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(54) Method and apparatus for continuous sectional magnetic encoding to measure torque on large shafts

Verfahren und Vorrichtung zur kontinuierlichen sektionalen magnetischen Codierung zur Messung des Drehmoments an großen Wellen

Procédé et appareil de codage magnétique sectionnel continu pour mesurer le couple sur de grands arbres

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Description

[0001] This invention relates generally to magnetic encoding of a shaft and in particular to an apparatus and method for sectional encoding of the shaft for use in determining one or more of rotational angle, rotational speed, bending moments and torque, especially on large shafts.
Conventional systems may, for example, use magnetized torque transducer elements of the type disclosed in WO 00/57150.

[0002] Sustainable energy sources, for example wind turbines, are gaining widespread popularity due to increased energy demands and the desire to reduce consumption of natural resources.

[0003] A typical wind turbine comprises a plurality of rotor blades, located atop a high tower, for converting the wind energy to rotational energy for driving a main shaft. The main shaft is coupled to an electric generator either directly or through a gearbox (transmission). The gearbox converts low speed wind-driven rotation to high speed rotation as required for driving the generator to generate electricity. The wind turbine also includes a structural support component, such as a tower, and a rotor pointing mechanism.

[0004] Wind turbine control tends to be complex, as wind speeds fluctuate in both intensity and direction. Horizontal and vertical wind shears, mechanical oscillations, and yaw misalignment, together with natural wind turbulence and tower motion, also induce dynamic and asymmetric loads on the rotor blades. These loads are transferred to the rotating main turbine shaft where they appear as forces or bending/twisting/torque moments. Specifically, these loads generate large torques, bending moments, twisting moments, stress forces and strain forces. For a wind turbine, the shaft torque may also have dynamic components induced by current flowing on the electrical grid and the turbine control system. These dynamic components are also of interest from a design, control and reliability standpoint.

[0005] The forces imposed by these operating conditions, sometimes referred to as loads, also increase the number of fatigue cycles accumulated by the wind turbine. Such loads and fatigue cycles can lead to premature system failure, operational inefficiencies, and damage to the wind turbine components.

[0006] To ensure reliable and efficient operation, wind turbine control systems should accurately measure the forces and the bending/twisting/torque moments acting on the shaft and control one or more operational parameters of the wind turbine system, such as the blade pitch, revolutions per second and/or yaw angle, to limit these forces. Accurate measurement of rotational speed of the shaft and shaft position (i.e., an angle a fixed point on the shaft makes with a fixed point external to the shaft) are also required for proper and safe operation of the wind turbine. The accuracy of these measurements must be maintained over a relatively long period. Wind turbine control also becomes more complex as the wind turbine size and energy output increase. In addition to using these measured values to control the wind turbine, the measured values can be used in wind turbine design.

[0007] To address the design and operation of any equipment using a rotating shaft, it is desired to measure any external force-induced deformations at the shaft surface. These measurements can be used to numerically determine the bending/twisting/torque and moments and other forces imposed on the shaft.

[0008] Conventional shaft control technologies employ a number of different sensors and/or systems to sense or measure these forces and shaft operating parameters. These sensors include, but are not limited to, strain gauge systems, encoder/tooth systems, acoustic wave systems, elastic systems, magnetostrictive systems and magnetoelastic systems. Each of these systems has certain characteristics and applications, as well as specific advantages and disadvantages.

[0009] Strain gauges embedded in or attached to the shaft provide local shaft strain measurements. These gauges require an electrical coupling to the rotating shaft, i.e., a physical connection (e.g., slip rings) or a wireless connection, and the signals produced have a relatively low signal-to-noise ratio. The strain gauges also suffer from low stability, limited bandwidth and tend to require frequent calibration. The limited operating temperature range of strain gauges limits their use in harsh environments. Also, strain gauges may fail after a short period of use due to the large stresses imposed on the shaft in applications with large diameter shafts in high power applications. Thus strain gauges are seldom used in commercial power train equipment.

[0010] An encoder/tooth-wheel torque sensor requires some mechanical interaction with the rotating shaft, such as by a magnetic tooth-wheel. But the tooth-wheel design tends to be costly and impractical for many applications. Such a design is not practical for higher speed applications, imposes reliability issues in a harsh environment and although stable, lacks high resolution.

