delta y} \right)$$

Equation 10

$$\rho = \text{hypot} (\Delta y, \Delta z)$$

[0025] Note that for the transformation stated above in equation 10 for the fixed global coordinate system, the assumed sign convention is a right-handed coordinate system with the X axis pointing vertically down. As will be understood, other conventions and transformations may be used. In the above described algorithm, the algorithm recursively converges over several drilling cycles until the error vector from points A to O approximates to being parallel to the stored path and the normal path from point C' to A in FIG. 2 approaches zero length.

[0026] For attitude hold, where the tool is required to track a fixed azimuth and inclination, it is possible to modify the trajectory following algorithm by generating the target path on-line and using a different methodology to generate the demand attitude vector optimally in the sense that the set point trajectory can be constructed to have a specified nominal absolute curvature. The target path is generated online based on the target azimuth and inclination and nominal  $V_{rop}$ :

$$\dot{x} = V_{rop} \cos(\theta_{inc})$$

$$\dot{y} = V_{rop} \cos(\theta_{azi}) \sin(\theta_{inc})$$

$$\dot{z} = V_{rop} \sin(\theta_{inc}) \sin(\theta_{azi})$$

Equation 11

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Equation 11 is then numerically integrated using the starting position of the attitude hold section as initial conditions to obtain the target path. Note that the assumption is made that the coordinates of the initial plan position in the beginning of the attitude hold section are coincident. The hold algorithm therefore can be seen to predict the path following target path from a given position with the required attitude.

[0027] Referring to FIG. 3, the demand attitude to pass the inner IAH feedback loop is taken as the attitude of the start tangent to a curve fitted between the tool position A and the intersection of a correction path of absolute curvature  $\rho$  with the predicted target path, also at tangent (point B'). In FIG. 3, point C is a point on the target path several sample periods prior to the point of minimum distance between the tool (point A) and the target path, labeled as point C'. Point B is a point arbitrarily along the target path from point C. With this planar geometry two assumptions are made, these being 1) angle CAB is  $90^\circ$  2) AC'B and AC'C are similar triangles. The objective, therefore is to define the Cartesian coordinates of the vector joining points A (the tool) and point O (the intersection of the start tangent of the correction path with the target path). The vector joining points A and O then define recursively the demand attitude for the inner IAH feedback loop as evaluated from equation 10 previously. With these objectives and assumptions, the geometric construction proceeds as described below.

[0028] The Cartesian components of the target path tangent are evaluated from the backward difference of the on-line generated target path derived from Equation 11 factored by an arbitrary preview distance S as follows.

$$L_t S \left( \frac{\Delta_t}{\|\Delta_t\|_2} \right), t = x, y, z \quad \text{Equation 12}$$

Where  $\Delta = \{x_n - x_{n-1}, y_n - y_{n-1}, z_n - z_{n-1}\}^t$ .

[0029] A preview point B can be defined by projecting the arbitrary preview distance S (where distance  $S \gg d + d'$ ) ahead of point C as follows:

$$B_t = C_t + L_t, t = x, y, z \quad \text{Equation 13}$$



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[0030] A vector  $c$  can be defined joining point A and the arbitrary preview point B on the target path. Using the right angled approximation for angle CAR it can be deduced that:

$$a = \sqrt{s^2 + |c|^2} \quad \text{Equation 14}$$

where:

$$|c| = \| (B_i) - (A_i) \|_2, \quad i = x, y, z \quad \text{Equation 15}$$

[0031] To solve for dimension  $a'$  it can be deduced using the similar triangles approximation (AC' B & AC' C) that:

$$a' = a \cos \phi, \phi = \arccos \left( \frac{|c|}{s} \right) \quad \text{Equation 16}$$

[0032] With reference to FIG. 3 dimension  $d$  from points  $C'$  to O can be evaluated by noting points A and B' or on a curve with curvature  $p$  and a common center of curvature  $A^1$ . With the construction shown (similar triangles ADA' and AC'O) it can be deduced that:

$$d = a' \tan \gamma \quad \text{Equation 17}$$

Where

$$\gamma = \arcsin (1 - a' p) \quad \text{Equation 18}$$

Dimension  $d'$  is evaluated as:

$$d = a \sin \phi \quad \text{Equation 19}$$

[0033] As a result, dimension  $d + d'$  can be used to find the coordinates of point O relative to point C enabling the attitude of the vector from point A to point O to be evaluated.

[0034] The preceding attitude and trajectory control algorithms were tested using a drilling simulator. The simulator used Equations 1 and 2 as the plant model was able to feed  $U_{dis}$  and  $U_{tr}$  commands to the plant either from a well-planned with respect to measured depth open loop or from the prototype closed loop trajectory following or attitude hold algorithms. In the example embodiment, the drilling simulator transformed the  $\Theta_{inc}$  and  $\Theta_{azl}$  responses from the plant into globally reference Cartesian coordinates for automated steering introductory response display purposes.

