



(51) International Patent Classification:

E21B 47/04 (2006.01) *E21B 47/26* (2012.01)
E21B 41/00 (2006.01) *E21B 44/02* (2006.01)

(21) International Application Number:

PCT/US2020/041902

(22) International Filing Date:

14 July 2020 (14.07.2020)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

16/928,199 14 July 2020 (14.07.2020) US

(71) Applicant: **LANDMARK GRAPHICS CORPORATION** [US/US]; 3000 N. Sam Houston Parkway E., Houston, Texas 77032 (US).

(72) Inventor: **SAMUEL, Robello**; 11306 Dawnheath Drive, Cypress, Texas 77433 (US).

(74) Agent: **GARDNER, Jason, D.** et al.; Kilpatrick Townsend & Stockton LLP, IP Docketing - 22nd Floor, 1100 Peachtree Street NE, Suite 2800, Atlanta, Georgia 30309 (US).

(81) Designated States (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, IT, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(54) Title: PREDICTING AND REDUCING VIBRATIONS DURING DOWNHOLE DRILLING OPERATIONS

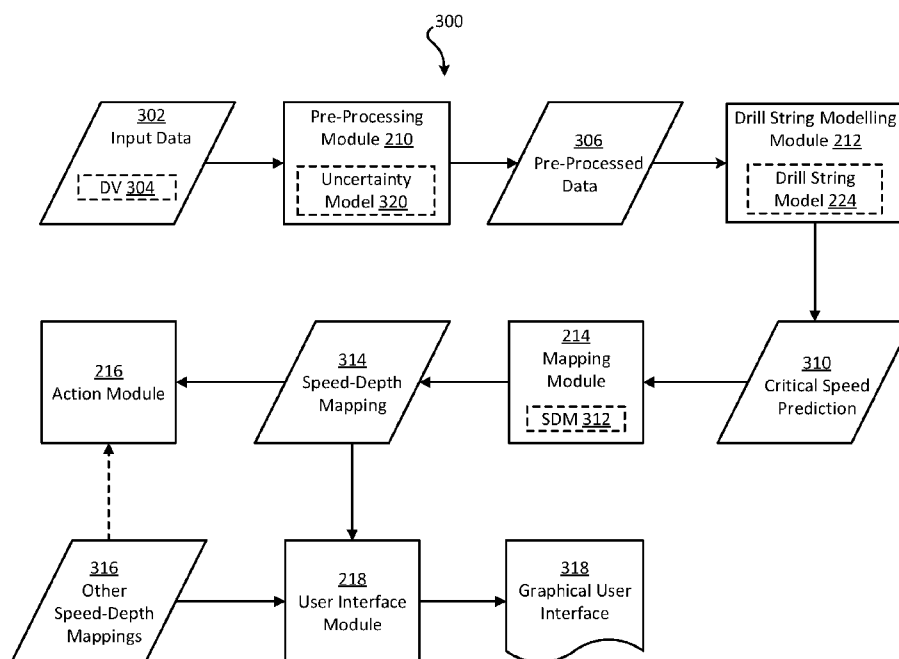


FIG. 3

(57) Abstract: Vibrations occurring during downhole drilling operations can be predicted and reduced according to some examples. One particular example includes a system that can receive drilling parameter values associated with a drilling operation involving drilling a wellbore through a subterranean formation using a drill string. The system can receive a depth value associated with the drilling parameter values. The system can provide the drilling parameter values as input to a drill string model to receive a critical speed prediction as output from the drill string model. The system can then generate a speed-depth mapping based on the critical speed prediction and the depth value. The speed-depth mapping can be used to avoid the critical speed at the depth in the wellbore, which may prevent a failure of the drill string resulting from associated vibrations.

(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

PREDICTING AND REDUCING VIBRATIONS DURING DOWNHOLE DRILLING OPERATIONS

TECHNICAL FIELD

[0001] The present disclosure relates generally to drilling systems for hydrocarbon extraction. More specifically, but not by way of limitation, this disclosure relates to predicting and reducing vibrations during downhole drilling operations.

BACKGROUND

[0002] Well systems for extracting hydrocarbons from a subterranean formation are typically formed by drilling a wellbore through the subterranean formation using a drill string. A drill string is an assembly made from long sections of pipe and a motor configured to rotate a drill bit. Examples of such the motor can include mud motors, electric motors, and air motors. Rotation of the drill bit advances the drill string through the subterranean formation to form the wellbore.

[0003] As a drill string engages in a drilling operation to drill a wellbore, vibrations can be introduced into the drill string due to a variety of factors. For example, vibrations can be introduced by rotation of the drill bit, by the motor used to rotate the drill bit, by imbalance in the drill string, and so on. Such vibrations can cause components of the drill string to prematurely wear or fail. Of particular concern are vibrations that vibrate drill-string components at resonance. For example, a catastrophic failure can occur if a drill bit is rotated at a speed that vibrates the drill string at its resonant frequency.

Brief Description of the Drawings

[0004] FIG. 1 is a cross-sectional view of an example of a well system according to some aspects of the present disclosure.

[0005] FIG. 2 is a block diagram of a computing device for predicting and reducing downhole vibrations according to some aspects of the present disclosure.

[0006] FIG. 3 is a data flow diagram of a process for predicting and reducing downhole vibrations according to some aspects of the present disclosure.

[0007] FIG. 4 is a graph of speed-depth mappings according to some aspects of the present disclosure.

[0008] FIG. 5 is a flow chart of an example of a process implemented by a

drill string model according to some aspects of the present disclosure.

[0009] FIG. 6 is a flow chart of an example of a process for determining a critical speed according to some aspects of the present disclosure.

DETAILED DESCRIPTION

[0010] Certain aspects and features of the present disclosure relate to predicting and avoiding critical speeds that may impart significant vibrations on a drill string prior to engaging, or while engaging, in a drilling operation. A critical speed is a rotational speed of a drill bit at which the magnitudes of the resultant vibrations in the drill string will likely exceed a predefined threshold limit, also referred to herein as a “critical threshold limit,” which may lead to a failure of one or more drill-string components. A drill string model can be used to predict critical speeds occurring at various depths during a drilling operation, whereby such predicted critical speeds can then be used by a well operator or an automated control system to avoid those critical speeds at their corresponding depths. To improve the accuracy of the predictions, the drill string model can take into account the properties of a mud motor or another type of motor associated with the drill string.

[0011] There are many characteristics of a drill-string motor that can affect the vibrations in the drill string. For example, motors can themselves emit vibrations due to imbalances resulting from their center of mass being offset from their axis of rotation. Additionally, motors can influence vibrations originating from other sources. How a motor affects the vibrations in a drill string can depend on the motor’s design, such as its lobe configuration, rotor mass, rotor-rotation eccentricity, and damping materials. As a result, it can be challenging to determine how a motor will influence vibrations in a drill string. But selecting the correct operating parameters to avoid critical speeds that can result in catastrophic vibrations is important. To that end, some examples of the present disclosure include a drill string model that can determine which drill-bit rotation speeds are likely to impart such severely damaging vibrations on the drill string, so that those rotation speeds can be avoided.

[0012] In some examples, the drill string model can be based on a forced frequency response (FFR) analysis that solves for resonant frequencies associated with vibrations, which in turn can be used to determine which speeds

result in those resonant frequencies. Damping effects can also be taken into account by the drill string model, such as damping effects from viscous, axial, torsional, and structural damping mechanisms. For example, the damping effects resulting from interactions with the formation, drilling fluid effects, inertial effects of acceleration of mud outside the drill string, and mass damping produced by the bottom hole assembly can be modeled. Using these techniques, the drill string model can determine three-dimensional vibrational responses of the drill string at various speeds ("excitation speeds"), to determine if any of those speeds are critical speeds resulting in vibrations at resonant frequencies. The critical speeds determined using the drill string model can then be output to a well operator or an automated control system, so that the critical speeds can be avoided. Other drilling parameter values that are likely to cause damaging vibrations can also be determined and highlighted for a well operator, so that those values can be avoided.

[0013] The drill string model can be used to analyze drill-string behavior, including motor behavior, over a specified range of operating parameters such as rotating speed, weight-on-bit, and mud weight. From this analysis, critical speeds can be determined at which a drill string may encounter damaging vibrations. Vibration control guidelines, such as a specification of weight-on-bit and RPM windows, can then be developed to minimize those vibration effects. Other forces can also be dynamically simulated and estimated using the drill string model. Examples of such forces can include relative bending stresses, shear forces, and lateral displacements around the motor (or another target area of interest).

[0014] These illustrative examples are given to introduce the reader to the general subject matter discussed here and are not intended to limit the scope of the disclosed concepts. The following sections describe various additional features and examples with reference to the drawings in which like numerals indicate like elements but, like the illustrative examples, should not be used to limit the present disclosure.

[0015] FIG. 1 is a cross-sectional view of a well system 10 according to some examples of the present disclosure. The well system 10 can include a wellbore 12 extending through various earth strata in an oil and gas formation 14 (e.g., a subterranean formation) located below the well surface 16. The wellbore 12 may be formed of a single bore or multiple bores extending into the formation 14, and

disposed in any orientation. The well system 10 can include a derrick or drilling rig 20. The drilling rig 20 may include a hoisting apparatus 22, a travel block 24, and a swivel 26 for raising and lowering casing, drill pipe, coiled tubing, and other types of pipe or tubing strings or other types of conveyance vehicles, such as wireline, slickline, and the like. The wellbore 12 can include a drill string 30 that is a substantially tubular, axially-extending drill string formed of a drill pipe joints coupled together end-to-end.

[0016] The drilling rig 20 may include a kelly 32, a rotary table 34, and other equipment associated with rotation or translation of drill string 30 within the wellbore 12. For some applications, the drilling rig 20 may also include a top drive unit 36. The drilling rig 20 may be located proximate to a wellhead 40, as shown in FIG. 1, or spaced apart from the wellhead 40, such as in the case of an offshore arrangement. One or more pressure control devices 42, such as blowout preventers (BOPs) and other well equipment may also be provided at wellhead 40 or elsewhere in the well system 10. Although the well system 10 of FIG. 1 is illustrated as being a land-based drilling system, the well system 10 may be deployed offshore.

