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(54) **Title:** METHOD OF TESTING CUTTING ELEMENTS USING INTERMITTENT CUT OF MATERIAL

(57) **Abstract:** A method includes simulating a cutting tool drilling an earth formation to determine cyclic loading on a cutting element disposed on the cutting tool and designing a test to subject a physical cutting element to physical cyclic loading corresponding to the simulated cyclic loading.

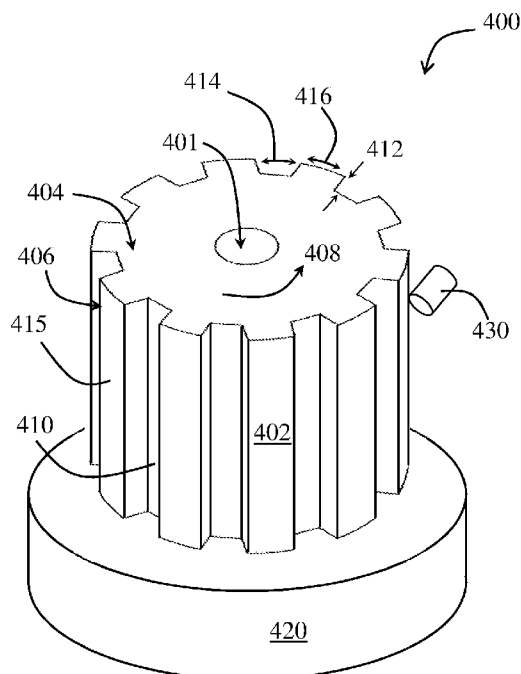


FIG. 4



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METHOD OF TESTING CUTTING ELEMENTS USING INTERMITTENT CUT OF MATERIAL

[0001] Operations, such as geophysical surveying, drilling, logging, well completion, hydraulic fracturing, steam injection, and production, are typically performed to locate and gather valuable subterranean assets, such as valuable fluids or minerals. The subterranean assets are not limited to hydrocarbons such as oil or gas. After gathering valuable subterranean assets, operations such as well abandonment may involve the sealing of a well to safely and economically decommission a well.

[0002] Significant expense is involved in the design and manufacture of drilling, production, and other downhole equipment, such as drill bits. Having accurate models for predicting and analyzing drilling and performance characteristics of drill bits and other downhole tools can greatly reduce the cost associated with manufacturing downhole equipment and designing drilling operations because these models can be used to more accurately predict the performance of bits prior to their manufacture and/or use for a particular drilling application. For these reasons, models have been developed and employed for the analysis and design of drill bits.

[0003] Two of the most widely used methods for modeling the performance of drill bits or designing drill bits are disclosed in Sandia Report No. SAN86-1745 by David A. Glowka, printed September 1987 and titled "Development of a Method for Predicting the Performance and Wear of PDC drill Bits" and U.S. Pat. No. 4,815,342 to Bret, et al. and titled "Method for Modeling and Building Drill Bits." While these models have been useful in that they provide a means for analyzing the forces acting on the bit, using them may not result in a most accurate reflection of drilling because these models rely on generalized theoretical approximations (typically some equations) of cutter and formation interaction that may not be a good representation of the actual interaction between a particular cutting element and the particular formation to be drilled. Assuming that the same general relationship can be applied to all cutters and all earth formations, even though the constants in the relationship are adjusted, may result in an inaccurate prediction of the response of an actual bit drilling in earth formation.

[0004] Throughout this document, the terms “oilfield” and “oilfield operation” may be used interchangeably with the terms “field” and “field operation” to refer to a site where any types of valuable fluids or minerals can be found and the activities required to extract them. The terms may also refer to sites where substances are deposited or stored by injecting them into subterranean structures using boreholes and the operations associated with this process. Further, the term “field operation” refers to a field operation associated with a field, including activities related to field planning, wellbore drilling, wellbore completion, production using the wellbore (also referred to as borehole), and abandonment of a well after production has completed (well sealing).

SUMMARY

[0005] This summary is provided to introduce a selection of concepts that are further described below in the detailed description. This summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used as an aid in limiting the scope of the claimed subject matter.

[0006] In one aspect, embodiments of the present disclosure relate to a method that includes simulating a cutting tool drilling an earth formation to determine cyclic loading on a cutting element disposed on the cutting tool and designing a test to subject a physical cutting element to physical cyclic loading corresponding to the simulated cyclic loading.

[0007] In another aspect, embodiments of present disclosure relate to a method that includes contacting a cutting element to a test fixture under cyclic loading conditions for a duration, each cycle of the cyclic loading conditions including contact between the cutting element and the test fixture at a velocity for a loading period and determining if a test condition is met after subjecting the cutting element to the cyclic loading conditions.

[0008] In yet another aspect, embodiments of the present disclosure relate to a testing fixture that includes a body moveable in a direction, the body having a top side bordered by an outer side, wherein at least one of the top side and the outer side comprises an alternating pattern along the direction.

[0009] Other aspects and advantages of the disclosure will be apparent from the following description and the appended claims.

BRIEF DESCRIPTION OF DRAWINGS

- [0010] FIGS. 1A-B show a side and axial view, respectively, of an idealized helical path of a cutting element during a drilling simulation.
- [0011] FIGS. 1C-D show a side and axial view, respectively, of a true trajectory of a cutting element during a drilling simulation according to embodiments of the present disclosure.
- [0012] FIGS. 2A-D show a method in accordance with one or more embodiments of the present disclosure.
- [0013] FIG. 3 shows simulation results according to embodiments of the present disclosure.
- [0014] FIG. 4 shows a testing fixture according to embodiments of the present disclosure.
- [0015] FIG. 5 shows a testing fixture according to embodiments of the present disclosure.
- [0016] FIG. 6 shows a testing fixture according to embodiments of the present disclosure.
- [0017] FIG. 7 shows a testing fixture according to embodiments of the present disclosure.
- [0018] FIG. 8 shows a physical test according to embodiments of the present disclosure.
- [0019] FIG. 9 shows a method according to embodiments of the present disclosure.

DETAILED DESCRIPTION

- [0020] Embodiments are shown in the above-identified drawings and described below. In describing the embodiments, like or identical reference numerals are used to identify common or similar elements. The drawings are not necessarily to scale and certain features may be shown exaggerated in scale or in schematic in the interest of clarity and conciseness.
- [0021] Embodiments of the present disclosure may relate to analysis, design and/or testing of cutting elements for use with cutting or drilling tools in drilling operations. Improved testing methods for cutting elements may be designed by corresponding or mimicking the test conditions to real world conditions in a drilling operation to help

design and/or select better performing cutting elements in the drilling operation. Real world conditions of a drilling operation may be determined and/or modeled through simulation of the drilling operation. For example, simulation of a drilling operation may reveal cyclic loading on one or more cutting elements during drilling. One or more tests based on parameters determined from the simulated drilling operation may be designed and/or performed on cutting elements to test their performance in the drilling operation, including a cyclic loading test having test conditions corresponding to cyclic loading in the simulated real world conditions.

[0022] As used herein, “cyclic loading” on a cutting element may refer to loads applied to the cutting element during a cutting operation, where the loads are applied in load periods at a frequency for a duration of the cutting operation. Load periods are the times at which a load is being applied to the cutting element. For example, a load period may be defined as the period for which a load of greater than 500 lbs is applied to the cutting element, or in some embodiments, the period for which a load of greater than 1000 lbs is applied to the cutting element. The frequency of cyclic loading is the interval at which each load period occurs. For example, frequencies at which load is applied to a cutting element during cyclic loading may range from less than 10 hertz in some embodiments, and less than 5 hertz in some embodiments. Cyclic loading may include load periods occurring at a constant or intermittent interval. According to embodiments of the present disclosure, an average frequency for loading periods may be used when defining cyclic loading parameters for cyclic loading having load periods at an intermittent interval. The duration of cyclic loading is the length of time over which the cyclic loading is defined. For example, the duration of cyclic loading in a simulation of a drilling operation may be the length of time of the simulated drilling operation, and the duration of cyclic loading in a physical test may be the length of time of the physical test.

[0023] According to embodiments of the present disclosure, cutting elements may be subjected to cyclic loading during drilling operations designed to contact and scrape the cutting elements against a formation in order to abrade the formation, in which case the cyclic loading may be a by-product of the drilling parameters or conditions, or the cyclic loading may occur by design (e.g., a drilling operation designed to minimize cyclic loading). Loads applied to a cutting element during cyclic loading occurring

from a drilling operation designed to abrade the formation may be different from loads applied to cutting elements in impact conditions, e.g., in terms of magnitude and the direction of the load applied to the cutting element. For example, a cutting element subjected to impact loading may have increased loads applied in a normal direction to its working surface when compared to a cutting element subjected to abrasive loading. Thus, by designing and/or implementing cyclic loading tests according to embodiments of the present disclosure, cyclic loading effects on a cutting element may be more accurately analyzed when compared with other methods of testing cutting elements (such as impact testing).

[0024] As used herein, a “drilling simulation” is a dynamic simulation of a drilling tool used in a drilling operation. The drilling simulation is referred to as being “dynamic” because the drilling is a “transient time simulation,” meaning that it is based on time or the incremental rotation of the drilling tool assembly. Methods for such simulations are known to the assignee of the current application, such as those disclosed in U.S. Patent Nos. 6,516,293, 6,873,947, 7,844,426, 7,139,689, 6,785,641, 7,693,695, 8,401,831, and 7,464,013 as well as U.S. Patent Application Nos. 10/749,019, 10/852,574, 10/851,677, 10/888,358, and 10/888,446, all of which are incorporated by reference in their entirety.

[0025] Individual cutting elements on a downhole cutting tool may be subjected to different forces during a drilling operation, depending on, for example, the cutting element location on the drilling tool and the drilling operation. According to embodiments of the present disclosure, a true path of cutting elements on a downhole cutting tool during a drilling operation may be modeled to more accurately simulate real world conditions the individual cutting elements may be subjected to during the drilling operation. As used herein, a “true path” of a cutting element refers to an actual or more accurately predicted path of the cutting element during downhole operations. For example, a true path of a cutting element may be calculated relative to the axis of the cutting tool on which the cutting element is disposed as opposed to the axis of the wellbore or direction of drilling.

[0026] In accordance with one aspect of the present disclosure, modeling the true path of one or more cutting elements may be conducted in a separate step from modeling the path of a cutting tool on which the cutting elements are disposed. For example, a

method of modeling a true path of a cutting element may include generating a geometric model of a downhole cutting tool (e.g., a drill bit) and a geometric model of the earth formation to be represented as drilled. The modeled cutting tool may then be incrementally rotated on the formation, and the interaction between the cutting elements on the cutting tool and the earth formation during the incremental rotation may be calculated. In an additional step, the true path of the cutting elements may be determined based on data from a cutting element/formation interaction model and the calculated interaction between the bit and the earth formation. From determining the true path of the cutting elements on a cutting tool, the inventors of the present disclosure have found that during operation, cutting elements may be subjected to more cyclical loading than was otherwise known. Cyclical loading may occur, for example, from bit bounce, bit whirl, unexpected movements during drilling, from assemblies having multiple axes of rotation or assemblies subjected to opposing forces. Further, a dynamic work of cutting elements may be determined by determining the true path of the cutting elements. As used herein, “dynamic work” refers to a changing work of a cutting element as the cutting element moves.

[0027] Unexpected or expected vibrational forces from, for example, bit bounce and bit whirl, as well as unexpected or expected forces from multiple nodes, for example, from roller cone drill bits, wellbore departure tools and directional drilling equipment, may affect performance of the drilling equipment. For example, in some cases, a driller might desire that the direction of the well bore be maintained for a certain distance. To achieve the direction, the driller may require that an angle be “built” (“build angle”) into the well. A build angle is the rate that the direction of the longitudinal axis of the well bore changes, which is commonly measured in degrees per 100 feet. The extent of the build angle may also be referred to as the “dogleg severity.” Another important directional aspect is the “walk” rate. The walk rate refers to the change in azimuthal (compass) direction of the well bore. Control and prediction of the drilling direction is important for reaching target zones containing hydrocarbons.

[0028] Further, while drilling, an actual weight on bit (“WOB”) is not constant. Some of the fluctuation in the force applied to the bit or reamer may be the result of the bit contacting with surfaces having harder and softer portions that break unevenly.

However, in most cases, the majority of the fluctuation can be attributed to drilling tool assembly vibrations. Drilling tool assemblies can extend more than a mile in length while being less than a foot in diameter. As a result, these assemblies are relatively flexible along their length and may vibrate when driven rotationally by the rotary table. Drilling tool assembly vibrations may also result from vibration of the bit during drilling. Several modes of vibration are possible for drilling tool assemblies. In general, drilling tool assemblies may experience torsional, axial, and lateral vibrations. Although partial damping of vibration may result due to viscosity of drilling fluid, friction of the drill pipe rubbing against the wall of the well bore, friction of the casing rubbing against the wall of the well bore, energy absorbed in drilling, and drilling tool assembly impacting with borehole, these sources of damping are typically not enough to suppress vibrations completely.