[0035] The plant attitude response and globally referenced gravity and magnetic field vectors are

used to simulate three axis magnetometer and accelerometer sensor signals as typically used for attitude sensing arrangements. The signals are signal conditioned in order to generate attitude feedback signals for automated steering. In the example embodiment, the drilling simulator includes realistic engineering constraints such as the drilling cycle, attitude measurement feedback delays, input dynamics as well as noise. The relevant drilling and model parameters in the example are shown in Table 1. The two cases simulated are attitude hold and trajectory following. To demonstrate a practical feature of the attitude hold algorithm that is required in the field at between 600 and 1200 feet of measured depth the tool is positioned in the inclinations so that the target inclination changes to 93° and then back to 90° to simulate the typical on-line adjustments made by the directional driller when following a geological feature. The trajectory following test case uses the same parameters in initial conditions as the attitude hold test case with the exception that rather than the target path being generated online, a stored path is used instead. The stored path was created such that it had an 8° per 100 feet maximum curvature and the closed loop run assumed a tool with a 15° per hundred foot curvature capacity, providing a curvature tolerance between the path the tool followed and the curvature capacity of the tool.

Table 1

## TRANSIENT SIMULATION PARAMETERS

|                              |                                                                               |
|------------------------------|-------------------------------------------------------------------------------|
| $\theta_{inc}, \theta_{azi}$ | 90° 270° initial attitude respectively                                        |
| $V_{rop}$                    | 100 ft/hr with 20 ft/hr standard deviation noise                              |
| $K_{dis}$                    | 15°/100 ft tool capacity & 8°/100 ft well plan                                |
| $h_{lag}$                    | $U_H$ dynamics                                                                |
| $h_1$                        | feedback delay corresponding to 10 ft @ $V_{rop}$                             |
| $h_2$                        | drilling cycle delay 90s, equivalent to 180s drilling cycle                   |
| $\omega_a$                   | $2\pi/1.0 \times 10^4$ rad/s design $\theta_{azi}$ response natural frequency |
| $\omega_i$                   | $2\pi/1.5 \times 10^4$ rad/s design $\theta_{inc}$ response natural frequency |
| $V_{dr}$                     | Drop rate bias 1.0°/100 ft                                                    |
| $V_{tr}$                     | Turn rate bias 0.5°/100 ft                                                    |
| $T_z$                        | Fixed step ode3 Bogaki-Shampine solver, 10s step size                         |
| Preview                      | 30 & 3281 ft, trajectory following & attitude hold                            |

[0036] Referring to FIG. 4, three response plots from the method of attitude hold are presented. In the top plot illustrated, the noisy  $V_{rop}$  input into the model is illustrated due to the 20 ft/hr standard deviation random noise added to the nominal 100 ft/hr. The middle plot shows the  $U_{dis}$  output from the attitude controller, and it can be seen that apart from the beginning and end of the nudge section, the steering ratio is reasonably constant at around 50%, which is logical given the constant  $V_{dr}$  and  $V_{tr}$  at around 50% which is logical given the constant  $V_{dr}$  &  $V_{tr}$  disturbances. The

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lower plot shows the TVD (true vertical displacement) response which for attitude hold is a variable of interest. As presented, the TVD response for the first 600 feet where the inclination is held close to the start TVD but between 600 and 1200 feet the tool builds by 30 feet as the attitude hold maintains the tool at 93° inclination. After 1200 feet, the target inclination is again 90° and hence the tool remains at a same true vertical displacement.

[0037] Referring to FIG. 5, the attitude response for an attitude hold simulation is presented. The 3° attitude nudge can be seen between the 600 and 1200 foot level where the inclination changes from 90° to 93° and back again while the azimuth is maintained at  $270^\circ \pm 1^\circ$ .

[0038] Referring to FIG. 6, a trajectory following simulation response is illustrated with the response tracking the stored path trajectory well. In the illustrated embodiment, the positive direction for the global coordinate system axes are shown at the start of the stored path trajectory. As presented, the tool mostly drilled in the negative z-axis direction with the azimuth being close to 270°.

[0039] In the illustrated embodiment, the drilling simulator used for the fixed global reference frame is a right-handed coordinate system with the X axis pointing vertically down. For these simulations, the dipping inclination angles of the magnetic field vector were assumed zero such that the magnetic field vector was parallel to the positive y-axis and the gravitational field vector was taken as being parallel to the positive X axis of the fixed global coordinate system respectively.

[0040] Referring to FIG. 7, a zoomed view of the tool face control output and response for the trajectory following simulation is presented. In FIG. 7, for example, it can be seen that the input tool face dynamics indicate that there is a considerable difference between the demand from the trajectory following algorithm and the response due to the tool face lag. From the trajectory following algorithm in FIG. 6, however, the system is acceptable despite the tool face lag.