[0017] A drilling or service fluid source 52 may supply a drilling fluid 58 pumped to the upper end of the drill string 30 and flowed through the drill string 30. The fluid source 52 may supply any fluid utilized in wellbore operations, including drilling fluid, drill-in fluid, acidizing fluid, liquid water, steam, or some other type of fluid.

[0018] The well system 10 may have a pipe system 56. For purposes of this disclosure, the pipe system 56 may include casing, risers, tubing, drill strings, subs, heads or any other pipes, tubes or equipment that attaches to the foregoing, such as the drill string 30, as well as the wellbore and laterals in which the pipes, casing, and strings may be deployed. In this regard, the pipe system 56 may include one or more casing strings 60 cemented in the wellbore 12, such as the surface 60a, intermediate 60b, and other casing strings 60c shown in FIG. 1. An annulus 62 is formed between the walls of sets of adjacent tubular components, such as concentric and non-concentric casing strings 60 or the exterior of drill string 30 and the inside wall of the wellbore 12 or the casing string 60c.

[0019] Where the subsurface equipment 54 is used for drilling and the conveyance vehicle is a drill string 30, the lower end of the drill string 30 may

include a bottom hole assembly 64, which may carry at a distal end a drill bit 66. During drilling operations, a weight-on-bit is applied as the drill bit 66 is rotated, thereby enabling the drill bit 66 to engage the formation 14 and drill the wellbore 12 along a predetermined path toward a target zone. In general, the drill bit 66 may be rotated with the drill string 30 from the drilling rig 20 with the top drive unit 36 or the rotary table 34, or with a downhole motor 68 (e.g., a mud motor) within the bottom hole assembly 64.

[0020] The bottom hole assembly 64 or the drill string 30 may include various other tools, including a power source 69, a rotary steerable system 71, and measurement equipment 73. The measurement equipment 73 can include sensors configured to detect characteristics of the drill string 30, the wellbore 12, or the formation 14. Examples of the sensors can include temperature sensors, pressure sensors, fluid-flow sensors, fluid-type sensors, accelerometers, strain gauges, gyroscopes, cameras, microphones, or any combination of these. The sensors can transmit sensor data to a computing device 90 for use in predicting and reducing vibrations during downhole drilling operations according to some aspects.

[0021] Sensor data and other information from the measurement equipment 73 may be communicated using electrical signals, acoustic signals, or other telemetry that can be received at the well surface 16 to, among other things, monitor the performance of the drill string 30, the bottom hole assembly 64, and the associated drill bit 66. Sensor data may also be communicated to monitor the conditions of the environment to which the bottom hole assembly 64 is subjected, such as a flow rate of the drilling fluid 58.

[0022] The drilling fluid 58 may be pumped to the upper end of drill string 30 and flow through a longitudinal interior 70 of the drill string 30, through the bottom hole assembly 64, and exit from nozzles formed in the drill bit 66. At the bottom end 72 of the wellbore 12, the drilling fluid 58 may mix with formation cuttings, formation fluids and other downhole fluids and debris. The drilling fluid mixture may then flow upwardly through an annulus 62 to return formation cuttings and other downhole debris to the well surface 16.

[0023] While drilling through the formation 14, the measurement equipment 73 can provide (e.g., in real time) sensor data to the computing device 90. The computing device 90 can analyze the sensor data from the measurement

equipment 73 to determine a critical speed associated with the depth of the drill string 30 in the wellbore 12.

[0024] In some examples, the computing device 90 can form part of an automated control system. In some such examples, the computing device 90 can generate one or more electronic signals based on the determined critical speed. The computing device 90 can then transmit the electronic signals to one or more components of the well system 10 to adjust a rotation speed of the drill bit 66 so as to avoid the critical speed. For example, the computing device 90 can transmit an electronic signal to the motor 68 for adjusting a speed of the motor 68 so as to avoid the critical speed. In some examples, this process can be automatically repeated at various depths. For example, as the drill bit 66 continues to drill the wellbore 12, the computing device 90 may automatically continue to adjust drilling parameter values based on the sensor data to avoid critical speeds at various depths.

[0025] While the computing device 90 is depicted as surface equipment, in some examples the computing device 90 can be implemented downhole within the wellbore 12. For example, the computing device 90 can be positioned as part of the bottom hole assembly 64. By installing the computing device 90 at the bottom hole assembly 64, communications lag may be avoided (e.g., from communicating information from the measurement equipment 73 to the surface, and returning communications from the surface to the rotary steerable system 71) such that critical-speed avoidance measures may be implemented in a quicker manner when compared to a surface position of the computing device 90. Additionally, while FIG. 1 depicts the computing device 90 operating in a land-based drilling environment, the computing device 90 may also be implemented in an offshore drilling environment.

[0026] FIG. 2 is a block diagram of a computing device 90 usable for predicting and reducing vibrations in downhole drilling operations according to some examples. The computing device 90 includes a processor 202 communicatively coupled to a user input device 220, a display device 222, and a memory 204 by a bus 206. Although these components are shown in FIG. 2 as being internal to a housing of the computing device 90, it will be appreciated that in other examples these components can be distributed and remote from one

another.

[0027] The processor 202 can include one processor or multiple processors. Non-limiting examples of the processor 202 include a Field-Programmable Gate Array (FPGA), an application-specific integrated circuit (ASIC), a microprocessor, etc. The processor 202 can execute instructions 208 stored in the memory 204 to perform operations. In some examples, the instructions 208 can include processor-specific instructions generated by a compiler or an interpreter from code written in any suitable computer-programming language, such as C, C++, C#, etc.

[0028] The user input device 220 can include one user input device or multiple user input devices. Examples of such user input devices can include a keyboard, mouse, or touch-screen display.

[0029] The display device 222 can include one display device or multiple display devices. Examples of such display devices can include a liquid crystal display (LCD) and a light-emitting diode (LED) display.

[0030] The memory 204 can include one memory or multiple memories. The memory 204 can be non-volatile and may include any type of memory that retains stored information when powered off. Non-limiting examples of the memory 204 include electrically erasable and programmable read-only memory (EEPROM), flash memory, or any other type of non-volatile memory. At least some of the memory can include a non-transitory computer-readable medium from which the processor 202 can read instructions 208. The non-transitory computer-readable medium can include electronic, optical, magnetic, or other storage devices capable of providing the processor 202 with computer-readable instructions or other program code. Examples of the non-transitory computer-readable medium include magnetic disk(s), memory chip(s), ROM, random-access memory (RAM), an ASIC, a configured processor, optical storage, or any other medium from which a computer processor can read the instructions 208.

[0031] In the example shown in FIG. 2, the instructions 208 include various software modules, such as a pre-processing module 210, a drill string modelling module 212, a mapping module 214, an action module 216, a user interface module 218, or any combination of these. But other examples can include more modules, fewer modules, or different modules than are shown in FIG. 2. The

modules 208-218 can be executed by the processor 202 to implement the process 300 shown in FIG. 3, as detailed below.

[0032] The process 300 begins with the receipt of input data 302. The input data 302 can include any number and combination of parameter values. For example, the input data 302 can include wellbore parameter values. A wellbore parameter value is a value for a wellbore parameter, where a wellbore parameter characterizes a wellbore drillable in a subterranean formation. Examples of wellbore parameters can include a size (e.g., radius or diameter), a target depth, an inclination, and a trajectory of the wellbore. Wellbore parameter values are generally relatively static throughout the course of a drilling operation. Additionally or alternatively, the input data 302 can include drilling parameter values. A drilling parameter value is a value for a drilling parameter, where a drilling parameter characterizes a drilling operation for drilling a wellbore in a subterranean formation. Examples of drilling parameters can include a weight-on-bit; a rotation speed of a drill bit; a rotary speed; an inclination of the drill string; and a mud property such as a flow rate, weight, or viscosity of the mud. Drilling parameter values are generally relatively dynamic throughout the course of a drilling operation. Additionally or alternatively, the input data 302 can include motor parameter values. A motor parameter value is a value for a motor parameter, where a motor parameter characterizes a motor in a drill string. Examples of motor parameters can include an eccentricity of the motor, a weight of the motor's rotor, an elastomer of the motor, motor configuration such as a lobe configuration, and a position of the motor in the drill string. Motor parameter values are generally relatively static throughout the course of a drilling operation. Other parameter values can also be included in the input data 302.

[0033] The input data 302 may also include a depth value (DV) 304 indicating a depth of a drill string component in the wellbore. The depth value 304 can correspond to the parameter values. For example, the depth value 304 can indicate a depth of the drill-string motor in the wellbore when the parameter values were measured by one or more sensors.

[0034] In some examples, the input data 302 can be received as user input via a user input device 220. A well operator may provide the input data 302 as user input prior to engaging in a drilling operation to obtain valuable information about the drilling operation ahead-of-time, which may aid the well operator in

reducing or avoiding vibrations that can lead to preemptive wear or failure of drill-string components. In other examples, the input data 302 can be received while a drilling operation is ongoing, for example as real-time data streamed from one or more sensors during the drilling operation. Examples of such sensors can include temperature sensors, pressure sensors, fluid-flow sensors, fluid-type sensors, accelerometers, strain gauges, depth sensors, inclinometers, gyroscopes, cameras, microphones, or any combination of these. The sensors can be coupled to the drill string or positioned elsewhere in the well system for obtaining the input data 302.

[0035] Next, the input data 302 can be provided as input to the pre-processing module 210. The pre-processing module 210 may perform one or more data-cleansing operations on the input data 302 to generate pre-processed data 306. For example, the pre-processing module 210 can detect incomplete, incorrect, inaccurate, or irrelevant parts of the input data 302 and correct those parts of the input data 302 by replacing, modifying, or deleting those parts of the input data 302, in order to generate pre-processed data 306.

