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(71) Applicant (for CA only): **SCHLUMBERGER CANADA LIMITED** [CA/CA]; 125 - 9 Avenue SE, Calgary, Alberta T2G 0P6 (CA).

(71) Applicant (for FR only): **SERVICES PETROLIERS SCHLUMBERGER** [FR/FR]; 42 rue Saint Dominique, 75007 Paris (FR).

(71) Applicant (for all designated States except CA, FR, US): **SCHLUMBERGER TECHNOLOGY B.V.** [NL/NL]; Parkstraat 83-89m, NL-2514 JG The Hague (NL).

(71) Applicant (for US only): **SCHLUMBERGER TECHNOLOGY CORPORATION** [US/US]; 300 Schlumberger Drive, Sugar Land, Texas 77478 (US).

(72) Inventors: **BA, Samba**; 21646 Live Oaks Spring Dr., Katy, Texas 77450 (US). **CARIVEAU, Peter T.**; 8833 Larston St., Houston, Texas 77055 (US). **PUSHKAREV,**

**Maxim**; 3306 Windsor Ranch Lane, Katy, Texas 77494 (US). **KOLYSHKIN, Anton**; 3102 Aylesworth Ct., Katy, Texas 77494 (US).

(74) Agents: **BALLEW, Kimberly** et al.; 10001 Richmond Avenue, IP Administration Center of Excellence, Room 4720, Houston, Texas 77042 (US).

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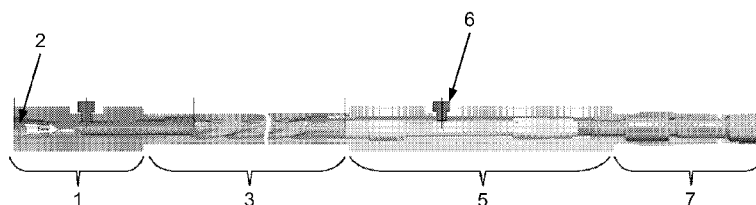


FIG. 1A

(57) Abstract: A method for designing and/or manufacturing a progressive cavity or positive displacement pump or motor, such as a mud motor. The method for designing such a pump/motor includes simulating the pump/motor dynamically via a processor, displaying a simulation result based on the pump/motor simulation, adjusting a value of at least one design parameter for the pump/motor, and repeating the simulating, displaying, and adjusting to change a simulated performance of the pump/motor. The pump/motor may also be manufactured based on the simulated performance.

# **MUD MOTOR DESIGN BASED UPON ANALYTICAL, COMPUTATIONAL AND EXPERIMENTAL METHODS**

## **CROSS-REFERENCE TO RELATED APPLICATIONS**

**[0001]** The present application claims the benefit of, and priority to, U.S. Provisional Patent Application No. 62/098383, filed December 31, 2014, which is hereby incorporated by reference in its entirety.

## **BACKGROUND**

**[0002]** In general, operations, such as geophysical surveying, drilling, logging, well completion, hydraulic fracturing, steam injection, and production, are 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.

**[0003]** To gather subterranean assets, a well may be drilled. Drilling may include breaking up and removing portions of a geological formation to form a wellbore by a drill bit. In some cases, power may be supplied to the drill bit by a mud motor. A mud motor may be a hydraulic motor that generates power in response to receiving a flow of fluid. After gathering valuable subterranean assets, operations such as well abandonment may involve the sealing of a well to safely and economically decommission a well.

## **SUMMARY**

**[0004]** Described herein are one or more embodiments of a method for designing and/or manufacturing a Moineau-type pump or motor, such as a progressive cavity or positive displacement pump or motor. One or more embodiments may include designing and/or manufacturing such a pump or motor (*e.g.*, a mud motor) for downhole drilling or other operations.

**[0005]** In one embodiment, the method for designing a pump/motor includes simulating a pump/motor dynamically via a processor, displaying the simulation result based on the pump/motor simulation, adjusting a value of at least one design parameter for the pump/motor, and repeating the simulating, displaying, and adjusting to change a simulated performance of the pump/motor. The pump/motor may also be manufactured based on the simulated performance.

**[0006]** In another embodiment, the method for designing a pump/motor includes generating a plurality of surface elements of a mesh of a computational model, corresponding to the pump/motor, based on a cross section of the pump/motor, applying boundary conditions to a surface element of the plurality of surface elements based on a material property of the stator of the pump/motor, determining a behavior of the pump/motor by simulating the computational model, and determining a characteristic of the stator of the pump/motor based on the simulation.

**[0007]** In another embodiment, a non-transitory computer readable medium (CRM) storing instructions for designing a pump/motor is disclosed. The instructions include functionality for generating a plurality of surface elements of a mesh of a computational model, corresponding to the pump/motor, based on a cross section of the pump/motor, applying boundary conditions to a surface element of the plurality of surface elements based on a material property of the stator of the pump/motor, determining a behavior of the pump/motor by simulating the computational model, and determining a characteristic of the stator of the pump/motor based on the simulation.

**[0008]** In yet another embodiment, a method for designing a pump or motor includes receiving pump/motor parameters, generating a computational model of the pump/motor based on the pump/motor parameters, simulating the computational model of the pump/motor based on the pump/motor parameters, determining a working life of the stator of the pump/motor based on a simulation of the computational model, and modifying a portion of the pump/motor based on the computational simulation.

**[0009]** The above referenced summary section is provided to introduce a selection of concepts in a simplified form that are further described below in the detailed description section. The summary is not intended to be used to limit the scope of the claimed subject matter. Furthermore, the claimed subject matter is not limited to embodiments that solve disadvantages noted in any part of this disclosure.

### BRIEF DESCRIPTION OF DRAWINGS

**[0010]** Certain embodiments of the disclosure will be described with reference to the accompanying drawings. However, the accompanying drawings illustrate only certain aspects or implementations of the disclosure by way of example and are not meant to limit the scope of the claims.

**[0011]** FIG. 1A shows a cross section along the length of a mud motor in accordance with one or more embodiments of the disclosure.

**[0012]** FIG. 1B shows an enlarged cross section along a length of a mud motor in accordance with one or more embodiments of the disclosure.

**[0013]** FIG. 1C shows a cross section of a mud motor in accordance with one or more embodiments of the disclosure.

**[0014]** FIG. 1D shows a cross section and travel path of a mud motor in accordance with one or more embodiments of the disclosure.

**[0015]** FIG. 2 shows a method of simulating a mud motor in accordance with one or more embodiments of the disclosure.

**[0016]** FIGs. 3A-3E show an interface of a software tool in accordance with one or more embodiments of the disclosure.

**[0017]** FIGs. 3.F1-3.F4 show an interface of a software tool in accordance with one or more embodiments of the disclosure.

- [0018] FIGs. 4A-4B show an instrumentation setup of a mud motor in accordance with one or more embodiments of the disclosure.
- [0019] FIG. 4C shows a stator of a mud motor in accordance with one or more embodiments of the disclosure.
- [0020] FIG. 5 shows a generated mesh of a rotor in accordance with one or more embodiments of the disclosure.
- [0021] FIG. 6 shows an annotated mesh of a rotor in accordance with one or more embodiments of the disclosure.
- [0022] FIG. 7 shows an interface of a software tool in accordance with one or more embodiments of the disclosure.
- [0023] FIG. 8 shows an interface of a software tool in accordance with one or more embodiments of the disclosure.
- [0024] FIG. 9 shows an example of a mesh in accordance with one or more embodiments of the disclosure.
- [0025] FIG. 10 shows an example of a mesh in accordance with one or more embodiments of the disclosure.
- [0026] FIG. 11 shows an interface of a software tool in accordance with one or more embodiments of the disclosure.
- [0027] FIG. 12 shows an interface of a software tool in accordance with one or more embodiments of the disclosure.
- [0028] FIG. 13 shows a method of simulating a mud motor in accordance with one or more embodiments of the disclosure.
- [0029] FIG. 14 shows a method of predicting an operational life of a mud motor in accordance with one or more embodiments of the disclosure.
- [0030] FIG. 15 shows a computing system in accordance with one or more embodiments of the disclosure.

- [0031] FIG. 16 shows a method of designing a mud motor in accordance with one or more embodiments of the disclosure.
- [0032] FIG. 17 shows a method of designing a mud motor in accordance with one or more embodiments of the disclosure.
- [0033] FIG. 18 shows a method of designing or manufacturing a mud motor in accordance with one or more embodiments of the disclosure.
- [0034] FIG. 19 shows a method of simulating a mud motor in accordance with one or more embodiments of the disclosure.

#### DETAILED DESCRIPTION

- [0035] Specific embodiments will now be described with reference to the accompanying figures. In the following description, numerous details are set forth as examples of the disclosure. It will be understood by those skilled in the art that one or more embodiments of the present disclosure may be practiced without these specific details and that numerous variations or modifications may be possible without departing from the scope of the disclosure. Certain details known to those of ordinary skill in the art are omitted to avoid obscuring the description.
- [0036] Embodiments disclosed herein are directed toward mud motors. A mud motor, sometimes referred to as a drilling motor, is a device that may apply power to a drill bit. A drill bit, as known in the art, may be a cutting, crushing, or gouging component that breaks apart rock or other materials within a geological formation. The drill bit may operate by receiving power from the mud motor. The mud motor may be a hydraulic motor that generates power in response to receiving a pressurized fluid. The mud motor may be connected to the drill bit through a linkage that transmits power generated by the mud motor to the drill bit. In one or more embodiments of the disclosure, the mud motor may generate power as rotational torque and transmit the rotational torque to the drill bit. In response to receiving the rotational torque, the drill bit may cut, crush,

gouge, or otherwise break apart a portion of the geological formation in direct contact with the drill bit.

**[0037]** In one or more embodiments of the disclosure, the mud motor may be part of a drill string. A drill string may be a string of pipes that receives drilling fluid, sometimes referred to as drilling mud, from a drilling rig, located at the surface of a well, and transmits the drilling fluids to a drill bit coupled to the drill string. The mud motor may be located near the drill bit, along the drill string, and receive a portion or all of the drilling fluid. By pressurizing drilling fluid input to the drill string (*e.g.*, at the surface via pumps), pressurized drilling fluid may be transmitted to the mud motor. The mud motor may generate power (*e.g.*, via conversion of hydraulic energy to mechanical energy) in response to receiving the pressurized drilling fluid.

**[0038]** The mud motor may include a first port that receives the drilling fluid and a second port that exhausts the drilling fluid. For example, the first port may be attached to the drill string and receive pressurized drilling fluid while the second port may exhaust fluids into the wellbore surrounding the drill string. Thus a pressure differential between the first port and the second port may be created. The mud motor may include a rotor and stator disposed between the first port and the second port. The rotor may rotate within the stator in response to the pressurized fluid and transmit the rotation to the drill bit by a linkage.

**[0039]** FIG. 1A shows a diagram of a mud motor in accordance with one or more embodiments of the disclosure. The mud motor may include a top sub (1) that includes the first port (2) that receives a pressurized fluid. The top sub (1) may direct the received pressurized fluid into a power section (3). The power section (3) may generate rotational power in response to receiving the pressurized fluid. Rotational power generated by the power section (3) may be transmitting to a transmission section (5). The transmission section (5) may include the second port (6) and exhaust pressurized fluids received from the power section (4). The transmission section (5) may transmit the received rotational power to a drive section (7) that transmits the power to the drill bit.

**[0040]** FIG. 1B shows a diagram of the power section (3) of a mud motor in accordance with one or more embodiments of the disclosure. The power section (3) may include a rotor (10) having a helical shape including a number of lobes. The rotor (10) may have a shape corresponding to an extruded, two dimensional shape that rotates about the axis of extrusion. In other words, the rotor (10) may be a shape defined by a cross section that rotates as it translates in a single dimension. A 360 degree rotation of the cross-section defining the shape of the rotor is referred to as the pitch of the rotor. The number of 360 degree rotations of the cross section defining the shape of the rotor (10) may be referred to as the number of stages. In one or more embodiments, the rotor (10) may be a structural material such as an alloy of aluminum, stainless steel, or titanium.

**[0041]** Due to the operation of the power section (3), which is described below, the rotor (10) may travel in an eccentric path as the rotor (10) rotates. The upstream end of the rotor (10) may be connected to a stabilizing shaft (20) by a first flexible linkage (25). An upstream end of the stabilizing shaft (20) may be connected to a single rotary joint (not shown) and the downstream end of the stabilizing shaft (20) may be connected to the upstream end of the rotor (10) by the flexible linkage (25). Connecting the rotor (10) to the stabilizing shaft (20) may stabilize the eccentric path of the upstream end of the rotor (10) when the mud motor is generating power.

**[0042]** The downstream end of the rotor (10) may be connected to a transmission shaft (30) by a second flexible linkage (35). A downstream end of the transmission shaft (30) may be connected to a bearing (not shown) and the upstream end of the transmission shaft (30) may be connected to the downstream end of the rotor (10) by the second flexible linkage (35). Connecting the rotor (10) to the transmission shaft (20) may stabilize the eccentric path of the downstream end of the rotor (10) when the mud motor is generating power and transmit rotational power generated by the power section (3) to the transmission section (5).

**[0043]** During operation of the mud motor, pressurized fluids apply pressure to the rotor (10), stabilizing shaft (20), first flexible linkage (25), transmission shaft (30), and second flexible linkage (35). The applied pressures may cause any of the aforementioned components to deform, bend, or otherwise change shape in response to



the applied pressures. The deformation, bending, or change of shape of any of the aforementioned components may change the operation of the mud motor.

**[0044]** The power section (3) may include a stator (15) having a helical shape, corresponding to the rotor (10), including a number of lobes that is greater than the number of lobes of the rotor (10). The stator (15) may include an interior surface defined by a second cross section that rotates as it translates in a single dimension, similar to the rotor (10). However, the second cross section that defines the interior surface of the stator (15) is different than the cross section that defines the rotor (10). The number of stages of the stator (15) may correspond to the number of stages of the rotor (10). In one or more embodiments of the disclosure, the stator (15) may be constructed at least in part of an elastomeric material such as nitrile or acrylonitrile butadiene rubber.

**[0045]** FIG. 1C shows a diagram of an example cross section of a power section (3) of the mud motor in accordance with one or more embodiments of the disclosure. The example cross section includes an outer sleeve (40). The outer sleeve (40) may be a structural material such as aluminum, steel, or titanium. The outer sleeve (40) may be in the form of a hollow cylinder. The outer sleeve (40) may house the rotor (10) and the stator (15).

**[0046]** The stator (15), illustrated with solid hatching in FIG. 1C, may be disposed on an interior surface of the outer sleeve (40). As discussed above, the stator may be constructed at least in part of an elastomeric material or deformable material. However, the stator (15) may not be homogenous and may include regions of different materials having different materials properties as discussed below.

**[0047]** The rotor (10), illustrated with dashed hatching in FIG. 1C, may be disposed within the stator (15). The rotor (10) may be a structural material such as steel, aluminum, or other metal alloy. During operation of the mud motor, the rotor may rotate in response to pressurized fluids flowing through the mud motor.

**[0048]** An exterior surface of the rotor (10) may directly contact an inner surface of the stator (15). When the rotor (10) and stator (15) are in direct contact and receiving pressurized drilling fluid, discrete pockets may be formed between the rotor (10) and

stator (15) corresponding to the number of stages due to the difference in the number of lobes of the rotor (10) and stator (15), respectively. When a pocket is located near the first port (2), drilling fluid may apply a pressure to the rotor (10) that causes the rotor (10) to rotate. As the rotor (10) rotates, the pocket may translate along the length of the rotor (10) toward the second port (6). When the pocket reaches the second port (6), drilling fluid contained in the pocket may be exhausted out of the second port (6). So long as pressurized fluid is applied to the rotor (10) and stator (15) by the first port (2), the rotor (10) may continue rotating and therein generate power.

**[0049]** As the mud motor operates, both the rotor (10) and the stator (15) may dynamically deform due to stresses within the motor. Due to the cross sectional shapes of the rotor (10) and the stator (15), the rotation center of the rotor (10) is not at the center of the stator (15). Thus, the rotor (10) exhibits eccentricity during normal operation.

**[0050]** FIG. 1D shows the diagram of an example cross section of a power section (3) of the mud motor as illustrated in FIG. 1C and a superimposed rotation diagram in accordance with one or more embodiments of the disclosure. The hatching of the rotor (10) and stator (15) has been removed for clarity. As seen from FIG. 1D, the rotor (10) has an exterior surface (100) and the stator (15) has an interior surface (110). The exterior surface (100) of the rotor (10) includes four rotor lobes (105) and the interior surface (110) of the stator (15) includes five stator lobes (115). However, one of ordinary skill in the art will appreciate that the exterior surface (100) of the rotor (10) may have any number of rotor lobes (105) and the interior surface (110) of the stator (15) may have a number of stator lobes (115) greater than the number of rotor lobes (105). The interior surface (110) of the stator (115) circumscribes the rotor (10) and therein enables the rotor (10) to rotate within the stator (15). As seen from FIG. 1D, the cross section of the rotor (10) and stator (15) are complex. Each rotor lobe (105) may have a different shape than the other rotor lobes or some of the rotor lobes may have similar shapes. Similarly, each stator lobe (115) may have a unique shape.

**[0051]** To clarify the eccentricity of the rotor (10), the center of the rotor (120) has been marked with a square box and the center of the stator (125) has been marked with a

cross. As the rotor (10) rotates, the center of the rotor (120) moves with respect to the center of the stator (125). Specifically, the center of the rotor (120) may follow a path defined by a circle (130) as the rotor (10) rotates, under ideal operating conditions. Due to the eccentricity of the rotor (100) and forces applied to the rotor (10) by the drilling fluid, the rotor (10) may deform during rotation. The deformation of the rotor (10) may depend on the properties of the rotor material, the pressures applied to the power section (3) by the stator (15) and pressurized fluids, and the deformation of the stator (15).

**[0052]** Under normal operating conditions, the eccentric path of the rotor (10) may not be circular as shown in FIG. 1D. The path may be orbital, elliptical, or otherwise divert from the path defined by the circle (130) due to the connections between the rotor (120) and other shaft, variation of fluid pressures along the length of the mud motor, and other factors. Further, the path of the stator (10) may wobble, oscillate, or otherwise change over time during operation of the mud motor. Lastly, the path of the rotor (10) may not be consistent along the length of the mud motor. For example, an upstream portion of the rotor (10) may follow a path that is different from a second path followed by a downstream portion of the rotor (10).

**[0053]** As noted above, the stator (15) may deform during normal operation of the mud motor. The stator (15) may be constructed at least in part of an elastomeric material that deforms when in contact with the rotor (10). As the rotor (10) rotates, the rotor (10) may deform which displaces the center of the rotor (120) off the path defined by the circle (130), depending on the deformation of the rotor (110).

**[0054]** Thus, the operation of the mud motor is complex. The mechanical deformation of the rotor (10) and the stator (15) are an inherent part of the operation of the mud motor and are intrinsically linked. Further, the behavior of both the rotor (10) and the stator (15) are dependent on the pressures applied by the pressurized drilling fluid. Depending on the pressures applied by the drilling fluid to the rotor (10) and the stator (15), the flow of the drilling fluid through the mud motor as well as the deformation of the rotor (10) and the stator (15) will vary.

**[0055]** Due to the inherent complexity of any mud motor structure, considerable expense is involved in evaluating a potential mud motor design. With reference to FIG. 1D, a

single cross section of a mud motor incorporates multiple curved surfaces. Further, due to the twisting of the cross section of each stage of the mud motor, the overall shape of the mud motor may not be easily expressed analytically. Additionally, due to the complexity of the structure of a potential mud motor design and the materials, such as elastomers, used in mud motor design, determining the behavior of a potential mud motor design may not be easily determined by laboratory experimentation due to the sheer number of variables in the potential design of a mud motor.

**[0056]** In view of the aforementioned complexity of determining the behavior of a mud motor, engineers may not have access to the resources, such as time or money, for designing, testing, or manufacturing of a potential mud motor design. For example, an engineer may have an idea to improve a mud motor but due to the complexity of the mud motor cannot determine if the idea will improve the mud motor or if an unforeseen problem will render the idea unsuccessful. Further, even if an idea shows promise, a potential mud motor design may need refinement, due to the deformation of the rotor, stator, or other component.

**[0057]** Further, successful field operations of the mud motor may depend on having established an operational life of the mud motor. The operational life of the mud motor may depend on the deformation of the rotor (10), stator (15), or other factors during operation. Thus, field operations of a mud motor depend on evaluation of the mud motor, before use of the mud motor.

**[0058]** Additionally, due to the principle of operation of mud motors, mud motors may fail by a number of causes. As a mud motor operates, deformation of the stator (15) may lead to chunking of the stator (15) where portions of the stator (15) are worn away. Also, as the mud motor operates, temperatures within the mud motor may vary based on the operation of the mud motor. Portions of the stator (15) may debond from the outer sleeve (40) if temperatures near the stator (15)/outer sleeve (40) interface exceed a threshold. Due to the eccentric motion of the rotor (10), connections between the rotor (10), the stabilizing shaft (20), and the transmission shaft (30) may degrade and fail during normal use. Lastly, the shape of the stator (15) may change when exposed to fluids during normal operation.

**[0059]** Accordingly, embodiments disclosed herein provide methods and techniques to design, model, and simulate the behavior of mud motors under conditions commensurate with conditions to which the mud motor will be exposed to during field operation. More particularly, one or more embodiments disclosure herein provide for methods of rapidly generating meshes and associated boundary conditions for a mud motor. The generated meshes and boundary conditions may be used to determine the potential performance of the mud motor. Additional embodiments include software tools, developed by the inventor(s) and referred to as Power Designer 6 (PD6), which may be used to rapidly generate meshes and associated boundary conditions for mud motors in an automatic manner. The generated meshes and boundary conditions may be output to a finite element analysis solver that may determine the behavior of the mud motor.