[0041] FIG. 8 shows similar plots as FIG. 4 but for a trajectory following simulation using one aspect of the disclosure. For this trajectory following simulation, there is more variation in steering ratio because although the  $V_{dr}$  &  $V_{tr}$  disturbances are still constant, the tool demand attitude is changing, hence leading to the varying average steering ratio over the simulation. The TVD (true vertical displacement) variation over the run can also be seen in the bottom plot of FIG. 8, only this is less significant this time as the response merely follows the TVD variation of the stored

path trajectory. FIG. 9 illustrates the simulated accelerometer and magnetometer signals for the trajectory following simulation. The top two plots in FIG. 9 shows the on-tool axis aligned sensor response which is non-oscillatory and as expected small in magnitude due to the on tool axis sensors being mostly perpendicular to both the magnetic and gravitational fields. In the lower four plots in FIG. 9, however, which show the radio accelerometer and magnetometer signals, the collar rotation of the tool can be seen as the sensor signals oscillate at the collar rotation frequency at near plus minus full signal due to the orientation of the tool.

[0042] In one embodiment, a method for directional control of a drilling system is presented, comprising using an inclination and azimuth hold system to develop a path to be followed by the drilling system, wherein the inclination and azimuth hold system calculates a set point attitude (in terms of azimuth and inclination ) recursively for a inner loop attitude tracking controller to follow such that the path generated is of a prescribed curvature (dogleg); and hence controlling the drilling system to drill along the generated path obtained by the inclination and azimuth hold system.

[0043] In another embodiment, the method may further comprise controlling an attitude of the path to be followed by the drilling system.

[0044] In another embodiment, the method may be performed wherein the attitude of the path to be followed by the drilling system is based on a target azimuth and inclination and nominal rate of penetration.

[0045] In another embodiment, the method may further comprise tracking the path obtained by the inclination and azimuth hold system.

[0046] In another embodiment, the method may further comprise displaying the path obtained by the inclination and azimuth hold system.

[0047] In another embodiment the method may further comprise feeding back signals from the drilling system drilling along the path obtained by the inclination and azimuth hold system to develop a revised path developed by the inclination and azimuth hold system.

[0048] In a still further embodiment, the method may further comprise obtaining a true vertical displacement response from a bottom hole assembly during the controlling the drilling system to

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drill along the path obtained by the inclination and azimuth hold system.

[0049] In another embodiment, the method may further comprise displaying the true vertical displacement response of the bottom hole assembly.

[0050] In another embodiment, the method may further comprise displaying the path to be followed by the drilling system and displaying an actual path followed by the drilling system.

[0051] It will be understood that recursive variable horizon trajectory control for directional drilling may be used in embodiments described. This trajectory control may use elliptical helixes, as a non-limiting embodiment. In certain embodiments, MPC strategy may be used. Direction and inclination sensors and a rate of penetration may be used to determine a spatial position. In embodiments, a set-point trajectory may be set which meets a horizon. The set-point trajectory, for example, may be dependent on using a method to fit a curve from a tool's position to one of a path which satisfies curvature constraints. Once this position is available, a curve may be fitted which joins points and matches tangents. Such curves may be elliptical helix curves.

[0052] While the aspects described have been disclosed with respect to a limited number of embodiments, those skills in the art, having the benefit of this disclosure, will appreciate numerous modifications and variations therefrom. It is intended that the appended claims cover such modifications and variations as within the true spirit and scope of the aspects described.

## WHAT IS CLAIMED IS:

1. A method for directional control of a drilling system, comprising:
  - using an inclination and azimuth hold system to develop a path to be followed by the drilling system, wherein the inclination and azimuth hold system calculates an inclination angle of a tool face and an azimuth angle of the tool;
  - generating a set point attitude to establish the path to be followed by the drilling system; and
  - controlling the drilling system to drill along the path obtained by the inclination and azimuth hold system.
2. The method according to claim 1, further comprising:
  - controlling an attitude of the path to be followed by the drilling system.
3. The method according to claim 2, wherein the attitude of the path to be followed by the drilling system is based on a target azimuth and inclination and nominal rate of penetration.
4. The method according to claim 1, further comprising:
  - tracking the path obtained by the inclination and azimuth hold system.
5. The method according to claim 4, further comprising:
  - displaying the path obtained by the inclination and azimuth hold system.
6. The method according to claim 1, further comprising:
  - feeding back signals from the drilling system drilling along the path obtained by the inclination and azimuth hold system to develop a revised path developed by the inclination and azimuth hold system.
7. The method according to claim 1, further comprising:
  - obtaining a true vertical displacement response from a bottom hole assembly during the controlling the drilling system to drill along the path obtained by the inclination and azimuth hold system.

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8. The method according to claim 7, further comprising:  
displaying the true vertical displacement response of the bottom hole assembly.
  
9. The method according to claim 1, further comprising:  
  
displaying the path to be followed by the drilling system; and  
  
displaying an actual path followed by the drilling system.