[0029] In some drilling operations, it may be desired to change the trajectory of a borehole. For example, it may be desired to change the trajectory of a substantially vertically drilled borehole to a substantially horizontally drilled borehole (or vice versa). The transition from vertical drilling to horizontal drilling (or vice versa) is known as directional drilling. The aforementioned problems may be increasingly significant when dealing with directional wells.

[0030] When drilling a long horizontal well (not necessarily a long-radius horizontal well), WOB may not effectively be transferred from the surface to the bit due to the large horizontal distance and axial friction from the drillstring. In addition, as the length of a well increases, the ROP of a drill bit may be reduced as WOB and/or surface RPM capabilities may not be sufficient in maintaining a specific ROP. Further, in long substantially horizontal wells, friction acting on the drill string, BHA, and/or drill bit may deleteriously affect the performance of the drilling operation and drill string and bit wear may be amplified. Of course, those having skill in the art will appreciate that many other reasons may affect the performance and/or drilling operation.

[0031] To attenuate or reduce friction, various drilling tools may be used to induce a vibration, hammering effect, or reciprocation in the drill string. For example, a shock sub may be used with an axial vibration tool to generate an axial force at a specified frequency, causing an axial vibration which oscillates the drill string and reduces

friction. To generate the axial force, the axial vibration tool may be used to create and apply cyclical pressure pulses to a pump open area of the shock sub. In another example, the cyclical pressure pulses of the axial vibration tool may produce a water hammering effect, causing the axial vibration needed to oscillate the drill string and reduce friction. Further, certain tools may need an external prime mover, such as a mud motor or turbine, in order to produce the cyclical pressure pulses.

[0032] In other embodiments, axial vibration tools may be used without a shock sub.

In such embodiments, the pressure pulses produced by the axial vibration tool may generate a water hammering effect, such that the pressure pulses may cause an axial vibration which travels up and down a drill string. In turn, the axial vibration may oscillate the drill string and reduce friction.

[0033] Accordingly, embodiments disclosed herein provide models that may more accurately reflect the effect of such forces, for example, by determining a true path of the cutting elements on a cutting tool (in addition to simulating the cutting tool).

According to some embodiments of the present disclosure, methods and techniques are provided to model the behavior of various BHA packages, including, for example, straight hole motor BHAs, bent motor BHAs, and other directional drilling BHAs, under multiple conditions to achieve an optimal BHA package for a given drilling operation.

[0034] According to some embodiments of the present disclosure, a method may be provided to model a true path of one or more cutting elements disposed on a cutting tool, for example, to better match the modeled path of the cutting elements with a modeled path of the cutting tool on which they are disposed and to more accurately predict cutting element behavior during operation. By modeling the path of the cutting elements (separately from the cutting tool on which they are disposed), multiple types of motions (e.g., vibrations, rotations along multiple axes, etc.) may be accounted for in determining and designing suitable downhole equipment.

[0035] In some embodiments, a method may be provided to simulate or model a cutting tool drilling an earth formation that includes incrementally rotating the cutting tool at a time interval, determining a true path of a plurality of cutting elements disposed on the cutting tool during drilling, and determining a dynamic work of the cutting elements based on the true path and forces acting on the cutting elements at

each interval of time. The simulation of the cutting tool drilling an earth formation may include modeling movement of the cutting tool having up to six degrees of freedom, where a degree of freedom refers to a type of movement. For example, embodiments disclosed herein may include simulating or predicting movement of a BHA and/or components thereof along the axes of an x-y-z coordinate system, including translations of the components along each of the axes and rotations of the components around each of the axes.

[0036] For example, in a BHA having a bent motor, the drilling assembly may rotate along two axes, intersecting one another at the bend angle. Such BHAs may be modeled according to embodiments of the present disclosure using more than two degrees of freedom, which may account for irregular movements, such as vibrational movements. In previous simulation methods, cutting elements were modeled based on an idealized helix configuration (accounting for only two degrees of freedom, translation and rotation along a single axis). FIGS. 1A and 1B illustrate a side and axial view, respectively, of an idealized helical path of a cutter during an example drilling simulation. The helical path illustrated in FIG. 1A may be determined by the radial distance of the cutting element from the central bit axis and the calculated rate of penetration (axial progression) of the bit during a drilling simulation. The axial view in FIG. 1B illustrates a circular path of the cutter through the simulated formation. It assumes a steady, constant, forward progression of the cutter as the bit progresses. Such idealized paths may assume that the cutters remain at the same radial distance from the drilling axis/direction throughout the drilling simulation.

[0037] However, by modeling cutting element trajectories based on a more accurate reflection of the type of movement they undergo (e.g., using up to six degrees of freedom), the true path of the cutting elements may be determined and analyzed, for example, for use in improved designing and predicting methods. FIGS. 1C and 1D illustrate a side and axial view, respectively, of an exemplary true path of a cutter during a drilling simulation. FIG. 1C illustrates the vibrations of the cutter in six directions as it advances into the formation, according to an embodiment. FIG. 1D illustrates the manifestation of a dual axis BHA system, e.g. a bent motor, in a cyclical true path of a cutter, according to an embodiment. The cutter trajectories shown in FIGS. 1C and 1D are being simulated based on the actual movements of the bit on

which they are disposed (as well as rotational movements from rotating around the bit axis), rather than tracking in a constant radial distance from the direction of drilling.

In other words, the true path of the cutters in FIGS. 1C and 1D is calculated in relation to the bit axis and accounts for movement in six degrees of freedom, while the path of the cutters in FIGS. 1A and 1B is calculated in relation to an idealized helical path through the wellbore. FIG. 1D, when compared with FIG. 1B, shows how the true path of a cutter may be substantially longer than an idealized circular path. The longer path indicates that a cutter is performing significantly more work per revolution of the bit than has been previously measured by drilling simulations.

[0038] For a given time interval, the true path of a cutter may be in the direction of the BHA rotation, no motion, or opposite to the direction of BHA rotation. Certain cutters are designed to withstand conventional forces experienced when the cutter engages the formation on a leading surface, as determined using an idealized, helical path. The true path of a cutter, as disclosed herein, may provide a better understanding of unconventional forces experienced by cutters, such as those on non-leading surfaces, leading to improved design of cutting structures, drilling parameters, and BHAs to mitigate or tolerate unconventional forces.

[0039] A system for simulation of a BHA and cutting elements used thereon is shown in FIGS. 2A-D. In one or more embodiments, one or more of the modules and elements shown in FIGS. 2A-D may be omitted, repeated, and/or substituted. Accordingly, embodiments of the present disclosure should not be considered limited to the specific arrangements of modules shown in FIGS. 2A-D.

[0040] As shown in FIG. 2A, the method includes selecting or otherwise inputting parameters for a dynamic simulation. Parameters provided as input may include drilling parameters 202, bit design parameters 204, cutter/formation interaction data and cutter wear data 206, and bottomhole parameters for determining the initial bottomhole shape 208. Other input parameters may include, but are not limited to, other cutting tool parameters (e.g., drill bit parameters for a baseline bit), BHA parameters (e.g., from a bent motor BHA), actual well survey information, and other drilling operating parameters. The data and parameters provided as input for the simulation can be stored in an input library and retrieved as need during simulation calculations.

[0041] Drilling parameters 202 may include any parameters that can be used to characterize drilling. In the method shown, the drilling parameters 202 provided as input include the rate of penetration (ROP), the rotation speed of the drill bit (revolutions per minute, RPM), the total bit revolutions, BHA and well information.

[0042] Bit design parameters 204 may include any parameters that can be used to characterize a bit design. In the method shown, bit design parameters 204 provided as input include the cutter locations and orientations (e.g., radial and angular positions, heights, profile angles, rake angles, side rake angles, etc.) and the cutter sizes (e.g., diameter), shapes (i.e., geometry) and bevel size. Additional bit design parameters 204 may include the bit profile, bit diameter, number of blades on bit, blade geometries, blade locations, junk slot areas, bit axial offset (from the axis of rotation), cutter material make-up (e.g., tungsten carbide substrate with hardfacing overlay of selected thickness), etc. Those skilled in the art will appreciate that cutter geometries and the bit geometry can be meshed, converted to coordinates and provided as numerical input. Methods for obtaining bit design parameters 204 for use in a simulation may include the use of 3-dimensional CAD solid or surface models for a bit to facilitate geometric input.

[0043] Cutter/formation interaction data 206 includes data obtained from experimental tests or numerically simulations of experimental tests which characterize the actual interactions between selected cutters and selected earth formations, as previously described in detail above. Wear data 206 may be data generated using any wear model known in the art or may be data obtained from cutter/formation interaction tests that included an observation and recording of the wear of the cutters during the test. A wear model may comprise a mathematical model that can be used to calculate an amount of wear on the cutter surface based on forces on the cutter during drilling or experimental data which characterizes wear on a given cutter as it cuts through the selected earth formation. U.S. Pat. No. 6,619,411 issued to Singh et al. discloses methods for modeling wear of roller cone drill bits. This patent is assigned to the present assignee and is incorporated by reference in its entirety. Wear modeling for fixed cutter bits (e.g., PDC bits) will be described in a later section. Other patents related wear simulation include U.S. Pat. Nos. 5,042,596, 5,010,789, 5,131,478, and 4,815,342. The disclosures of these patents are incorporated by reference.

[0044] Bottomhole parameters used to determine the bottomhole shape at 208 may include any information or data that can be used to characterize the initial geometry of the bottomhole surface of the well bore. The initial bottomhole geometry may be considered as a planar surface, but this is not a limitation on the invention. Those skilled in the art will appreciate that the geometry of the bottomhole surface can be meshed, represented by a set of spatial coordinates, and provided as input. In one implementation, a visual representation of the bottomhole surface is generated using a coordinate mesh size of 1 millimeter.

[0045] Once the input data (202, 204, 206) is entered or otherwise made available and the bottomhole shape determined (at 208), the steps in a main dynamic simulation loop can be executed. A dynamic simulation may account for multiple nodes, each having six degrees of freedom (e.g., multiple directions of rotation and translation).

[0046] Within the dynamic simulation, drilling is simulated by “rotating” the bit (numerically) by an incremental amount, $\Delta\theta_{\text{bit},i}$, 212. The rotated position of the bit at any time can be expressed as

$$\theta_{\text{bit}} = \sum^i \Delta\theta_{\text{bit},i}$$

212. $\Delta\theta_{\text{bit},i}$ may be set equal to 3 degrees, for example. In other implementations, $\Delta\theta_{\text{bit},i}$ may be a function of time or may be calculated for each given time step. The new location of each of the cutters is then calculated, 214, based on the known incremental rotation of the bit, $\Delta\theta_{\text{bit},i}$, and the known previous location of each of the cutters on the bit. At this stage, 214, the new cutter locations only reflect the change in the cutter locations based on the incremental rotation of the bit. The newly rotated location of the cutters can be determined by geometric calculations known in the art.

[0047] As shown at the top of FIG. 2B, the axial displacement of the bit, $\Delta d_{\text{bit},i}$, during the incremental rotation is then determined, 216. In this implementation the rate of penetration (ROP) was provided as input data (at 202), therefore axial displacement of the bit is calculated based on the given ROP and the known incremental rotation angle of the bit. The axial displacement can be determined by geometric calculations known in the art. For example, if ROP is given in ft/hr and rotation speed of the bit is given in revolutions per minute (RPM), the axial displacement, $\Delta d_{\text{bit},i}$, of the bit resulting for the incremental rotation, $\Delta\theta_{\text{bit},i}$, may be determined using an equation such as:

$$\Delta d_{\text{bit},i} = (ROP_i / RPM_i) \cdot (\Delta \theta_{\text{bit},i}) / 60.$$

[0048] Once the axial displacement of the bit, $\Delta d_{\text{bit},i}$, is determined, the bit is “moved” axially downward (numerically) by the incremental distance, $\Delta d_{\text{bit},i}$, 216 (with the cutters at their newly rotated locations calculated at 214). Then the new location of each of the cutters after the axial displacement is calculated 218. The calculated location of the cutters now reflects the incremental rotation and axial displacement of the bit during the “increment of drilling”. Then each cutter interference with the bottomhole is determined, 220. Determining cutter interaction with the bottomhole includes calculating the depth of cut, the interference surface area, and the contact edge length for each cutter contacting the formation during the increment of drilling by the bit. These cutter/formation interaction parameters can be calculated using geometrical calculations known in the art.

[0049] Once the correct cutter/formation interaction parameters are determined, the axial force on each cutter (in the Z direction with respect to a bit coordinate system) during increment drilling step, i , is determined, 222. The force on each cutter is determined from the cutter/formation interaction data based on the calculated values for the cutter/formation interaction parameters and cutter and formation information.