**[0060]** Additional embodiments disclosed herein may provide a method and software tool to design, model, and simulate the behavior of mud motors by generating two dimensional meshes of cross sections of the mud motor design along the length of the mud motor in an automatic manner. Linked, two dimensional finite element analysis simulations for each generated two dimensional mesh may then be conducted in an automatic manner. Based on the finite element analysis simulations, the behavior of potential mud motor designs may be determined. The software tools are newly developed by the inventor(s) and are referred to as REnergy.

**[0061]** Further embodiments disclosed herein may provide a method of incorporating experimental or analytically derived data into a computational model of a mud motor. In one or more embodiments of the disclosure, measurements of the strain, pressures, deformation, or general operation of a mud motor design may be incorporated into a simulation model of a potential mud motor design. By incorporating the experimental data or analytically derived data into the computational model, the operation of a potential mud motor design may be more accurately estimated. Improving the accuracy of the estimated operation of the potential mud motor design may reduce the number of design iterations of a potential mud motor design, decrease the cost associated with designing a mud motor, and reduce the time to design a mud motor.

- [0062]** In additional embodiments disclosed herein, methods of designing mud motors may include predicting the operation of a potential mud motor design based on computational modeling, analytically derived data, or a combination of computational modeling and analytically derived data. Utilizing a combination of computational and analytical techniques may reduce the cost of designing a mud motor.
- [0063]** FIG. 2 shows a flowchart (200) according to one or more embodiments of the disclosure. The method depicted in FIG. 2 may be used to determine the behavior of a mud motor in accordance with one or more embodiments of the disclosure. One or more items shown in FIG. 2 may be omitted, repeated, and/or performed in a different order among different embodiments.
- [0064]** At Item 2000, a number of mud motor parameters are received. In one or more embodiments of the disclosure, the mud motor parameters include a cross section profile of a rotor (10, FIG. 1), cross sectional profile of a stator (15, FIG. 1), and a cross sectional profile of an outer sleeve (40, FIG. 1). In one or more embodiments of the disclosure, the rotor profile, stator profile, and sleeve profile are input into a computational tool, such as PD6 or REnergy. The rotor profile, stator profile, and sleeve profile may be a cross section of the rotor (10, FIG. 1), stator (15, FIG. 1), and outer sleeve (40, FIG. 1), respectively. The computational tool may include a graphical interface for entering the profiles.
- [0065]** FIG. 3A shows an example of an interface (300) in PD6 for receiving the rotor profile, stator profile, and sleeve profile in accordance with one or more embodiments of the disclosure. The interface (300) includes a first input button (305) that activates a routine to retrieve a rotor profile file. The rotor profile file includes points that define the profile. Each point included in the rotor profile have two coordinate elements that define a location in a two dimensional plane. The interface (300) includes additional buttons that activates routines to input a stator profile file or a sleeve profile file. Each input profile file includes points that define the geometric information that describes the cross section of a rotor, stator, and sleeve, respectively. Each profile file may include coordinate points that define the geometry of each cross section.

- [0066]** The interface (300) also includes a display area (315) that shows a graphical representation of the rotor profile, stator profile, and sleeve profile. As seen in the display area (315) of FIG. 3, the display area (315) may display one or more of the input profiles.
- [0067]** While the profiles displayed in the display area (315) of FIG. 3A are relatively simple, profiles for more complex cross sectional profiles may be received without departing from the scope of the disclosure. Further, a plurality of cross sectional profiles for the rotor, stator, or outer sleeve may be received without departing from the scope of the disclosure. The multiple profiles may be used, for example, to define the variation of the rotor, stator, or outer sleeve along the length mud motor. Profile files are further clarified by way of examples shown in FIGs. 3B-3F.
- [0068]** FIG. 3B shows an example of importing a rotor profile (330), stator profile (335), and outer sleeve profile (340) into a software tool in accordance with one or more embodiments of the disclosure. As seen, the display area (315) in FIG. 3B shows that the imported profile files are relatively simple and include a homogeneous rotor, stator, and hollow circular outer sleeve.
- [0069]** FIG. 3C shows a second example of importing a rotor profile (330), stator profile (335), and outer sleeve profile (340) into a software tool in accordance with one or more embodiments of the disclosure. As seen, the display area (315) in FIG. 3C shows that the imported rotor profile (330) is simple. In contrast, the imported stator profile (335) is more complex and includes a portion that defines the interior surface of the stator and five additional portions that divide the imported stator profile (335) into five separate sections. By dividing the stator profile (335) into separate sections, a stator having separate materials for each section may be modeled. While FIG. 3C shows the stator divided into five sections and separated at valleys of the stator profile, a stator profile (335) may include any number of divisions and each division located at any position and in any orientation. Further, the rotor or outer sleeve may also be divided.
- [0070]** FIG. 3D shows a third example of importing a rotor profile (330), stator profile (335), and outer sleeve profile (340) into a software tool in accordance with one or more embodiments of the disclosure. As seen, the display area (315) in FIG. 3D shows that

the imported rotor profile (330) is simple. In contrast, the imported stator profile (335) includes a first profiles and a second profile that circumscribes the first profile. The two profiles of the imported stator profile (335) may be used to model a stator having a liner on the interior surface of a first material and the area between the liner and the outer sleeve filled with a second material.

**[0071]** FIG. 3E shows a fourth example of importing a rotor profile (330), stator profile (335), and outer sleeve profile (340) into a software tool in accordance with one or more embodiments of the disclosure. As seen, the display area (315) in FIG. 3E shows that the imported rotor profile (330) is relatively complex and includes four lobes of different shapes and sizes. In contrast, the imported stator profile (335) is relatively simple.

**[0072]** FIGs. 3.F1-3F4 show a series of display areas (315) as a fifth example of importing a number of rotor profiles (330), stator profiles (335), and outer sleeve profiles (340) into a software tool in accordance with one or more embodiments of the disclosure. As seen from the display area (315) in Panels F1-F4 of FIG. 3F, each imported rotor and stator profile changes in size. Each of the imported rotor and stator profiles may correspond to a cross section of the mud motor along the length of the mud motor. By importing a discrete number of cross sections a computational model of a mud motor having a cross section that varies may be created.

**[0073]** Thus, as seen from the examples of FIGs. 3B-3F, embodiments of the disclosure may enable a mud motor may be defined by one or more cross sectional profiles of the mud motor. Any of the examples shown in FIGs. 3B-3F may be combined without departing from the scope of the disclosure. Thus, embodiments of the disclosure may enable nearly any mud motor geometry to be defined in terms of cross sections as mud motor parameters.

**[0074]** In one or more embodiments of the disclosure, the mud motor parameters may include additional profiles corresponding to other components of the mud motor. For example, with reference to FIG. 1B, profiles corresponding to the stabilizing shaft (20), transmission shaft (30), the first flexible linkage (25), the second flexible linkage (25) or other portion of the mud motor may be included as a mud motor parameter. In



accordance with embodiments of the disclosure, the aforementioned additional profiles may define, for example the interconnection of portions of the mud motor, the structure of other components of the mud motor, or fluid restrictions or ports along the mud motor.

**[0075]** In one or more embodiments of the disclosure, the mud motor parameters include a number of pieces of data gathered by laboratory experimentation. In one or more embodiments of the disclosure, the data may include measurements of stresses, strains, or pressures measured within a prototype mud motor. In one or more embodiments of the disclosure, the data may include temperature measurements within a prototype mud motor. In one or more embodiments of the disclosure, the data may include rotational power generated by a prototype mud motor under controlled conditions. In one or more embodiments of the disclosure, the data may include measurements of the path of the rotor of a prototype mud motor under controlled conditions.

**[0076]** In one or more embodiments of the disclosure, the pieces of data gathered as mud motor parameters may be used to improve the accuracy of a computational model of a mud motor. As described above, the operation of a mud motor is condition dependent. By incorporating experimental data into a computational model, the computational model may better predict the operation of the mud motor.

**[0077]** For example, measurements of the pressure exerted on a stator by fluids flowing within a prototype mud motor during operation may be measured. FIG. 4A shows a photo of an instrumented setup of a prototype mud motor during operation including a number of the sensors, respectively. The sensors may be pressure taps and the instrumented setup includes the pressure taps along the length of the mud motor. The pressure taps extend into the stator and measure the local pressure. By measuring the pressures along the stator of the mud motor, a pressure profile may be measured. In one or more embodiments of the disclosure, the pressure profile may be input as a mud motor parameter to a software tool, such as PD6. The pressure profile may be used to refine boundary conditions in a computational model, discussed in greater detail below.

**[0078]** In another example, measurements of the eccentric path of a rotor within a prototype mud motor may be made during operation of the mud motor. FIG. 4B shows

a diagram of the locations of the sensors used in a second instrumented setup of a prototype mud motor during operation. The second instrumented setup includes position sensors disposed along the length of the mud motor. The position sensors measure the position of the rotor, stabilizing shaft, and the transmission shaft. By measuring the position of the aforementioned shaft during operation of the mud motor, the path of the rotor may be determined. In one or more embodiments of the disclosure, the path of the rotor may be input as a mud motor parameter to a software tool, such as PD6. The path of the rotor of the mud motor may be used to refine the stiffness of the rotor and incorporated into boundary conditions of a computational model of the mud motor.

**[0079]** Returning to FIG. 2, at Item 2010, a prototype computational model is generated based on the received mud motor parameters. As discussed above, generation of a computation model for a mud motor may be time consuming. In accordance with one or more embodiments of the disclosure, a software tool such as PD6 may generate a computation model, based on the mud motor parameters.

**[0080]** Returning to FIG. 3A, the PD6 interface (300) includes graphical input fields that receive the stator pitch, number of pitches, and sections per pitch. The stator pitch is the length of one stage of the rotor or stator. The number of pitches is the number of stages of the rotor and stator. The sections per pitch define the level of discretization of a resulting computational model generated by PD6 which is described in greater detail below. The graphical input fields may also receive additional parameters relating to the mud motor include the type of linkages between the stabilizing shaft, rotor, and transmission shaft.

**[0081]** FIG. 4C shows a cut view of an example stator (400) in accordance with one or more embodiments of the disclosure. The example stator (400) includes a first profile (405). Along the length of the example stator (400), the first profile (405) is rotated following a helical path (410). The helical path (410) completes a full, 360 degree rotation for each stage of the stator. The stator pitch is the length of each stage of the example stator (400).

**[0082]** A second profile (415) has been included in FIG. 4C to clarify the rotation of the cross section of the example stator (400) along the length of the example stator (400). As seen in FIG. 4C, the first profile (405) touches the helical path (410) at the apex of a lobe. The second profile (415) is identical to the first profile (405) except that it has been rotated so the corresponding point of the first profile (405) intersecting the helical path (410) also intersects the second profile (415). Thus, the interior surface of the stator (400) corresponds to the first profile (405) translated along and rotated according to the helical path (415).

**[0083]** Using the mud motor parameters input to a software tool such as PD6, as described above, a computation model may be generated based on the mud motor parameters. Generation of the computational model of a mud motor by the software tool such as PD6 is further clarified by way of an example shown in FIG. 5.

**[0084]** FIG. 5 shows an example of a computation model (500) of a rotor in accordance with one or more embodiments of the disclosure. The computational model includes a surface mesh of the rotor generated by PD6. As seen from FIG. 5, a number of surface elements (505) have been generated to represent the complex exterior surface of the rotor on which the computation model (500) is based. Each surface element (500) is a portion of a surface defined by four points. PD6 generates each surface element (500) based on the mud motor parameters including the rotor profile, the stator pitch, number of pitches, and sections.

**[0085]** In one or more embodiments of the disclosure, each surface element (500) may be generated by translation of the rotor profile received by PD6 as a mud motor parameter. As discussed above, the received rotor profile includes a number of points that define the cross section of the rotor and the number of sections defines the discretization of the mesh along the length of the rotor. Each surface element (505) may be generated by first selecting two adjacent points in the rotor profile. The locations of two points corresponding to the selected points are calculated for a rotated rotor profile that is rotated by an amount corresponding to the number of sections. The two initially selected points and the calculated corresponding points may then be stored as a surface element. Additional surface elements (500) may be calculated for each set of two

adjacent points on the rotor profile. The above process may then be repeated to calculate the surface elements (500) along the length of the rotor. Generation of the surface elements (500) of the computational model is further clarified by way of an example shown in FIG. 6.

**[0086]** FIG. 6 shows an expanded view of the computation model (500) of the rotor in accordance with one or more embodiments of the disclosure. A rotor profile (600) is superimposed on the generated mesh. As discussed above, each surface element (505) is generated by selecting two adjacent points on the rotor profile (600). In this example, a first point (620) and a second point (630) have been selected. A point corresponding to the first point (625) and a point corresponding to the second point (630) have been calculated. Each corresponding point was calculated by determining the position of each point of the rotor profile (600) translated along the length of the rotor by the length of the stage divided by the number of sections per stage and rotated about the length of the rotor by a complete rotation divided by the number of section. For convenience, a translated and rotated input rotor profile (610) has been superimposed on the generated mesh. Thus, as seen from the mesh, the calculated points (620, 625, 630, and 635) define the surface element (505).

**[0087]** The example shown in FIG. 6 may be repeated for the entire surface of the rotor and therein may be used to generate a mesh corresponding to the entire rotor. If multiple rotor profiles are input, the location along the mud motor of each rotor profile may also be input. A mesh corresponding to the rotor may be generated by interpolating a new rotor profile for each section based on the location of the new rotor profile with respect to defined rotor profiles.

**[0088]** The process may be repeated for the stator or outer sleeve, using the stator profile or outer sleeve profiles respectively, to generate meshes corresponding to the stator and outer sleeve. Additional meshes corresponding to the rest of the mud motor may be generated based on the mud motor parameters.

**[0089]** By automatically generating a mesh using a software tool such as PD6, embodiments of the disclosure enable potential mud motor designs to be rapidly evaluated. Generating a mesh for a computational model of a mud motor using a

software tool such as PD6 does not need user intervention beyond initially inputting the mud motor parameters and input characteristics such as the number of stages of the mud motor.

**[0090]** In one or more embodiments of the disclosure, surface boundary conditions may be applied to the generated meshes in an automated method. Finite element analysis, or other computation analysis methods as known in the art, may calculate the behavior of a structure based on the geometry of the structure and boundary conditions applied to the structure. PD6 may generate boundary conditions corresponding to each surface element so that a computational analysis solver may receive the computation model and simulate the behavior of the mud motor based on the computation model.

**[0091]** In one or more embodiments of the disclosure, a user may select materials for various portions of the rotor, stator, and the outer sleeve. As shown in FIGs. 3A-3F, each profile may divide the rotor, stator, or outer sleeve into any number of portions. One or more embodiments of the disclosure may enable a user to assign material parameters to each of the portions. Thus, embodiments of the disclosure may enable rapid generation of a computational model of a multi-material or complex shaped component of the mud motor.

**[0092]** The user may also input a fluid pressure at the inlet to the mud motor and the pressure at the outlet to the mud motor. Based on the materials and the input pressures, a software tool such as PD6 may generate surface boundary conditions for each of the meshes in the computation model based on the material parameters assigned to each portion of the component, the received pressures at the inlet and exhaust of the mud motor, and experimental data received as a mud motor parameter.

**[0093]** For example, the stator may be a homogeneous elastomeric material. The user may select an elastomeric material for the stator. A software tool such as PD6 may include a material model of the elastomeric material, such as an Ogden material model, that relates applied pressure to the deformation of the material. The software tool may generate a boundary condition for each surface element of a surface mesh corresponding to the stator. If the stator includes portions of multiple materials,

material parameters for each portion may be selected and boundary conditions may be applied to each portion based on the assigned material parameters.

**[0094]** By generating meshes for each of the components of the mud motor and applying boundary conditions for each surface element of each mesh, the computation model of the mud motor generated by a software tool in accordance with one or more embodiments of the disclosure may be simulated by any finite element analysis solver. For example, the computation model generated by DP6 may be input to a commercial finite element analysis suite such as Abaqus® or any other solver. Accordingly, embodiments of the disclosure may enable the rapid generation of computation models of mud motors that may be simulated with a variety of solvers rather than relying on a single finite element analysis solver.

**[0095]** Returning to FIG. 2, at Item 2020, the behavior of the mud motor is simulated based on the generated computational model. In one or more embodiments of the disclosure, the behavior of the mud motor may be simulated by sending the prototype computational model to a finite element analysis solver program. In one or more embodiments of the disclosure, the finite element analysis solver may be Abaqus®. The finite elements analysis solver may receive a run command from PD6, after receiving the computation model, and simulate the computation model in response to receiving the run command.

**[0096]** At Item 2030, a response of the mud motor is determined based on the simulated mud motor behavior. In one or more embodiments of the disclosure, the response is the deformation, temperature, strain, or other characteristic of the stator, rotor, sleeve, linkage, shaft, or other component of the mud motor. As discussed above, pressures applied to the rotor, stator, or other component during operation may cause the rotor, stator, or other component to deform, heat, or otherwise change during operation. By simulating the prototype computational model, an estimate of the deformation, heating or other change of the rotor, stator, or other component may be made and used to refine the geometry of the mud motor. In one or more embodiments of the disclosure, the response of the mud motor may be determined based on a simulation result received

from the finite analysis simulation tool by PD6. PD6 may receive the simulated response of the mud motor and graphically represent the result.

**[0097]** FIG. 7 shows a second interface (700), within PD6, that graphically displays the determined response of the mud motor. In one or more embodiments of the disclosure, the response of the mud motor is calculated by the finite elements solver and displayed in a dynamically generated plot (710).

**[0098]** Returning to FIG. 2, at Item 2040, the stator stiffness is varied. For each variation, the deformation of the rotor is calculated by PD6. Values of the stator stiffness may be input by an input field (720, FIG. 7) in the second interface (700, FIG. 7). The stator stiffness is varied until the deformation of the rotor calculated by PD6 matches the deformation of the stator calculated by the finite element analysis solver.

**[0099]** For example, with reference to FIG. 7, values for the stator stiffness may be input into PD6 sequentially by the input field (720). For each value of stator stiffness, PD6 may calculate a deformation of the stator and plot the deformation of the stator calculated by PD6 along with the deformation of the stator calculated by the finite element analysis solver. The value of the stator stiffness may be varied until the plotted deformation of the rotor by PD6 and the finite elements analysis solver match.

**[00100]** Returning to FIG. 2, at Item 2050, a final computational model may be generated based on the adjusted stator stiffness. PD6 includes a final computational model generation interface (800) as shown in FIG. 8. A user may input the stiffness of the stator as determined in 2040. The final computational model generation interface (800) may include a stator stiffness input field (810) to input the stiffness of the stator.

**[00101]** The final computational model generation interface (800) includes a number of graphical buttons and input fields. By setting the graphical buttons and input fields, a user may generate a final computational model including a stator that includes a liner, a liner and a sleeve, or a liner, sleeve, and an intermediate layer (referred to as a “composite”). The final computational model export settings are further clarified by way of examples. FIGs. 9-10 show example of computational models generated by PD6.

- [00102] FIG. 9 shows an example of a final computational model (900) of a rotor and stator in accordance with one or more embodiments of the disclosure. Specifically, FIG. 9 shows an example of a final computational model having a stator mesh (910) generated using a liner and sleeve. As seen from FIG. 9, the stator mesh (910) is thick and includes the liner and sleeve.
- [00103] FIG. 10 shows a second example of a final computational model (1000) of a rotor and stator in accordance with one or more embodiments of the disclosure. Specifically, FIG. 10 shows a second example of a final computational model having a stator mesh (1010) generated using a liner. As seen from FIG. 9, the stator mesh (910) includes the liner and thus has a ridged exterior mesh.
- [00104] Thus, as may be understood from FIGs. 9-10, embodiments of the disclosure may enable the rapid generation of complex surface meshes and associated boundary conditions. The surface meshes and boundary conditions may be generated and incorporated into a computational model in an automatic manner.
- [00105] Returning to FIG. 2, at Item 2060, the behavior of the mud motor is determined based on the final computational model. In one or more embodiments of the disclosure, the behavior of the mud motor may be determined by simulating the final computational model by a finite element analysis solver. In one or more embodiments of the disclosure, the final computational model is simulated by Abaqus® or any other solver as discussed in 2020.
- [00106] As discussed above, embodiments of the disclosure may include a method of determining the behavior of a mud motor based on generating two dimensional meshes that are linked. The generated two dimensional meshes may be generated in an automatic fashion. By automating the mesh generation, the behavior of a potential mud motor design may evaluated rapidly.
- [00107] FIG. 11 shows a simulation interface (1100) of REnergy in accordance with one or more embodiments of the disclosure. The simulation interface (1100) may include a number of profile input fields (1110). The number of profile input fields (1110) may activate routines for receiving a rotor profile file and a stator profile file. Each profile,



as discussed above, may include points that define a surface of a rotor and stator, respectively.

**[00108]** The simulation interface (1110) may include a display area (1120). The display area (1120) may graphically display the rotor profile file, stator profile file, and behavior of the rotor and stator, which will be further described below.

**[00109]** The simulation interface (1110) may include a number of mud motor parameter input fields (1130). The mud motor parameter input fields (1130) may receive parameters relating to a potential mud motor design. The parameters may include the eccentricity, diameter, fit, pitch, and length of the mud motor.

**[00110]** Based on the inputs received by the simulation interface (1110), a number of two dimensional meshes may be generated in an automatic fashion. Each two dimensional mesh may be generated based on a cross section of the mud motor along the length of one stage of the mud motor. As described above, the cross section of a mud motor rotates along a helical path along the length of the mud motor. Thus, each generated two dimensional mesh corresponds to a rotated rotor cross section, received by the input rotor profile file, and a rotated stator cross section, received by the input stator profile file.