[0036] In some examples in which the input data 302 is real-time data streamed from sensors, the pre-processing module 210 can account for uncertainty in the input data 302 by applying one or more uncertainty models 320 to the input data 302. Uncertainty can arise in the input data 302 due to any number of factors, such as downhole temperature and pressure fluctuations, inconsistencies and degradations of the sensors, interference and noise, and so on. Uncertainty models 320 can be used to remedy such uncertainties.

[0037] Each of the uncertainty models 320 can correspond to one specific input parameter, such as a wellbore parameter or drilling parameter. An uncertainty model can include a predefined probability-distribution representing a distribution of values for that specific input parameter. The values in the distribution may come from one or more samples, which may have been previously synthesized or collected. Each value's position in the distribution can be dictated by the number of times the value occurred in the samples. The distribution can indicate a probability that a value of the specific input parameter provided in the input data 302 is correct. The pre-processing module 210 can use the one or more uncertainty models 320 to identify and correct values in the input data 302 that may be inaccurate.

[0038] Next, the pre-processed data 306 can be provided as input to the drill string modelling module 212. The drill string modelling module 212 can include a drill string model 224 configured to simulate vibrational properties of a drill string during a drilling operation. The drill string modelling module 212 can receive the pre-processed data 306 and generate a critical speed prediction 310 based on the pre-processed data 306. A critical speed prediction is a prediction of a critical speed. The drill string modelling module 212 can provide the critical speed prediction 310 as output.

[0039] To generate the critical speed prediction 310, the drill string model 224 may jointly consider aspects of both the drill string itself and a motor associated with the drill string. For example, the drill string model 224 can take into account damping effects of substances (e.g., materials and fluids) inside the drill string and a rotational speed of the drill string. The drill string model 224 can also take into account a lobe configuration, eccentricity, and rotational speed of the motor. To that end, the drill string model 224 may include one or more sub-models, such as motor model 226, which can simulate vibrational properties of the motor. These and other features of the drill string model 224 are described in greater detail later on with respect to FIG. 5.

[0040] In some examples, the drill string modelling module 212 may also generate other outputs using the drill string model 224. For example, the drill string modelling module 212 can use the drill string model 224 to determine displacement characteristics (e.g., axial displacement and torsional displacement) of the drill string when operating at the predicted critical speed 310. The drill string modelling module 212 may then output such displacement characteristics.

[0041] Next, the critical speed prediction 310 can be provided as input to a mapping module 214. The mapping module 214 can generate an association (or “mapping”) between the critical speed prediction 310 and the depth value 304 provided in the input data 302. Such associations are referred to herein as speed-depth mappings (SDMs). In this example, the mapping module 214 can generate an SDM 312 indicating the predicted critical speed 310 at the particular depth 304 in the wellbore.

[0042] In some examples, the process described above can be repeated for other input data to generate other speed-depth mappings 316. Each of the other

speed-depth mappings 316 can also indicate a predicted critical speed at a corresponding depth in the wellbore. The combination of the speed-depth mapping 314 and the other speed-depth mappings 316 can form a roadmap that can aid a well operator in developing a drilling plan. For example, the speed-depth mapping 314 and the other speed-depth mappings 316 can be provided as input to the user interface module 218, which can generate a graphical user interface 318 for output on the display device 222 based on the speed-depth mappings. In one such example, the graphical user interface 318 can include a plot with the critical speeds along the X-axis and depth values along the Y-axis (or vice-versa), such as the plot 500 shown in FIG. 5. A well operator can view the graphical user interface 318 and use the speed-depth mappings therein to develop a drilling plan in which the critical speed at each depth is avoided during a drilling operation. This may reduce the likelihood of drill-string failure caused by vibrations imparted at the critical speeds.

[0043] In some examples, one or more of the speed-depth mappings (e.g., speed-depth mapping 314 and the other speed-depth mappings 316) can be provided as input to the action module 216. The action module 216 can be configured to automatically perform one or more operations based on the speed-depth mappings, for example to avoid the critical speed at each depth. In some such examples, the action module 216 can execute operations configured to adjust one or more parameter values associated with an ongoing drilling operation to avoid the critical speed at each depth. For instance, the operations can be configured to adjust a drill-bit rotation speed or another drilling parameter value so as to avoid a critical speed at a particular depth. The action module 216 may repeat this process at each depth to avoid the critical speed corresponding to that depth. This may prevent vibrations from exceeding the critical threshold limit at each depth.

[0044] It will be appreciated that although FIG. 3 shows a certain number and arrangement of steps, other examples can include more steps, fewer steps, different steps, or a different order of the steps than is shown in FIG. 3. Other examples may also involve more, fewer, or different components than are described with respect to FIG. 3. For instance, in an alternative example the process 300 may exclude the pre-processing module 210 and act on the raw input data 302, rather than the pre-processed data 306.

[0045] As noted above, a drill string model 224 can be used to determine critical speed values and other information associated with a drilling operation. FIG. 5 is a flow chart of an example of a process implemented by the drill string model 224 to determine such information. But other examples can include more steps, fewer steps, different steps, or a different order of the steps than is shown in FIG. 5. While the following process is described as being implemented by the drill string model 224, it will be appreciated that this may involve the processor 202 executing the process based on the drill string model 224.

[0046] In block 502, the drill string model 224 receives parameter values as input. The parameter values can be derived from the input data 302. In some examples that lack pre-processing, the parameter values can come from the raw input data 302. And in some examples that include pre-processing, the parameter values can come from the pre-processed data 306.

[0047] The parameter values can include wellbore parameter values, drilling parameter values, motor parameter values, or any combination of these. Examples of the motor parameter values can include a location of a motor in the drill string, a motor length, a mass of a rotor in the motor, an eccentricity of the motor, and a lobe configuration of the motor.

[0048] In block 504, the drill string model 224 determines stiffness matrices associated with the drill string while taking into account the motor parameter values. Examples of the stiffness matrices can include a linear stiffness matrix, a geometric stiffness matrix, a contact stiffness matrix, a friction stiffness matrix, or any combination of these. A linear stiffness matrix can indicate a stiffness of the components of the drill string, including the motor. A geometric stiffness matrix can indicate a stiffness of the drill string based on the dimensions of the motor, such as the outside diameter and inside diameter of the motor. A contact stiffness matrix can indicate the stiffness of a component of the drill string contacting a wall of the wellbore. A friction stiffness matrix can indicate a stiffness of the drill string as a result of a contact between the component of the drill string and the wall of the wellbore. Each of these stiffness matrices can represent a system of linear equations to be solved to ascertain an approximate solution to a differential equation while performing a finite element analysis.

[0049] Some examples can include a user selectable option for turning on or off contact dynamics. If contact dynamics are activated, the contact stiffness

matrix can be generated based on the friction stiffness matrix. For example, the friction stiffness matrix can be generated and added to the contact stiffness matrix, so that the contact stiffness matrix dynamically changes based on the friction stiffness matrix. If contact dynamics are deactivated, the friction stiffness matrix may not be generated.

[0050] In block 506, the drill string model 224 determines boundary conditions. Examples of the boundary conditions can include a weight-on-bit, a rotational speed, a friction level. The boundary conditions can serve to bound aspects of the fine element analysis to arrive at a reliable solution. In some examples, determining the boundary conditions can involve the drill string model 224 receiving the boundary conditions as user input. For example, the boundary conditions may be provided as part of the input data 302 of FIG. 3. In other examples, the boundary conditions may be predefined. For example, the boundary conditions may be preprogrammed into the drill string model 224.

[0051] In block 508, the drill string model 224 generates damping matrices indicating the damping effects of various substances associated with a drilling operation. The damping effects can arise from viscous, axial, torsional, and structural damping mechanisms, some or all of which may be taken into account in calculating the damping matrices.

[0052] In some examples, the damping matrices can include a structural damping matrix and a fluid damping matrix. The structural damping matrix can indicate a damping effect of a structural material of the drill string. The fluid damping matrix can indicate a damping effect of a drilling fluid such as a drilling mud. Since fluid can behave differently in response to different vibration frequencies, yielding both static damping components (that do not change as a function of vibration frequency) and dynamic damping components (that change as a function of vibration frequency).

[0053] In block 510, a critical speed can be determined based on the stiffness matrices, the boundary conditions, and the damping matrices. In some examples, the critical speed can be determined by performing a loop over a range of candidate speeds. For example, a vibration response of the drill string can be determined for each speed in the range of candidate speeds (based on the stiffness matrices, the boundary conditions, and the damping matrices). If the vibration response of the drill string for a particular speed exceeds a critical

threshold level, for example due to the resultant vibrations being at a resonant frequency, then that speed can be determined to be a critical speed. An example of this looping process is described in greater detail later on with respect to FIG. 6.

[0054] The vibration response of the drill string can depend on the vibration response of the motor at a particular speed. The vibration frequency for the motor can be represented as a function of the variables effecting the frequency. For example, the vibration frequency can be represented mathematically as follows:

$$f_n = f(w, e, i, N, \mu_e, C_e)$$

where f_n is the vibration frequency, w is the weight of the rotor, e is the eccentricity of the motor, i is the lobe configuration of the rotor, N is the speed of the rotor, μ_e is the sliding/rolling friction of the rotor stator, and C_e is the rotor/stator coefficient. In some examples, the drill string model 224 can take into account some or all of these factors in determining the vibration response of the motor, which in turn can be used to determine the vibration response of the drill string.

[0055] In block 512, the drill string model 224 outputs the critical speed prediction 310. In some examples, outputting the critical speed prediction 310 may involve returning the critical speed prediction 310 to a main loop or another function of a computer program executed by the processor 202. Additionally or alternatively, outputting the critical speed prediction 310 may involve storing the critical speed prediction 310 in memory, such as memory 204. This may enable the critical speed prediction 310 to be accessed by processor 202 or another hardware component of the computing device 90.