[0050] The normal force, cutting force, and side force on each cutter may be determined from cutter/formation interaction data based on the known cutter information (cutter type, size, shape, bevel size, etc.), the selected formation type, the calculated interference parameters (i.e., interference surface area, depth of cut, contact edge length) and the cutter orientation parameters (i.e., back rake angle, side rake angle, etc.). For example, the forces may be determined by accessing cutter/formation interaction data for a cutter and formation pair similar to the cutter and earth formation interacting during drilling. Then the values calculated for the interaction parameters (depth of cut, interference surface area, contact edge length, back rack, side rake, and bevel size) during drilling may be used to look up the forces required on the cutter to cut through formation in the cutter/formation interaction data. If values for the interaction parameters do not match values contained in the cutter/formation interaction data, records containing the most similar parameters may be used and values for these most similar records may be used to interpolate the force required on the cutting element during drilling.

[0051] In cases during drilling wherein the cutting element makes less than full contact with the earth formation due to grooves in the formation surface made by previous contact with cutters, an equivalent depth of cut and an equivalent contact edge length can be calculated to correspond to the interference surface area and used to look up the force required on the cutting element during drilling.

[0052] Once the forces (e.g., F_N , F_{cut} , F_{side}) on each of the cutters during the incremental drilling step are determined, 222, these forces may be resolved into bit coordinate system, $O_{ZR\theta}$, (axial (Z), radial (R), and circumferential θ). Then, all of the forces on the cutters in the axial direction may be summed to obtain a total axial force F_Z on the bit. The axial force required on the bit during the incremental drilling step is taken as the weight on bit (WOB) required to achieve the given ROP, 224.

[0053] The displacement of each of the cutters is calculated based on the previous cutter location, $p_{j,i-1}$, and the current cutter location, $p_{j,i}$, 226. As shown at the top of FIG. 2C, the lateral forces, both radial and circumferential, on each cutter are then determined from cutter/formation interaction data based on the cutter lateral movement, penetration depth, interference surface area, contact edge length, and other bit design parameters (e.g., back rake angle, side rake angle, and bevel size of cutter), 228. The cutter velocity and work on each of the cutters may be calculated based on previous cutter location, $p_{j,i-1}$, new cutter location, $p_{j,i}$, and forces acting on the cutters, 229, such as described below with reference to FIG. 5. Cutter wear may also be calculated for each cutter based on the forces on each cutter, the interaction parameters, and the wear data for each cutter, 230. The cutter shape is modified using the wear results to form a worn cutter for subsequent calculations, 232.

[0054] The bottomhole pattern may be updated 234 by removing the formation in the path of interference between the bottomhole pattern resulting from the previous incremental drilling step and the path traveled by each of the cutters during the current incremental drilling step.

[0055] Output information, such as forces on cutters, weight on bit, and cutter wear, may be provided as output information, at 236. The output information may include any information or data which characterizes aspects of the performance of the selected drill bit drilling the specified earth formations. For example, output information can include forces acting on the individual cutters during drilling, scraping

movement/distance of individual cutters on hole bottom and on the hole wall, total forces acting on the bit during drilling, and the weight on bit to achieve the selected rate of penetration for the selected bit. Other simulation results may include other drilling performance parameters, such as downhole assembly lateral, axial or torsional vibrations, bit displacement, bit rotation, and other forces acting on the downhole assembly. From the simulation results, additional performance parameters may be determined as output information, including dynamic work and cyclic loading on the cutting elements.

[0056] As shown in FIG. 2C, output information may be used to generate a visual display of the results of the drilling simulation, at 238. The visual display 238 can include a graphical representation of the well bore being drilled through earth formations. The visual display 238 can also include a visual depiction of the earth formation being drilled with cut sections of formation calculated as removed from the bottomhole during drilling being visually “removed” on a display screen. The visual representation may also include graphical displays, such as a graphical display of the forces on the individual cutters, on the blades of the bit, and on the drill bit during the simulated drilling, the dynamic work on the cutters, and the cyclic loading on individual cutters. The means used for visually displaying aspects of the drilling performance is a matter of choice for the system designer, and is not a limitation on the invention.

[0057] As shown in FIG. 2D, output information may be used to analyze and modify cutter design. For example, output information related to the cutters, such as cyclic loading on individual cutters, dynamic work on the cutters, and other performance parameters may be used as conditions for FEA (finite element analysis), 240. The FEA may be conducted for various types of cutting elements (including cutting elements made of different materials and/or having different geometries) to determine which type of cutting element best performs under the conditions outputted from the dynamic simulation. A modified cutter design, 242, may be selected based on the FEA results, which may then be used as inputs for the cutting element parameters, inputted at 204 (shown in FIG. 2A) in another dynamic simulation loop.

[0058] The performance parameters determined from the simulation results and from any cutting element FEA performed may be compared with results gathered from the

field (e.g., results from a drilling operation or from a test drill run, where the BHA and wellbore characteristics are the same or substantially the same as the parameters inputted into the simulation). When the performance parameters do not match or substantially correspond with those measured or seen in the field, it may be an indication that the input parameters did not substantially match or accurately reflect the conditions of the drilling operation being simulated. In such instances, the input parameters may adjusted, and the simulation may be rerun. When the performance parameters match or substantially correspond with those measured or seen in the field, the failures or less than desired performance of any of the components in the BHA may be analyzed to determine a cause. Once a cause of any failures or less than desired performance is determined, a new design of one or more components of the BHA may be proposed to improve performance of the BHA. In some embodiments, one or more altered input parameters reflecting the new design may be inputted to simulate the new design.

[0059] For example, as shown in FIG. 2D, output information from 236 may be compared to field results (from drilling operations having similar parameters as those inputted into the dynamic simulation), 244. Based on the comparison between actual field results and the output information from 236, the true trajectory of the cutters may be analyzed, 246, to determine if the BHA and/or cutting tool design is sufficient for achieving a desired performance. If the performance of the simulated BHA is not sufficient, the design of the BHA and/or cutting tool may be modified, 248, which may then be used as inputs for the cutting tool parameters, inputted at 204 in FIG. 2A, (or as inputs for the BHA or drilling operation parameters, inputted at 202 in FIG. 2A), in another dynamic simulation loop.

[0060] An ending condition, such as the total depth to be drilled, can be given as a termination command for the simulation, the incremental rotation and displacement of the bit with subsequent calculations in the simulation loop will be repeated until the selected total depth drilled, e.g.,

$$D = \sum^i \Delta d_{\text{bit}, i}$$

is reached. Alternatively, the drilling simulation can be stopped at any time using any other suitable termination indicator, such as a selected input from a user.

[0061] In one or more embodiments, a system for simulating or modeling a BHA and/or a drilling operation using a selected BHA may include a computing device having one or more computing processors, one or more storage devices (*e.g.*, a hard disk, an optical drive such as a compact disk (CD) drive or digital versatile disk (DVD) drive, a flash memory stick, *etc.*), memory (*e.g.*, random access memory (RAM), cache memory, flash memory, *etc.*), and a graphical user interface (GUI). The computing processor(s) may be an integrated circuit for processing instructions. For example, the computing processor(s) may be one or more cores, or micro-cores of a processor. The storage device(s) (and/or any information stored therein) may be a data store such as a database, a file system, one or more data structures (*e.g.*, arrays, link lists, tables, hierarchical data structures, *etc.*) configured in a memory, an extensible markup language (XML) file, any other suitable medium for storing data, or any suitable combination thereof. The storage device(s) may be a device internal to the computing device. Alternatively, the storage device(s) may be an external storage device operatively connected to the computing device. Additionally, the computing device may include numerous other elements and functionalities.

[0062] The computing device may be communicatively coupled to a network (*e.g.*, a local area network (LAN), a wide area network (WAN) such as the Internet, mobile network, or any other type of network) through wires, cables, fibers, optical connectors, a wireless connection, or a network interface connection (not shown).

[0063] The system may also include one or more input device(s), such as a touchscreen, keyboard, mouse, microphone, touchpad, electronic pen, or any other type of input device. Further, the system may include one or more output device(s), such as a screen (*e.g.*, a liquid crystal display (LCD), a plasma display, touchscreen, cathode ray tube (CRT) monitor, projector, 2D display, 3D display, or other display device), a printer, external storage, or any other output device. One or more of the output device(s) may be the same or different from the input device(s). The input and output device(s) may be locally or remotely (*e.g.*, via the network) connected to the computer processor(s), memory, storage device(s), and GUI. Many different types of systems exist, and the aforementioned input and output device(s) may take other forms.

[0064] The GUI may be operated by a user (e.g., an engineer, a designer, an operator, an employee, or any other party) using one or more input devices, and the GUI may be visualized on one or more output devices coupled to the computing device. The GUI may include one or more buttons (e.g., radio buttons), data fields (e.g., input fields), banners, menus (e.g., user input menus), boxes (e.g., input or output text boxes), tables (e.g., data summary tables), sections (e.g., informational sections or sections capable of minimizing/maximizing), screens (e.g., welcome screen or home screen), and/or user selection menus (e.g., drop down menus). In addition, the GUI may include one or more separate interfaces and may be usable in a web browser or as a standalone application.

[0065] The output device(s) may be communicatively coupled to the computing device, or the output device(s) may be a component of the computing device.

[0066] The computing device may be capable of simulating a BHA. The BHA to be simulated may be selected, by a user, from a pre-existing library of BHAs (not shown) or a BHA may be customized, by the user, using the GUI of the computing device. The user may customize the BHA by inputting or selecting a variety of drilling components. In one or more embodiments, the user may select a number of axial vibration tools and/or a number of shock subs. Further, the user may also customize a number of parameters associated with each of the selected axial vibration tools or shock subs. For example, the user may modify a distance between a selected axial vibration tool or shock sub with respect to the drill bit of the BHA. Further, the user may also select a distance between the selected vibration tool and shock sub.

[0067] Additionally, the simulation may be customized by inputting or selecting a variety of well bore parameters and drilling operating parameters. To modify the BHA and/or customize the BHA or simulation, the user may access storage device(s) using any input means known in the art (e.g., input device(s)). The storage device(s) may be capable of having data stored thereon and may include, for example, rock profiles, BHA parameters and components, and/or drilling operating parameter, among many others. Once the user customizes the BHA and other simulation parameters, the computing device may execute instructions on the computing processor(s) to perform a simulation based on the customized BHA and the parameters selected or input by the user.

[0068] By using more accurate prediction models or simulations of a downhole cutting tool and cutting elements disposed thereon during a drilling operation, a more accurate representation of the real world conditions of the drilling operation may be determined, which may be used in designing improved tests for physical cutting elements. For example, simulations including a model of a true path of cutting elements on a downhole cutting tool during drilling operations may reveal real world conditions including cyclic loading.

[0069] According to embodiments of the present disclosure, one or more simulations of a cutting tool drilling an earth formation may be conducted to determine cyclic loading on a cutting element disposed on the cutting tool. For example, referring to FIG. 3, an example of a cutting tool for use in a downhole operation is shown. The cutting tool is a drill bit 300 having cutting blades 310 extending outwardly from a bit body 305 and a plurality of cutting elements 320 disposed in rows along the blades 310. The drill bit 300 may be simulated in the downhole operation, including modeling the true path of the cutting elements 320. An output from the simulation may include a graphical display of the forces on the individual cutting elements. For example, a graph 330 of the normal forces on a cutting element 325 as a function of time during the simulated downhole operation may be generated from the simulation. Other forces on individual cutting elements, e.g., cutting force and side force, may be determined (e.g., from cutter/formation interaction data from the simulation) and graphed as a function of time during the simulated downhole operation. As shown in FIG. 3, the graph 330 may show cyclic loading on the cutting element 325, where during the simulated downhole operation, the modeled true path of the simulated cutting element 325 is subjected to interval periods of loading.

[0070] After identifying cyclic loading through simulation, a physical test may be designed to subject a physical cutting element to physical cyclic loading corresponding to or mimicking the simulated cyclic loading. As used herein, a test (or physical test) refers to physical testing of a physical cutting element, such as in a lab or in a downhole test. Physical tests are different from simulations and modeling analyses performed on a simulated cutting element (e.g., FEA of a cutting element) which may include inputting parameters of a cutting element and/or the cutting tool on which a cutting element is disposed into a computing system for simulated testing. Tests for

physical cutting elements may be useful, for example, for analyzing real world performance of a physical cutting element and/or comparing physical testing results to simulated testing results, which may be used in improving the simulations.

[0071] According to some embodiments of the present disclosure, a physical test for a cutting element may be designed by first determining cyclic loading conditions the cutting element is likely to be exposed to during a downhole operation, which may be determined, for example, by simulating the cutting element during the downhole operation or by using other prediction models. For example, in some embodiments, designing a physical test may include determining a simulated linear velocity and a simulated loading period of the simulated cutting element during the cyclic loading, such as described above. Simulated linear velocity and simulated loading period may be outputted from a simulation and/or calculated based on one or more simulation parameters. For example, referring still to FIG. 3, the linear velocity and linear distance of the cutting element 325 determined using the simulated bit parameters. An associated linear velocity V of the cutting element 325 may be calculated from the diameter D of the bit and the angular velocity W of the bit. From the graph 330, a loading period T of cyclic loading on the cutting element 325 may be determined. The linear distance S that the cutting element 325 travels during the loading period T may then be calculated based on the linear velocity V of the cutting element 325. A physical test may then be designed to have test conditions with a cutting element linear velocity and loading period that is similar to or substantially equal to the determined simulated linear velocity and loading period of the cutting element simulation.