[0011] An acoustic wave system utilizes sensors, such as surface acoustic wave (SAW) and bulk acoustic wave (BAW) sensors, mounted on the shaft for measuring shaft strain. Slip rings or a wireless system are required to carry the signals indicating shaft deformations and forces imposed on the shaft to an external detector.

[0012] Elastic torque systems measure the twisting of the shaft by measuring angular displacement of markers disposed across a length of the shaft. This system may not be sufficiently accurate for large diameter shafts and may have practical implementation problems.

[0013] Proximity sensors are also employed to measure shaft bending moments. These sensors require a stiff reference (i.e., a stiff support structure) and are vulnerable to deflection of the support structure and sensor drift, leading to errors in measured values. Since the main shaft system is stiff, small offset errors in the measured, such as 0.1 mm, correspond to high errors in the bending moment analysis, such as an error of 200 kNm. These errors can cause improper operation of the shaft control system.

[0014] Shaft position can be determined by angular encoders that employ optical gratings. The shaft is encoded prior to installation and the encoded regions detected to determine shaft position. But these sensors are prone to contamination and failure in dirty environments.

[0015] Magnetic shaft force sensors, as described by NCT Engineering GmbH. (Erlenhof-Park. Inselkammerstr. 10, 82008 Unterhaching, Germany) and others, cannot be applied to large shafts in a cost efficient manner, e.g. on shaft diameters greater than about 200 mm, due to the high power required to encode the shaft.

[0016] Another approach to measuring forces imposed on the shaft is based on the magnetostrictive effect on ferromagnetic shaft material or on ferromagnetic material regions applied to or formed in the shaft. Magnetostrictive measurements are based on the phenomenon that a material changes dimensions when magnetized. For certain materials the magnetostrictive effect is very small.

[0017] A conventional magnetostrictive torque sensor comprises a primary coil that generates a high frequency magnetic field and secondary coils that measure the magnetic flux of the resulting field. The total measured flux from all of the secondary coils indicates whether a torque is present. This approach does not require encoding of the shaft.

[0018] Typical magnetostrictive coefficients, in the form $\Delta l/l$, are on the order of 1×10^{-6} to 25×10^{-6}. The use of the direct (i.e., no encoding of the ferromagnetic material) magnetostrictive effect for measuring torque on large shafts of ferromagnetic material is expensive, requires complex sensor arrangements, difficult calibration procedures and typically results in measurements with limited accuracy.

[0019] However, the magnetostrictive effect can be advantageously used with improved accuracy and reduced installation costs by combining the magnetostrictive effect with a magnetically encoded shaft or with magnetically encoded regions applied to the shaft. The shaft material or the material regions are encoded by passing current through the shaft or material regions during shaft manufacture or after installation of the shaft. The encoding is permanent when applied to a suitable material and when created by a current with a sufficiently high current density.

[0020] Encoding electrodes are electrically coupled to the shaft to support current flow from one or more input electrodes through regions of the shaft to one or more output electrodes. The current induces a magnetic field that creates magnetically polarized encoded regions within the shaft. When the encoding current and the resultant encoding magnetic field are applied to a ferromagnetic material, the boundaries between magnetic domains shift and the domains rotate. Both of these effects change dimensions of the material along the magnetic axis. Preferably the encoding electrodes are disposed to create a plurality of uniform magnetic regions on the shaft.

[0021] Conversely, one or more magnetic parameters of the material change when subjected to a mechanical force or a bending/ twisting/torque moment. Specifically, these forces change the material properties and in turn cause a change in an external component of the magnetic field. These changes in the magnetic field can be detected by magnetostrictive sensors, such as fluxgate sensors.

[0022] A typical magnetostrictive torque sensor employs total shaft encoding, with the magnetization created by axial current flow along the shaft. The encoding is circumferentially uniform (circumferentially uniform) as the magnetic encoding requires magnetization of the entire cross-section. To create these uniform circumferential magnetic regions, multiple electrodes are disposed in ring-like arrays around the shaft and current is simultaneously applied to all electrodes. The magnetization is created (i.e., the shaft is encoded) by directing current to flow in an axial direction along the shaft from input electrodes to output electrodes.