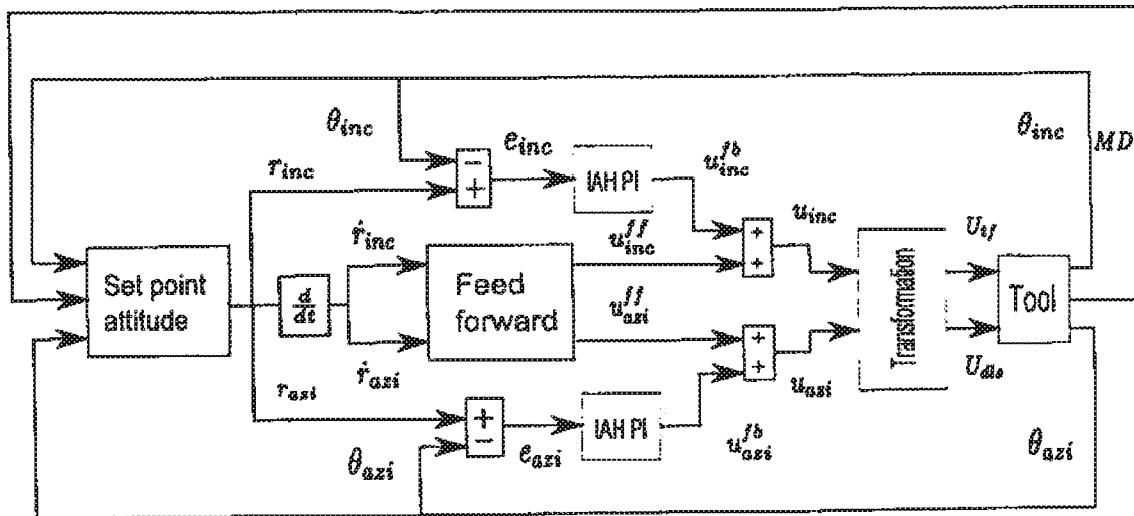


FIG. 1



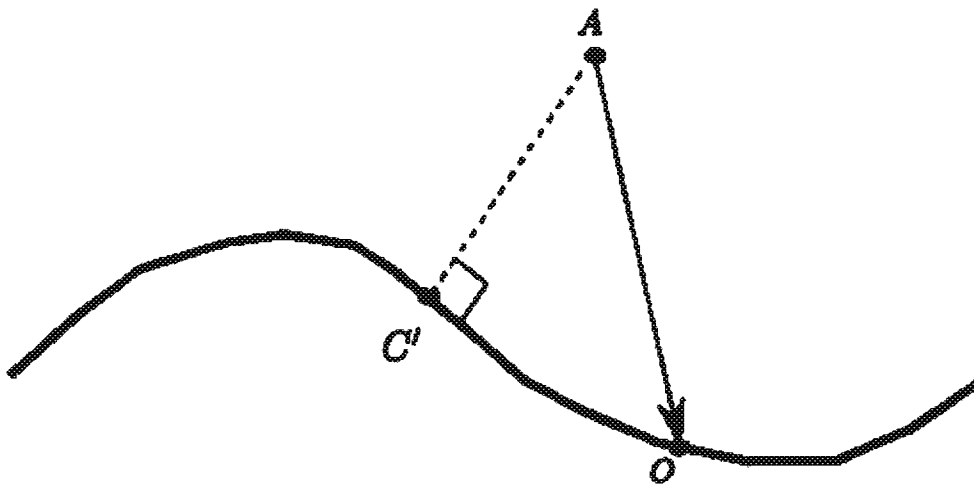


FIG. 2

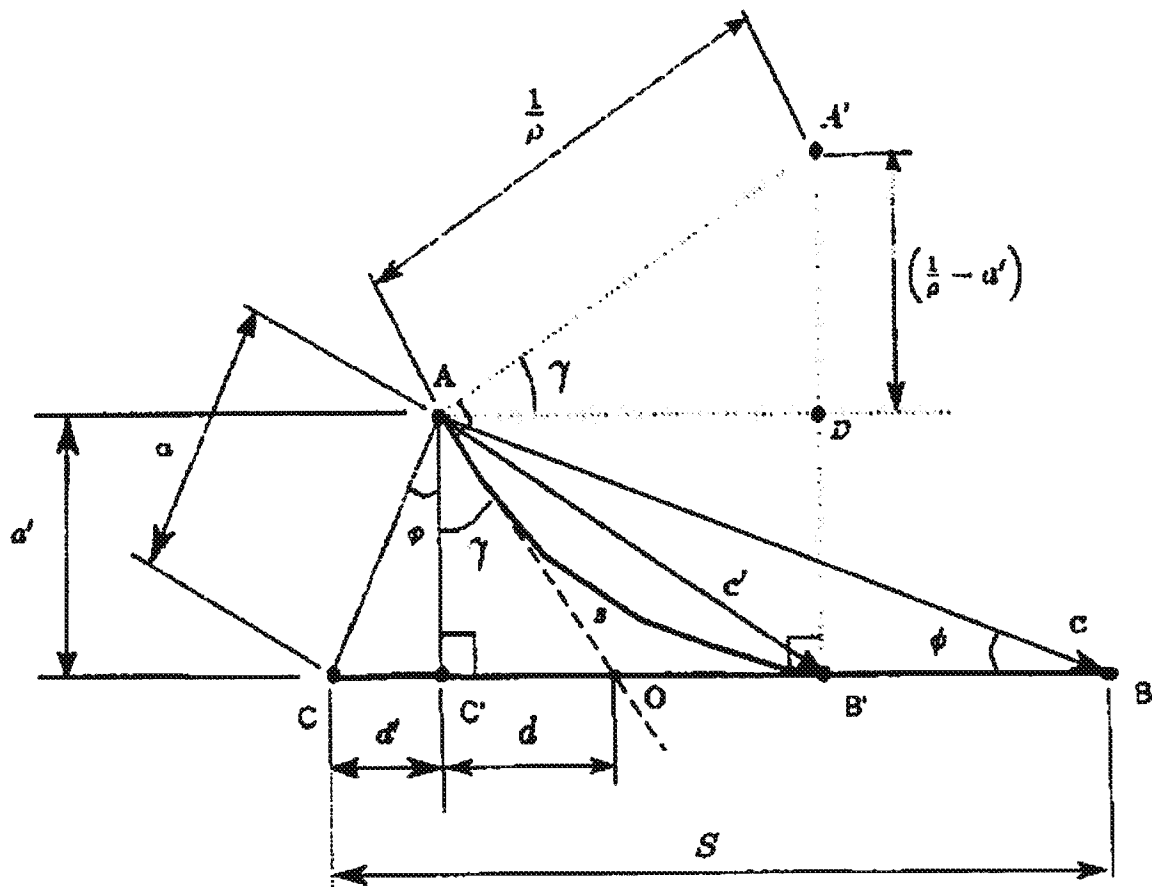