[0056] FIG. 6 is a flow chart of an example of a process for determining a critical speed according to some aspects. But other examples can include more steps, fewer steps, different steps, or a different order of the steps than is shown in FIG. 6. While the following process is described as being implemented by the drill string model 224, it will be appreciated that this may involve the processor 202 executing the process based on the drill string model 224.

[0057] In block 602, the drill string model 224 determines a range of candidate bit speeds. A bit speed is a speed at which a drill bit of a drill string is rotated. The bit speeds can be determined based on input settings provided by the user. Examples of the input settings can include a starting bit speed, an ending

bit speed, and a step increment. The step increment can be an increment at which the speed is to be increased.

[0058] Bit speeds can depend on a rotational speed of the motor (“motor speed”) and a rotational speed of the drill string (“string speed”). As a result, three general scenarios typically occur. A first scenario can involve the string speed remaining constant and equal to zero, while the motor speed varies by the step increment. One particular example can involve an initial motor speed of 100 RPM, a constant string speed of 0 RPM, a step increment of 10 RPM, and an ending string speed of 150 RPM. In that example, the calculated range of candidate bit speeds can be 100 RPM (100 motor speed + 0 string speed), 110 RPM (110 motor speed + 0 string speed), 120 RPM (120 motor speed + 0 string speed), 130 RPM (130 motor speed + 0 string speed), 140 RPM (140 motor speed + 0 string speed), and 150 RPM (150 motor speed + 0 string speed).

[0059] A second of the three scenarios can involve the string speed varying, while the motor speed remains constant and greater than zero. In this second scenario, any of the following circumstances can occur:

- a) the starting string speed < the motor speed, and the ending string speed > the motor speed;
- b) the starting string speed < the motor speed, and the ending string speed < the motor speed;
- c) the starting string speed < the motor speed, and the ending string speed ≤ the motor speed;
- d) the starting string speed ≤ the motor speed, and the ending string speed ≤ the motor speed;
- e) the starting string speed > the motor speed, and the ending string speed < the motor speed;
- f) the starting string speed > the motor speed, and the ending string speed > the motor speed; and
- g) the starting string speed ≥ the motor speed, and the ending string speed > the motor speed.

But if the drill string model 224 enforces a condition that the starting string speed is greater than or equal to the motor speed, and that the ending string speed is greater than the starting speed, then there is only one circumstance (g) that can result.

[0060] A third scenario of the three scenarios can involve the string speed remaining constant and greater than zero, while the motor speed varies by the step increment. One particular example can involve an initial motor speed of 100 RPM, a constant string speed of 20 RPM, a step increment of 10 RPM, and an ending string speed of 150 RPM. In that example, the calculated range of candidate bit speeds can be 120 RPM (100 motor speed + 20 string speed), 130 RPM (110 motor speed + 20 string speed), 140 RPM (120 motor speed + 20 string speed), and 150 RPM (130 motor speed + 20 string speed).

[0061] In block 604, the drill string model 224 determines if a stopping condition is satisfied. An example of the stopping condition may be that all of the candidate bit speeds have been analyzed. Another example of the stopping condition may be that a critical speed has been identified. If the stopping condition is satisfied, the process may proceed to block 616 at which the process can end. Otherwise, the process can proceed to block 606.

[0062] In block 606, the drill string model 224 selects a candidate bit speed (e.g., the next candidate bit speed in the range) for analysis.

[0063] In block 608, the drill string model 224 determines a vibration response at the candidate bit speed. The drill string model 224 can determine the vibration response based on the matrices described above with respect to FIG. 5. For example, the stiffness matrices can be summed into a complex stiffness matrix, which can form the basis of a system Jacobean matrix. A lumped mass matrix can then be added to the Jacobean matrix. The structural damping matrix and fluid damping matrix can also be added to the Jacobean matrix. Other damping matrices, such as a viscous damping matrix, can also be added to the Jacobean matrix. A vibration response can then be generated based on the Jacobean matrix.

[0064] In some examples, the vibration response can be provided in the form of one or more normalized numerical values corresponding to one or more target parameters of interest. Each numerical value for each target parameter can be determined by dividing (i) a calculated value for the target parameter at the candidate bit speed by (ii) a maximum possible value for that target parameter. For example, a numerical value for a target parameter can be determined using the following equation:

$$V_i = E_i/E_{peak}$$

where V_i is the numerical value for the target parameter E , E_i is the calculated value for that target parameter at the candidate bit speed, and E_{peak} is the maximum possible value for that target parameter (e.g., the value at resonance). Examples of the target parameter E can include rotational stress, displacement, moment, shear, etc. Using the above equation, the numerical values V_i for the target parameter E will fall between 0 and 1. Normalizing the numerical values in this way can assist with quantifying vibration intensities, which in turn may enable comparisons to be made between motor designs. For example, motors with different lobe configurations can yield different vibration-intensity levels at the same bit speeds. These different vibration-intensity levels can be quantified using the normalized numerical values described above, so that the vibration-intensity levels may be easily compared to one another.

[0065] In some examples, the vibration response can be determined based on a phase angle between the motor of the drill string and the drill bit. Phase angles can be useful in determining a vibration response when several vibration sources are considered in a drill string. For example, the value of a target parameter can be determined using the following mathematical equation:

$$x(t) = x_m \cos(\omega t - \phi)$$

where $x(t)$ is the value for a target parameter (e.g., stress, force, displacement, or moment) being measured as a function of time; x_m is the maximum magnitude of the target parameter; ω is rotor speed; t is time; j is the degree of freedom number; and ϕ is the phase angle, where $\phi_{dj} = \tan^{-1}(u_{sj}/u_{cj})$ with s and c being displacements in two directions. The largest value of the target parameter ($x(t)$) can occur when $\omega t - \phi = 0$, and the smallest value of the target parameter ($x(t)$) can occur when $\omega t - \phi = \pi/2$. Using the above equation, phase angles can be determined for one or more target parameters. The phase angles can depend on the motor's design. For example, motors with different lobe configurations can yield different phase angles, and thus different vibration intensities, at the same bit speeds.

[0066] In block 610, the drill string model 224 determines if the vibration response exceeds a threshold limit, which can be predefined. In some examples, the vibration response can exceed the threshold limit if at least one of the

numerical values associated with at least one of the target parameters described above response exceeds the threshold limit.

[0067] If the vibration response exceeds the threshold limit, the process can proceed to block 612 at which the candidate bit speed can be flagged as a critical speed. Otherwise, the process can proceed to block 614 at which the candidate bit speed can be flagged as a non-critical speed. Either way, the process may then return to block 604, at which point the next candidate-bit speed can be selected and the process can iterate accordingly. At the conclusion of the process shown in

FIG. 6, the drill string model 224 may have identified one or more critical speeds associated with the drill string. These critical speeds may then be output to the well operator or an automated control system, for example so that the critical speeds can be avoided.

[0068] Some aspects and features of the present disclosure can be implemented according to one or more of the following examples:

[0069] Example #1: A system of the present disclosure can include a processor and a memory including instructions that are executable by the processor to perform operations. The operations can include receiving a plurality of sets of drilling parameter values associated with a drilling operation involving drilling a wellbore through a subterranean formation using a drill string. The operations can include receiving a plurality of depth values associated with the plurality of sets of drilling parameter values. Each depth value can correspond to a particular set of drilling parameter values in the plurality of sets of drilling parameter values. The operations can include providing the plurality of sets of drilling parameter values as input to a drill string model to receive a plurality of critical speed predictions as output from the drill string model. Each critical speed prediction can be determined by the drill string model based on a respective set of drilling parameter values of the plurality of sets of drilling parameter values. The operations can include generating a plurality of speed-depth mappings based on the plurality of critical speed predictions and the plurality of depth values. Each speed-depth mapping can include (i) a respective critical-speed prediction from among the plurality of critical speed predictions and (ii) a respective depth-value associated with the respective set of drilling parameter values used by the drill string model to determine the respective critical-speed prediction. The operations

can include generating a graphical user interface including the plurality of speed-depth mappings for display on a display device. The plurality of speed-depth mappings in the graphical user interface can be usable to reduce vibrations in the drill string at the plurality of depth values during the drilling operation.

[0070] Example #2: The system of Example #1 may feature the memory further including instructions for the drill string model. The drill string model can be configured to generate a range of candidate bit speeds. For each candidate bit speed in the range of candidate bit speeds, the drill string model can: determine a respective vibration response associated with the candidate bit speed; determine if the respective vibration response exceeds a predefined threshold limit; and flag the candidate bit speed as a critical speed if the respective vibration response is greater than or equal to the predefined threshold limit; or flag the candidate bit speed as a non-critical speed if the respective vibration response is below the predefined threshold limit.

[0071] Example #3: The system of any of Examples #1-2 may feature the drill string model being configured to determine a respective vibration response based on a damping effect of substance in the drill string.

[0072] Example #4: The system of any of Examples #1-3 may feature the drill string model being configured to determine a respective vibration response based on one or more characteristics of a motor of the drill string.

[0073] Example #5: The system of Example #4 may feature the one or more characteristics including a lobe configuration of the motor.

[0074] Example #6: The system of any of Examples #1-5 may feature the memory further including instructions that are executable by the processor for causing the processor to receive the plurality of sets of parameter values from one or more sensors coupled to the drill string.

[0075] Example #7: The system of any of Examples #1-6 may feature the memory further including instructions that are executable by the processor for causing the processor to adjust a drilling parameter value associated with the drilling operation so as to prevent a drill bit of the drill string from rotating at a critical speed included in the plurality of critical speed predictions when the drill string is at a particular depth that is associated with the critical speed in the plurality of speed-depth mappings.