**[00111]** Boundary conditions are applied to each two dimensional mesh based on the material properties of the rotor and stator, as described above. The material properties of the rotor and stator may be received by a parameters interface.

**[00112]** FIG. 12 shows a parameters interface (1200) in accordance with one or more embodiments of the disclosure. The parameters interface (1200) may include an elastomer parameters input field (1210) that receives the material parameters of the elastomer. The boundary conditions of each two dimensional mesh are determined based on the material parameters of the elastomer.

**[00113]** Each two dimensional mesh may be linked to the other two dimensional simulations by linking the rotor in each of the two dimensional meshes. By linking the rotor in each mesh, the contribution of each portion of the mud motor to the overall behavior of the mud motor may be determined. For example, the displacement of the rotor may be linked in each two dimensional simulation.

- [00114] Each two dimensional mesh may be simulated using a finite element analysis solver, as known in the art. The software tool REnergy includes a finite element analysis solver that simulates the behavior of each two dimensional and associated boundary conditions.
- [00115] FIG. 13 shows a flowchart (1300) according to one or more embodiments of the disclosure. The method depicted in FIG. 13 may be used to determine the behavior of a mud motor in accordance with one or more embodiments of the disclosure. One or more items shown in FIG. 13 may be omitted, repeated, and/or performed in a different order among different embodiments.
- [00116] At Item 13000, a rotor profile and a stator profile are received. In one or more embodiments of the disclosure, the rotor profile and stator profile are input to REnergy. The rotor profile and the stator profile may be a cross section of the rotor and stator, respectively.
- [00117] At Item 13010, a number of two dimensional meshes may be generated based on the rotor profile and the stator profile. As described above, REnergy may receive a rotor and stator profile as well as characteristics of the mud motor. Each two dimensional mesh may be generated based on the received profiles and characteristics of the mud motor, as described above.
- [00118] At Item 13020, the portion of each mesh of the plurality of two dimensional meshes are linked based on the rotor profile. As described above, each two dimensional mesh corresponds to different cross sectional profiles of the mud motor along a section of the mud motor. By linking the portion of each mesh corresponding to the rotor profile, each mesh may be linked and therein the contribution of each portion of the mud motor to the behavior of the mud motor may be determined.
- [00119] At Item 13030, boundary conditions may be applied to each mesh of the plurality of two dimensional meshes based on the material properties of a rotor and as stator. As described above, REnergy includes input fields to receive the material properties of the stator. Boundary conditions representing these material properties may be generated and applied to each mesh based on the received material properties of the stator.

- [00120] At Item 13040, a behavior of the mud motor may be simulated based on the plurality of meshes. As described above, REnergy includes a finite element analysis solver. Accordingly, the behavior of the mud motor may be simulated by the finite element analysis solver within REnergy.
- [00121] Thus, the method disclosed in FIG. 13 may be used to determine the behavior of a mud motor in a rapid, efficient, and automated fashion. A user of REnergy may determine the behavior of a complete mud motor with a minimal investment of time and energy.
- [00122] The methods disclosed in FIGs. 2 and 13 may be further incorporated into additional methods. Specifically, by determining the behavior of the mud motor, information such as the expected operation life of a mud motor may be determined based on the strain energy density of the elastomer used in the stator. More specifically, both of the methods shown in FIGs. 2 and 13 and the associated software tools, PD6 and REnergy, may be used to determine the strain energy density of each portion of the mud motor during operation. By determining the strain energy of each portion of the motor, the operational life of the mud motor may be determined.
- [00123] FIG. 14 shows a flowchart (1400) according to one or more embodiments of the disclosure. The method depicted in FIG. 14 may be used to estimate the operational life of a mud motor in accordance with one or more embodiments of the disclosure. One or more items shown in FIG. 14 may be omitted, repeated, and/or performed in a different order among different embodiments.
- [00124] At Item 14000, a rotor profile and a stator profile of a mud motor are determined. The mud motor may be an existing mud motor or a potential mud motor design. A rotor profile file and stator profile file may be generated based on the determined rotor profile and the stator profile, respectively.
- [00125] At Item 14010, the mud motor may be simulated based on the determined profiles. The behavior of the mud motor may be simulated by the methods shown in FIGs. 2 and 13.
- [00126] At Item 14020, the strain energy density of each portion of the motor may be determined based on the simulation. The REnergy tool may directly calculate the strain

energy density as part of the simulation. As shown in FIG. 11, REnergy includes a radio button for displaying the strain energy density.

**[00127]** At Item 14030, the operational life of the mud motor may be estimated based on the strain energy density and a material property of the stator. Failure analysis of an elastomer used in the stator may be performed to determine a fatigue life based on strain energy density. By calculating the strain energy density of each portion of the stator, failure life of the stator may be estimated. The failure life of the mud motor may be estimated based on the estimated failure life of the stator.

**[00128]** The methods disclosed in FIGs. 2 and 13 may also be used to rapidly design or evaluate mud motor design. Specifically, by generating computer models including the meshes and boundary conditions, a device may be designed in a rapid fashion. In one or more embodiments of the disclosure, a mud motor may be designed by simulating a mud motor design as shown by the method of FIGs. 2 and 13.

**[00129]** FIG. 16 shows a flowchart (1600) according to one or more embodiments of the disclosure. The method depicted in FIG. 16 may be used to improve the life of a stator of a mud motor in accordance with one or more embodiments of the disclosure. One or more items shown in FIG. 16 may be omitted, repeated, and/or performed in a different order among different embodiments.

**[00130]** At Item 16000, mud motor parameters including a profile of a stator are received. The stator profile may include portion associated with each lobe of the stator profile.

**[00131]** At Item 16010, a computational model of a mud motor is generated based on the stator profile. The behavior of the mud motor may be generated by the methods shown in FIGs. 2 and 13.

**[00132]** At Item 16020, the working life of the stator is determined based on the computational model. The REnergy tool may directly calculate the working life of the tool based on the strain energy density as part of the simulation. As shown in FIG. 11, REnergy includes a radio button for displaying the strain energy density. Thus, the strain may be determined and displayed.

**[00133]** At Item 16030, a portion of the mud motor is modified based on the determined working life. By displaying the strain energy density, a portion of the rotor that may be

reducing the working life of the stator may be identified. The portion of the stator profile corresponding to the identified area of high strain energy modified. For example, the profile of the stator in the identified area may be modified. A liner having a more resilient material may be incorporated into the stator near the identified area. The thickness of the stator in the identified area may be reduced.

**[00134]** FIG. 17 shows a flowchart (1700) according to one or more embodiments of the disclosure. The method depicted in FIG. 17 may be used to improve the life of a linkage between a stator and another shaft of a mud motor in accordance with one or more embodiments of the disclosure. One or more items shown in FIG. 17 may be omitted, repeated, and/or performed in a different order among different embodiments.

**[00135]** At Item 17000, mud motor parameters including a profile of the first linkage and a first linkage type are received.

**[00136]** At Item 17010, a computational model of a mud motor is generated based on the received mud motor parameters. The computational model of the mud motor may be generated by the methods shown in FIGs. 2 and 13.

**[00137]** At Item 17020, a strain on the linkage is determined based on the computational model. The REnergy tool may directly calculate the strain of the linkage. As shown in FIG. 11, REnergy includes a radio button for displaying the strain. Thus, the strain may be determined and displayed.

**[00138]** At Item 17030, the linkage is modified based on the determined strain. By displaying the strain, a portion of the rotor may be modified to reduce the strain on the linkage. Decreasing the deformation of the rotor may decrease strain on the linkage.

**[00139]** The methods disclosed in FIGs. 16 and 17 may also be used to rapidly design or evaluate a mud motor design. Specifically, by refining a design based on strain or working life determined according to one or more embodiments of the disclosure, a mud motor design may be refined rapidly and cost effectively. However, embodiments of the disclosure are not limited to the specific components refined in FIGs. 16 and 17. Any component of a mud motor may be rapidly and cost effectively refined without departing from the scope of the disclosure. Further, embodiments of the disclosure

include evaluating components based on simulated pressures, strain, deformation, or other mechanical change of a mud motor.

**[00140]** FIG. 18 shows a flowchart (1800) according to one or more embodiments of the disclosure. The method depicted in FIG. 18 may be used to design and/or manufacture a mud motor in accordance with one or more embodiments of the disclosure. One or more items shown in FIG. 18 may be omitted, repeated, and/or performed in a different order among different embodiments.

**[00141]** At Item 18000, a mud motor is simulated dynamically. The simulation may be performed on a computing system including a processor. Simulating dynamically may include adjusting one or more simulation parameters based on experimental data. The simulation parameters may describe a structure of the mud motor and are used by the simulation to determine a behavior of the mud motor. The simulation parameters may be any known to those of ordinary skill in the art and may include, without limitation, one or more of a stator shape, rotor shape, motor stages, motor size (diameter, etc.), rotor material(s), stator material(s), rotor/stator fit, upstream connections, downstream connections, stator profile, housing profile, intermediate layer profile, intermediate layer material(s); or a physical or thermodynamic property of any of the materials. The behavior of the mud motor may be the eccentric path of the rotor, friction/wear between surfaces of the mud motor, deflection of a component of the mud motor, the rotor rotational speed, a pressure drop per stage, the contact pressure between two surface of the mud motor, motor efficiency, or the estimated mud motor operational lifespan. The experimental data may be a measured behavior of a mud motor. The measured behavior of the mud motor may be, without limitation, the eccentric path of the rotor, friction/wear between surfaces of the mud motor, deflection of a component of the mud motor, the rotor rotational speed, a pressure drop per stage, the contact pressure between two surface of the mud motor, motor efficiency, or the estimated mud motor operational lifespan.

**[00142]** At Item 18010, a simulation result is displayed based on the stimulation of the mud motor. The simulation result may be any of the mud motor behaviors described in item 18000.

- [00143]** At Item 18020, a value of at least one design parameters for the mud motor is adjusted based on the displayed simulation result. The displayed simulation result may indicate a location, within the mud motor, of any of the behaviors listed in item 18000. A value of a design parameter may be adjusted based on the displayed behavior and location.
- [00144]** At Item 18030, items 1800, 18010, and 18020 may be repeated to change a simulated performance of the mud behavior. The simulated performance may be a behavior listed in item 18000. For example, the simulated performance may be an operational lifetime or a motor efficiency. Item 18030 may be repeated until the simulated performance reaches a performance goal.
- [00145]** At Item 18040, a mud motor may be manufactured based on the simulated performance. When the simulated performance reaches a performance goal, the mud motor may be considered as a completed design. A mud motor may be manufactured based on the completed design.
- [00146]** FIG. 19 shows a flowchart (1900) according to one or more embodiments of the disclosure. The method depicted in FIG. 19 may be used to simulate a mud motor in accordance with one or more embodiments of the disclosure. One or more items shown in FIG. 19 may be omitted, repeated, and/or performed in a different order among different embodiments. Further, the items shown in FIG. 19 may be used in conjunction with or to supplement the method shown in FIG. 18. Thus, one or more items shown in FIG. 19 may be omitted, repeated, and/or performed in a different order among different embodiments.
- [00147]** At Item 19000, a mesh for a mud motor design is generated. Generating a mesh may include generated a plurality of surface elements of a mesh based on a cross section of the mud motor. In one or more embodiments of the disclosure, the surface elements may be generated as shown in FIGs. 5 and 6.
- [00148]** At Item 19010, boundary conditions may be input or estimated. The boundary conditions may be input or estimated based on the generated mesh and the properties of the materials of the mud motor.

- [00149]** At Item 19020, material properties may be input or estimated. The material properties may be derived from laboratory measurements of materials to be used in a mud motor design or estimated based on an indirect measurement of one or more material properties.
- [00150]** At Item 19030, operating conditions of the mud motor may be input or estimated. For example, these operating conditions may include, without limitation, a temperature of operation, input/output pressures of pressurized fluids, flow rates of estimated fluids, fluid type, potential inclusions within the fluid, fluid additives, expected particulate concentration in fluids from pumping, or other conditions to which the motor will be exposed during operation.
- [00151]** At Item 19040, finite element analysis of the mud motor may be performed based on the generated mesh, boundary conditions, material parameters, and operating conditions. The finite element analysis may determine the behavior of the mud motor including determining the pressures, strains, temperatures, and other characteristics of the mud motor under the operating conditions.
- [00152]** Embodiments of the disclosure may be implemented on virtually any type of computing system, regardless of the platform being used. For example, the computing system may be one or more mobile devices (*e.g.*, laptop computer, smart phone, personal digital assistant, tablet computer, or other mobile device), desktop computers, servers, blades in a server chassis, or any other type of computing device or devices that includes at least the minimum processing power, memory, and input and output device(s) to perform one or more embodiments. For example, as shown in FIG. 15, the computing system (1500) may include one or more computer processor(s) (1502), associated memory (1504) (*e.g.*, random access memory (RAM), cache memory, flash memory, *etc.*), one or more storage device(s) (1506) (*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.*), and numerous other elements and functionalities. The computer processor(s) (1502) may be an integrated circuit for processing instructions. For example, the computer processor(s) may be one or more cores, or micro-cores of a



processor. The computing system (1500) may also include one or more input device(s) (1510), such as a touchscreen, keyboard, mouse, microphone, touchpad, electronic pen, or any other type of input device. The input devices(s) (1510) may, for example, be used to input information to either PD6 or REnergy. Further, the computing system (1500) may include one or more output device(s) (1508), such as a screen (*e.g.*, a liquid crystal display (LCD), a plasma display, touchscreen, cathode ray tube (CRT) monitor, projector, 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 computing system (1500) may be connected to a network (1512) (*e.g.*, a local area network (LAN), a wide area network (WAN) such as the Internet, mobile network, or any other type of network) via a network interface connection (not shown). The input and output device(s) may be locally or remotely (*e.g.*, via the network (1512)) connected to the computer processor(s) (1502), memory (1504), and storage device(s) (1506). Many different types of computing systems exist, and the aforementioned input and output device(s) may take other forms.

**[00153]** Software instructions in the form of computer readable program code to perform embodiments may be stored, in whole or in part, permanently, on a non-transitory computer readable medium such as a CD, DVD, storage device, a diskette, a tape, flash memory, physical memory, or any other non-transitory computer readable storage medium. Specifically, the software instructions may correspond to computer readable program code that when executed by a processor(s), is configured to perform embodiments.

**[00154]** Further, one or more elements of the aforementioned computing system (1500) may be located at a remote location and connected to the other elements over a network (1512). Further, one or more embodiments may be implemented on a distributed system having a plurality of nodes, where each portion such as the first program, second program, and the third program may be located on a different node within the distributed system. For example, PD6 may generate a computer model of a mud motor and send it to another program, for example a finite element analysis solver, for simulation. In one embodiment, the node corresponds to a distinct computing device.

In another embodiment, the node may correspond to a computer processor with associated physical memory. The node may correspond to a computer processor or micro-core of a computer processor with shared memory and/or resources.

**[00155]** Although only a few example implementations have been described in detail above, those skilled in the art will readily appreciate that many modifications are possible in the example implementations without materially departing from “Mud Motor Design Based Upon Analytical, Computational and Experimental Methods.” Accordingly, all such modifications are intended to be included within the scope of this disclosure. In the claims, means-plus-function clauses are intended to cover the structures described herein as performing the recited function and not only structural equivalents, but also equivalent structures. Thus, although a nail and a screw may not be structural equivalents in that a nail employs a cylindrical surface to secure wooden parts together, whereas a screw employs a helical surface, in the environment of fastening wooden parts, a nail and a screw may be equivalent structures. It is the express intention of the applicant not to invoke 35 U.S.C. § 112, paragraph 6 for any limitations of the any of the claims herein, except for those in which the claim expressly uses the words ‘means for’ together with an associated function.

## CLAIMS

What is claimed is:

1. A method of manufacturing a mud motor, comprising:
  - simulating dynamically, on a processor, a mud motor;
  - displaying a simulation result based on the mud motor simulation;
  - adjusting a value of at least one design parameter for the mud motor; and
  - repeating the simulating, displaying, and adjusting to change a simulated performance of the mud motor.
2. The method of claim 1, further comprising manufacturing a mud motor based on the simulated performance.
3. The method of claim 1, wherein the simulating comprises:
  - generating a mesh for a mud motor design;
  - inputting or estimating boundary conditions;
  - inputting or estimating material properties;
  - inputting or estimating operating conditions; and
  - performing finite element analysis of the mud motor design based on the generated mesh, boundary conditions, material parameters, and operating conditions.
4. The method of claim 3, wherein generating a mesh comprises:
  - generating a plurality of surface elements of a mesh based on a cross section of the mud motor.
5. The method of claim 3, wherein the operating conditions are one or more of a temperature of operation, an input pressure, an output pressure, a flow rate, a fluid type, an inclusion type, a fluid additive and a particle concentration.
6. The method of claim 1, wherein the simulating dynamically comprises adjusting one or more simulation parameters based on experimental data.

7. The method of claim 1, wherein the at least one design parameter is one or more selected from the group consisting of stator shape, rotor shape, motor stages, motor diameter, rotor material(s), stator material(s), rotor/stator fit, upstream connections, downstream connections, stator profile, housing profile, intermediate layer profile, intermediate layer material(s) and a physical or thermodynamic property of any of the rotor material(s) or stator material(s).
8. The method of claim 1, wherein the displaying a simulation result comprises displaying a determined behavior of the mud motor, the determined behavior being one or more selected from the group consisting of eccentric path, friction/wear, deflection, rotor rotational speed, pressure drop per stage, contact pressure, motor efficiency and estimated mud motor operational lifespan.
9. The method of claim 6, wherein the experimental data is a measured behavior, the measured behavior being one or more selected from the group consisting of eccentric path, friction/wear, deflection, rotor rotational speed, pressure drop per stage, contact pressure, motor efficiency and estimated mud motor operational lifespan.
10. The method of claim 9, wherein the one or more simulation parameters are adjusted to match a determined behavior of the mud motor to the measured behavior of the mud motor.
11. A method for designing a mud motor, the method comprising:
  - generating a plurality of surface elements of a mesh of a computational model, corresponding to the mud motor, based on a cross section of the mud motor;
  - applying boundary conditions to a surface element of the plurality of surface elements based on a material property of a stator of the mud motor;
  - determining a behavior of the mud motor by simulating the computational model; and
  - determining a characteristic of the stator of the mud motor based on the simulation.
12. The method according to claim 11, wherein a surface element of the plurality of surface elements is generated by calculating a rotation of the cross section of the mud motor along a length of the mud motor.

13. The method according to claim 11, wherein the behavior is a stress energy density of a surface element of the plurality of surface elements.
14. The method according to claim 11, wherein the characteristic is operational life.
15. The method according to claim 11, wherein the material property is a hyperelastic material property of the stator.
16. A non-transitory computer readable medium (CRM) storing instructions for designing a mud motor, the instructions comprising functionality for:
  - generating a plurality of surface elements of a mesh of a computational model, corresponding to the mud motor, based on a cross section of the mud motor;
  - applying boundary conditions to a surface element of the plurality of surface elements based on a material property of a stator of the mud motor;
  - determining a behavior of the mud motor by simulating the computational model; and
  - determining a characteristic of the stator of the mud motor based on the simulation.
17. The non-transitory CRM of claim 16, wherein a surface element of the plurality of surface elements is generated by calculating a rotation of the cross section of the mud motor along a length of the mud motor.
18. The non-transitory CRM of claim 16, wherein the behavior is a stress energy density of a surface element of the plurality of surface elements.
19. The non-transitory CRM of claim 16, wherein the characteristic is operational life.
20. The non-transitory CRM of claim 16, wherein the material property is a hyperelastic material property of the stator.
21. A method for designing a mud motor, the method comprising:
  - generating a plurality of two dimensional meshes corresponding based on a cross section of the mud motor;
  - applying a boundary condition to a mesh of the plurality of two dimensional meshes based on a material property of a stator of the mud motor;

- linking a portion of each mesh of the plurality of two dimensional meshes corresponding to a rotor of the mud motor;
- determining a behavior of the mud motor by simulating the computational model comprising the plurality of two dimensional meshes; and
- determining a characteristic of the stator of the mud motor based on the simulation.
22. The method according to claim 21, wherein a mesh of the plurality of meshes is generated by calculating a rotation of the cross section of the mud motor along a length of the mud motor.
23. The method according to claim 21, wherein the behavior is a stress energy density of a surface element of the plurality of surface elements.
24. The method according to claim 21, wherein the characteristic is operational life.
25. The method according to claim 21, wherein the material property is a hyperelastic material property of the stator.
26. A non-transitory computer readable medium (CRM) storing instructions for designing a mud motor, the instructions comprising functionality for:
- generating a plurality of two dimensional meshes corresponding based on a cross section of the mud motor;
- applying a boundary condition to a mesh of the plurality of two dimensional meshes based on a material property of a stator of the mud motor;
- linking a portion of each mesh of the plurality of two dimensional meshes corresponding to a rotor of the mud motor;
- determining a behavior of the mud motor by simulating the computational model comprising the plurality of two dimensional meshes; and
- determining a characteristic of the stator of the mud motor based on the simulation.
27. The method according to claim 26, wherein a mesh of the plurality of meshes is generated by calculating a rotation of the cross section of the mud motor along a length of the mud motor.