[0023] However, large diameter shafts, such as wind turbine shafts (and gas turbine shafts), are typically not amenable to the conventional magnetic encoding technique as described immediately above. These techniques are suitable for relatively small diameter shafts but as the shaft diameter increases, the number of electrodes required to magnetically encode the shaft increases and the required current carried by each electrode also increases. For example, a current of several hundred amperes may be required for each electrode pair (a pair comprising an input and an output electrode). For accurate torque detection (or detection of any forces exerted on the shaft), the encoding must create a circumferentially uniform magnetic field; a difficult and costly effort to implement on large diameter shafts. Disadvantageously, the rotational speed of the shaft cannot be determined from a circumferentially uniform magnetic field.

[0024] Non-uniform magnetic fields are caused by non-homogeneity of the electrical and magnetic properties of the shaft. Further, the current is typically supplied as specifically-shaped current pulses, requiring complex electronic circuits to support the high-current. For all of these reasons, circumferentially uniformly encoding schemes applied to large diameter shafts tend to be difficult and very expensive to implement.

[0025] Examples of prior art magnetostrictive encoding and sensing is described with reference to Figures 1-4. Referring to Figure 1, a shaft 5 comprises a ferromagnetic material. Spaced-apart ring-like electrodes 10 and 15 are disposed about a shaft circumference to encode an axial region 20 between the electrodes 10 and 15. Both the electrodes 10 and 15 are in electrical contact with the shaft. Spacing the electrodes apart tends to promote a uniform magnetic flux density within the region 20, thereby creating a circumferentially uniform encoded region.

Uniformity of the flux density also depends on several other factors, including the shaft diameter. Additional pairs of electrodes (not shown), such as the electrodes 10 and 15, are axially disposed along the shaft to encode additional regions for detecting forces imposed at other shaft segments.

[0026] During the encoding process a current pulse 25 is applied to the electrode 15 to establish a current flow 30 along the longitudinal axis of the shaft 5 and within the region 20. After flowing along the region 20, the current is received by the electrode 10 to produce an output current 35. Current flow through the encoded region 20 induces a magnetic field that aligns the magnetic domains. Permanent magnetization of the shaft regions requires a high current density within that region.

[0027] All magnetic field sensor techniques that employ permanent magnetization of the shaft, such as described above, detect the externally-measurable magnetic field caused by the permanent magnetization. These field sensors also detect changes in the magnetic field that are caused by bending/twisting/torque and other forces. These forces change the magnetic permeability of the material, thereby altering some aspect of the magnetic field in the material and also altering the external magnetic field. Depending on the geometry of the unaltered field and the nature of the imposed forces, the forces may change the direction of the field or the intensity of the field (i.e., either a change in the field intensity or the flux density) or both.

[0028] Generally it is common in the art to refer to an altered magnetic field as one that includes changes in field strength or magnetic flux. A distorted field typically refers to changes only in a direction of the magnetic field.

[0029] When the shaft 5 is in operation, sensor coils 45 (only one shown in Figure 2) mounted proximate the rotating shaft 5 sense the magnetic field and produce a signal representative of that field. With no stress or torque applied, the sensors do not detect any magnetic field distortions or alterations. Such sensors typically exhibit a directionality characteristic, as uniaxial sensors cannot discriminate changes in direction and strength.

[0030] The sensor coils 45 comprise fluxgate sensors, or other magnetic field sensors such as coil sensors, inductive sensors, or Hall effect sensors.

[0031] When a torque is imposed on the shaft 5 or a region of the shaft 5, the altered magnetic field emerging from the encoded region 20 is detected by the sensor coils 45. The sensor coils 45 are typically coupled to electronic processing components for analyzing and displaying the magnetic field distortions and alterations, and for indicating the imposed forces, especially including torque.