[0076] Example #8: A method of the present disclosure can include

receiving a plurality of sets of drilling parameter values associated with a drilling operation involving drilling a wellbore through a subterranean formation using a drill string. The operations can include receiving a plurality of depth values associated with the plurality of sets of drilling parameter values. Each depth value can correspond to a particular set of drilling parameter values in the plurality of sets of drilling parameter values. The method can include providing the plurality of sets of drilling parameter values as input to a drill string model to receive a plurality of critical speed predictions as output from the drill string model. Each critical speed prediction can be determined by the drill string model based on a respective set of drilling parameter values of the plurality of sets of drilling parameter values. The method can include generating a plurality of speed-depth mappings based on the plurality of critical speed predictions and the plurality of depth values. Each speed-depth mapping can include (i) a respective critical-speed prediction from among the plurality of critical speed predictions and (ii) a respective depth-value associated with the respective set of drilling parameter values used by the drill string model to determine the respective critical-speed prediction. The method can include generating a graphical user interface including the plurality of speed-depth mappings for display on a display device. The plurality of speed-depth mappings in the graphical user interface can be usable to reduce vibrations in the drill string at the plurality of depth values during the drilling operation. Some or all of the method steps can be implemented by a processor.

[0077] Example #9: The method of Example #8 may involve the drill string model being configured to generate a range of candidate bit speeds. For each candidate bit speed in the range of candidate bit speeds, the drill string model can: determine a respective vibration response associated with the candidate bit speed; determine if the respective vibration response exceeds a predefined threshold limit; and flag the candidate bit speed as a critical speed if the respective vibration response is greater than or equal to the predefined threshold limit; or flag the candidate bit speed as a non-critical speed if the respective vibration response is below the predefined threshold limit.

[0078] Example #10: The method of any of Examples #8-9 may involve the drill string model being configured to determine a respective vibration response based on a damping effect of substance in the drill string.

[0079] Example #11: The method of any of Examples #8-10 may involve the

drill string model being configured to determine a respective vibration response based on one or more characteristics of a motor of the drill string.

[0080] Example #12: The method of Example #11 may involve the one or more characteristics including a lobe configuration of the motor.

[0081] Example #13: The method of any of Examples #8-12 may involve receiving the plurality of sets of parameter values from one or more sensors coupled to the drill string.

[0082] Example #14: The method of any of Examples #8-13 may involve adjusting a drilling parameter value associated with the drilling operation so as to prevent a drill bit of the drill string from rotating at a critical speed included in the plurality of critical speed predictions when the drill string is at a particular depth that is associated with the critical speed in the plurality of speed-depth mappings.

[0083] Example #15: A non-transitory computer-readable medium of the present disclosure can include program code that is executable by a processor to perform operations. The operations can include receiving a plurality of sets of drilling parameter values associated with a drilling operation involving drilling a wellbore through a subterranean formation using a drill string. The operations can include receiving a plurality of depth values associated with the plurality of sets of drilling parameter values. Each depth value can correspond to a particular set of drilling parameter values in the plurality of sets of drilling parameter values. The operations can include providing the plurality of sets of drilling parameter values as input to a drill string model to receive a plurality of critical speed predictions as output from the drill string model. Each critical speed prediction can be determined by the drill string model based on a respective set of drilling parameter values of the plurality of sets of drilling parameter values. The operations can include generating a plurality of speed-depth mappings based on the plurality of critical speed predictions and the plurality of depth values. Each speed-depth mapping can include (i) a respective critical-speed prediction from among the plurality of critical speed predictions and (ii) a respective depth-value associated with the respective set of drilling parameter values used by the drill string model to determine the respective critical-speed prediction. The operations can include generating a graphical user interface including the plurality of speed-depth mappings for display on a display device. The plurality of speed-depth mappings in the graphical user interface can be usable to manage vibrations in the drill string

at the plurality of depth values during the drilling operation.

[0084] Example #16: The non-transitory computer-readable medium of Example #15 may further include program code for the drill string model, where the program code for the drill string model is executable by the processor for causing the processor to perform operations. The operations can include generating a range of candidate bit speeds and, for each candidate bit speed in the range of candidate bit speeds: determining a respective vibration response associated with the candidate bit speed; determining if the respective vibration response exceeds a predefined threshold limit; and flagging the candidate bit speed as a critical speed if the respective vibration response is greater than or equal to the predefined threshold limit; or flagging the candidate bit speed as a non-critical speed if the respective vibration response is below the predefined threshold limit.

[0085] Example #17: The non-transitory computer-readable medium of any of Examples #15-16 may feature the drill string model being configured to determine a respective vibration response based on a damping effect of substance in the drill string.

[0086] Example #18: The non-transitory computer-readable medium of any of Examples #15-17 may feature the drill string model being configured to determine a respective vibration response based on one or more characteristics of a motor of the drill string.

[0087] Example #19: The non-transitory computer-readable medium of Example #18 may feature the one or more characteristics including a lobe configuration of the motor.

[0088] Example #20: The non-transitory computer-readable medium of any of Examples #15-19 may further include program code that is executable by the processor for causing the processor to adjust a drilling parameter value associated with the drilling operation so as to prevent a drill bit of the drill string from rotating at a critical speed included in the plurality of critical speed predictions when the drill string is at a particular depth that is associated with the critical speed in the plurality of speed-depth mappings.

[0089] The foregoing description of certain examples, including illustrated examples, has been presented only for the purpose of illustration and description and is not intended to be exhaustive or to limit the disclosure to the precise forms

disclosed. Numerous modifications, adaptations, and uses thereof will be apparent to those skilled in the art without departing from the scope of the disclosure. For instance, examples described herein can be combined together to yield still further examples.

Claims

1. A system comprising:
 - a processor; and
 - a memory including instructions that are executable by the processor for causing the processor to:
 - receive a plurality of sets of drilling parameter values associated with a drilling operation involving drilling a wellbore through a subterranean formation using a drill string;
 - receive a plurality of depth values associated with the plurality of sets of drilling parameter values, each depth value corresponding to a particular set of drilling parameter values in the plurality of sets of drilling parameter values;
 - provide the plurality of sets of drilling parameter values as input to a drill string model to receive a plurality of critical speed predictions as output from the drill string model, each critical speed prediction being determined by the drill string model based on a respective set of drilling parameter values of the plurality of sets of drilling parameter values;
 - generate a plurality of speed-depth mappings based on the plurality of critical speed predictions and the plurality of depth values, each speed-depth mapping including (i) a respective critical-speed prediction from among the plurality of critical speed predictions and (ii) a respective depth-value associated with the respective set of drilling parameter values used by the drill string model to determine the respective critical-speed prediction; and
 - generate a graphical user interface including the plurality of speed-depth mappings for display on a display device, the plurality of speed-depth mappings in the graphical user interface being usable to reduce vibrations in the drill string at the plurality of depth values during the drilling operation.
2. The system of claim 1, wherein the memory further includes instructions for the drill string model, and wherein the drill string model is configured to:
 - generate a range of candidate bit speeds; and
 - for each candidate bit speed in the range of candidate bit speeds:
 - determine a respective vibration response associated with the candidate bit speed;

determine if the respective vibration response exceeds a predefined threshold limit; and

flag the candidate bit speed as a critical speed if the respective vibration response is greater than or equal to the predefined threshold limit; or

flag the candidate bit speed as a non-critical speed if the respective vibration response is below the predefined threshold limit.

3. The system of claim 2, wherein the drill string model is configured to determine the respective vibration response based on a damping effect of substance in the drill string.

4. The system of claim 2, wherein the drill string model is configured to determine the respective vibration response based on one or more characteristics of a motor of the drill string.

5. The system of claim 4, wherein the one or more characteristics include a lobe configuration of the motor.

6. The system of claim 1, wherein the memory further includes instructions that are executable by the processor for causing the processor to receive the plurality of sets of parameter values from one or more sensors coupled to the drill string.

7. The system of claim 1, wherein the memory further includes instructions that are executable by the processor for causing the processor to adjust a drilling parameter value associated with the drilling operation so as to prevent a drill bit of the drill string from rotating at a critical speed included in the plurality of critical speed predictions when the drill string is at a particular depth that is associated with the critical speed in the plurality of speed-depth mappings.

8. A method comprising:

receiving, by a processor, a plurality of sets of drilling parameter values associated with a drilling operation involving drilling a wellbore through a subterranean formation using a drill string;

receiving, by the processor, a plurality of depth values associated with the plurality of sets of drilling parameter values, each depth value corresponding to a particular set of drilling parameter values in the plurality of sets of drilling parameter values;

providing, by the processor, the plurality of sets of drilling parameter values as input to a drill string model to receive a plurality of critical speed predictions as output from the drill string model, each critical speed prediction being determined by the drill string model based on a respective set of drilling parameter values of the plurality of sets of drilling parameter values;

generating, by the processor, a plurality of speed-depth mappings based on the plurality of critical speed predictions and the plurality of depth values, each speed-depth mapping including (i) a respective critical-speed prediction from among the plurality of critical speed predictions and (ii) a respective depth-value associated with the respective set of drilling parameter values used by the drill string model to determine the respective critical-speed prediction; and

generating, by the processor, a graphical user interface including the plurality of speed-depth mappings for display on a display device, the plurality of speed-depth mappings in the graphical user interface being usable to reduce vibrations in the drill string at the plurality of depth values during the drilling operation.

9. The method of claim 8, wherein the drill string model is configured to:

generate a range of candidate bit speeds; and

for each candidate bit speed in the range of candidate bit speeds:

determine a respective vibration response associated with the candidate bit speed;

determine if the respective vibration response exceeds a predefined threshold limit; and

flag the candidate bit speed as a critical speed if the respective vibration response is greater than or equal to the predefined threshold limit; or

flag the candidate bit speed as a non-critical speed if the respective vibration response is below the predefined threshold limit.

10. The method of claim 9, wherein the drill string model is configured to determine the respective vibration response based on a damping effect of substance in the drill

string.

11. The method of claim 9, wherein the drill string model is configured to determine the respective vibration response based on one or more characteristics of a motor of the drill string.