28. The method according to claim 26, wherein the behavior is a stress energy density of a surface element of the plurality of surface elements.
29. The method according to claim 26, wherein the characteristic is operational life.
30. The method according to claim 26, wherein the material property is a hyperelastic material property of the stator.
31. A method for designing a motor, the method comprising:  
receiving motor parameters;  
generating a computational model of the motor based on the motor parameters;  
simulating the computational model of the motor based on the motor parameters;  
determining a working life of a stator of the motor based on a simulation of the computational model; and  
modifying a portion of the motor based on the computational simulation.
32. The method according to claim 31, wherein the motor parameters comprise a rotor profile.
33. The method according to claim 31, wherein the motor parameters comprise a stator profile.
34. The method according to claim 31, wherein the motor parameters comprise a sleeve profile.
35. The method according to claim 31, wherein the motor parameters comprise a linkage profile.
36. The method according to claim 31, wherein the motor parameters comprise a stabilizing shaft profile.
37. The method according to claim 31, wherein the motor parameters comprise a transmission profile.
38. The method according to claim 31, wherein the stator profile comprises multiple portions.
39. The method according to claim 33, wherein the stator profile comprises a portion associated with a liner.

40. A method for designing a mud motor, the method comprising:
- receiving mud motor parameters;
  - generating a computational model of the mud motor based on the mud motor parameters;
  - simulating the computational model of the mud motor based on the mud motor parameters;
  - determining a deformation of a rotor of the mud motor based on the simulated computational model; and
  - modifying a portion of the rotor based on the deformation of the rotor.
41. A method for designing a mud motor, the method comprising:
- receiving mud motor parameters;
  - generating a computational model of the mud motor based on the mud motor parameters;
  - simulating the computational model of the mud motor based on the mud motor parameters;
  - determining a deformation of a stator of the mud motor based on the simulated computational model; and
  - modifying a portion of the stator based on the deformation of the stator.
42. A method for designing a mud motor, the method comprising:
- receiving mud motor parameters;
  - generating a computational model of the mud motor based on the mud motor parameters;
  - simulating the computational model of the mud motor based on the mud motor parameters;
  - determining a deformation of a linkage based on the simulated computational model; and
  - modifying a portion of the linkage based on the deformation of the linkage.



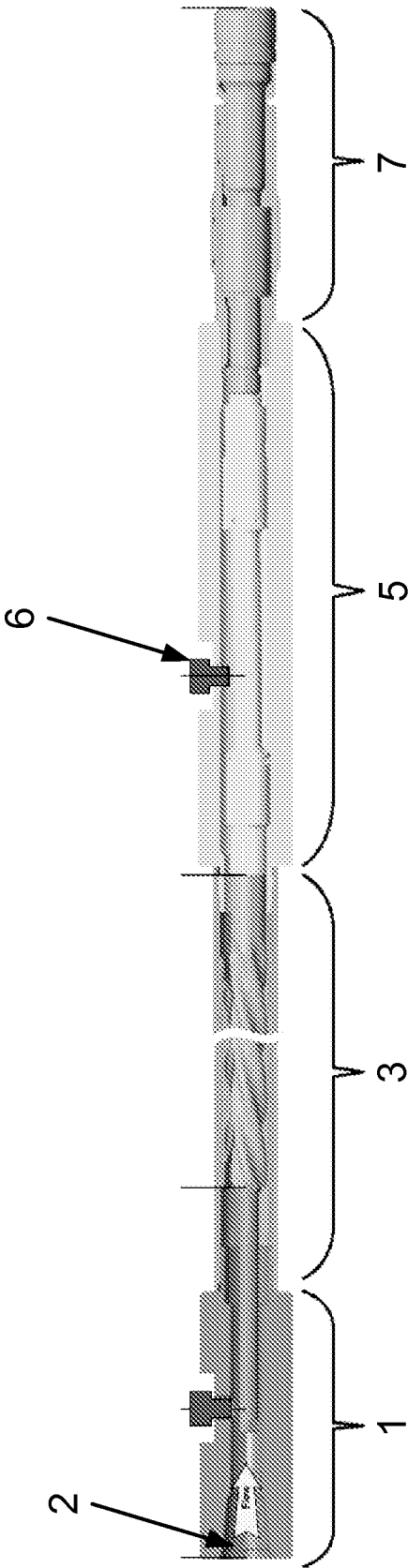


FIG. 1A

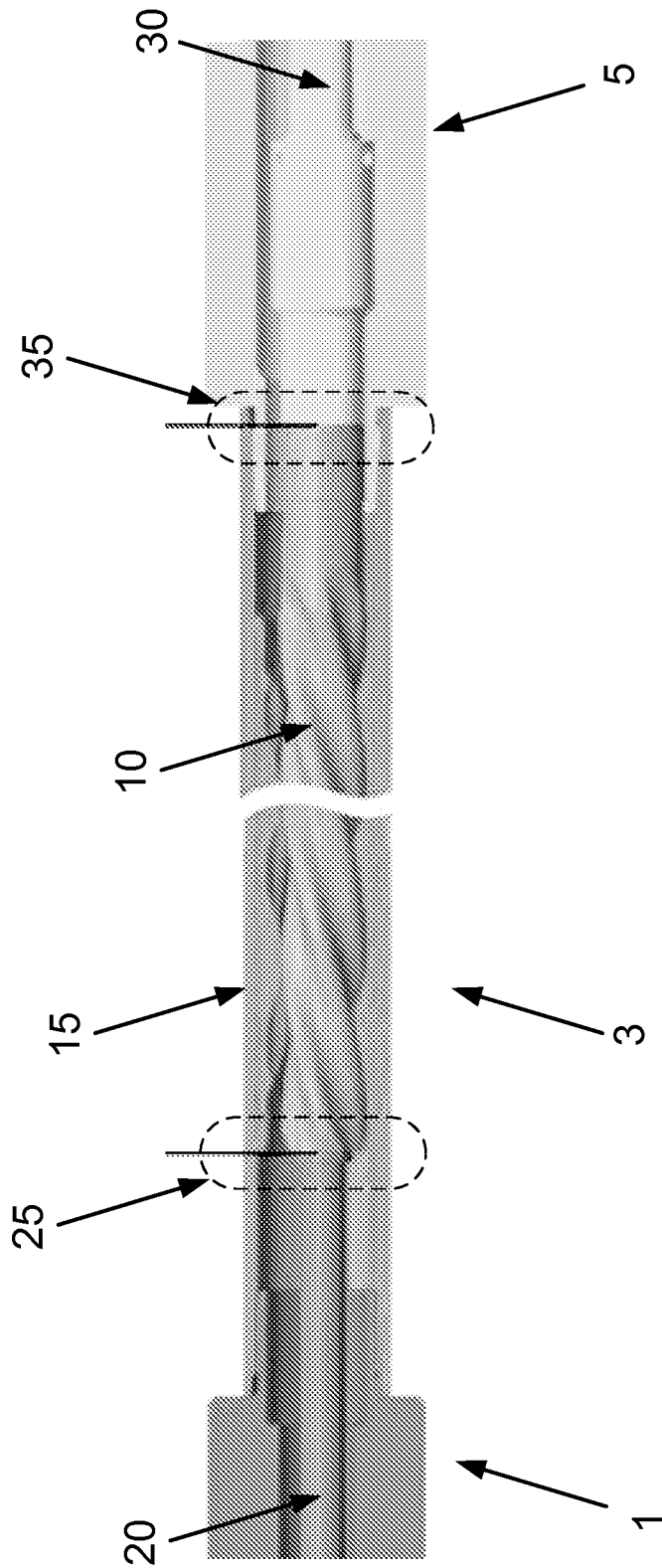


FIG. 1B

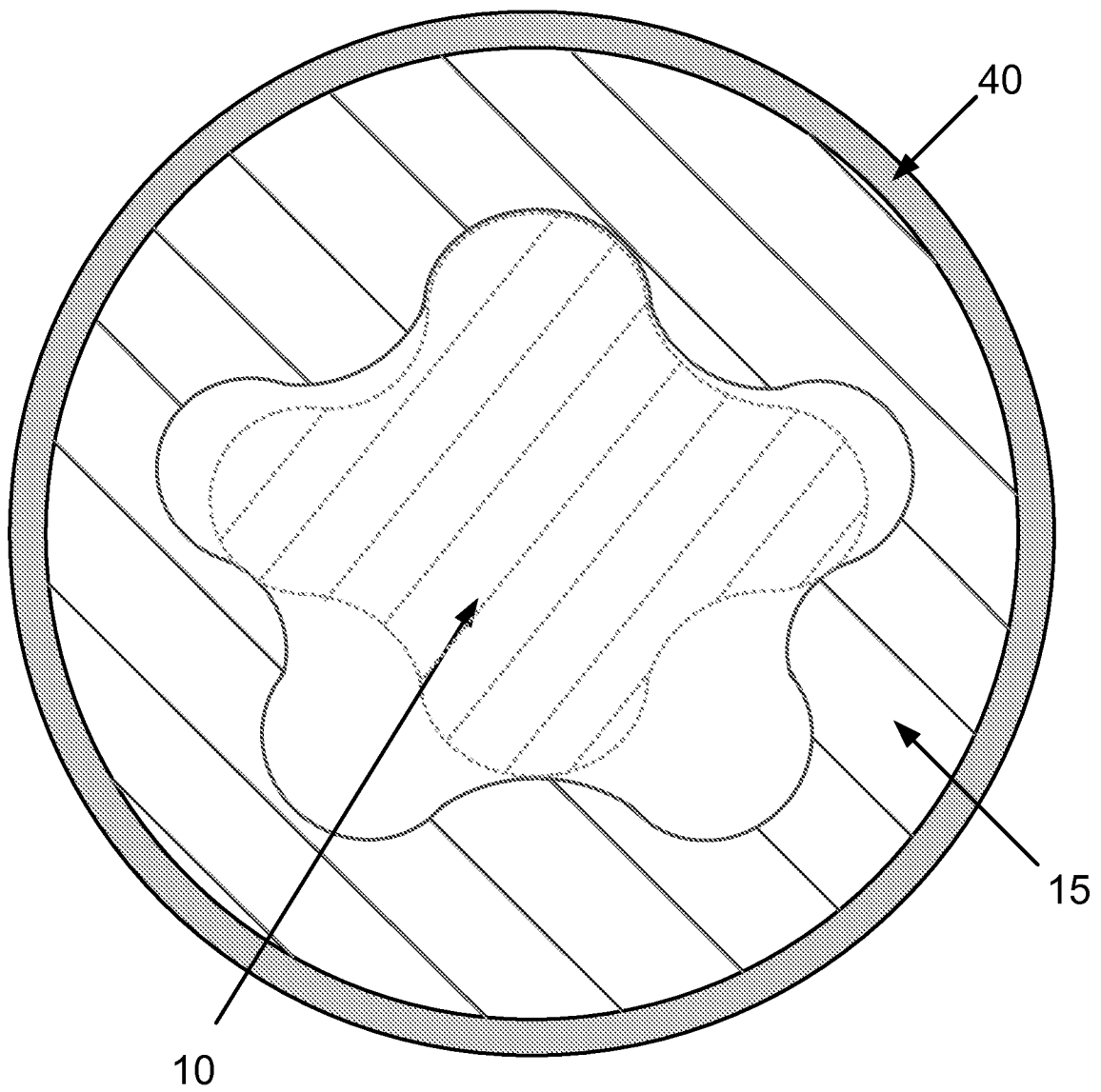


FIG. 1C

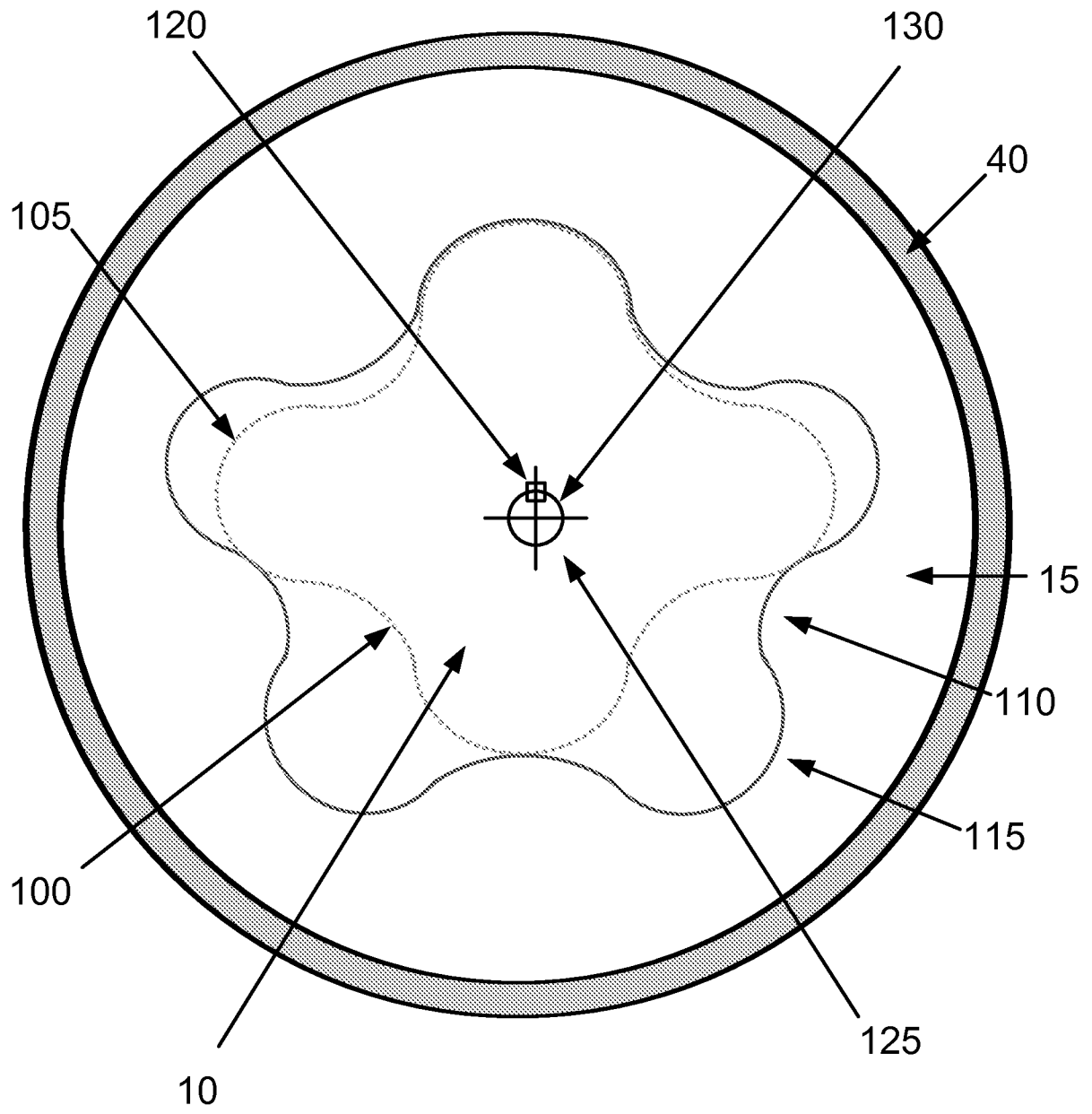


FIG. 1D

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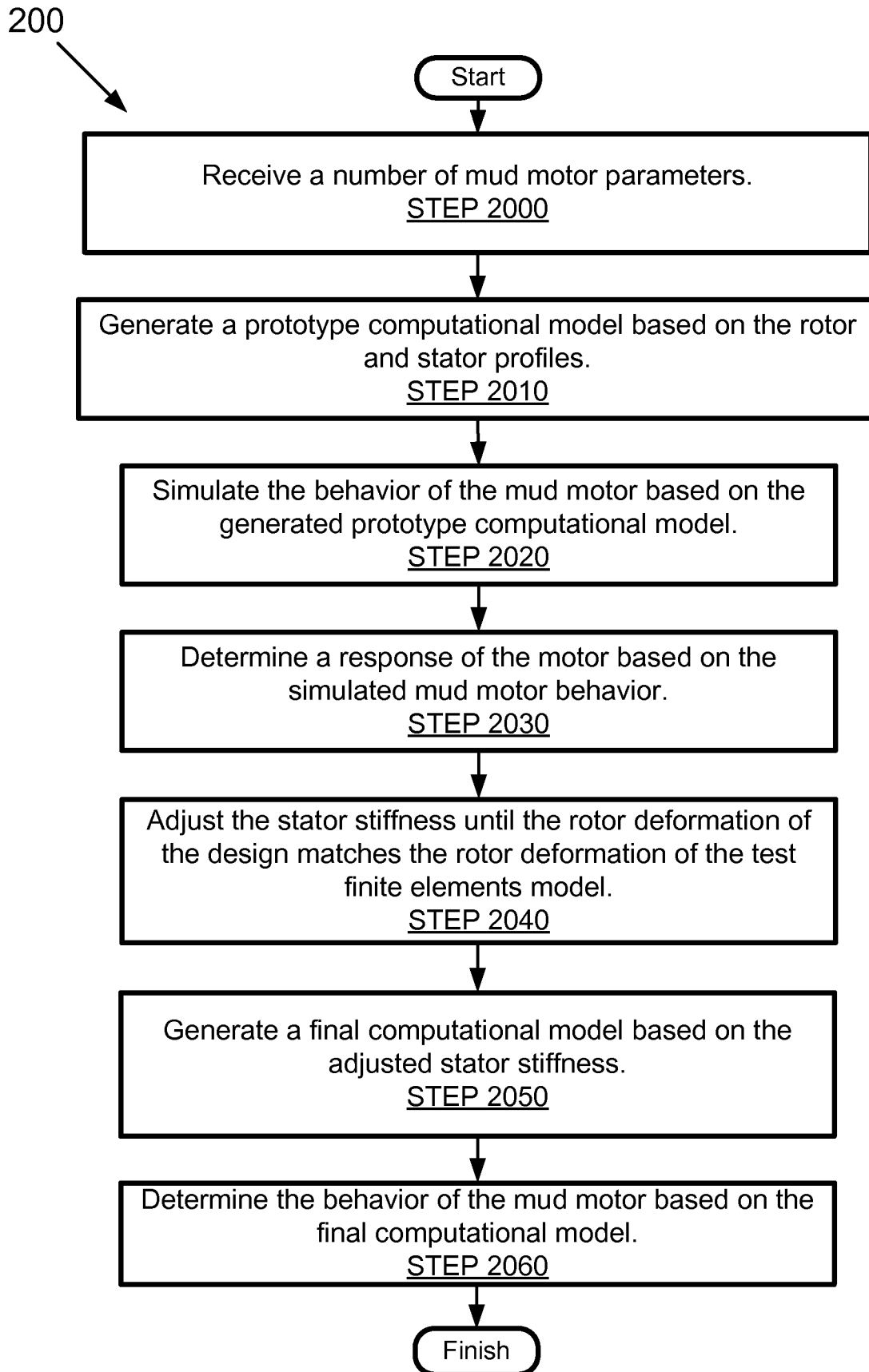