[0032] The prior art system as described above and illustrated in Figures 1 and 2 employs axial current flow to create uniform circumferentially uniform shaft magnetization. This technique requires magnetization of the entire shaft circumference and is therefore not practical for larger diameter shafts, as these shafts require a large encoding current to produce sufficient flux densities to create permanent and uniform magnetic regions in the shaft. While technically feasible and possible, the requirement for these large currents makes it expensive to achieve a uniform current distribution and density in a circumferential direction for large diameter shafts. Thus this encoding scheme is typically limited to smaller shafts below approximately 200 mm in diameter.

[0033] To alleviate concerns associated with large diameter shafts and the attendant requirement for large currents, one known technique uses multiple electrical connections to the shaft 5 as shown in Figure 3. Spaced-apart rings 50 and 55 are disposed proximate the shaft 5 and insulated from the shaft 5, with each ring 50/55 having multiple electrical conductors 60 that are attached to the shaft 5. An input current 65 supplied to the ring 50 flows through the conductors 60 then axially through the region 80 and emerges through the ring 55. Current flow through the region 80 produces multiple magnetized regions 75 (only one shown in Figure 3).

[0034] The complex encoding arrangement of Figure 3 requires a small spacing between the rings 50 and 55 relative to the shaft diameter. Otherwise, a sufficiently uniform magnetization in a circumferential direction is not achievable. Larger spacing between the rings 50 and 55 increases the length of the region 80, which causes implementation problems and additional expenses in many applications. In addition, individual currents applied to the electrical conductors 60 must all have the same amplitude, requiring precise control and considerable expense to implement in larger diameter shafts.

[0035] Co-owned patent application publication 2009/0301223 (application number 12/134,689) describes and claims yet another encoding scheme for use with large diameter shafts. Figure 4 depicts a shaft 205 having magnetically polarized encoded regions or channels formed by an encoding structure 210. A material of the shaft 205 comprises a ferromagnetic material or a ferromagnetic material affixed to the shaft 205. Alternating conducting members 215 and 217 are axially-positioned along a portion of the shaft 205 and supported by a non-conductive frame 212. The members 215 and 217 are disposed proximate the shaft 205 with a gap between each member 215 and 217 and a surface of the shaft 205. The positive encoding conducting members 215 alternate with negative encoding conducting members 217.

[0036] A first end of each conducting member 215 is coupled to a positive terminal of an encoding or current source 250 (only one illustrated in Figure 4) and a second end is coupled to the shaft 205 at an electrode 218 via a conductor 242. A negative terminal of the encoding source 250 is coupled to an electrode 247 disposed on the shaft 205.

[0037] A first end of each conducting member 217 is coupled to a negative terminal of an encoding or current source 252 (only one illustrated in Figure 4) and a second end is coupled to the shaft 205 at an electrode 220 via a conductor 243. A positive terminal of the encoding source 252 is coupled to an electrode 248 disposed on the shaft 205.

[0038] Electrical current from each conducting member 215 travels through the shaft 205 in a direction as indicated along a path 245 to generate a positive magnetically polarized channel 260 (only one shown in Figure 4) on the shaft 205. Similarly, electrical signals from each conducting member 217 travel through the shaft 205 in a direction as indicated along a path 249 to generate a negative magnetically polarized channel 262 (only one shown in Figure 4) on the shaft 205. The direction of current flow for the paths 245 and 249 are in opposite directions and thus the magnetic domains are oppositely polarized (positive or negative) within the magnetized channels 260 and 262.

[0039] When the shaft 205 is in operation, magnetic fields produced by the positive and negative magnetically polarized channels 260 and 262 have an expected shape and are detected by sensors (not shown in Figure 4). When a torque or another force acts on the shaft 205, the magnetic fields produced by the channels 260 and 262 are altered or distorted. The sensors detect these changes and responsive thereto indicate the presence of a force within the encoded regions (i.e., the region including the channels 260 and 262) of the shaft 205.

[0040] The technique described with reference to Figure 4 may be considered a form of sectional magnetic encoding, as only the regions (sections) or channels 260 and 262 are encoded. Depending on the orientation of the encoded sections on the shaft, this technique may be capable of measuring angle of rotation, rotational speed and forces imposed on the shaft, including bending/twisting/torque forces. But this technique is limited to measuring or detecting these parameters only on individual torque sensitive areas on the shaft, i.e., the encoded regions. When the shaft is sectionally encoded, continuous torque measurement is possible only by mounting a magnetic field sensor on the shaft such that the sensor rotates with the shaft. As the sensor rotates, it continuously measures parameters of interest. But requiring the sensor to rotate with the shaft adds complexity to the system, requiring slip rings or wireless data transmission systems and wireless power supplies or batteries.