12. The method of claim 11, wherein the one or more characteristics include a lobe configuration of the motor.

13. The method of claim 9, further comprising receiving the plurality of sets of parameter values from one or more sensors coupled to the drill string.

14. The method of claim 9, further comprising adjusting a drilling parameter value associated with the drilling operation so as to prevent a drill bit of the drill string from rotating at a critical speed included in the plurality of critical speed predictions when the drill string is at a particular depth that is associated with the critical speed in the plurality of speed-depth mappings.

15. A non-transitory computer-readable medium comprising program code that is executable by a processor for causing the processor to:

receive a plurality of sets of drilling parameter values associated with a drilling operation involving drilling a wellbore through a subterranean formation using a drill string;

receive a plurality of depth values associated with the plurality of sets of drilling parameter values, each depth value corresponding to a particular set of drilling parameter values in the plurality of sets of drilling parameter values;

provide the plurality of sets of drilling parameter values as input to a drill string model to receive a plurality of critical speed predictions as output from the drill string model, each critical speed prediction being determined by the drill string model based on a respective set of drilling parameter values of the plurality of sets of drilling parameter values;

generate a plurality of speed-depth mappings based on the plurality of critical speed predictions and the plurality of depth values, each speed-depth mapping including (i) a respective critical-speed prediction from among the plurality of critical

speed predictions and (ii) a respective depth-value associated with the respective set of drilling parameter values used by the drill string model to determine the respective critical-speed prediction; and

generate a graphical user interface including the plurality of speed-depth mappings for display on a display device, the plurality of speed-depth mappings in the graphical user interface being usable to manage vibrations in the drill string at the plurality of depth values during the drilling operation.

16. The non-transitory computer-readable medium of claim 15, further comprising program code for the drill string model, and wherein the program code for the drill string model is executable by the processor for causing the processor to:

generate a range of candidate bit speeds; and

for each candidate bit speed in the range of candidate bit speeds:

determine a respective vibration response associated with the candidate bit speed;

determine if the respective vibration response exceeds a predefined threshold limit; and

flag the candidate bit speed as a critical speed if the respective vibration response is greater than or equal to the predefined threshold limit; or

flag the candidate bit speed as a non-critical speed if the respective vibration response is below the predefined threshold limit.

17. The non-transitory computer-readable medium of claim 16, wherein the drill string model is configured to determine the respective vibration response based on a damping effect of substance in the drill string.

18. The non-transitory computer-readable medium of claim 16, wherein the drill string model is configured to determine the respective vibration response based on one or more characteristics of a motor of the drill string.

19. The non-transitory computer-readable medium of claim 18, wherein the one or more characteristics include a lobe configuration of the motor.

20. The non-transitory computer-readable medium of claim 15, further comprising program code that is executable by the processor for causing the processor to adjust a drilling parameter value associated with the drilling operation so as to prevent a drill bit of the drill string from rotating at a critical speed included in the plurality of critical speed predictions when the drill string is at a particular depth that is associated with the critical speed in the plurality of speed-depth mappings.