FIG. 2

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300

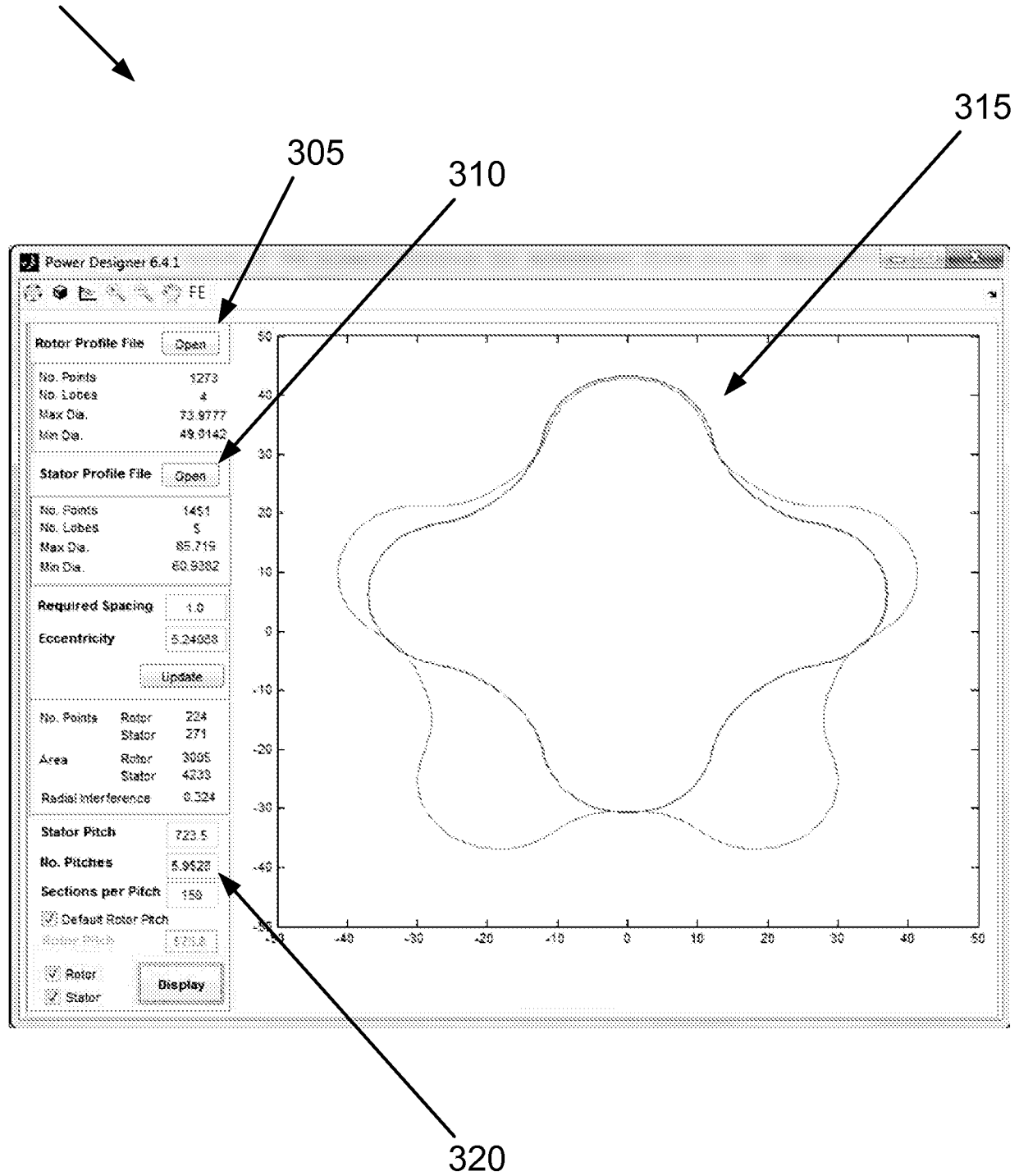


FIG. 3A

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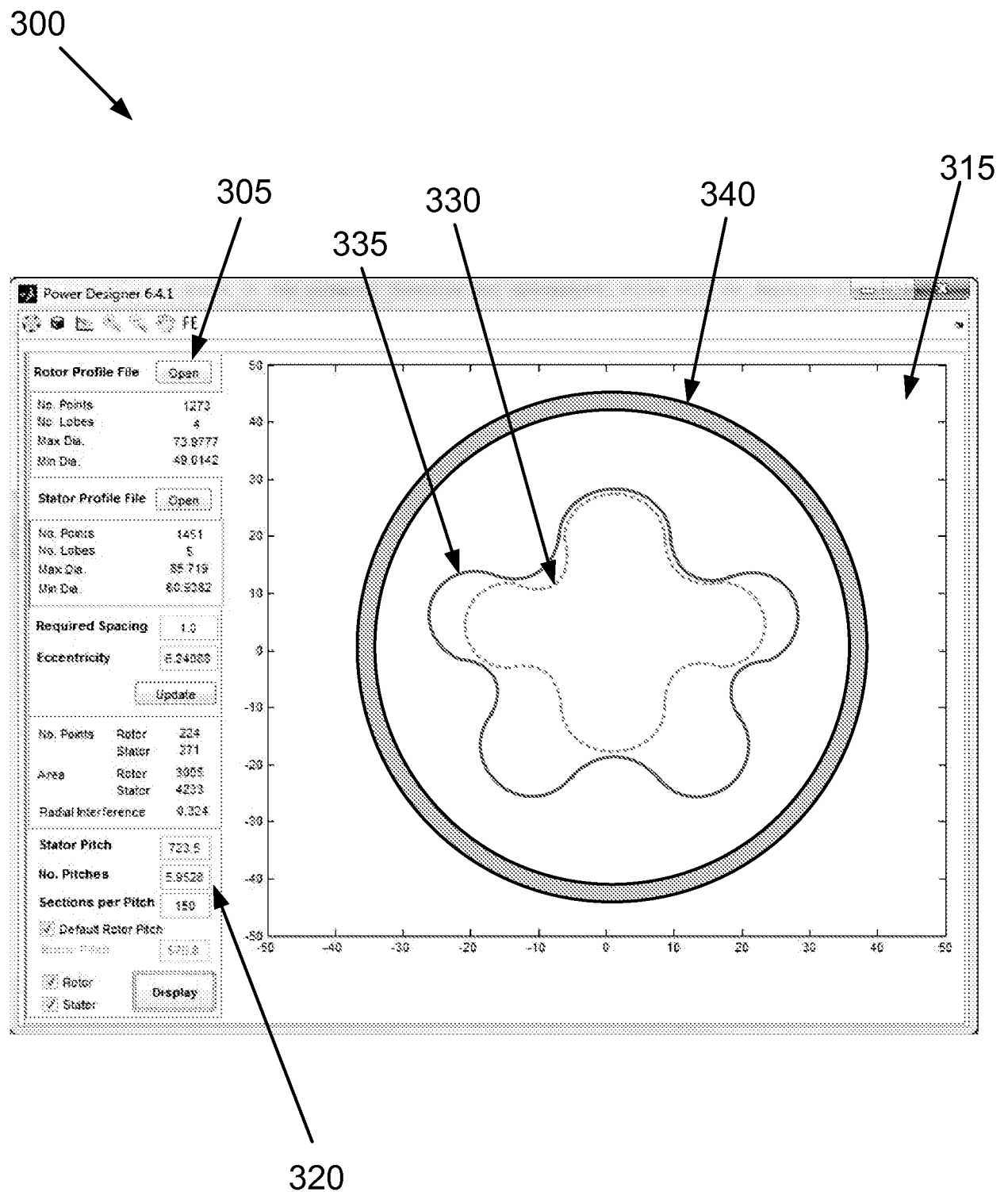


FIG. 3B

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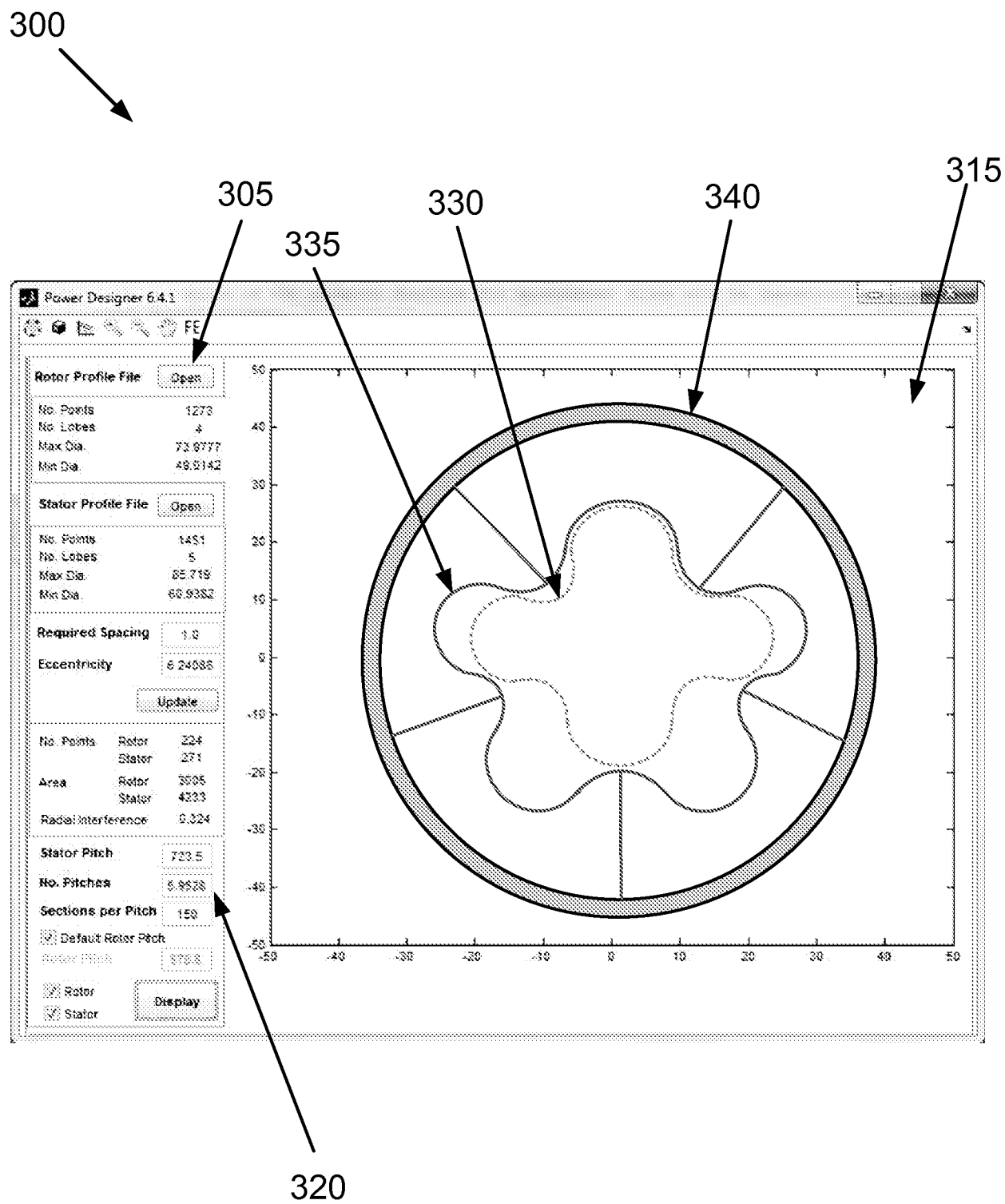


FIG. 3C



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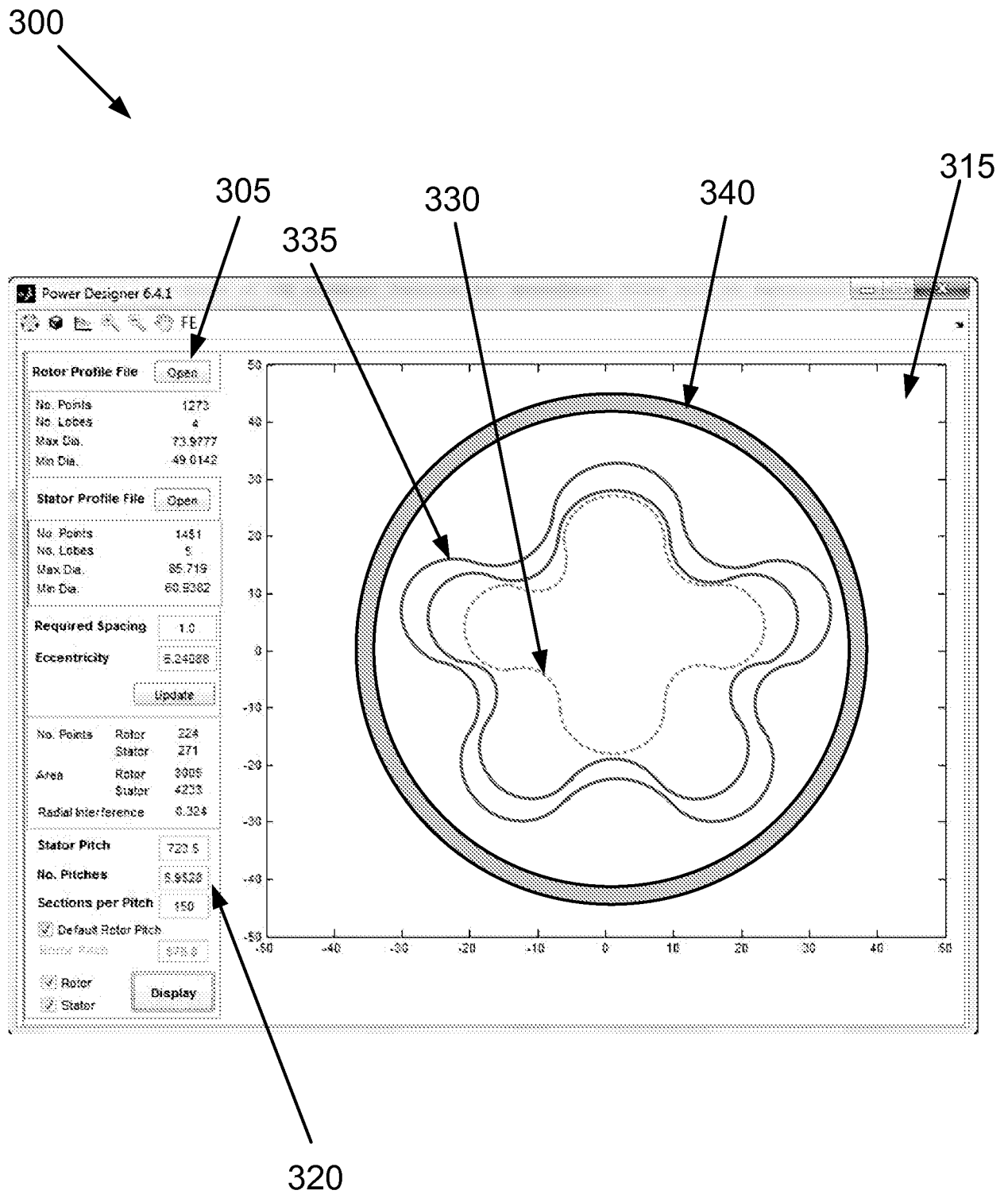
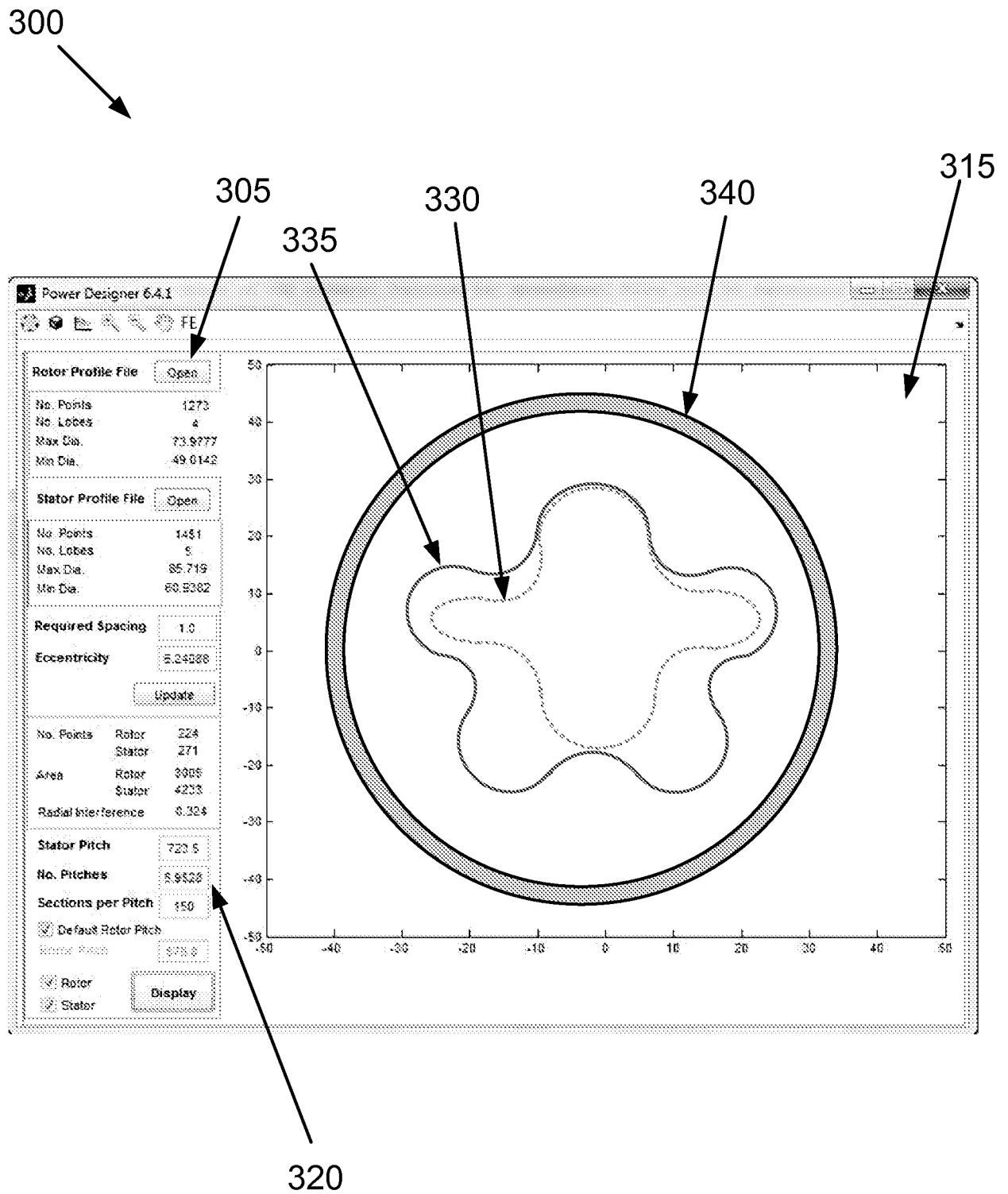


FIG. 3D

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**FIG. 3E**

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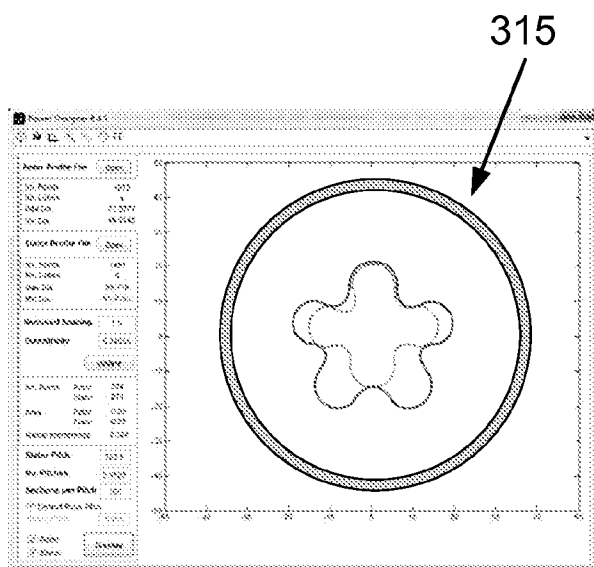


FIG. 3.F1

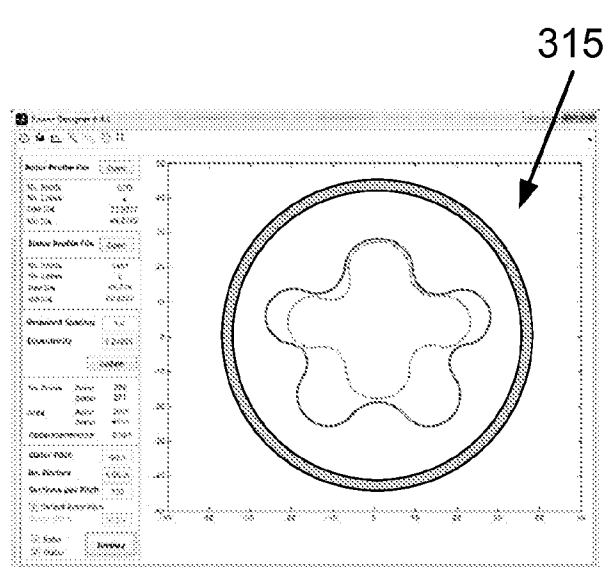


FIG. 3.F2

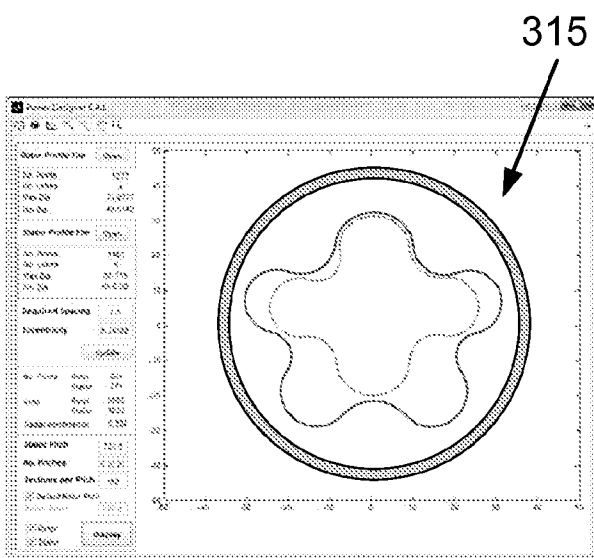


FIG. 3.F3

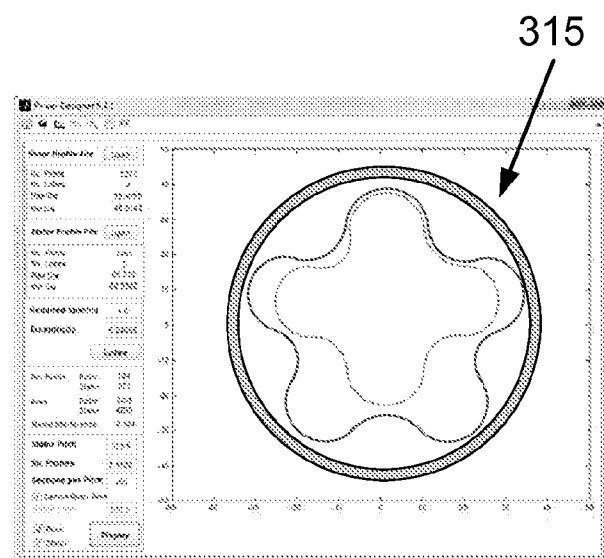


FIG. 3.F4

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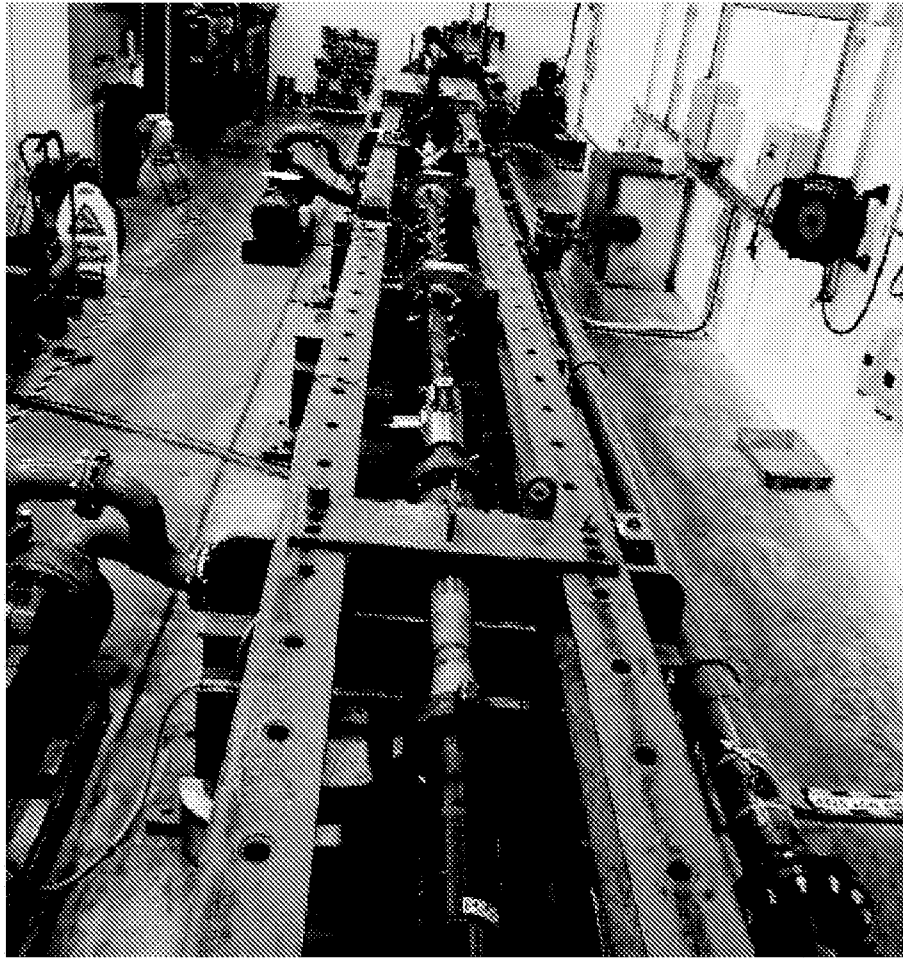