[0041] Various processes and systems have been used to provide accurate and reliable measuring capabilities for a rotating shaft, some of which have been described above. However continued improvements are needed, especially with respect to larger diameter shafts, and enhancements in operational efficiency are desired. The present invention presents a new and nonobvious technique for sectionally encoding the shaft and a pattern of sectionally encoded regions to measure forces imposed on the shaft, especially large diameter shafts. The pattern of encoded regions may also permit simultaneously determining a rotational angle and a rotational speed of the shaft. Various aspects and embodiments of the present invention are defined by the appended claims.

[0042] The present invention can be more easily understood and the advantages and uses thereof more readily apparent when the following detailed description of the present invention is read in conjunction with the figures wherein:

Figures 1- 4 illustrate prior art magnetostrictive encoding and sensing systems for shaft torque sensing.

Figure 5 illustrates a shaft having magnetic tracks encoded thereon for determining torque and other forces imposed on the shaft.

Figure 6 illustrates magnetic zones of one of the magnetic tracks of Figure 5.

Figure 7 illustrates an apparatus for forming the magnetic zones of Figure 6.

Figure 8 illustrates field lines of a magnetic field proximate an encoded shaft.

Figure 9 illustrates two magnetic tracks and a waveform indicating the magnetic fields associated with the magnetic tracks.

Figure 10 illustrates a plurality of axial magnetic tracks encoded on a shaft.

Figure 11 illustrates a plurality of magnetic tracks encoded on a shaft and waveforms associated with magnetic fields of the magnetic tracks.

Figure 12 illustrates spirally magnetically encoded bands.

Figure 13 illustrates a plurality of magnetic tracks on a shaft and a sensor for measuring the magnetic field of the magnetic tracks.

Figures 14 illustrates a waveform indicating the magnetic field amplitude from magnetic tracks as sensed by the sensor of Figure 13.

Figure 15 illustrates a shaft with a plurality of differently oriented magnetic tracks encoded thereon.

Figure 16 indicates sensitivities of magnetic tracks on a shaft with respect to the orientation of a force sensitive region.

Figures 17 and 18 illustrate shafts with spatially-offset tracks encoded thereon.

Figures 19 and 20 illustrate clusters of several magnetically-encoded tracks.

Figure 21 illustrates a shaft and a location of the magnetically-encoded tracks of Figures 19 and 20 relative to the shaft.

Figure 22 illustrates a shaft and sensors mounted proximate thereto.

[0043] In accordance with common practice, the various described features are not drawn to scale, but are drawn to emphasize specific features relevant to the inventions. Like reference characters denote like elements throughout the figures and text.

[0044] Before describing in detail the particular methods and apparatuses related to sectional magnetic encoding of shafts to measure shaft operating parameters and forces imposed on the shaft, it should be observed that the present invention resides primarily in a novel and non-obvious combination of elements and process steps. So as not to obscure the disclosure with details that will be readily apparent to those skilled in the art, certain conventional elements and steps have been presented with lesser detail, while the drawings and the specification describe in greater detail other elements and steps pertinent to understanding the inventions.

[0045] The various embodiments of the invention can detect one or more of torque, bending moments and other forces applied to the shaft. The various embodiments can also determine shaft angular position and shaft speed.

[0046] The accuracy of magnetostrictive measurement systems can be improved by using unique magnetically encoded regions created in the shaft or on a magnetically encoded material applied to the shaft. The magnetic encoding essentially turns the shaft into a component of the sensing system and produces a strong magnetic circuit within the shaft and magnetic field components external to the shaft. Detecting alterations or distortions in the external magnetic field indicate the presence of torque or another force on the shaft. Detection of the magnetic field can also be used to determine shaft angular position, shaft rotational speed.