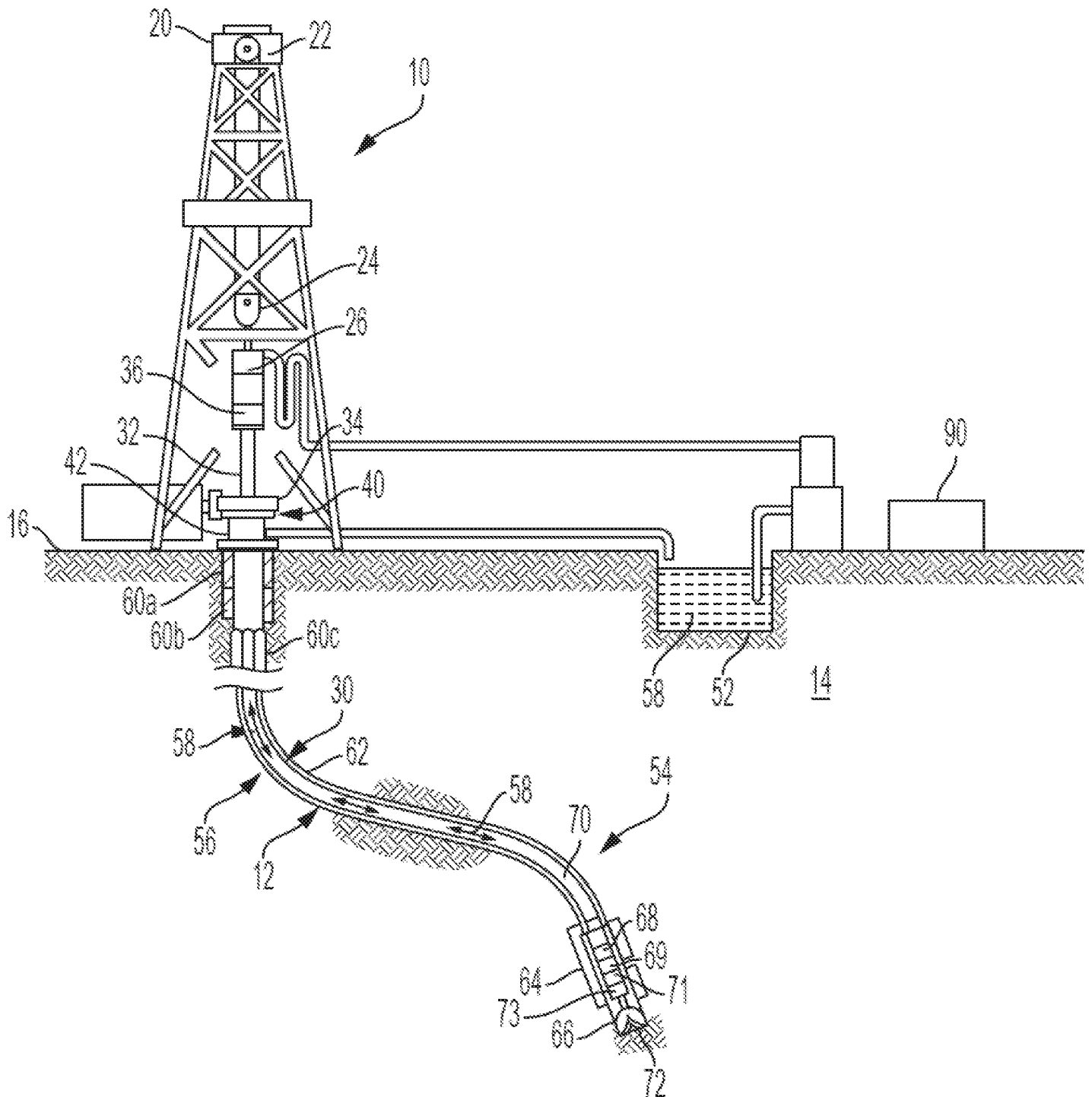


FIG. 1

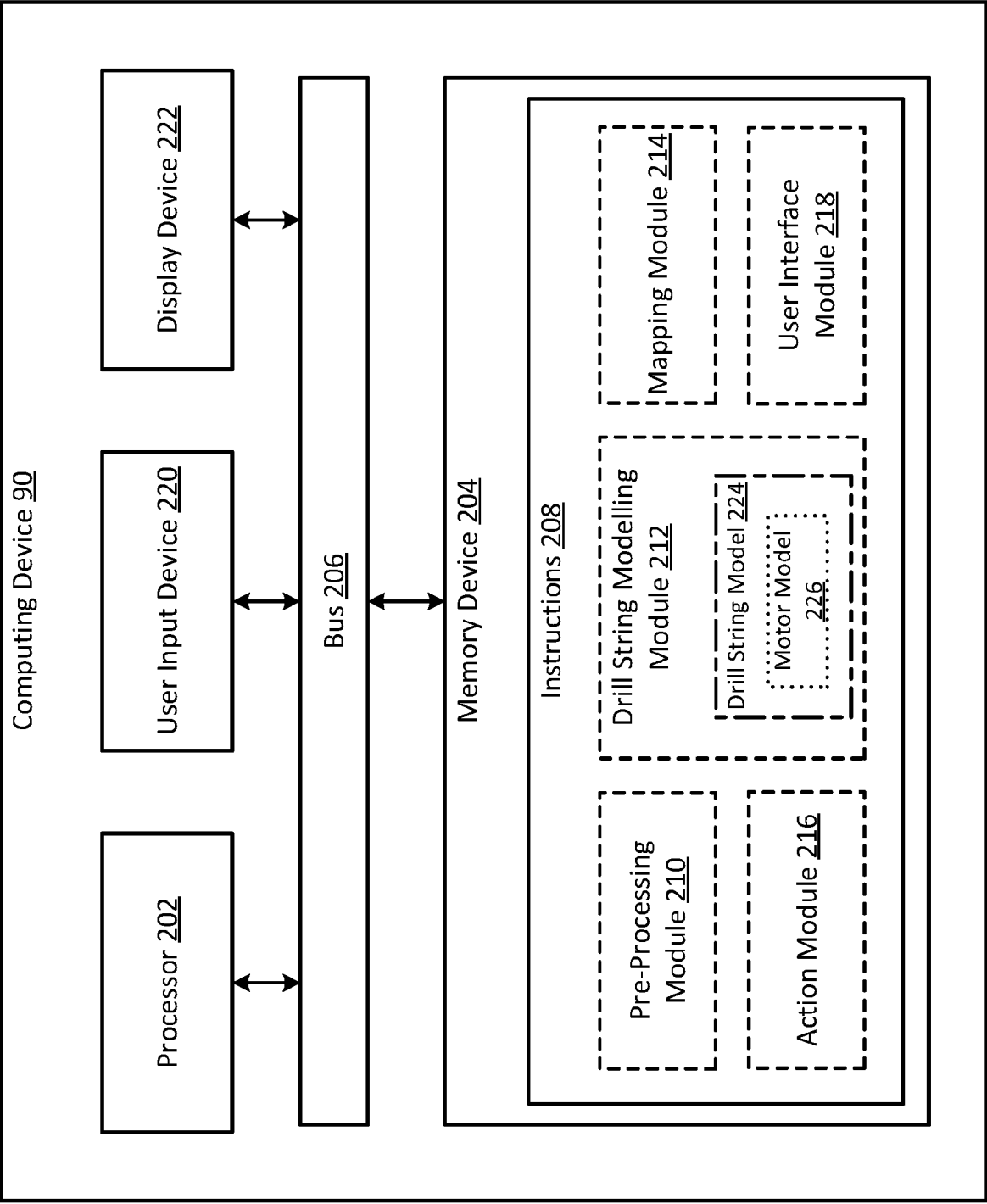


FIG. 2

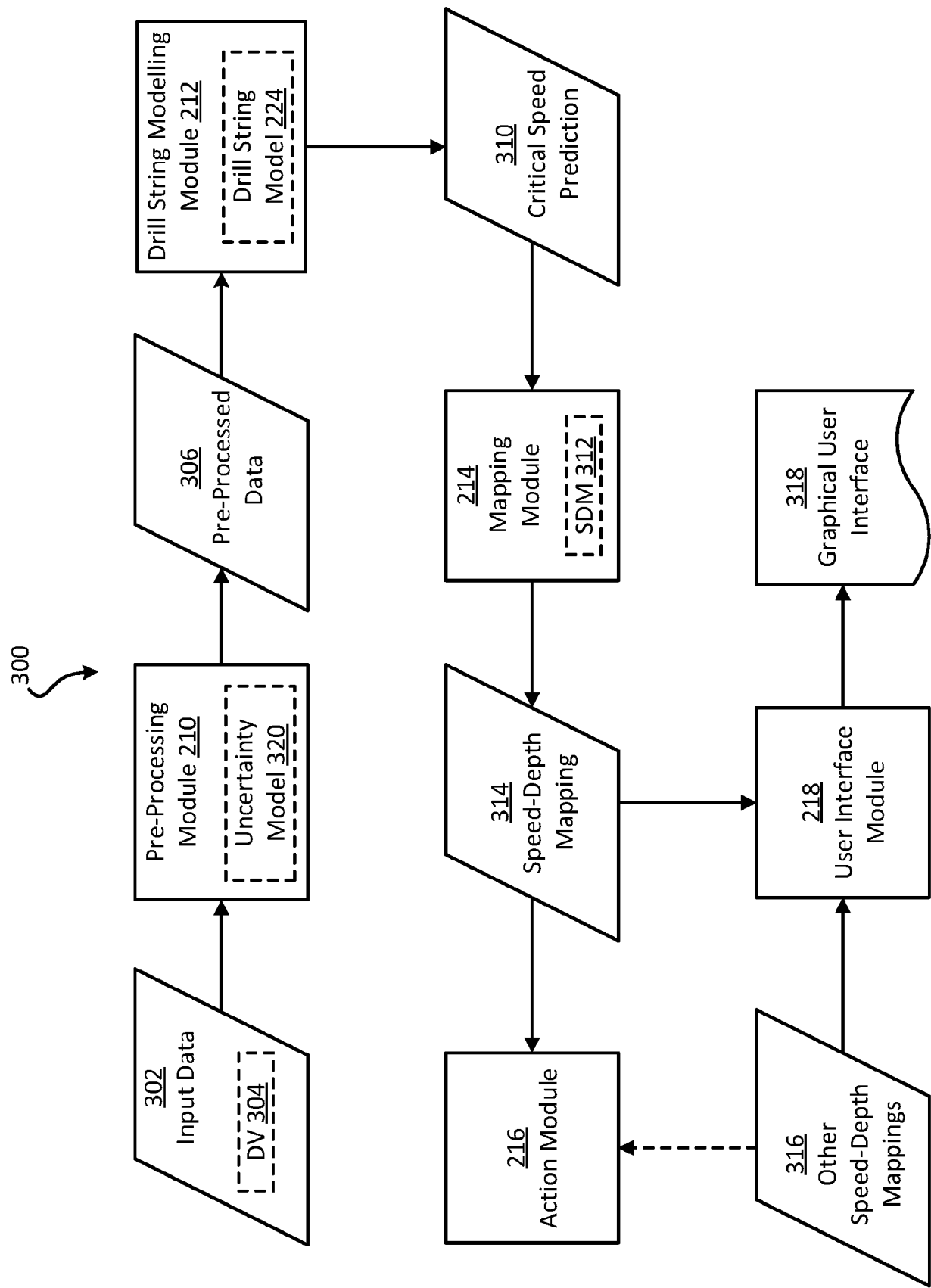


FIG. 3

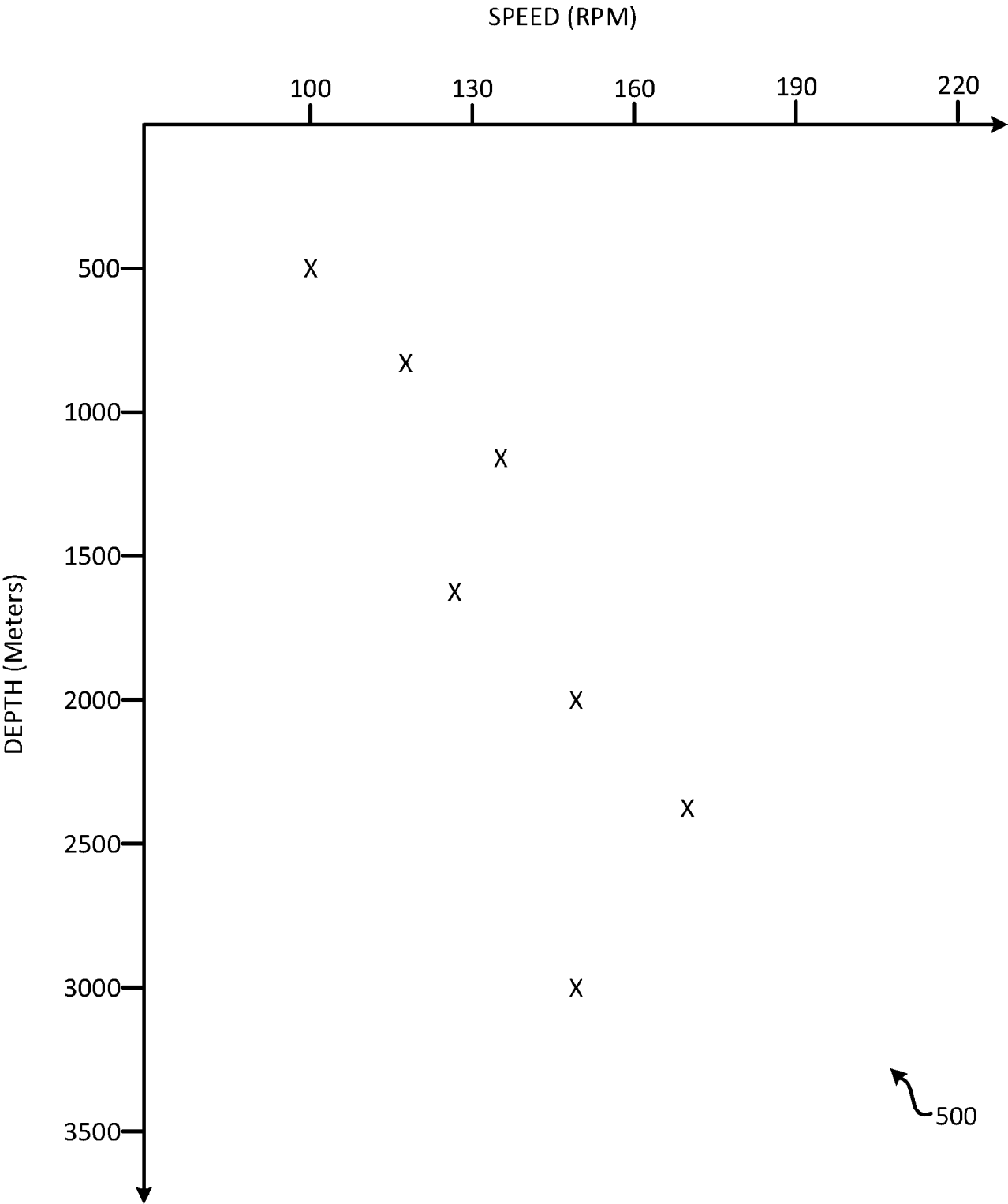
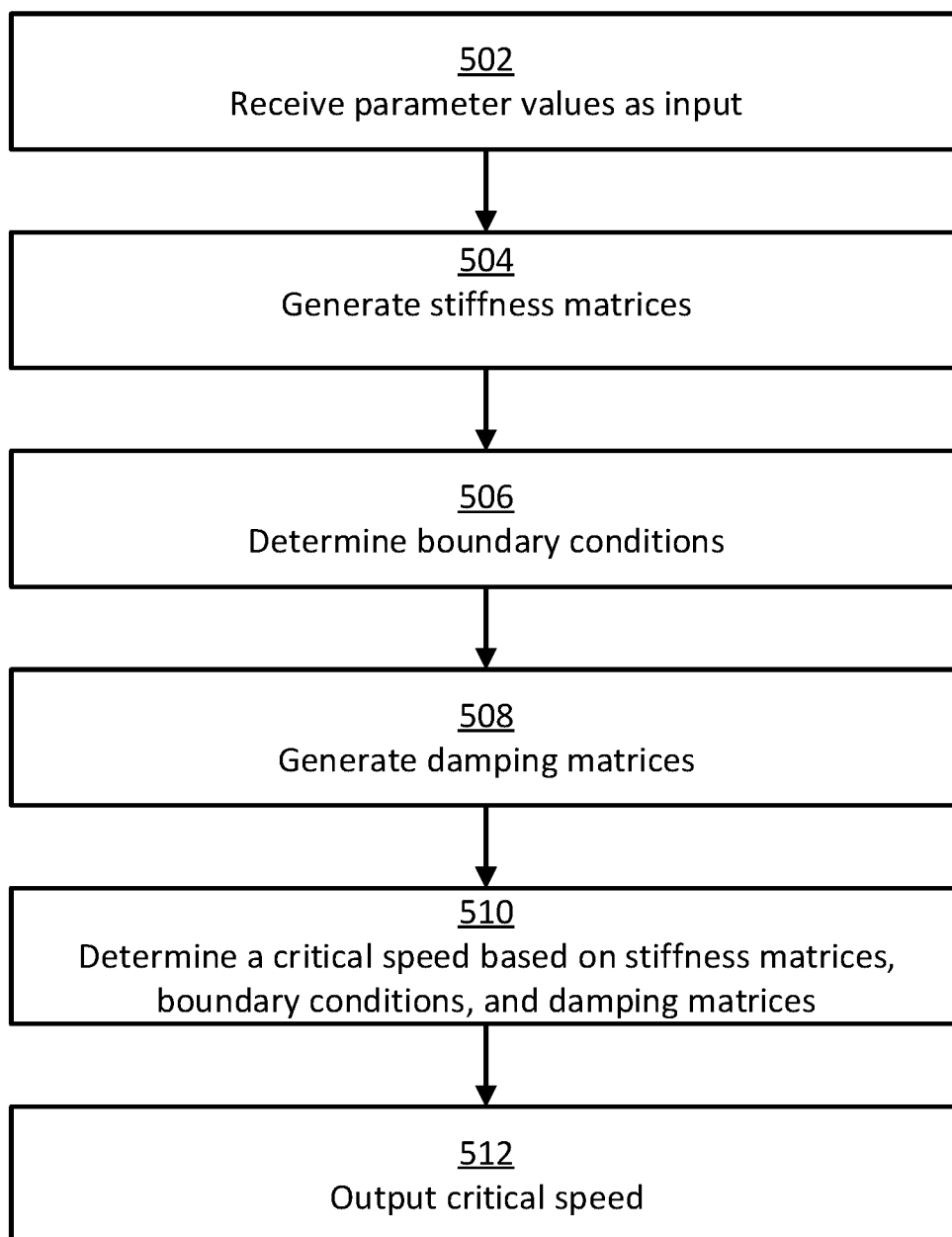
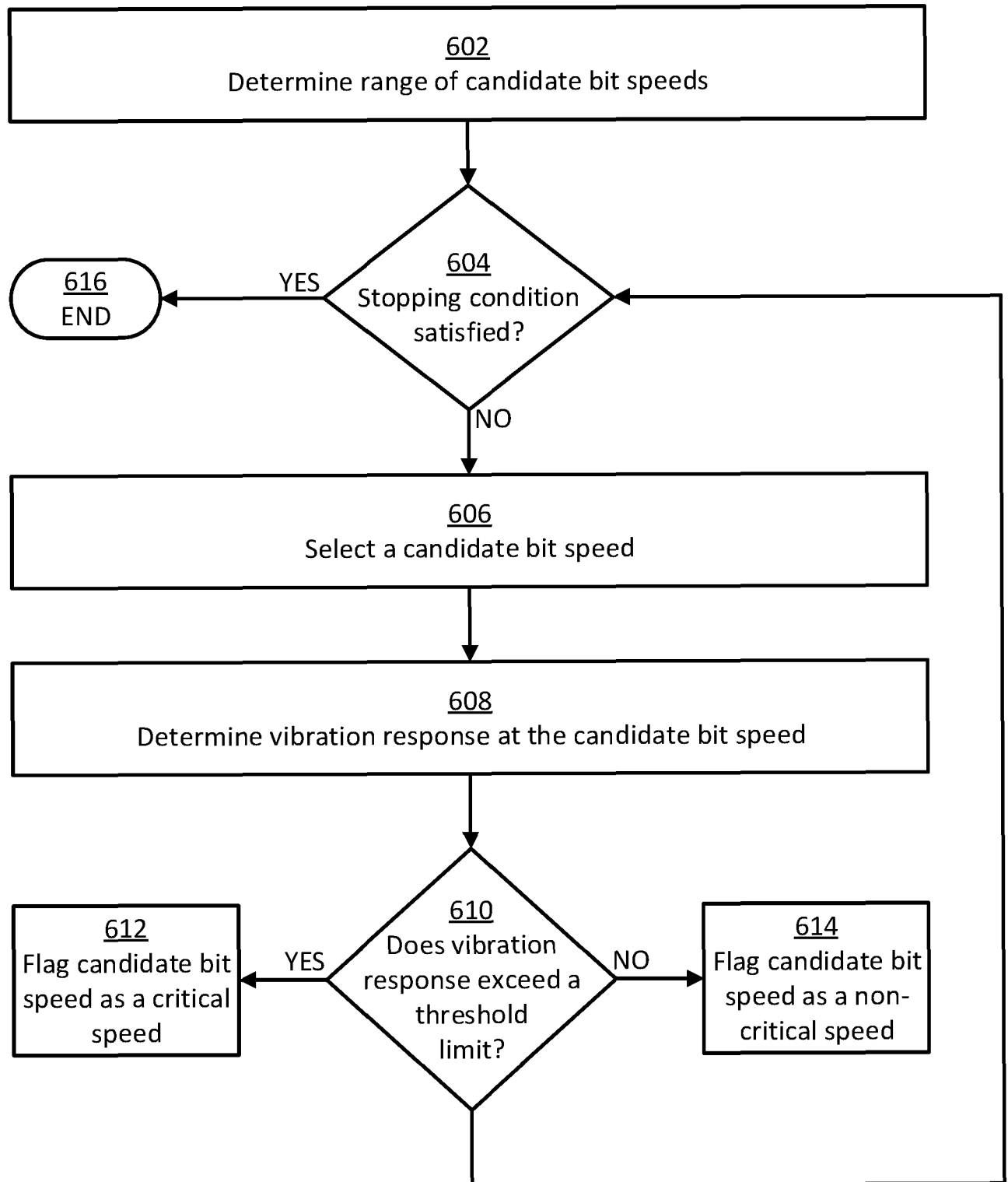


FIG. 4

**FIG. 5**

**FIG. 6**

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2020/041902

A. CLASSIFICATION OF SUBJECT MATTER E21B 47/04(2006.01)i; E21B 41/00(2006.01)i; E21B 47/26(2012.01)i; E21B 44/02(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) E21B 47/04(2006.01); E02D 13/00(2006.01); E21B 44/00(2006.01); G05B 19/02(2006.01); G06G 7/48(2006.01) 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: vibration, drilling parameter, depth value, drill string model, critical speed, speed-depth mapping, display		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2015-0083492 A1 (WASELL, MARK ELLSWORTH) 26 March 2015 (2015-03-26) paragraphs [0019], [0022], [0031]-[0034], [0050]-[0051], [0087]-[0088], [0094], [0096], [0106], [0111], claims 1, 4, 6, 10-11, and figures 1-9	1-20
Y	WO 2015-073387 A1 (SCHLUMBERGER CANADA LIMITED et al.) 21 May 2015 (2015-05-21) claims 1-2, 11 and figures 1-8B	1-20
A	WO 2015-042132 A1 (BAKER HUGHES INCORPORATED) 26 March 2015 (2015-03-26) claim 1 and figures 1-3	1-20
A	EP 2291792 B1 (EXXONMOBIL UPSTREAM RESEARCH COMPANY) 13 June 2018 (2018-06-13) claims 1, 3, 8 and figures 3-4	1-20
A	JP 2019-031839 A (OHBAYASHI CORP.) 28 February 2019 (2019-02-28) paragraphs [0023]-[0028] and figures 2-6	1-20
☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "D" document cited by the applicant in the international application "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 31 March 2021		Date of mailing of the international search report 01 April 2021