FIG. 4A

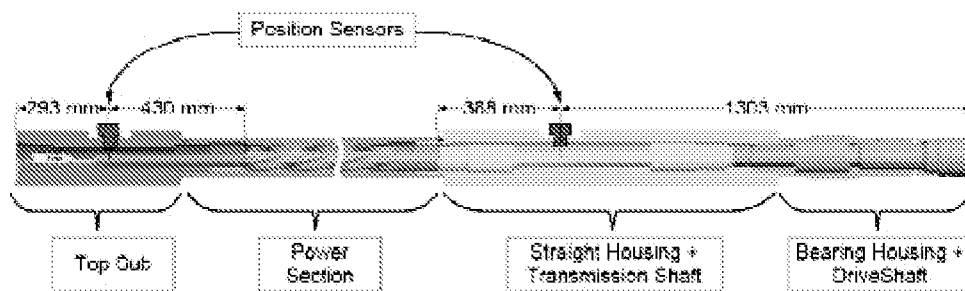


FIG. 4B

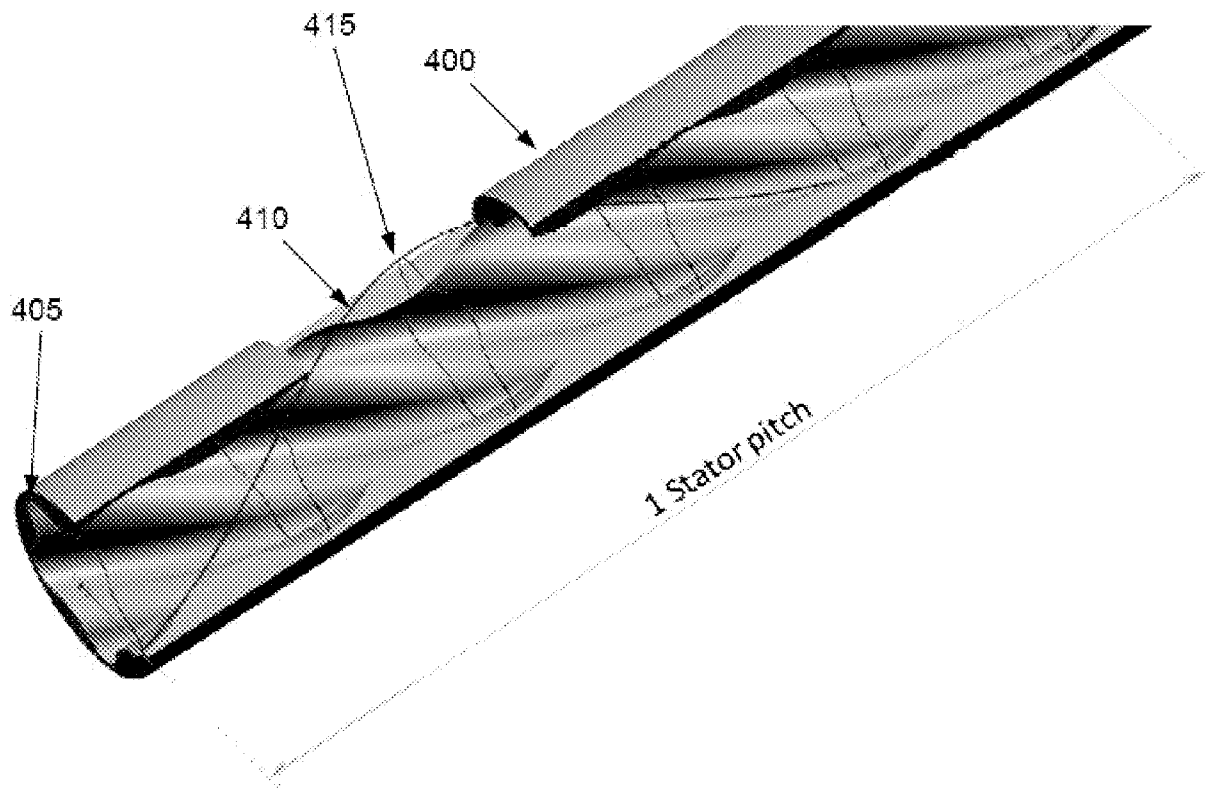


FIG. 4C

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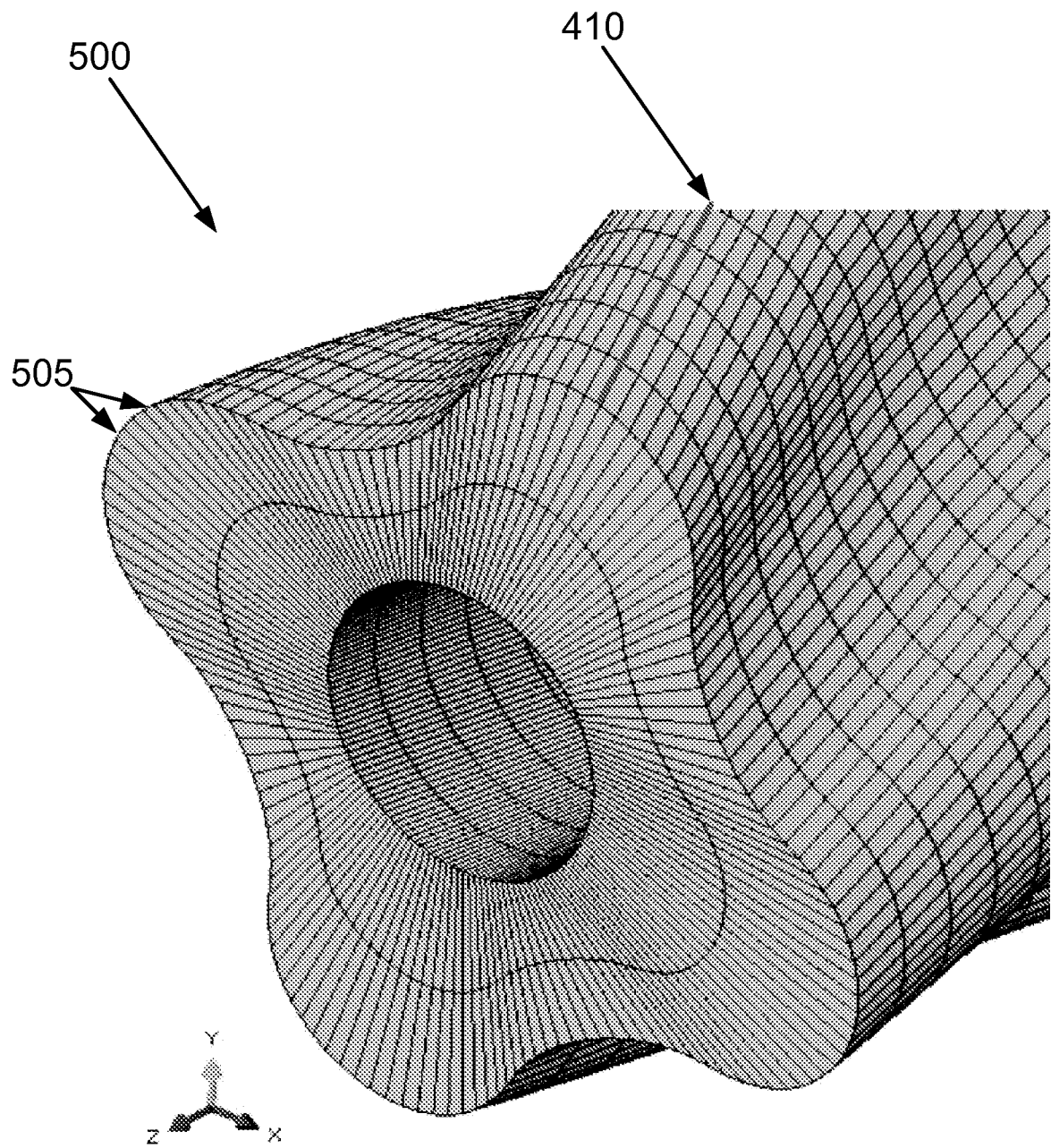


FIG. 5

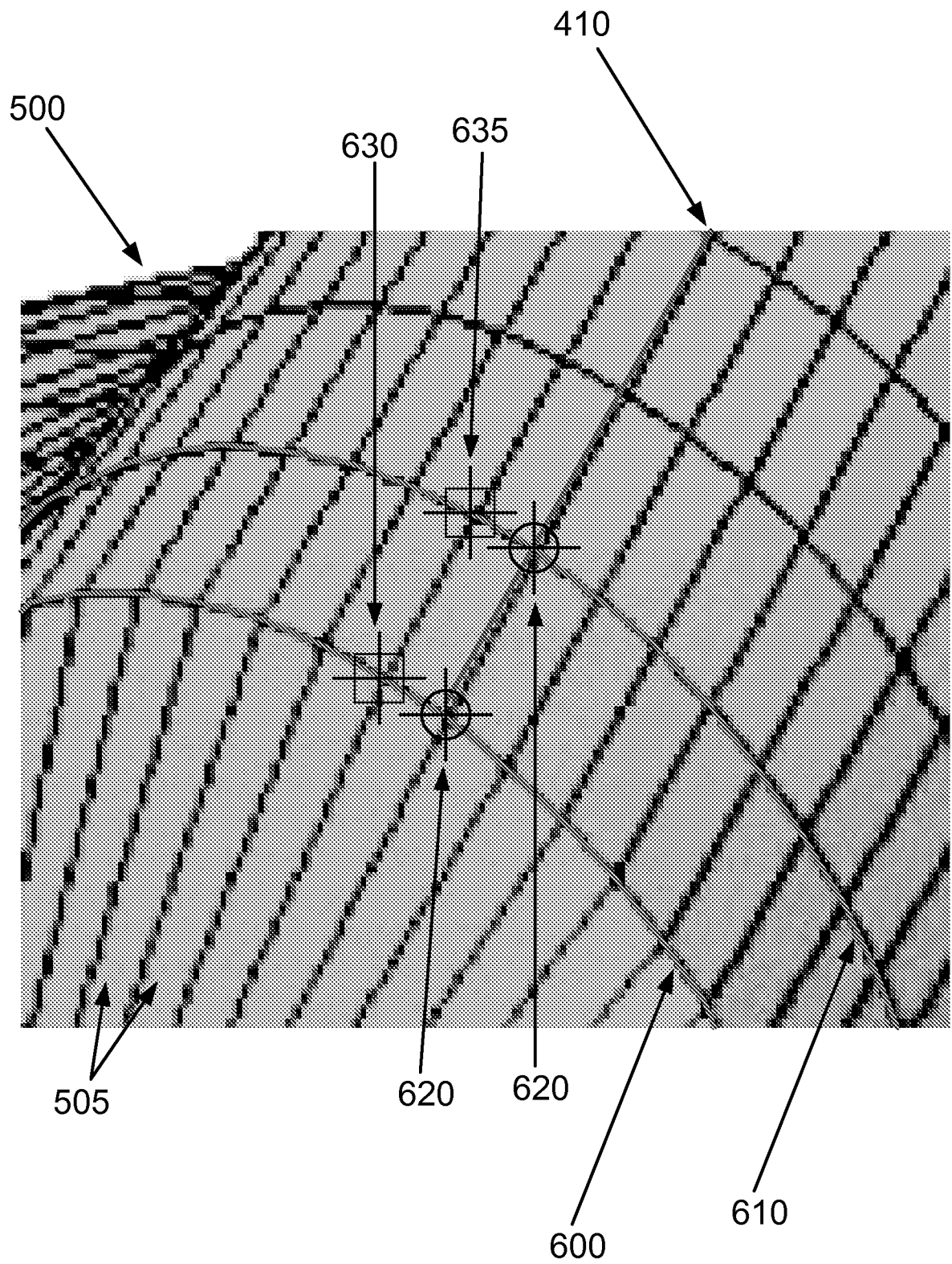


FIG. 6

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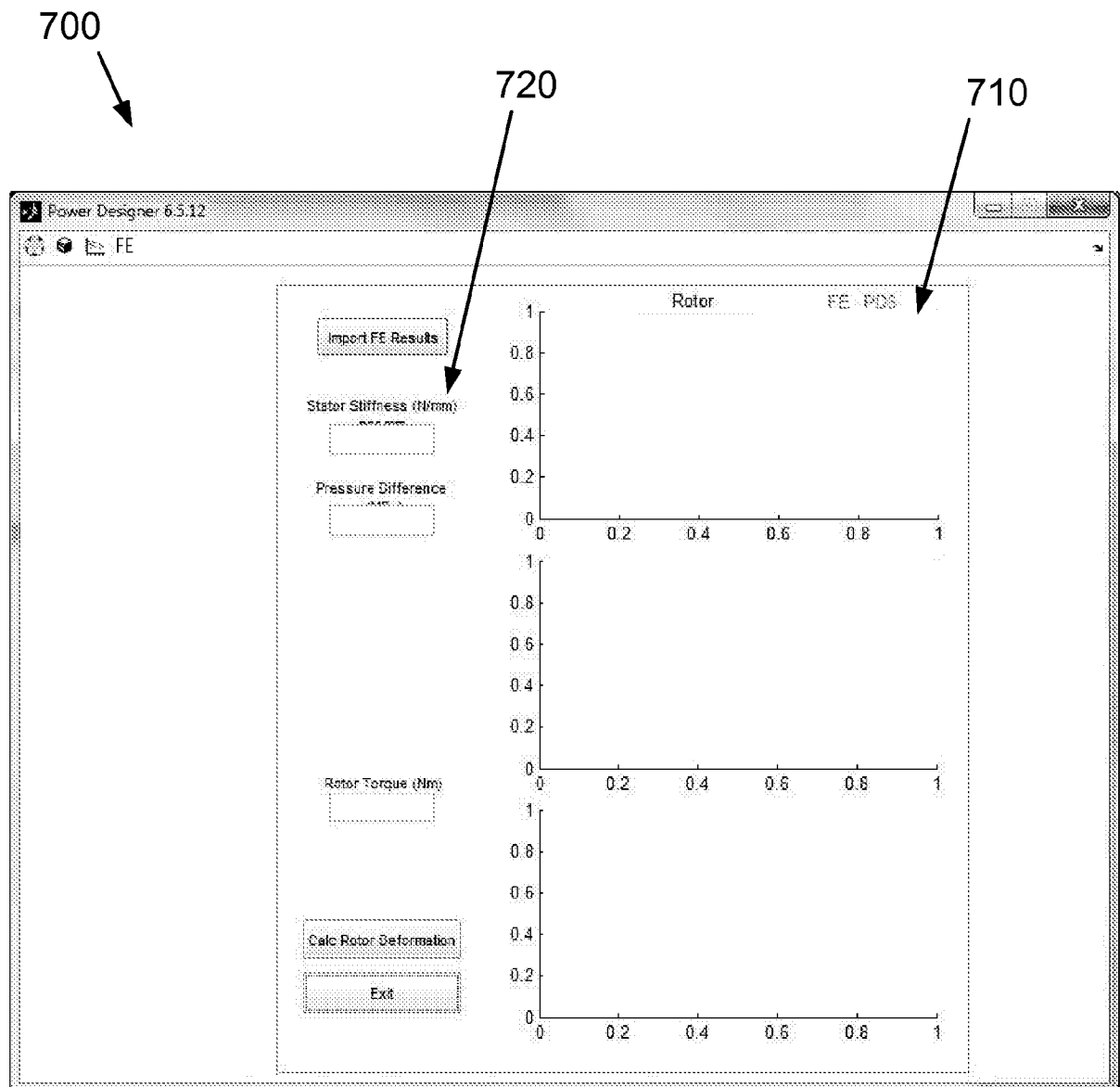


FIG. 7



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800

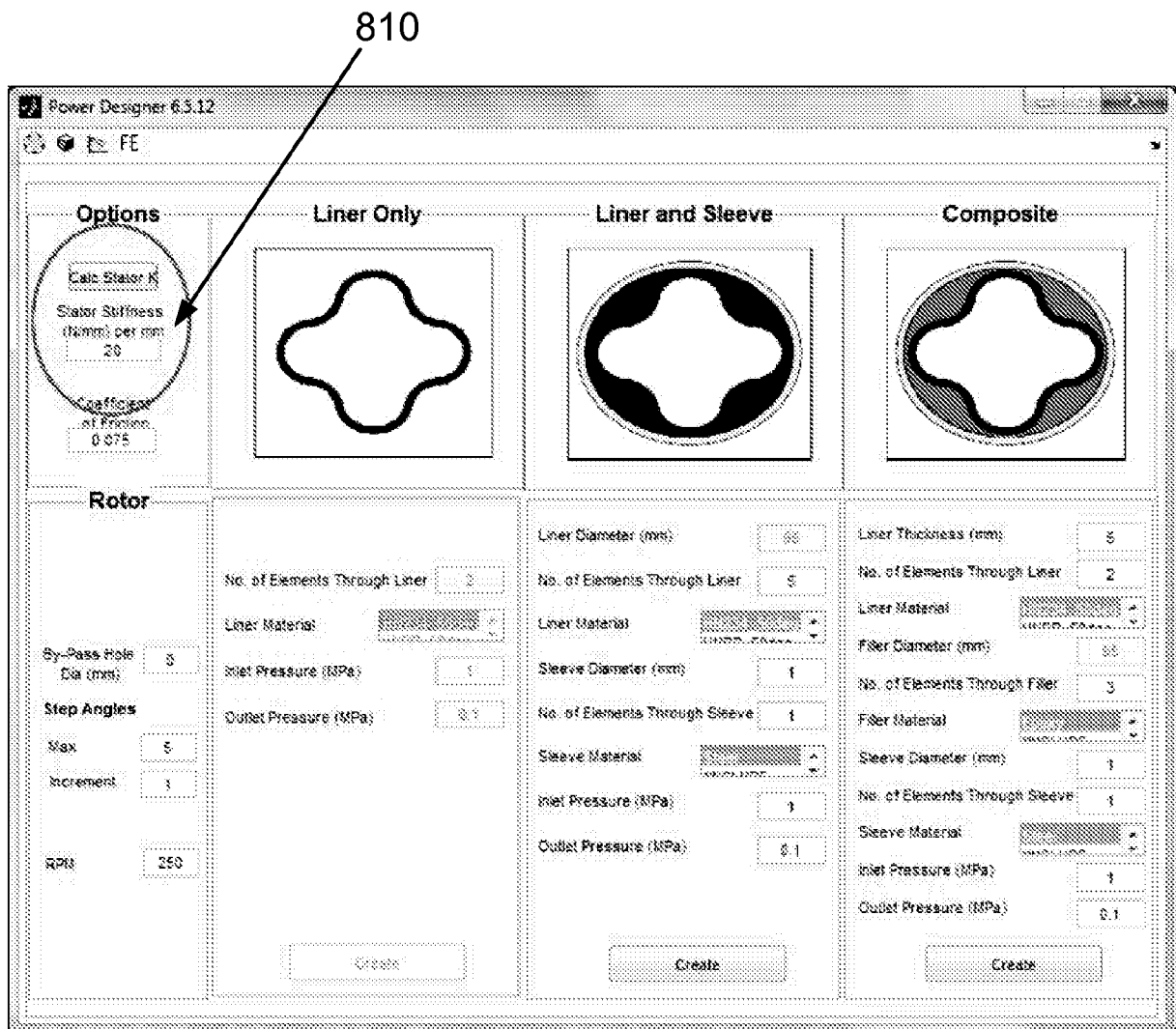


FIG. 8

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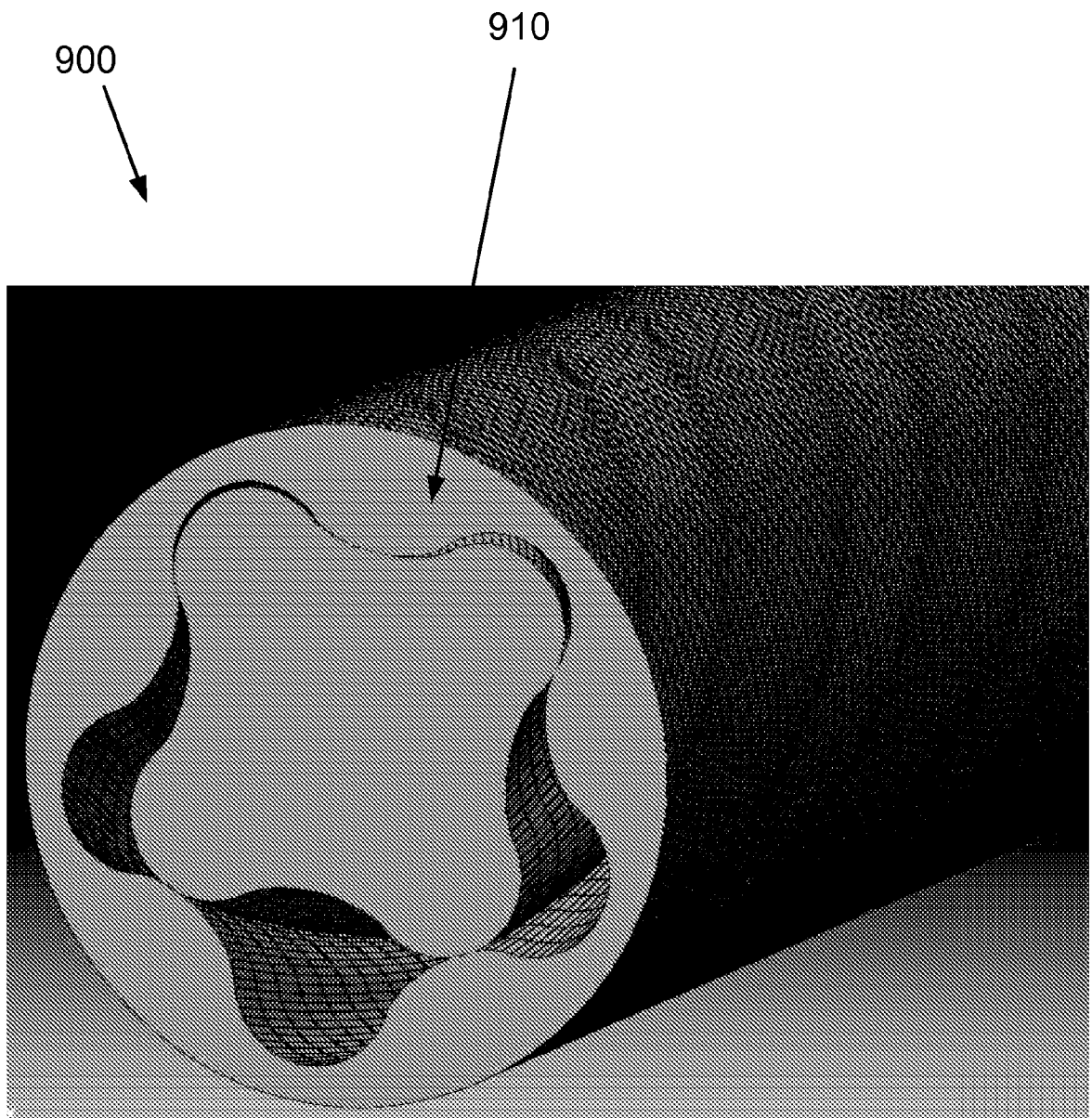