[0072] In some embodiments, a physical test for a cutting element may be designed without first determining cyclic loading conditions the cutting element is likely to be exposed to during a downhole operation. For example, in some embodiments, a physical test may be designed to test whether a cutting element meets selected cyclic loading parameters.

[0073] A test may be designed to test selected cyclic loading conditions by providing an appropriate testing fixture to meet the selected testing conditions. According to embodiments of the present disclosure, a testing fixture may include a body having a testing surface formed on one or more of the body's sides, where the testing surface may include an alternating pattern designed to provide cyclic loading conditions upon

contact with a physical cutting element being tested. In contrast to simulations of cutting elements under cyclic loading and other models analyzing a simulated cutting element under cyclic loading conditions, a testing fixture may be designed to contact with a physical cutting element being tested to subject the physical cutting element to physical cyclic loading.

[0074] According to embodiments of the present disclosure, a testing fixture may include a body moveable in a direction (e.g., using a motor) and having at least one side with an alternating pattern of surface topography and/or material type formed along outer surface in the direction in which the body is moveable. In some embodiments, a body having at least one side with an alternating pattern formed therein (e.g., an alternating pattern of surface topography and/or an alternating pattern of material type forming the outer surface of the side) may be stationary, while a physical cutting element being tested may be moved in a direction along the stationary testing fixture side with an alternating pattern formed therein.

[0075] An example of a testing fixture according to embodiments of the present disclosure is shown in FIG. 4. The testing fixture 400 includes a body 402 having a top side 404 bordered by an outer side 406. The body 402 may be moveable in a direction 408, for example, by positioning the body 402 on a lathe 420 rotatable by a motor. The body may be moveable, for example, in a rotational direction, either clockwise or counterclockwise, such as shown in FIG. 4, or in a linear direction. In the embodiment shown, the outer side 406 defines a cylindrical shape of the body 402, where the direction 408 is a rotational direction about a longitudinal axis of the body 402. The body 402 may have a bore 401 formed along and concentric with the longitudinal axis of the body 402, which may be used for rotating the body 402. For example, a gripping component (e.g., a threaded connection) may extend from the lathe 420 to grip at least a portion of the bore 401, such that when the lathe 420 is rotated, the testing fixture body 402 is rotated with the lathe 420.

[0076] The outer side 406 has an alternating pattern formed along the direction 408, where the pattern repeats in the same direction the body 402 is moveable. In some embodiments, an alternating pattern may be formed along a top side, alone, or along a combination of sides. As shown in FIG. 4, the alternating pattern may be an alternating pattern in the side's surface topography (the shape of the side's outer

surface) including a plurality of alternating slots 410 and protrusions 415. The slots 410 alternate with the protrusions 415 in the direction 408 of rotation, such that when the body 402 is rotating in the direction 408, the elements of the alternating pattern will alternate in the pattern (e.g., slot, protrusion, slot, protrusion, etc.) when viewed from a stationary position.

[0077] An outermost surface of the protrusions 415 may define an outer diameter of the body 402, and the deepest surfaces of the slots 410 may be a depth 412 from the outermost surface of the protrusions 415. The depth 412 measured between the outermost surface of each protrusion and a deepest surface of each adjacent slot may be equal, or in some embodiments, the depth may be different, for example, where one or more slots may extend deeper from an outermost surface of the protrusions than another slot on the same body.

[0078] Further, slots 410 are sized to provide a distance 414 between adjacent protrusions 415. The outermost surfaces of the protrusions 415 may extend a distance 416 equal to or unequal to the distance 414 between adjacent protrusions 415. In embodiments where a testing fixture body has an alternating pattern of protrusions defining an outer diameter of a generally cylindrically shaped body, the distance between adjacent protrusions and the distance of the protrusion outermost surfaces may be arc length segments of the outer perimeter of the cylinder defined by the protrusion outermost surfaces. The distance 414 between adjacent protrusions 415 and/or the distance 416 of the protrusion outermost surfaces may be designed, for example, to correspond with a loading period and a frequency of selected cyclic loading conditions when the body 402 is moved in the direction 408 at a certain speed.

[0079] A cutting element 430 may be held (e.g., using an apparatus that grips the cutting element or securing the cutting element to a coupon, such as by brazing) at a position relative to the testing fixture 400 such that a cutting face and/or cutting edge contacts the outermost surfaces of the protrusions 415.

[0080] According to embodiments of the present disclosure, the distance of the outermost surfaces of protrusions formed in a testing surface of a testing fixture may be designed to be equal to the relative speed between the testing fixture and a physical cutting element being tested on the testing fixture (e.g., the speed the testing fixture moves while holding the physical cutting element stationary or the speed the physical

cutting element is moved while holding the testing fixture stationary) times a loading period of cyclic loading conditions being tested. Similarly, the distance between adjacent protrusions formed in a testing surface of a testing fixture may be designed to be equal to the relative speed between the testing fixture and a physical cutting element being tested on the testing fixture times an unloaded period of the cyclic loading conditions being tested.

[0081] For example, FIG. 5 shows an example of a testing fixture 500, as viewed from the top side 504 of the testing fixture, where an alternating pattern of protrusions 515 are formed along the outer side 506 in a pattern extending in a direction 508 of rotation of the testing fixture. The outermost surfaces of the protrusions 515 may be designed to extend an arc length distance 516 that corresponds to a loading period of cyclic loading conditions when the testing fixture 500 is rotated in the direction 508 at a selected speed. The arc length distance 514 between adjacent protrusions 515 may be designed to correspond to an unloaded period (the time between loading cycles) of the cyclic loading conditions being tested when the testing fixture 500 is rotated in the direction 508 at the selected speed.

[0082] While the embodiments shown in FIGS. 4 and 5 have an alternating pattern along an outer side of the testing fixture body, some embodiments may have an alternating pattern formed along a top side of the testing fixture body (either in addition to being formed in the outer side or without being formed in the outer side).

[0083] For example, FIG. 6 shows an example of a testing fixture 600 according to embodiments of the present disclosure that includes a body 602 having a top side 604 bordered by an outer side 606, where an alternating pattern of protrusions 615 and grooves or slots 610 are formed in the top side 604 along a rotational direction 608 in which the body 602 is moveable. The body 602 has a cylindrical shape, rotatable about its central longitudinal axis, where the alternating pattern of protrusions 615 and slots 610 are rotationally symmetric about the longitudinal axis. The protrusions 615 may each have a width (distance 616) measured between two opposite side walls defining the protrusion 615, and each slot 610 may have a width (distance 614) measured between the two adjacent protrusions 615. The widths 616, 614 of each of the protrusions 615 and slots 610 may decrease along their lengths, where the widths

616, 614 of the protrusions 615 and slots 610 decrease in a direction from the top side 604 perimeter toward the longitudinal axis.

[0084] By providing an alternating pattern having varying dimensions, such as the protrusions and slots shown in FIG. 6 with varying widths along their lengths, a single testing fixture may be used to test physical cutting elements under various cyclic loading conditions. For example, using the test fixture shown in FIG. 6, a physical cutting element may be held in a first position to contact the protrusions 615 of the test fixture 600 near the perimeter of the top side 604 (where the widths 616 of the protrusions are relatively larger) as the test fixture 600 rotates at a rotational speed to test the physical cutting element under cyclic loading conditions having a first loading period and frequency. A physical cutting element may be held in a second position to contact the protrusions 615 of the same testing fixture 600 closer to its longitudinal axis (where the widths 616 of the protrusions are relatively smaller) as the test fixture 600 rotates at the same rotational speed to test the physical cutting element under cyclic loading conditions having a second loading period and frequency.

[0085] According some to embodiments of the present disclosure, an alternating pattern formed on a testing surface of a testing fixture may include alternating and adjacent segments of different materials, where each material type has a different strength. For example, FIG. 7 shows a top view of a testing fixture 700 having a plurality alternating segments of material 710, 715 formed along a testing surface in a direction 708 of movement. In the embodiment shown in FIG. 7, the testing surface is formed around the outer side 706 of the testing fixture, where the different material types of the alternating and adjacent segments of material 710, 715 are exposed to and form the testing surface at the outer side 706. In some embodiments, alternating and adjacent segments of different material types may form a top side of a testing fixture, where the different material types are exposed to and form the testing surface at the top side of the testing fixture.

[0086] The different material types may have different strengths, which may provide different forces on a cutting element when the cutting element is contacted to and moved against the testing surface, in order to provide cyclic loading conditions. For example, a first type of material forming a first type of material segments may include rock or casing material and a second type of material forming a second type of

material segments may include a relatively weaker rock or concrete (which may simulate interbedded formation, for example). Segments of different material types may be arranged in an alternating pattern to form a testing surface in order to provide cyclic loading conditions with a physical cutting element contacting and moving against material segments with relatively greater strength (providing increased forces between the cutting element and testing surface, where the cutting element is in a loading period of the cyclic loading conditions) and against material segments with relatively lesser strength (providing decreased forces between the cutting element and testing surface, where the cutting element is in an unloaded period of the cyclic loading conditions).

[0087] According to some embodiments of the present disclosure, more than two types of material segments may be arranged in an alternating pattern to form a testing surface of a testing fixture. In some embodiments, two or more types of material segments may be arranged in an alternating pattern with slots (gaps formed between two adjacent segments of material) to form a testing surface of a testing fixture.

[0088] Further, in some embodiments, segments of a type of material may be removable. For example, referring again to FIG. 7, in some embodiments, one of the types of segments 710 may be removed, whereby the second type of material segments 715 may remain to maintain an alternating pattern in the testing surface. In the embodiment shown in FIG. 7, segments of material 715 are formed integrally with and protrude outwardly from the testing fixture body 702. Segments of material 710 may be disposed between the segments of material 715, for example, by forming the segments of material 710 within the gaps between segments of material 715, by detachably retaining preformed segments of material 710 within the gaps between segments of material 715, by adhering preformed segments of material 710 within the gaps between segments of material 715, or by other methods of attachment to attach segments of material 710 between adjacent segments of material 715. The segments of material 710 may be removed, for example, by machining the segments of material 710 out or by detaching the segments of material 710 from the gaps between segments of material 715. According to embodiments of the present disclosure, more than one material type segment may be attached to or formed on a body outer surface, more

than one material type segment may be formed integrally with a testing fixture body, or each material type segment may be attached to or formed on a body outer surface.

[0089] The embodiments shown in FIGS. 4-7 show testing fixtures having a cylindrically shaped body. However, other body shapes are envisioned. For example, testing fixtures may have a prism shaped body, where a linear relative movement may be provided between the testing surface of the testing fixture and a physical cutting element being tested (e.g., by moving the testing fixture linearly relative to the cutting element, by moving the cutting element linearly relative to the testing surface, or both).

[0090] Referring now to FIG. 8, a testing fixture 800 has a body 802 with multiple sides, including a top side 804 forming a testing surface and a plurality of outer sides 806 bordering the top side. The body 802 has a rectangular prism shape; however, other prism (e.g., prisms with a polygonal base having 3, 4, 5, or more sides) and non-cylindrical shapes may be used. The testing surface has an alternating pattern of segments of two types of materials 810, 815.

[0091] A physical cutting element 830 may be held in a holder 840 (e.g., brazed in a cutter pocket formed in cutting tool material, or otherwise gripped by an apparatus to secure the cutting element in place). The physical cutting element 830 may be moved in a linear direction 808 along the alternating pattern of segments 810, 815 and/or the testing fixture 800 may be moved in the linear direction 808 relative to the cutting element 830. Relative movement between a cutting element being tested and a testing fixture may be provided by one or more motors and/or pistons (e.g., a hydraulic piston).

[0092] In some embodiments, a testing fixture having a non-cylindrical shaped body may be provided with a testing surface having an alternating pattern of protrusions and slots (gaps formed between adjacent protrusions) arranged in a direction of relative movement between a cutting element to be tested and the testing surface. For example, a testing fixture may be a slab of rock having a pattern of linear gaps spaced apart and arranged in rows along a direction of relative movement between a cutting element to be tested and the testing fixture. Physical cutting elements may be run linearly along the testing surface in the direction perpendicular to the length of the linear gaps, or the testing fixture may be moved linearly in the direction relative to a

physical cutting element to contact and move against the physical cutting element during testing.

[0093] According to embodiments of the present disclosure, a testing fixture may be designed to provide selected cyclic loading conditions by designing or selecting at least one testing fixture parameter to correspond to the cyclic loading conditions. For example, testing fixture parameters that may be designed to provide selected cyclic loading conditions may include but are not limited to a size of the testing fixture, an angular velocity of the testing fixture, a linear velocity of the testing fixture, material of the testing fixture, a shape of the testing fixture and an alternating pattern along a testing surface of the testing fixture. Further, other parameters of the testing may be designed to provide selected cyclic loading conditions, such as cutting element parameters. Cutting element parameters may include but are not limited to the size of the cutting element being tested, the shape of the cutting element, the angle at which the cutting element contacts the testing surface of the testing fixture, the velocity at which the cutting element moves against the testing surface, and the forces applied to the cutting element to contact and move against the testing surface.