[0047] A magnetically encoded region 270 on a shaft 271 is depicted in Figure 5. The encoded region 270 comprises four magnetically encoded tracks or magnetically encoded regions 272, 274, 276 and 278 disposed around a circumference of the shaft 271 in two bands or rings. A first band or ring of tracks comprises alternating tracks 272 and 276, and a second band or ring of tracks comprises alternating tracks 274 and 278. The tracks 272 and 276 are formed with a gap or dead zone 280 between alternating tracks 272 and 276. The tracks 274 and 278 are formed with a gap or dead zone 282 between alternating tracks 274 and 278. A gap 273 is disposed between the axially-aligned tracks 272 and 274 and a gap 277 is disposed between the axially-aligned tracks 276 and 278. The gaps 273 and 277 define regions that are torque-sensitive (and sensitive to other forces having one or more force vector components that pass through these regions) as described below.

[0048] A typical material of the shaft 271 comprises a standard steel alloy, such as 34CrNiMo8. Other materials suitable for use include: 1.2721 50NiCr13, 1.4313X 4CrNi13-4, 1.4542X 5CrNiCuNb16-4 and 30CrNiMo8.

[0049] Each of the tracks 272, 274, 276 and 278 comprises a plurality of magnetically encoded zones A, B, C, D, etc. as illustrated in the exemplary track of Figure 6.

[0050] The four tracks or encoded regions 272, 274, 276 and 278 and their constituent magnetically encoded zones are formed by an electrode array comprising four spaced-apart electrodes 300, 302, 306 and 308 as illustrated in Figure 7. The electrodes 300 and 302 are axially aligned and the electrodes 306 and 308 are axially aligned; the electrodes 300 and 302 (which form the encoded regions 272 and 276) are circumferentially displaced from the electrodes 306 and 308 (which form the encoded regions 274 and 278). All the electrodes 300, 302, 304 and 306 are separated by a fixed distance and move as a unit. This electrode array or another appropriately spaced and oriented electrode array can be used to encode magnetically polarized zones/tracks of any desired shape according to the teachings of the present invention.

[0051] The electrodes 300 and 302 are in physical contact with the shaft 271 at respective contact points 300A and 302A. The electrodes 306 and 308 each comprise three segments: upright segments 306A/308A, tangential segments 306B/308B and upright segments 306C/306C. The upright segments 306A/308A are not in contact with the shaft 271; the tangential segments 306B and 308B are not in contract with the shaft 271; only a contact point 306D/308D at a terminal end of the uprights segments 306C/308C is in contact with or at least closely proximate to the shaft 271.

[0052] To form the tracks 272 and 276, i.e., to encode the shaft 271, current pulses are supplied from a positive terminal of an encoding current source 309 to the electrode 300, current exits the electrode 300 at the contact point 300A, flows through a region 271A of the shaft 271, enters and flows through the upright segment 306C, flows through the tangential segment 306B, through the upright segment 306A and to a negative terminal of the encoding source 309. This current flow forms one of the magnetically polarized or encoded zones A, B, C, D, etc. in each of the tracks 272 and 276, as illustrated in Figure 5. A zone is formed by current that aligns the magnetic domains of the shaft material, i.e., magnetizing the material of the shaft.

[0053] The magnetically polarized zones comprising the tracks 274 and 278 are formed concurrently with formation of the zones that comprises the tracks 272 and 276. The magnetically polarized zones of the tracks 274 and 278 are formed by current pulses flowing from a positive terminal of an encoding current source 310 to the upright segment 308A, through the tangential segment 308B, through the upright segment 308C, through a shaft region 271B to the contact point 302B, up through the electrode 302 and to a negative terminal of the encoding source 310. The pulses are supplied from the encoding source 309 at the same time as the pulses are applied from the encoding source 310.

[0054] After each zone (for example, zone A) is formed the electrodes 300, 302, 306, and 308, which are mechanically supported by an array support structure and move as a unit, are stepped circumferentially as a unit to another location and current pulses applied again. This process creates another magnetically encoded zone, e.g., the zone B for each of the magnetic tracks 272, 274, 276 and 278. Thus application of a series of current pulse and circumferentially stepping the electrodes after each current pulse creates the individual zones A, B, C, D, etc.