FIG. 3

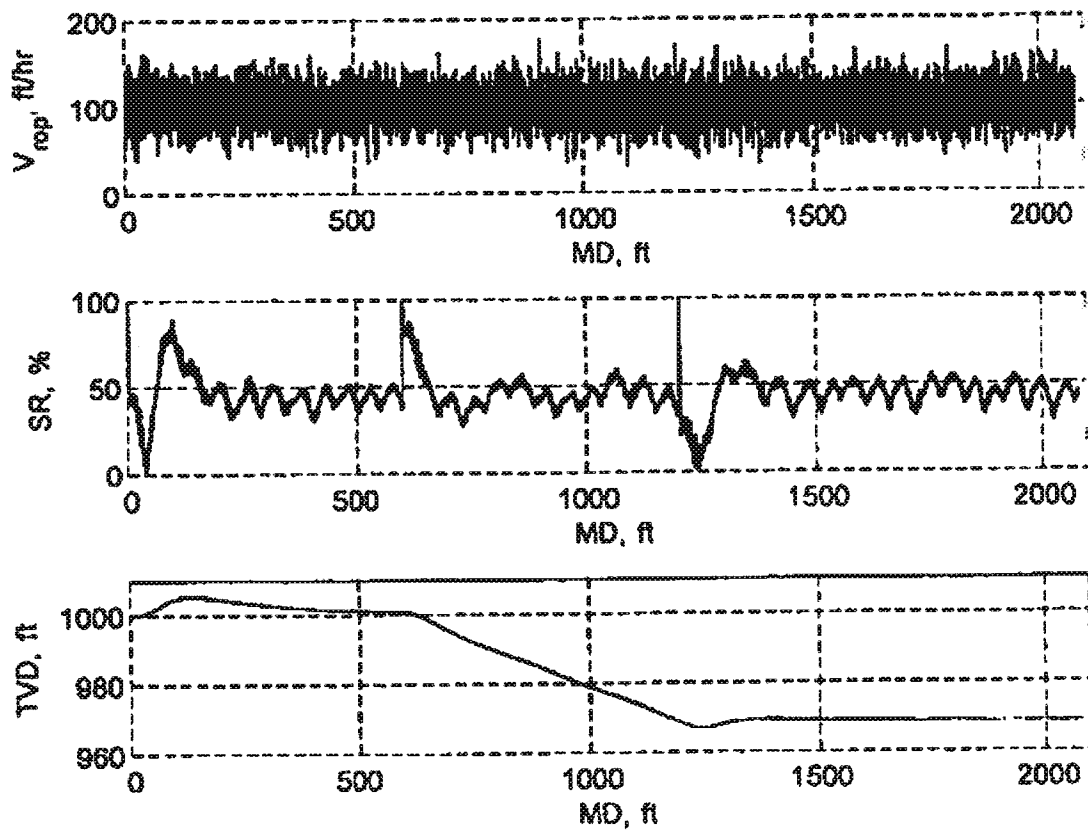


FIG. 4

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