Name and mailing address of the ISA/KR Korean Intellectual Property Office 189 Cheongsa-ro, Seo-gu, Daejeon 35208, Republic of Korea Facsimile No. +82-42-481-8578		Authorized officer BAHNG, Seung Hoon Telephone No. +82-42-481-5560

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/US2020/041902

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)			Publication date (day/month/year)
US	2015-0083492	A1	26 March 2015	CA	2864545	A1	25 March 2015
				CN	104453848	A	25 March 2015
				CN	104453848	B	04 June 2019
				GB	2518982	A	08 April 2015
				GB	2518982	B	06 June 2018
				US	10472944	B2	12 November 2019
WO	2015-073387	A1	21 May 2015	AU	2014-348913	A1	02 June 2016
				AU	2014-348913	B2	07 June 2018
				CA	2930534	A1	21 May 2015
				CA	2930534	C	03 November 2020
				US	2015-0142318	A1	21 May 2015
				US	9957790	B2	01 May 2018
WO	2015-042132	A1	26 March 2015	CA	2923898	A1	26 March 2015
				CA	2923898	C	17 July 2018
				EP	3047097	A1	27 July 2016
				EP	3047097	A4	28 June 2017
				US	2015-0088468	A1	26 March 2015
				US	9435187	B2	06 September 2016
EP	2291792	B1	13 June 2018	AU	2009-260477	A1	23 December 2009
				AU	2009-260477	B2	17 July 2014
				BR	PI0913218	A2	19 January 2016
				BR	PI0913218	B1	18 February 2020
				CA	2724453	A1	23 December 2009
				CA	2724453	C	12 August 2014
				EA	018946	B1	29 November 2013
				EA	201170037	A1	30 August 2011
				EP	2291792	A1	09 March 2011
				EP	2291792	A4	10 February 2016
				US	2011-0077924	A1	31 March 2011
				US	8589136	B2	19 November 2013
				WO	2009-155062	A1	23 December 2009
JP	2019-031839	A	28 February 2019	JP	658668	B2	09 October 2019