[0094] Methods of the present disclosure may include performing a physical test on a physical cutting element to test the physical cutting element under cyclic loading conditions provided by the physical test. The physical test may be designed to correspond to simulated or modeled cyclic loading experienced in downhole operations, such as by providing a testing fixture as described herein to contact with and move against the physical cutting element being tested. The physical cutting element being tested may be contacted to and moved against a testing fixture at a velocity equal to the simulated or predicted linear velocity of a corresponding cutting element in the modeled downhole operations for loading periods equal to the simulated or predicted loading periods in the modeled downhole operations.

[0095] Methods according to embodiments of the present disclosure may further include performing a designed test on a physical cutting element and comparing physical forces acting on the physical cutting element during the physical cyclic loading to simulated forces on a corresponding simulated cutting element during corresponding simulated cyclic loading. Comparing physical forces to simulated

forces may include plotting the physical forces and the simulated forces as a function of time.

[0096] At least one parameter of a physical test may be adjusted when a difference is determined between physical forces from the physical test and simulated forces from which the physical test was designed. For example, one or more testing fixture parameters may be altered, including, for example, a size of a testing fixture, an angular velocity of the testing fixture, a material of the testing fixture, and/or a shape of the testing fixture. Other parameters of the physical test that may be altered may include, for example, an engagement length between the physical cutting element and a testing fixture, a depth of cut, and/or a shape of the physical cutting element.

[0097] Referring now to FIG. 9, an example of methods according to embodiments of the present disclosure is shown. Methods of the present disclosure may include creating a simulation 910 of a downhole operation. Forces on a simulated cutting element from the simulation of the downhole operation may be plotted 920 to determine cyclic loading conditions in the downhole operation. Based on cyclic loading conditions determined from the simulation of the downhole operation, a physical lab test may be designed 930. The physical test may be designed to provide physical cyclic loading conditions corresponding to the simulated cyclic loading conditions when a physical cutting element is contacted to and moved against a physical testing fixture used in the physical test. The physical test may be performed 940, such as described above. Forces on a physical cutting element tested in the physical test may be plotted 950 to analyze cyclic loading from the physical test. The physical test forces may be compared to the simulated forces 960, and the comparison may be used to determine if the physical test forces match the simulated forces 970.

[0098] When the physical test forces match the simulated forces, the physical test may be repeated and/or used to design improved cutting elements to better withstand cyclic loading conditions of a downhole operation. When the physical test forces do not match the simulated forces, at least one test parameter of the physical test may be adjusted 980, and one or more modified physical tests may be conducted. One or more steps in the method shown in FIG. 9 may be repeated or omitted.

[0099] According to some embodiments of the present disclosure, one or more methods may include performing a physical test on one or more physical cutting

elements by contacting a physical cutting element to a test fixture under cyclic loading conditions for a duration, where each cycle of the cyclic loading conditions occurs during contact between the cutting element and the test fixture at a velocity for a loading period. Based on the physical test results, it may be determined if a failure criterion is met after subjecting the physical cutting element to the physical cyclic loading conditions. Failure criteria may include but is not limited to crack initiation, a minimum crack propagation distance, or a minimum fracture area.

[00100] In some embodiments, a test condition for a physical test may be set prior to conducting the physical test. For example, a test condition may be a number of cycles to meet the failure criterion, or a number of hours to meet the failure criterion. A physical cutting element may then be tested to determine if the physical cutting element meets the selected test condition after the duration of the cyclic loading testing.

[00101] If a failure criterion is met during the physical testing of a first cutting element, a second cutting element having at least one parameter different from the first cutting element may be designed and tested using the designed physical test.

[00102] Embodiments according to the present disclosure may allow for testing the performance of cutting elements in real world conditions that have not previously been evaluated. For example, whereas simulation of wear based cutting may be used to evaluate wear performance of cutting elements, and simulation of impact cutting may be used to evaluate performance of cutting elements in impact cutting applications, methods and applications according to embodiments of the present disclosure may be used for evaluating cutting element performance during intermittent cyclic cutting.

[00103] Although only a few example embodiments have been described in detail above, those skilled in the art will readily appreciate that many modifications are possible in the example embodiments without materially departing from this disclosure. Accordingly, all such modifications are intended to be included within the scope of this disclosure as defined in the following claims.

CLAIMS

What is claimed is:

1. A method, comprising:
simulating a cutting tool drilling an earth formation to determine cyclic loading on a cutting element disposed on the cutting tool; and
designing a test to subject a physical cutting element to physical cyclic loading corresponding to the simulated cyclic loading.
2. The method of claim 1, further comprising:
performing the test on the physical cutting element; and
comparing physical forces on the physical cutting element during the physical cyclic loading to simulated forces on the simulated cutting element during the simulated cyclic loading.
3. The method of claim 2, adjusting at least one parameter of the test when a difference is determined between the physical forces and the simulated forces.
4. The method of claim 3, wherein the at least one parameter comprises a testing fixture parameter selected from a size of a testing fixture, an angular velocity of the testing fixture, a material of the testing fixture, and a shape of the testing fixture.
5. The method of claim 3, wherein the at least one parameter comprises at least one of an engagement length between the physical cutting element and a testing fixture, a depth of cut, and a shape of the physical cutting element.
6. The method of claim 2, wherein the physical forces and the simulated forces are plotted as a function of time.
7. The method of claim 1, wherein designing the test comprises:
determining a simulated linear velocity and a simulated loading period of the simulated cutting element during the cyclic loading;
designing the test to include contacting the physical cutting element to a testing fixture at a velocity equal to the simulated linear velocity and for a loading period equal to the simulated loading period.

8. The method of claim 1, wherein designing the test comprises designing a testing fixture to contact with the physical cutting element to subject the physical cutting element to the physical cyclic loading.
9. The method of claim 8, wherein designing the testing fixture comprises designing at least one testing fixture parameter selected from a size of the testing fixture, an angular velocity of the testing fixture, a material of the testing fixture, a shape of the testing fixture and an alternating pattern along a side of the testing fixture.
10. A method, comprising:
contacting a cutting element to a test fixture under cyclic loading conditions for a duration, each cycle of the cyclic loading conditions comprising contact between the cutting element and the test fixture at a velocity for a loading period; and
determining if a test condition is met after subjecting the cutting element to the cyclic loading conditions.
11. The method of claim 10, further comprising:
setting the test condition prior to contacting, the test condition selected from one of a number of cycles to meet a failure criterion and a number of hours to meet a failure criterion; and
determining if the cutting element meets the test condition after the duration of the cyclic loading.
12. The method of claim 11, wherein the failure criterion is selected from a crack initiation, a minimum crack propagation distance, a minimum fracture area.
13. The method of claim 10, further comprising:
when the test condition is not met, designing a second cutting element having at least one cutting element parameter different from the cutting element.
14. A testing fixture, comprising:
a body moveable in a direction, the body having a top side bordered by an outer side, wherein at least one of the top side and the outer side comprises an alternating pattern along the direction.
15. The testing fixture of claim 14, wherein the alternating pattern comprises a plurality of alternating slots and protrusions.

16. The testing fixture of claim 15, wherein a distance between adjacent protrusions and a speed of the body correspond to a loading period and a frequency of cyclic loading conditions.
17. The testing fixture of claim 14, wherein the outer side defines a cylindrical shape of the body, and wherein the direction is a rotational direction about a longitudinal axis of the body.
18. The testing fixture of claim 17, wherein the alternating pattern is formed on the outer side, the protrusions defining an outer diameter of the cylindrical body.
19. The testing fixture of claim 14, wherein the alternating pattern comprises at least two types of materials positioned as adjacent segments of material, each type of material having a different strength.
20. The testing fixture of claim 19, wherein segments of one type of material are removable.

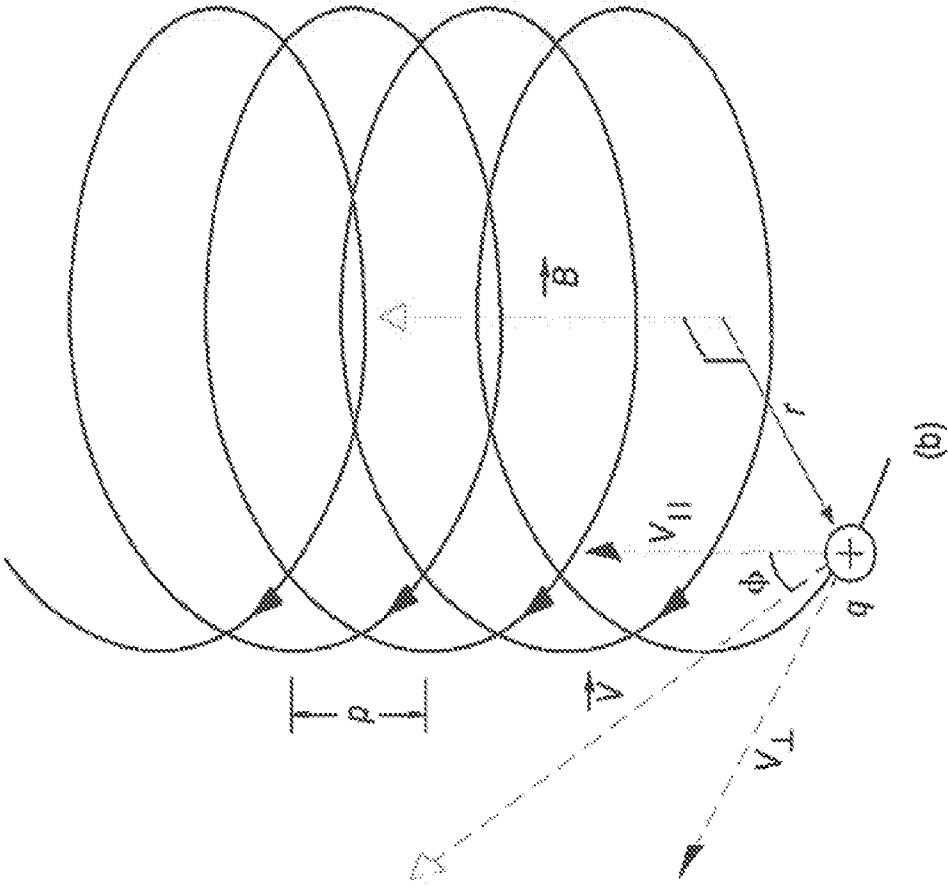
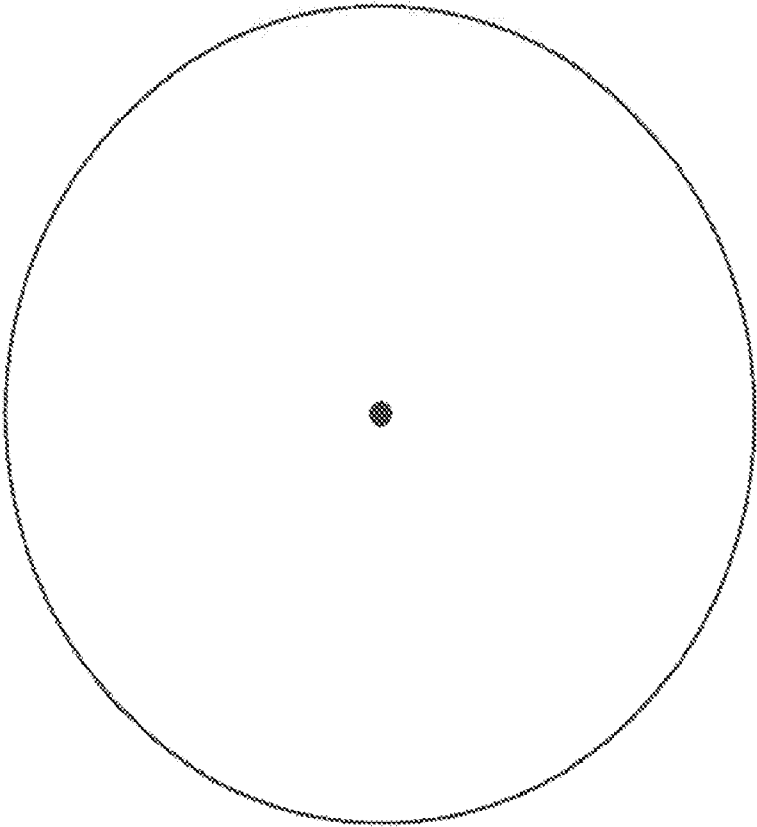