FIG. 9

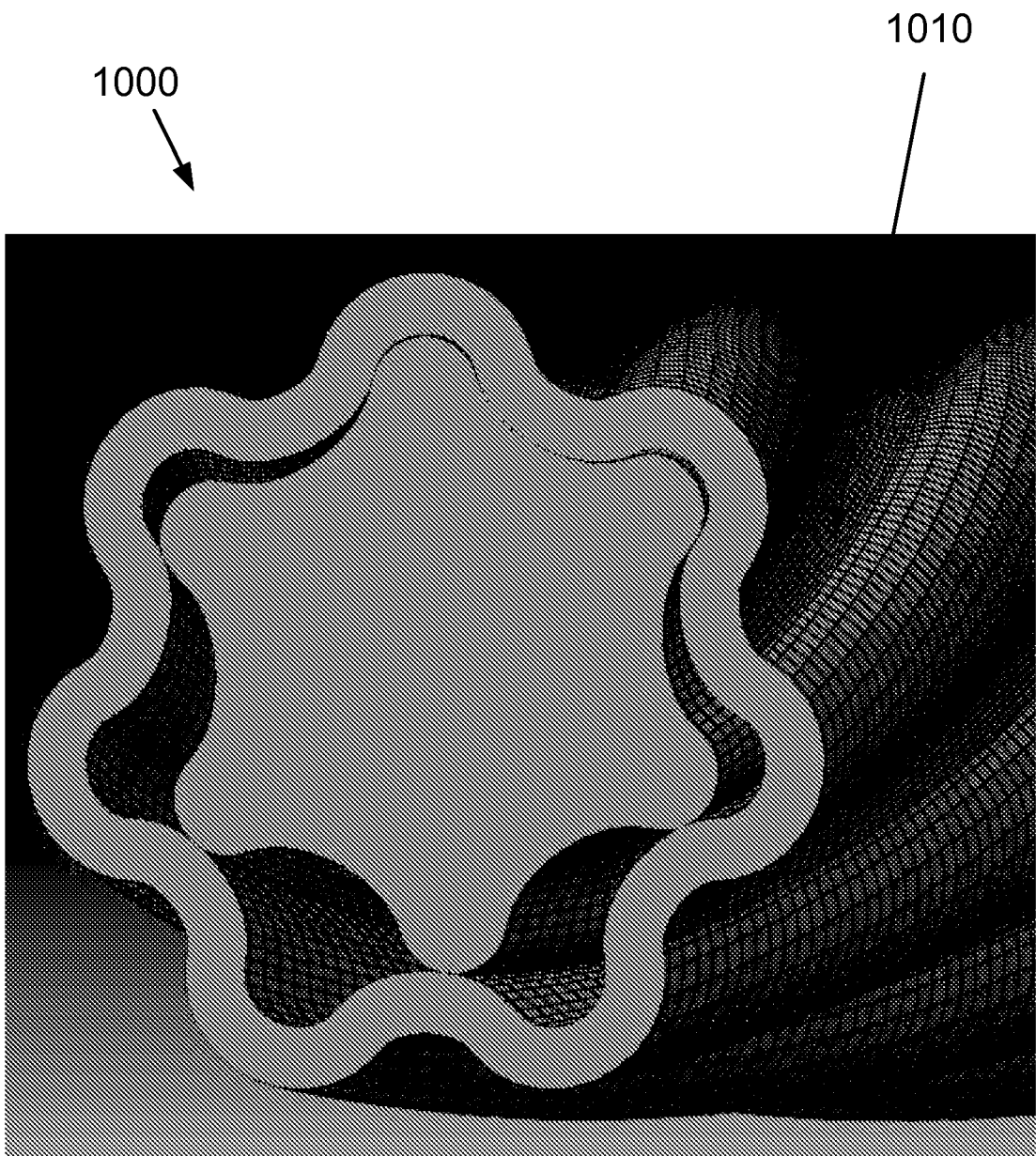


FIG. 10

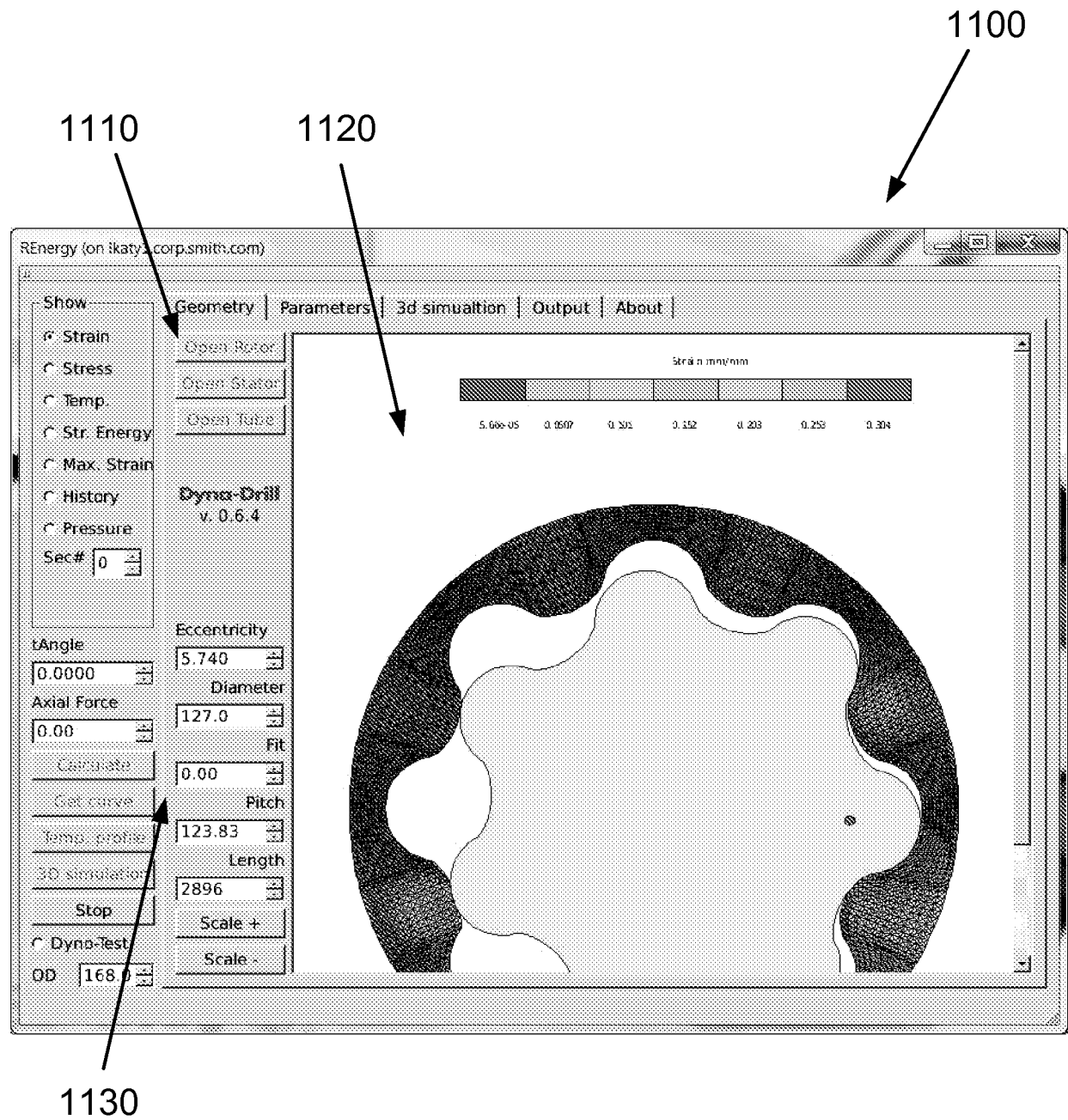


FIG. 11

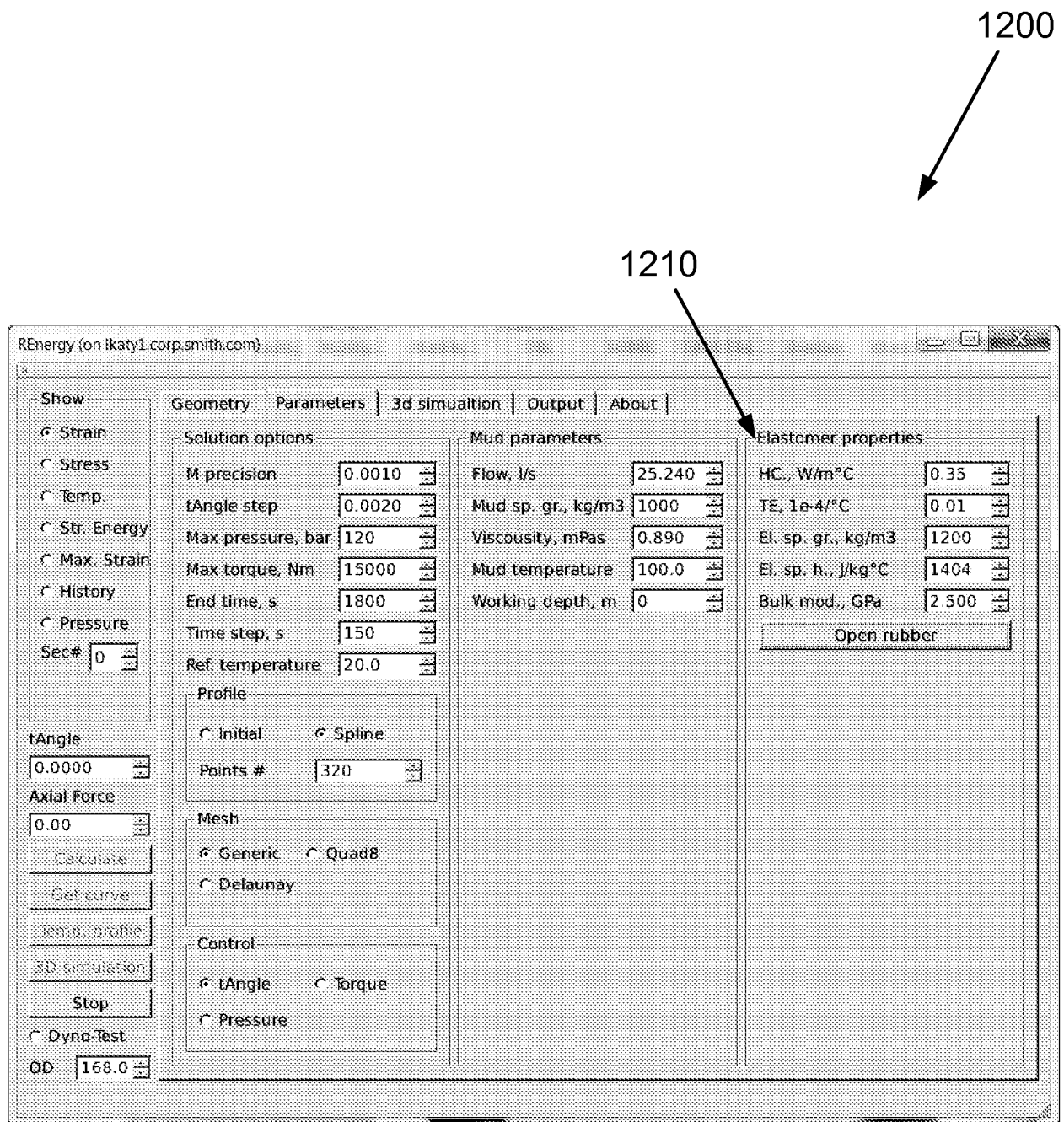


FIG. 12

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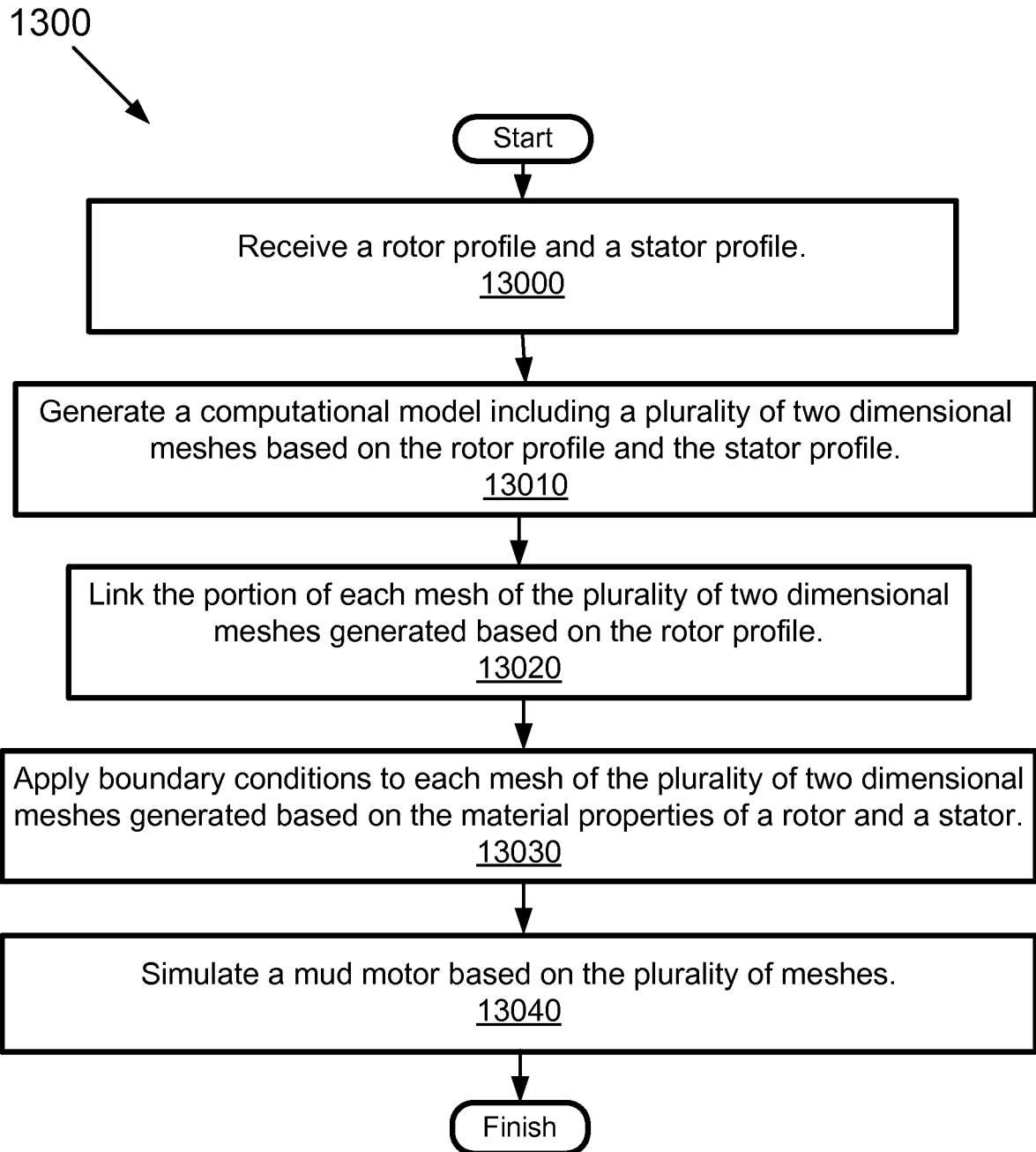