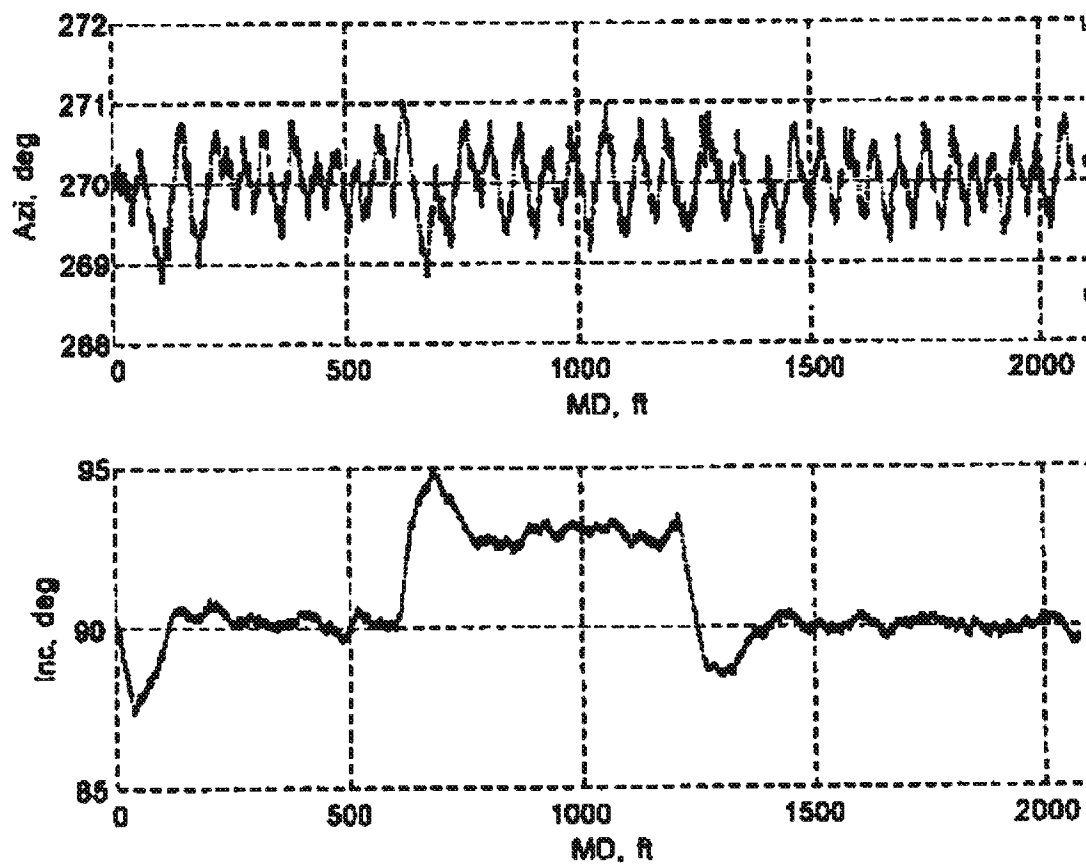


FIG. 5

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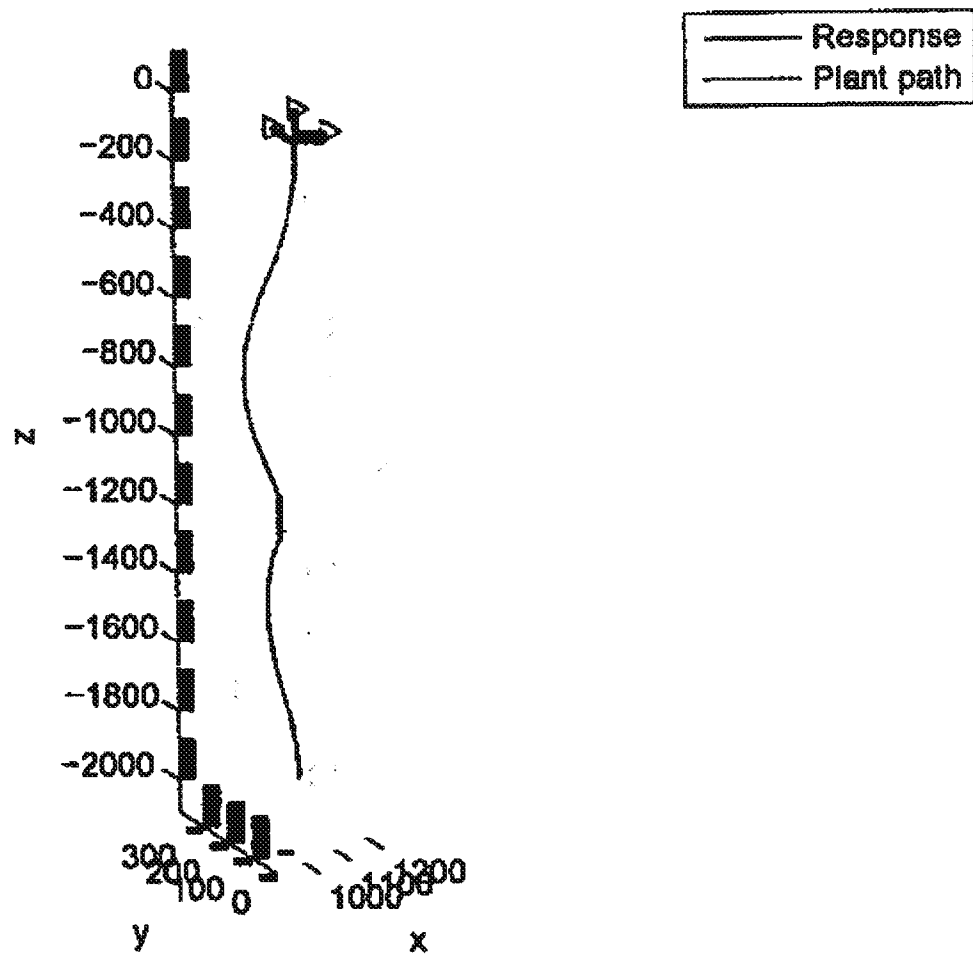