FIG. 1B



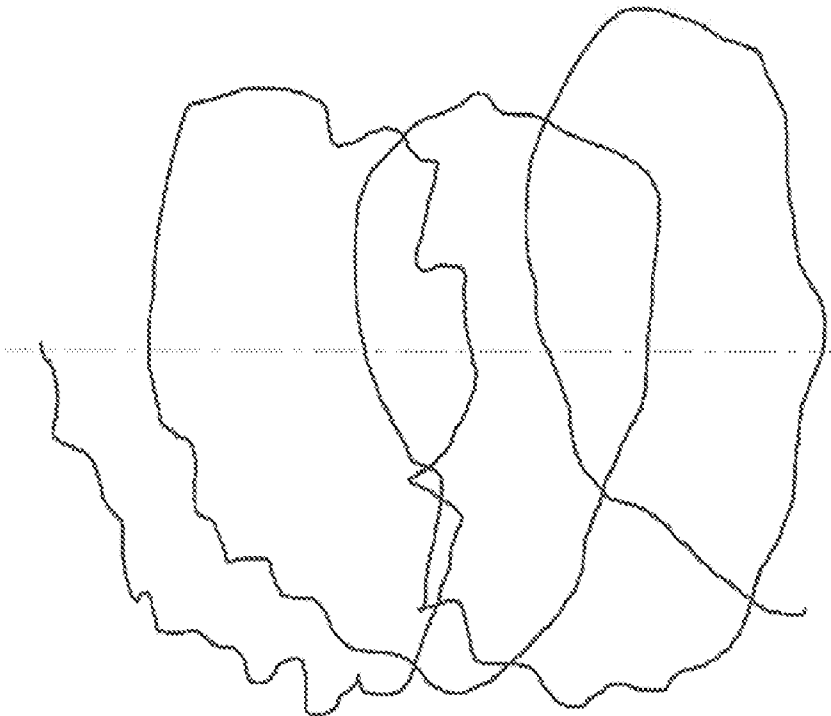


FIG. 1C

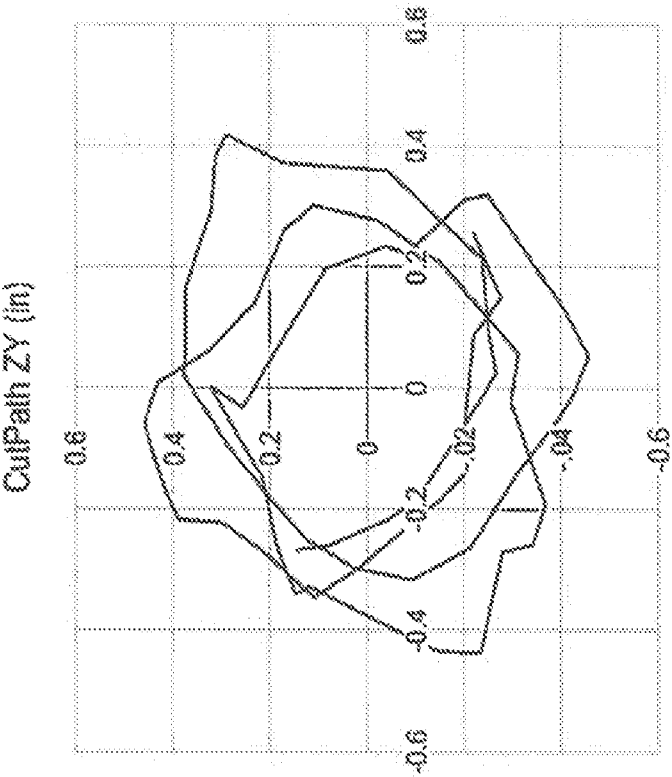


FIG. 1D

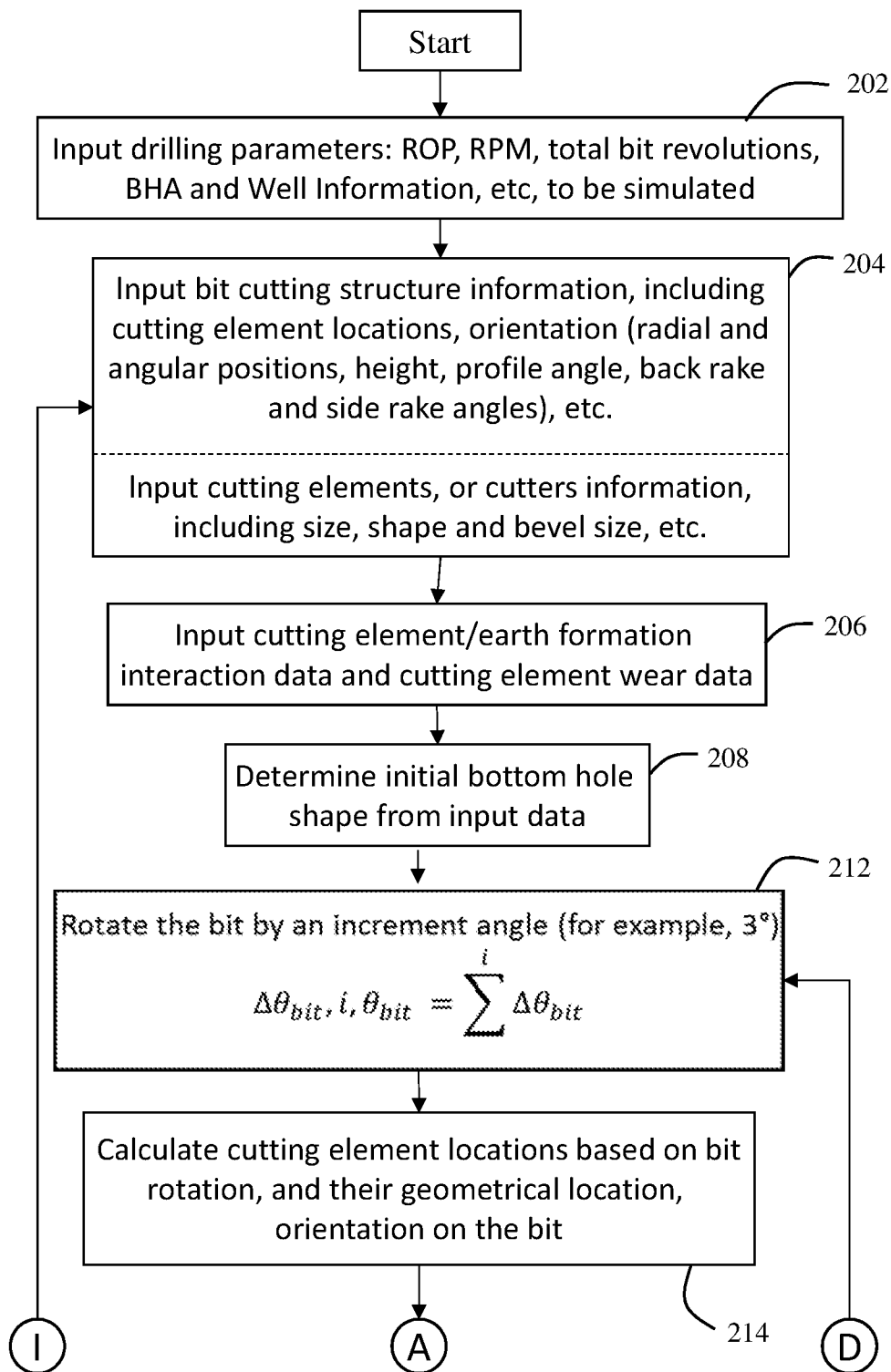


FIG. 2A

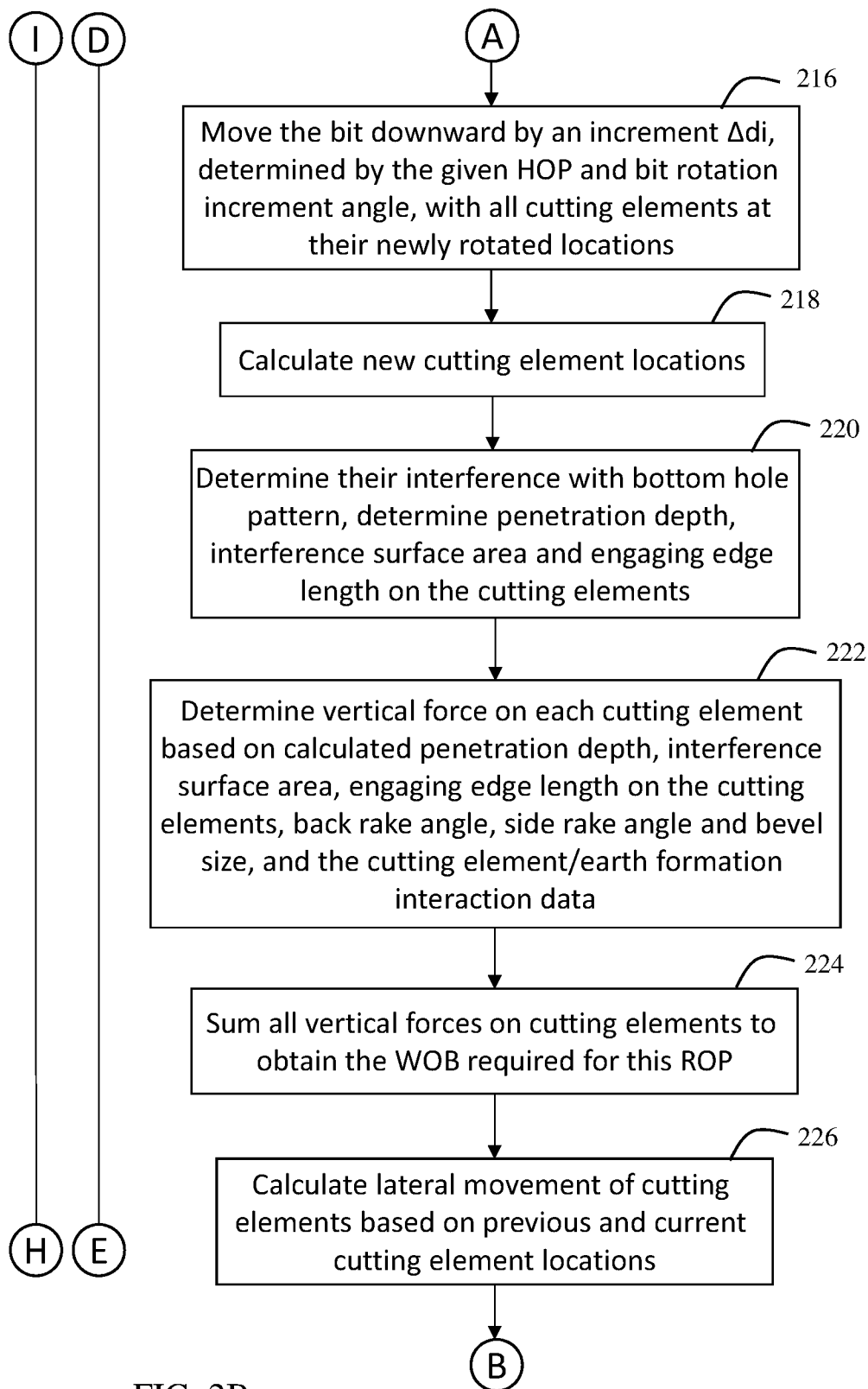
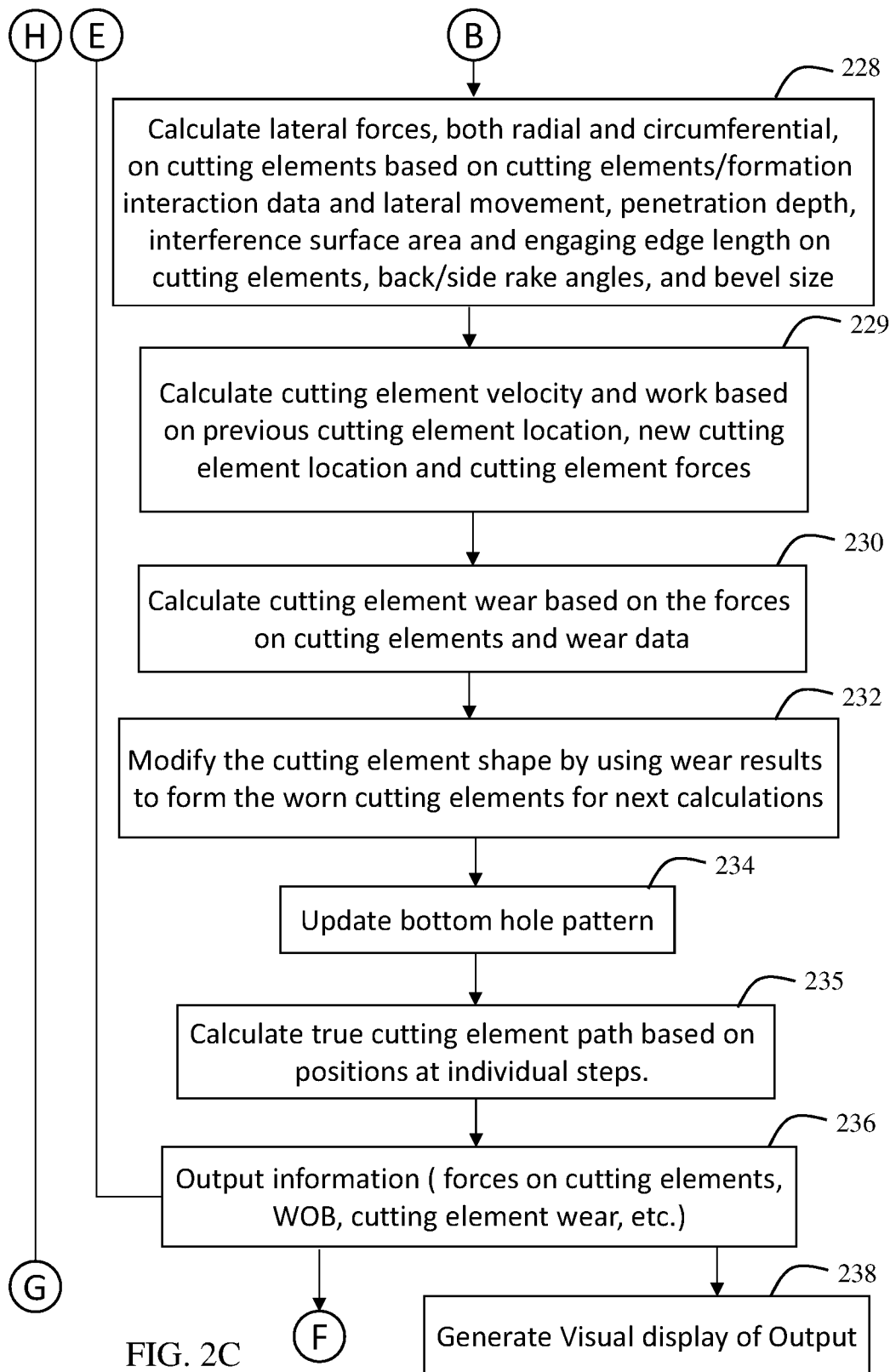