FIG. 13

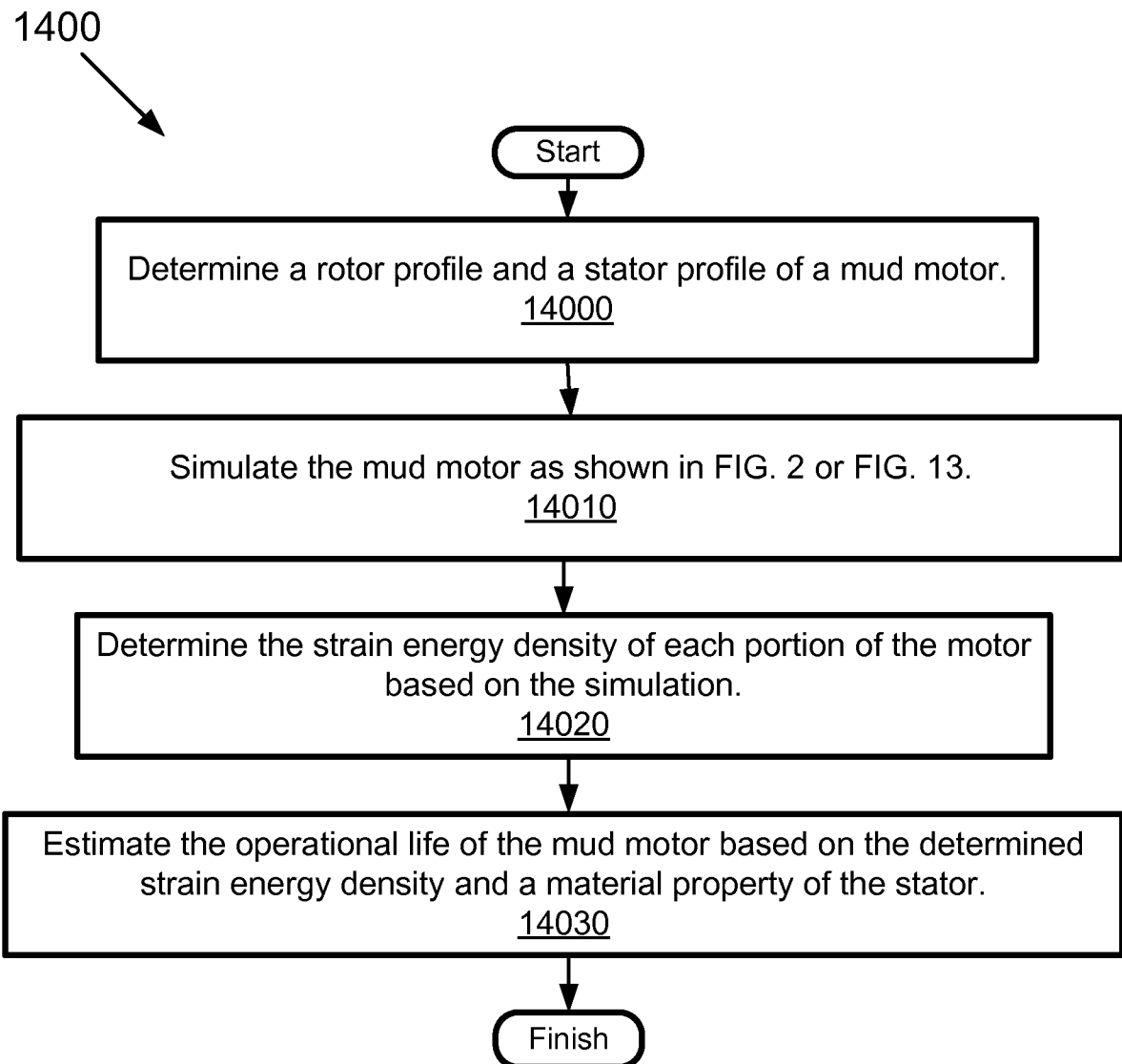


FIG. 14

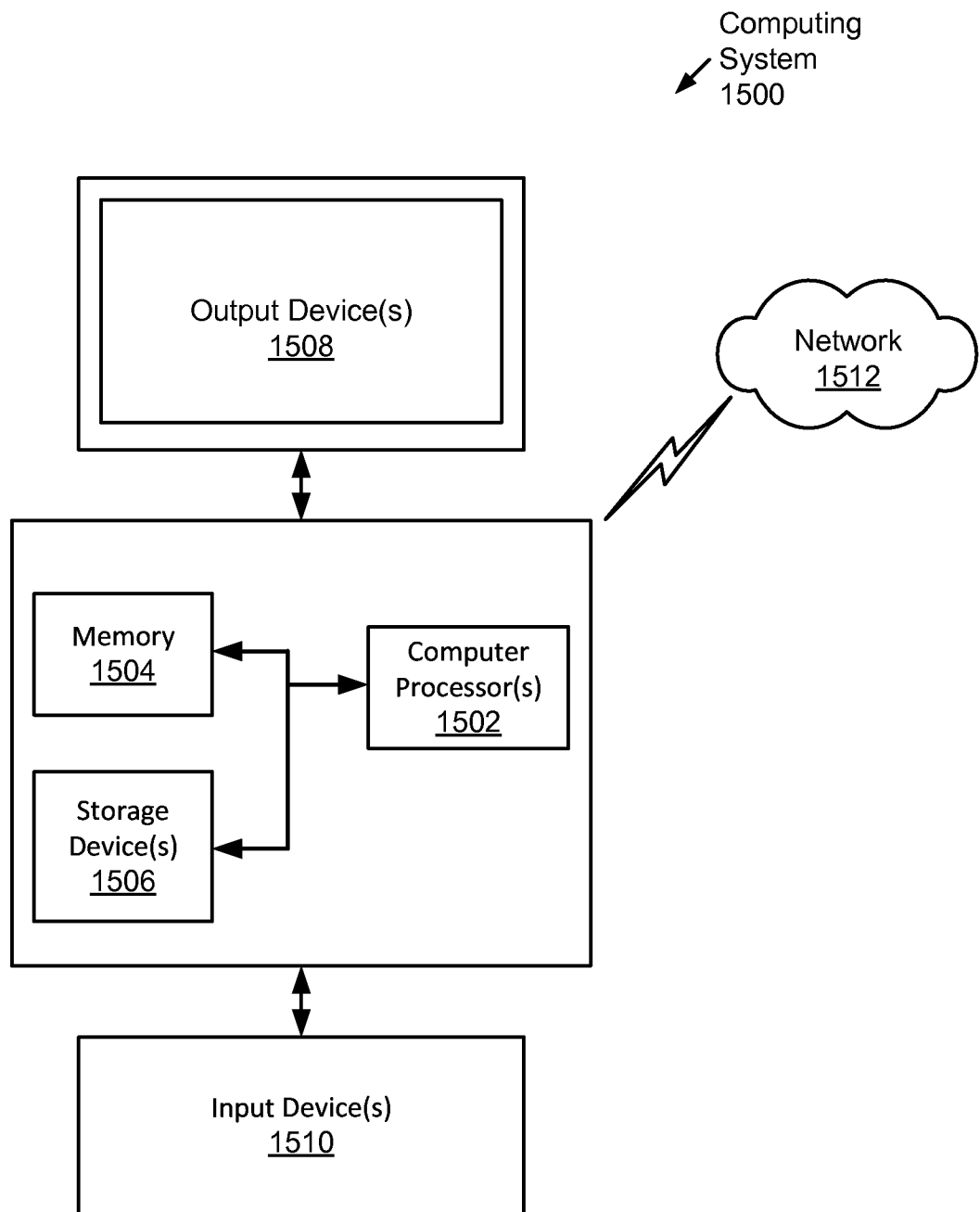


FIG. 15



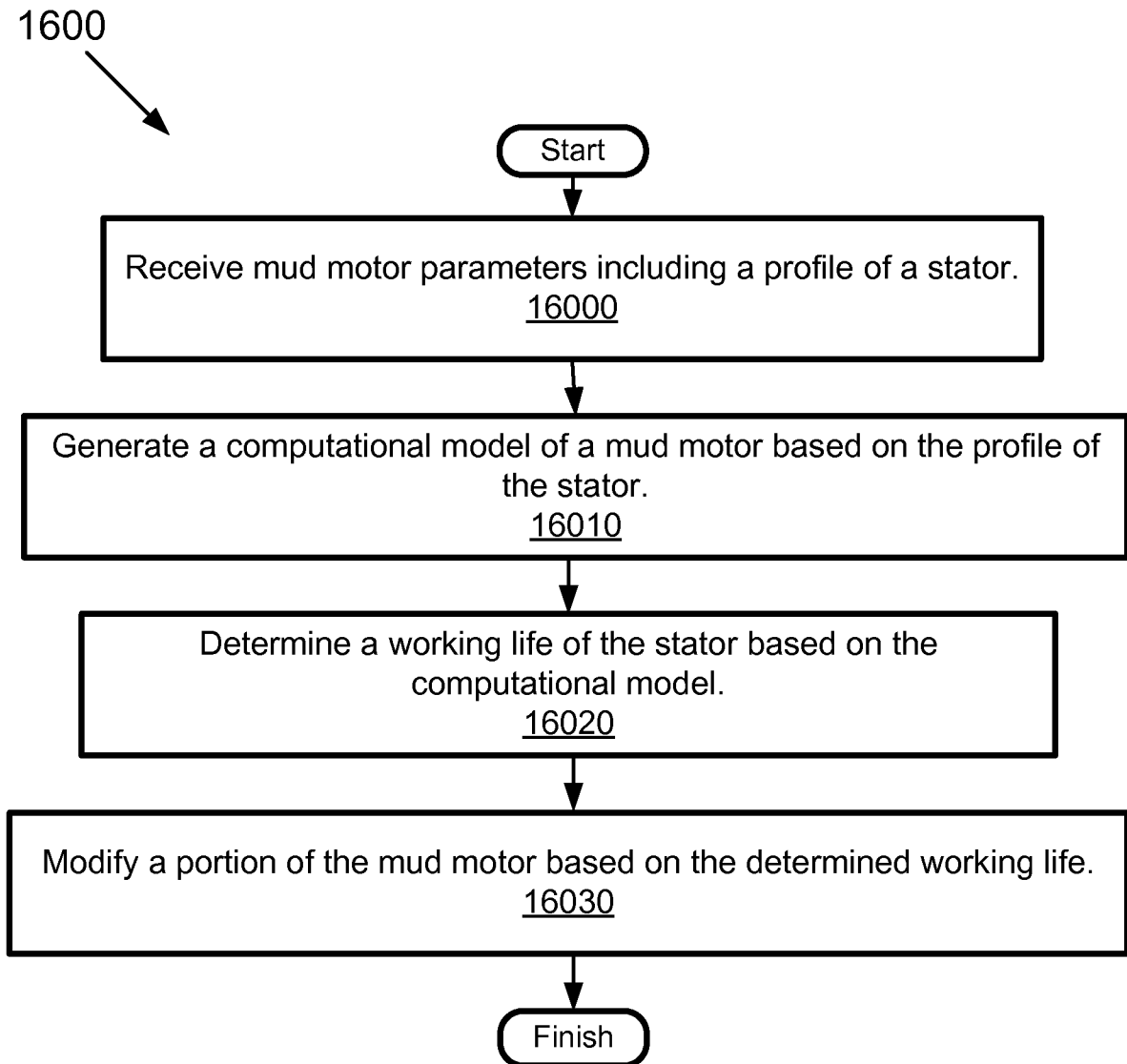


FIG. 16

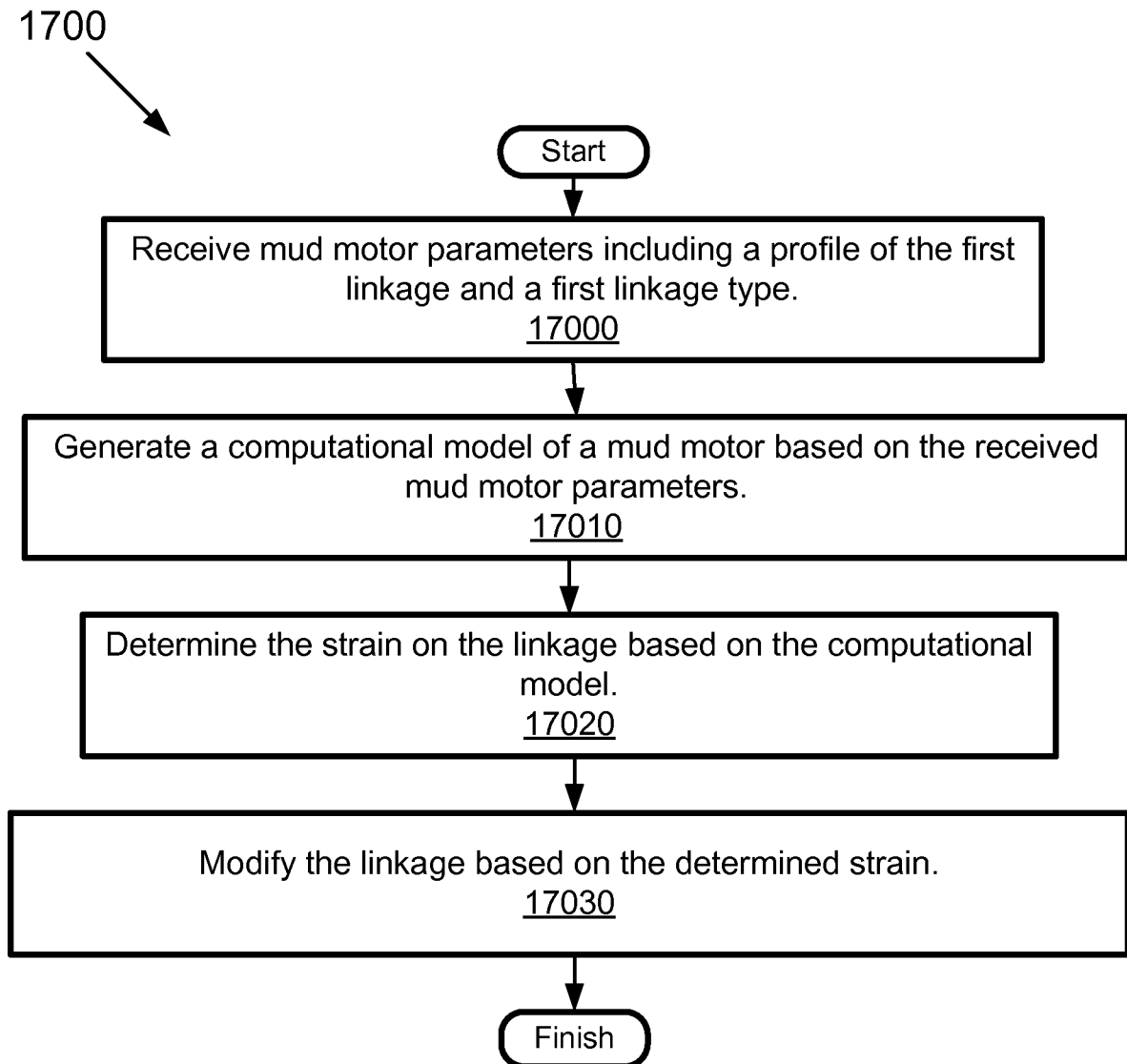


FIG. 17

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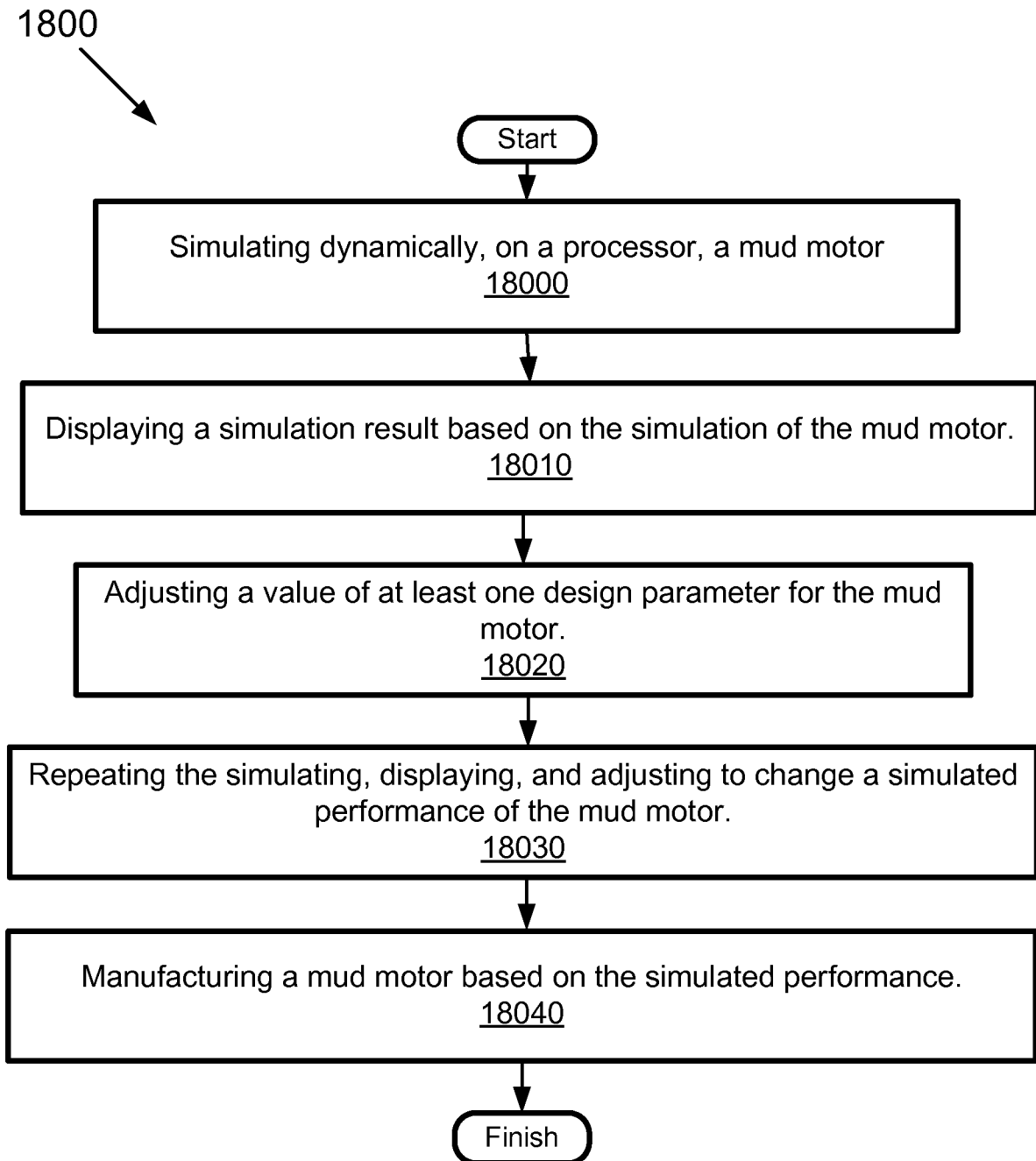


FIG. 18

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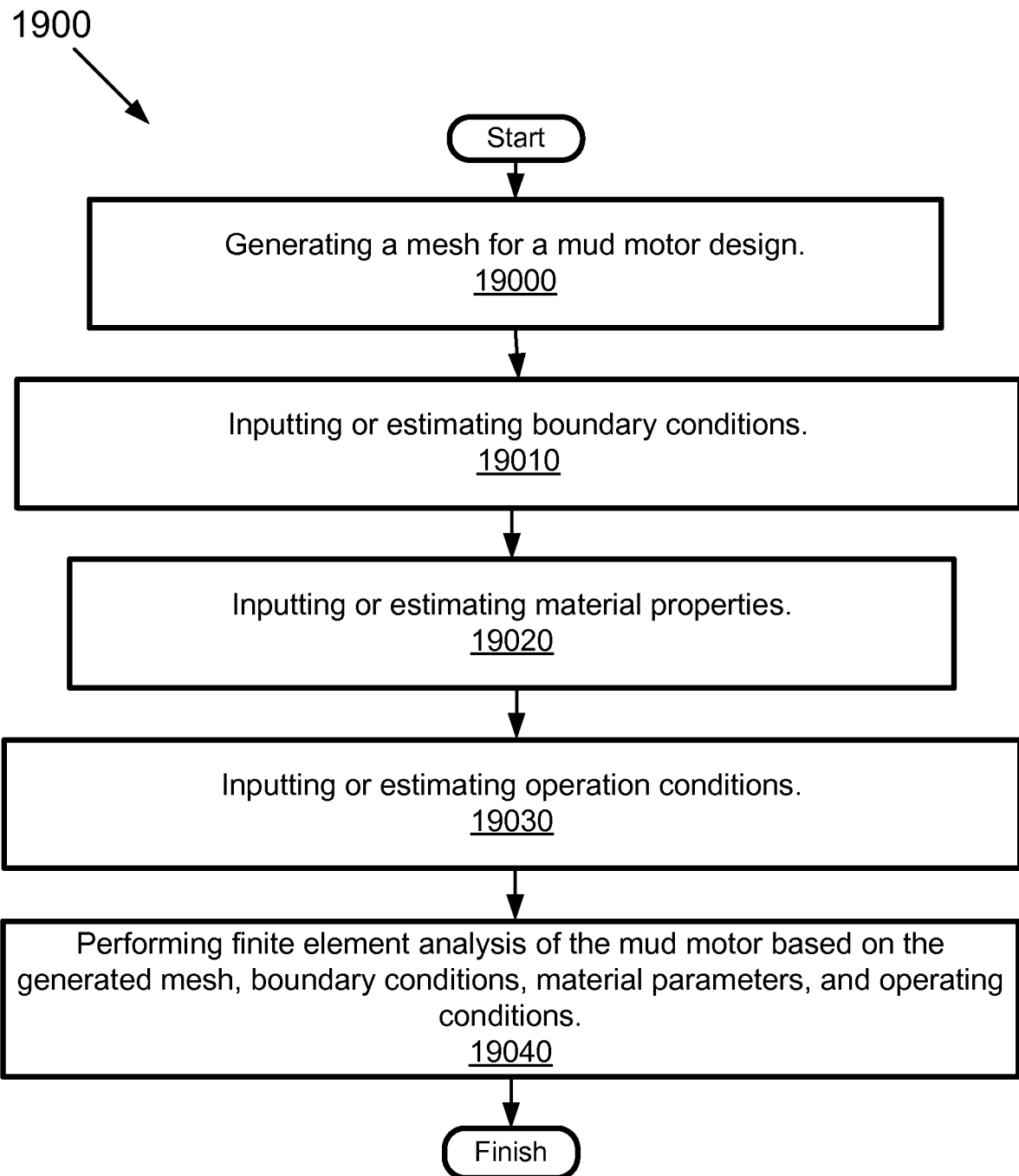


FIG. 19

## INTERNATIONAL SEARCH REPORT

International application No.  
**PCT/US2015/066530****A. CLASSIFICATION OF SUBJECT MATTER****G06F 17/50(2006.01)i, E21B 41/00(2006.01)i, E21B 17/00(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)

G06F 17/50; E21B 7/00; E21B 4/02; G06G 7/48; E21B 10/00; E21B 44/00; G06F 7/60; E21B 41/00; E21B 17/00

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) &amp; Keywords: mud motor, simulation, adjust, mesh, model, rotor, stator, drill, and similar terms.

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages                                                                                              | Relevant to claim No. |
|-----------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|
| Y         | US 2005-0133272 A1 (SUJIAN HUANG et al.) 23 June 2005<br>See paragraphs [0088] and [0186]–[0188]; claims 1 and 16; and figures 4A, 15, and 37.                                  | 1–30                  |
| A         |                                                                                                                                                                                 | 31–42                 |
| X         | US 2010-0163306 A1 (JAHIR A. PABON et al.) 01 July 2010<br>See paragraphs [0001], [0026]–[0028], [0034]–[0036], and [0047]–[0049]; claims 1–9 and 31; and figures 1–2 and 7–10. | 31–42                 |
| Y         |                                                                                                                                                                                 | 1–30                  |
| A         | US 2013-0054203 A1 (CHRISTIAN HERBIG et al.) 28 February 2013<br>See paragraphs [0029]–[0030] and [0060]; and figures 1 and 2A.                                                 | 1–42                  |
| A         | US 2011-0077924 A1 (MEHMET DENIZ ERTAS et al.) 31 March 2011<br>See paragraphs [0061]–[0067] and figure 2.                                                                      | 1–42                  |
| A         | US 2012-0234603 A1 (WILLIAM BANNING VAIL, III) 20 September 2012<br>See paragraphs [0428]–[0433]; and figures 2–2A and 20–20A.                                                  | 1–42                  |



Further documents are listed in the continuation of Box C.



See patent family annex.

\* Special categories of cited documents:

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"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

"&amp;" document member of the same patent family

Date of the actual completion of the international search

08 April 2016 (08.04.2016)

Date of mailing of the international search report

**08 April 2016 (08.04.2016)**

Name and mailing address of the ISA/KR

International Application Division

Korean Intellectual Property Office

189 Cheongsa-ro, Seo-gu, Daejeon, 35208, Republic of Korea

Facsimile No. +82-42-481-8578

Authorized officer

NHO, Ji Myong

Telephone No. +82-42-481-8528



**INTERNATIONAL SEARCH REPORT**

Information on patent family members

International application No.

**PCT/US2015/066530**

| Patent document<br>cited in search report | Publication<br>date | Patent family<br>member(s) | Publication<br>date |
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