FIG. 6

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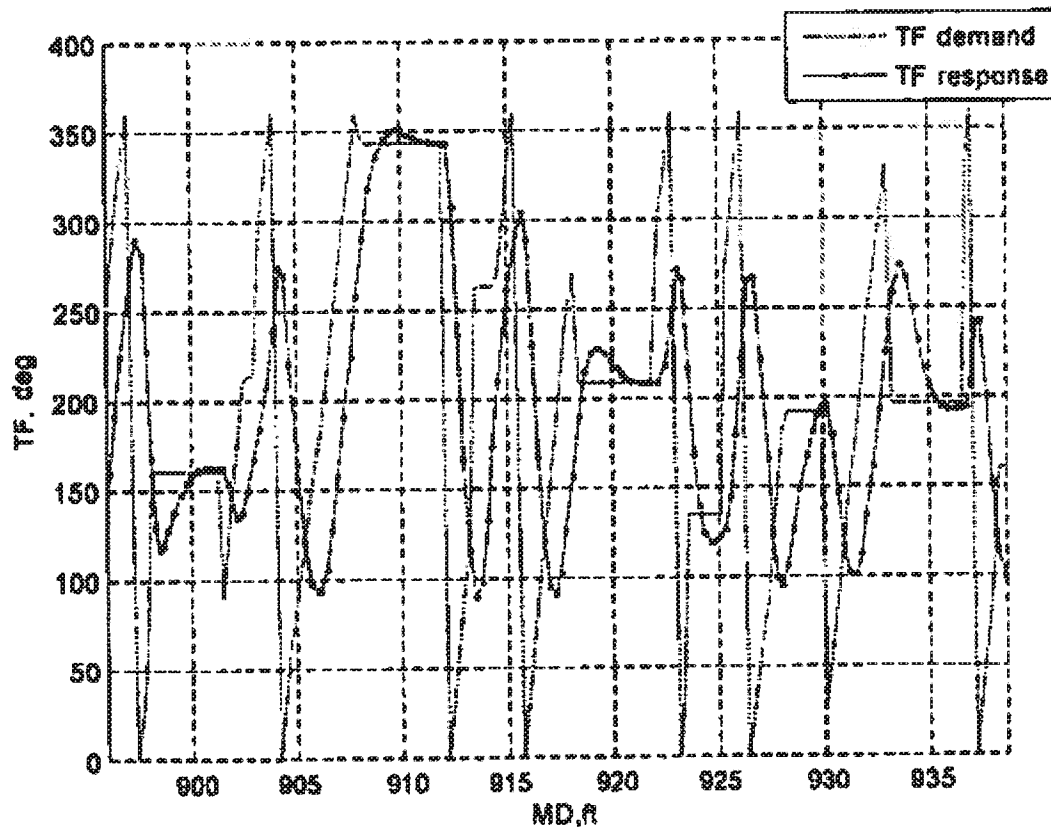