FIG. 2B



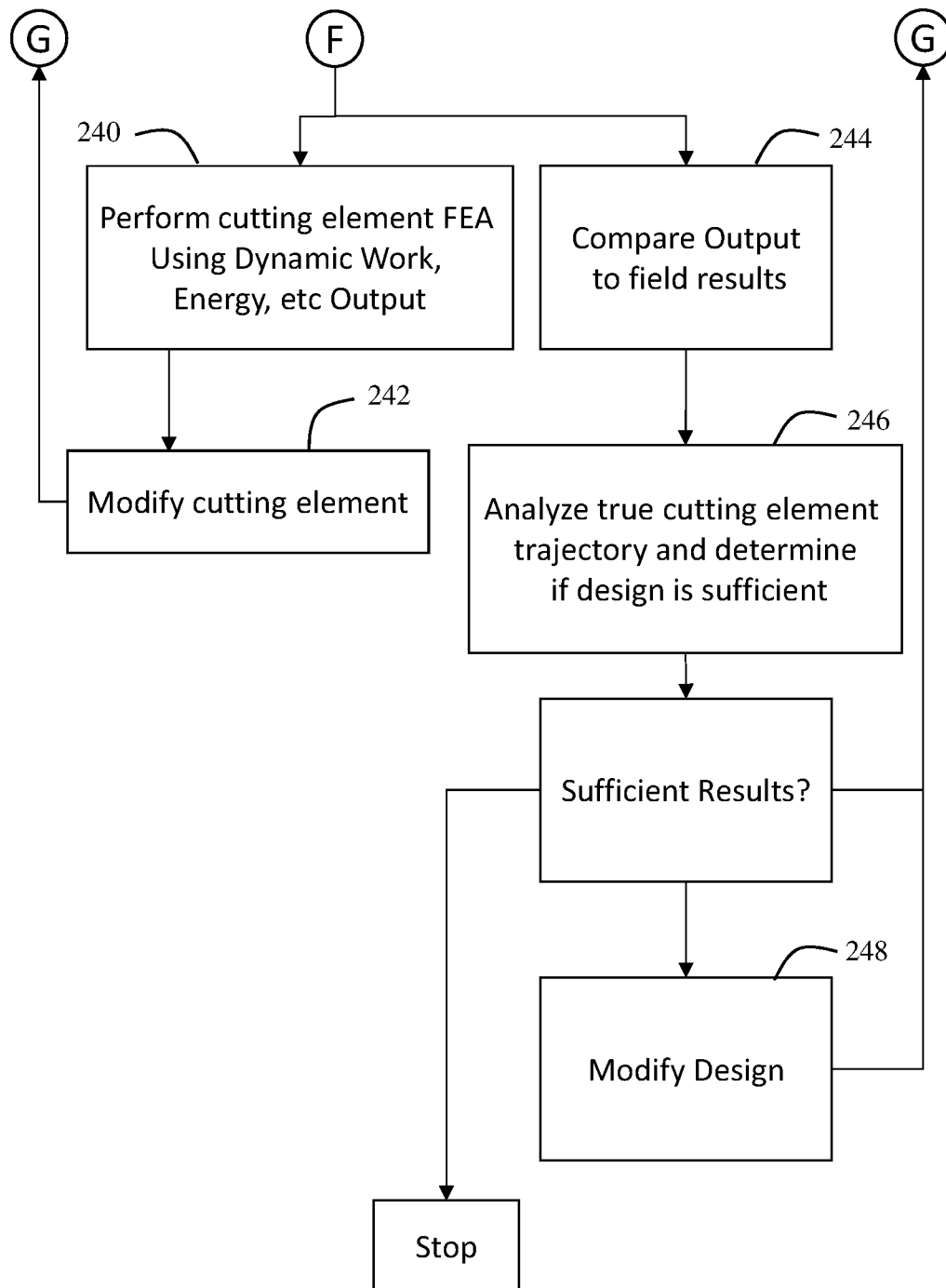


FIG. 2D

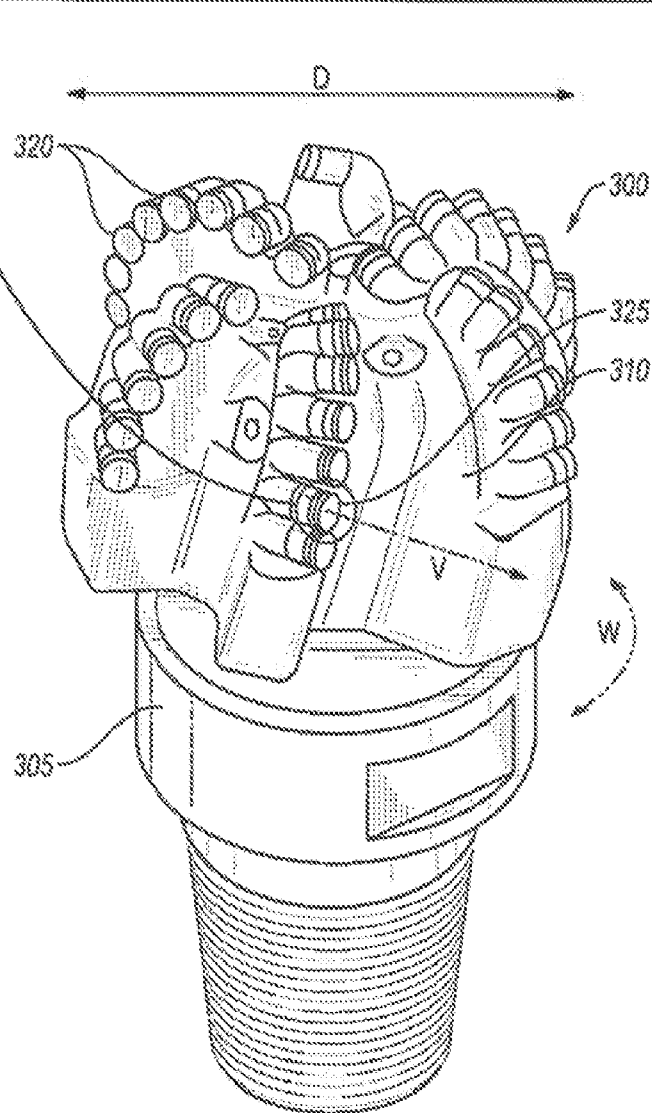
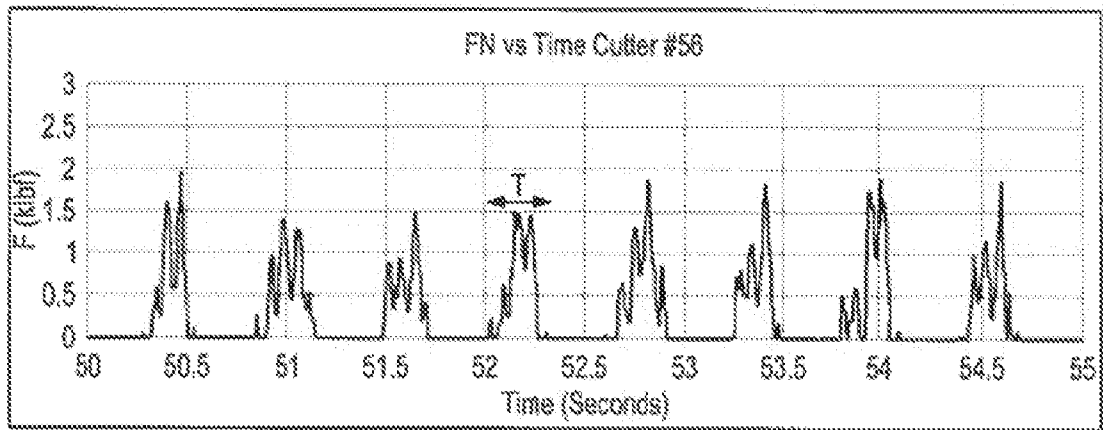