FIG. 7

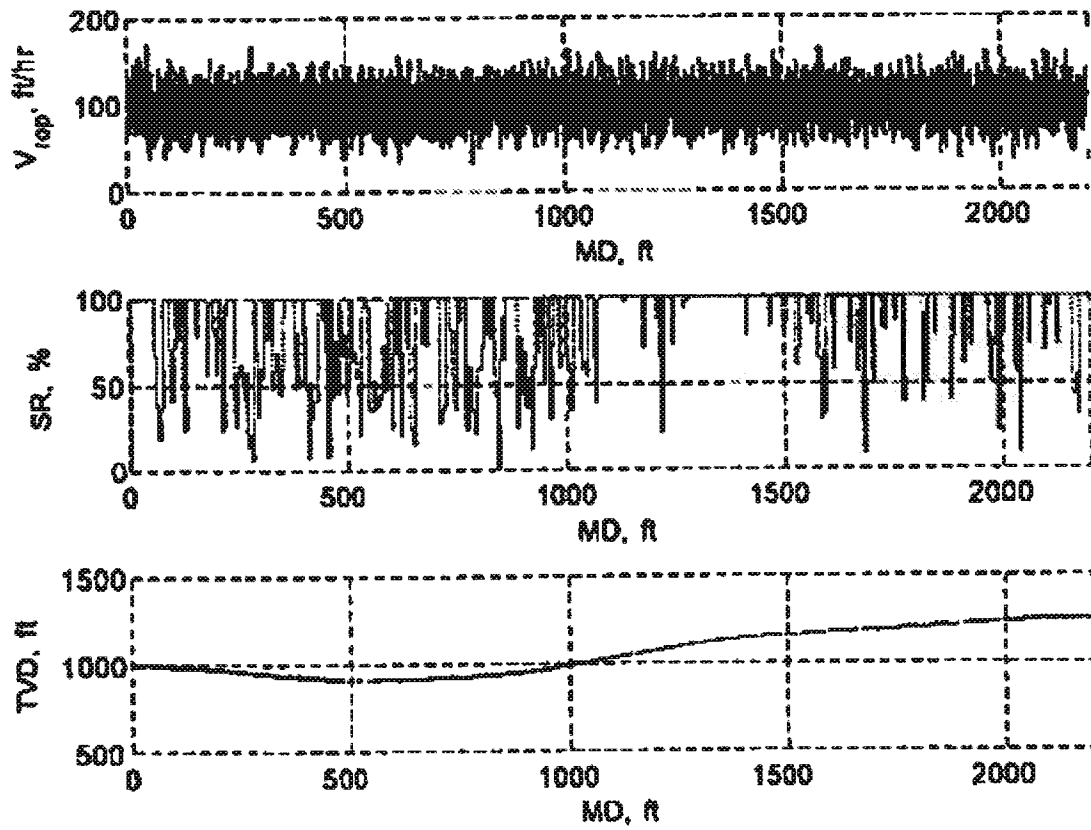


FIG. 8

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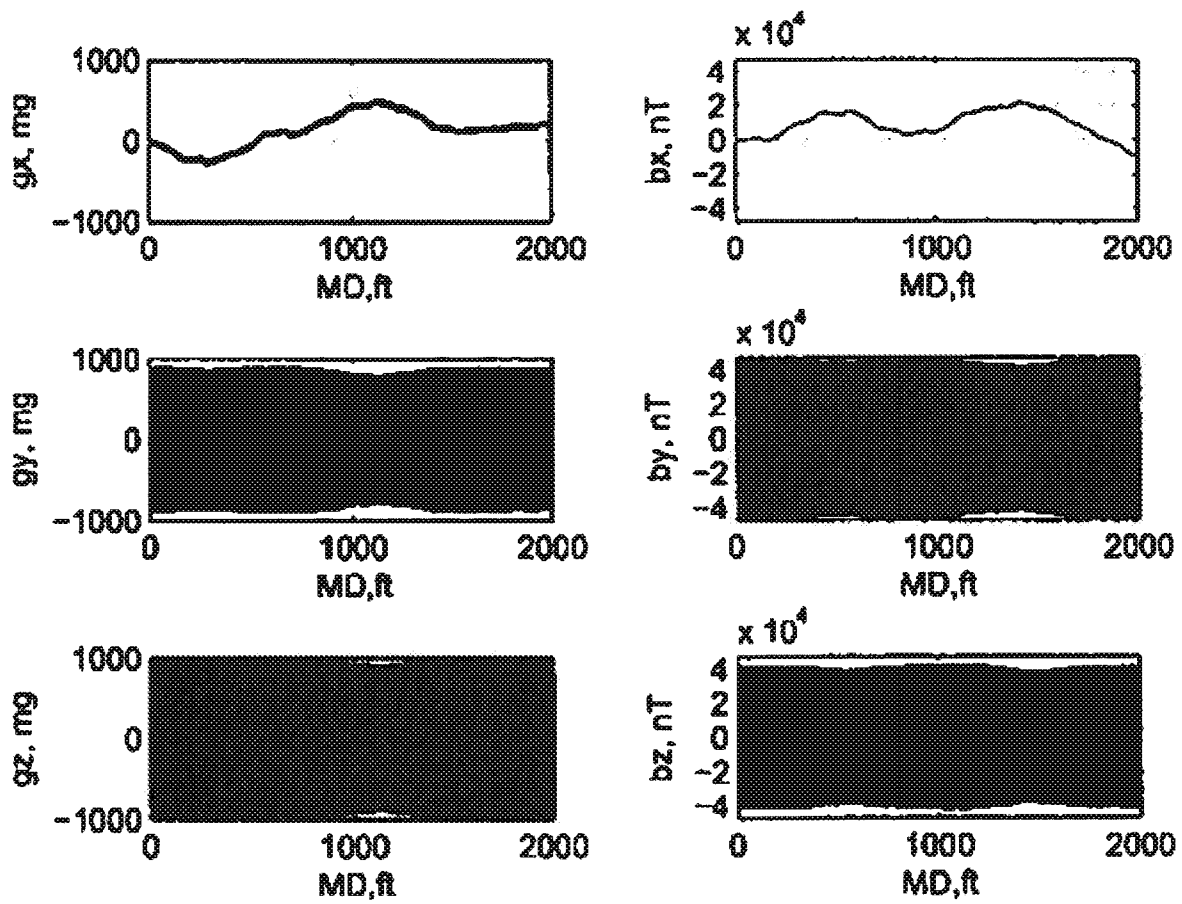


FIG. 9