FIG. 3

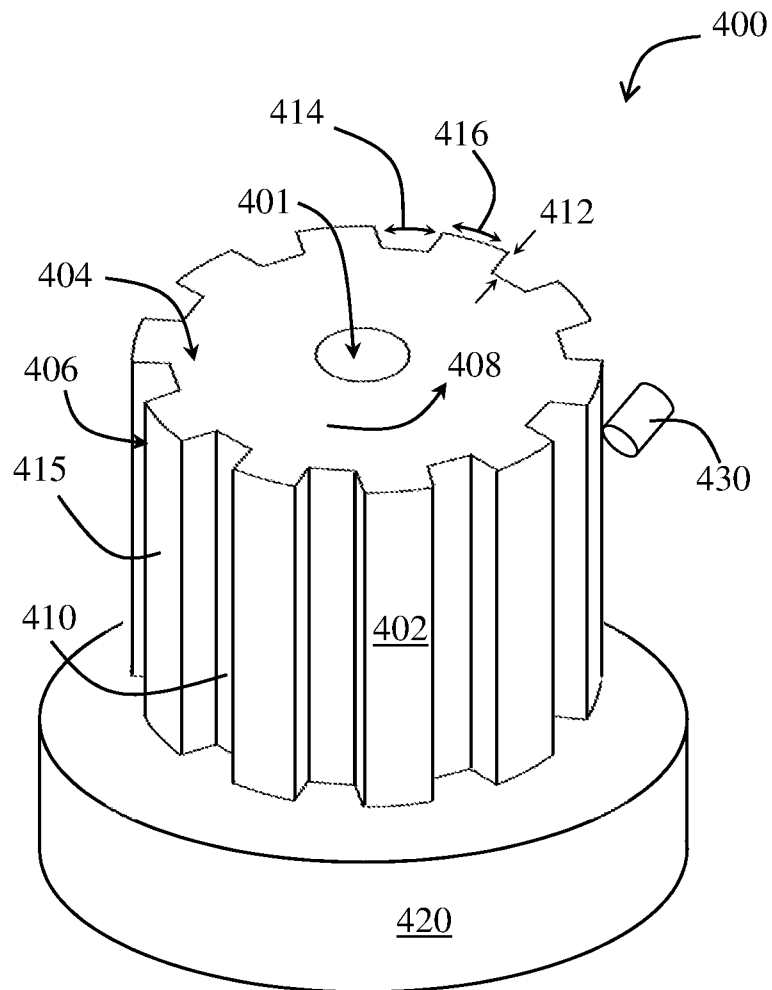


FIG. 4

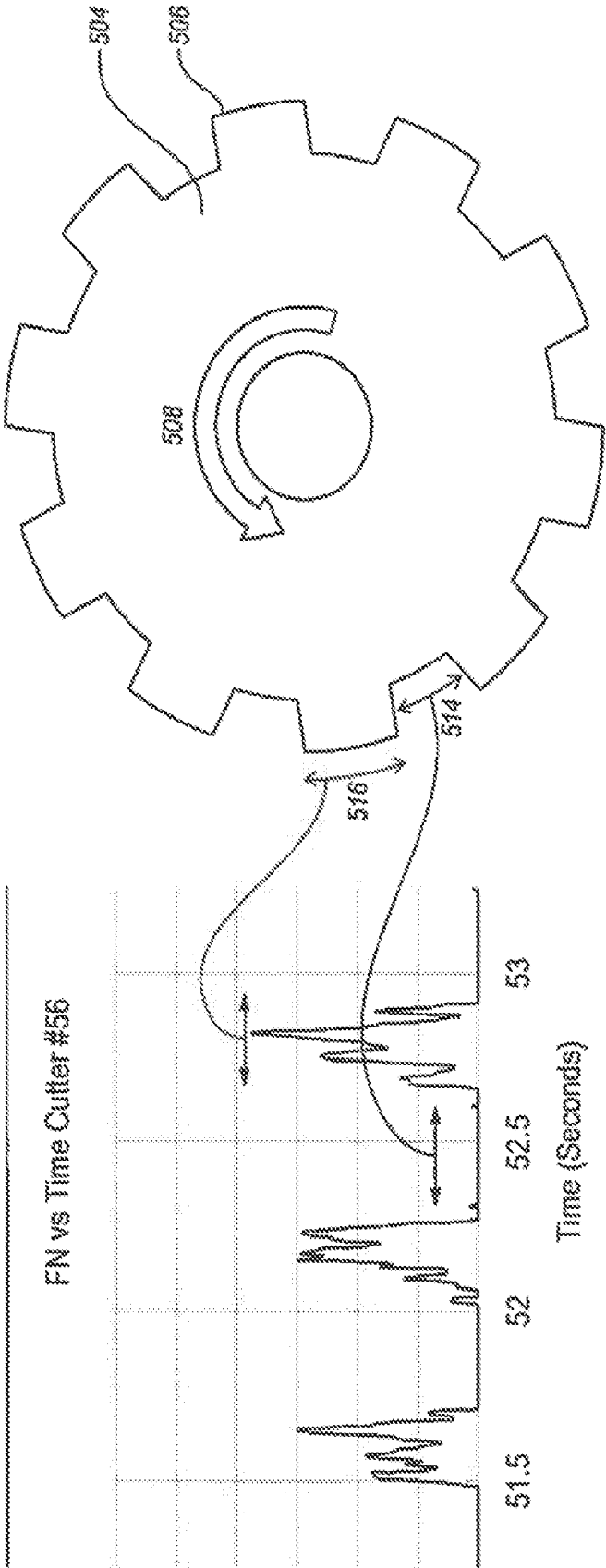


FIG. 5

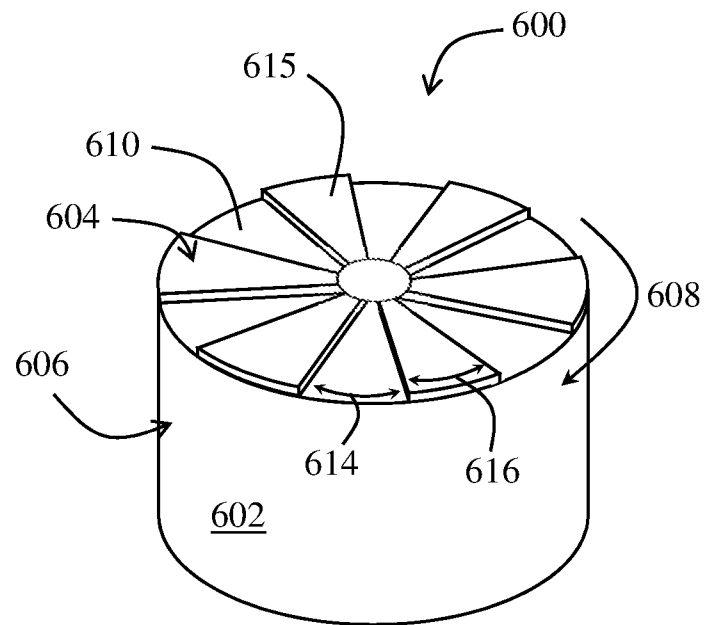


FIG. 6

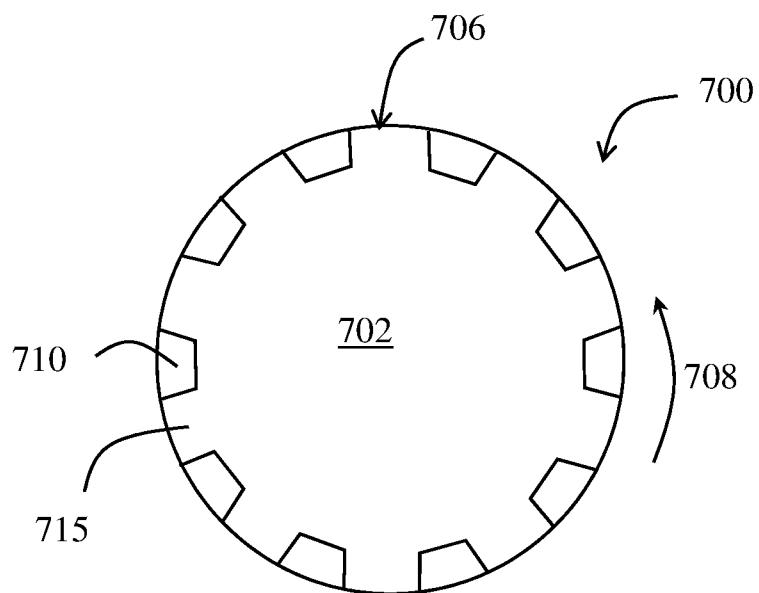


FIG. 7

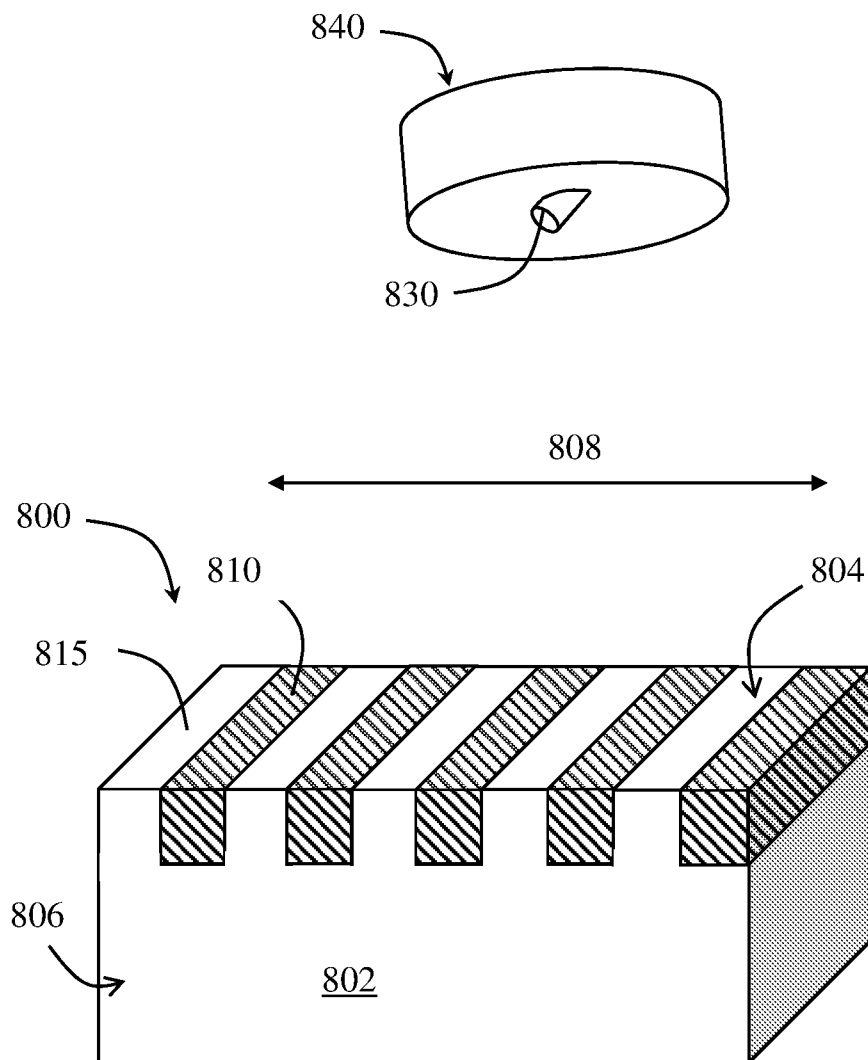


FIG. 8

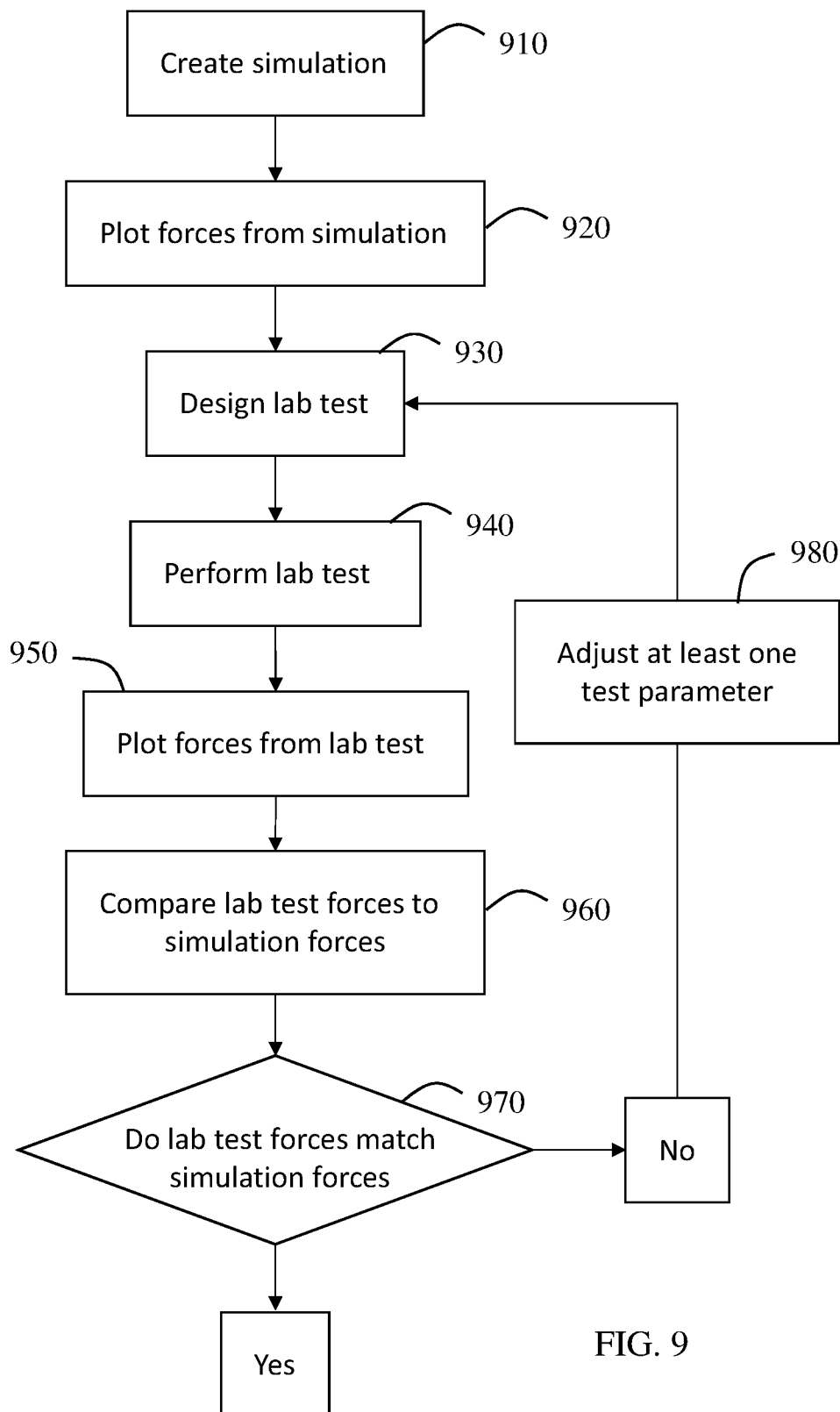


FIG. 9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/031892**A. CLASSIFICATION OF SUBJECT MATTER****G01N 1/28(2006.01)I, G01P 5/00(2006.01)I**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01N 1/28; B23B 27/18; G06F 17/50; B23Q 3/00; B22D 19/00; E21B 10/00; B23B 27/20; G01M 99/00; G01P 5/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & keywords: drill bit, model, simulation, test fixture and cyclic loading

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Y		10-13
A		1-9
Y	US 2014-0250994 A1 (DIAMOND INNOVATIONS, INC.) 11 September 2014 See abstract, paragraphs [0051], [0074] and claims 1, 8.	10-13
A	US 2005-0133272 A1 (HUANG et al.) 23 June 2005 See figure 3.	1-20
A	US 2014-0136168 A1 (SPENCER et al.) 15 May 2014 See figures 3, 4.	1-20
A	US 2010-0054875 A1 (HALL et al.) 04 March 2010 See figure 1.	1-20



Further documents are listed in the continuation of Box C.



See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search

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