The zones are spaced apart about 0.5 mm. Since the magnetic zones are slightly larger than the step size the magnetic zones fuse or merge to form the magnetic the tracks or encoded regions 272, 274, 276 and 278. The tracks 272, 274, 276 and 278 are also referred to as sectional tracks or sectional encoded regions as each encompasses a section of the shaft 271.

[0055] A direction of current flowing through the shaft 271 (i.e., into the shaft from one electrode and out from the shaft at the other electrode) determines the magnetic polarization (i.e., direction of the magnetic field lines) of the encoded zones, the tracks formed from those zones and the magnetic polarization of the surrounding areas of the shaft.

[0056] The location of maximum tangential (or axial) positive magnetic field strength is designated by an open or clear oval in Figure 5. The location of maximum tangential (or axial) negative magnetic field strength is depicted by a blackened oval. In the various presented embodiments, the regions of maximum positive magnetic field strength may be exchanged with the regions of maximum negative field strength without departing from the scope of the present invention. The terms positive and negative magnetic field strength reflect the direction of the magnetic field lines, e.g. positive magnetic field strength refers to field lines pointing to the right along the shaft 271 and negative magnetic field strength refers to field lines pointing to the left along the shaft 271. However, this definition is not required for proper operation of the invention.

[0057] The track 272 and its individual zones A, B, C, D, etc. are formed where the current pulses enter the shaft 271 and the track 276 and its constituent zones A, B, C, D, etc. are formed where the current pulses exit the shaft 271. Similarly, the encoded region 274 and its individual zones A, B, C, D, etc. are formed where the current pulses exit the shaft 271 and the track 278 and its constituent zones A, B, C, D, etc. are formed where the current pulses enter the shaft 271.

[0058] In one embodiment, the array of electrodes 300, 302, 304 and 308 are moved about 30 mm in between about 20 to 50 steps, forming a like number of encoded zones A, B, C, D, etc. Also, a circumference of the shaft determines whether the segments 306B and 308B are linear or a curved. For larger diameter (and therefore larger circumference) shafts, e.g., a diameter of about 730 mm, a linear segment 306B and 308B of about 30 mm in length is satisfactory. But a shaft having a diameter of about 60 mm requires using tangentially curved segments 306B and 308B.

[0059] Figure 8 is an axial cross-sectional view through the shaft 271, a portion of the magnetically polarized tracks 272 and 274 formed therein and the two axially-aligned electrodes 300 and 302. Thus the view illustrated in Figure 8 is defined by a plane passing through the tracks 272 and 274 and the axis of the shaft 271. The tracks 272 and 274 and the magnetic field lines 279 surrounding each of the tracks are depicted. A reference to the magnetic poles (north (N) and south (S)) is also included. Magnetic fields with the same characteristics repeat at each magnetically polarized track or region, i.e., tracks or regions having an orientation with a positive magnetically polarized region on the left and a negatively polarized region on the right. As is known to those skilled in the art, magnetic fields are three dimensional with only two dimensions illustrated in Figure 8.

[0060] The tracks 276 and 278 appear in another view (not illustrated) circumferentially displaced from the plane of Figure 8. However, for the track 276 (on the left) and the track 278 (on the right) the field directional arrowheads are reversed from the Figure 8 depiction.

[0061] Magnetic field sensors (or a magnetic field scanner or an array of sensors or scanners) used with the present invention are "blind" for all magnetic field components except the components in the axial direction. Thus the field sensors are most sensitive to the axial or tangential field components identified by a reference character 303 in Figure 8. Non-limiting examples of sensors used with the present invention can include, Hall effect sensors, magnetic field sensors, sensor coils with an air core, fluxgate sensors, anisotropic magnetostrictive sensors, an giant magneto-resistive (GMR) sensors. Additional non-limiting examples of magnetic field sensors include; fluxgate magnetometers, search coils, fiber-optic magnetometers, optically-pumped magnetometers, SQUIDS, and nuclear precession magnetometers.

[0062] Processing of the measured magnetic field is typically executed by a processor (not shown). The processor is further configured to compute various shaft parameters, based on the sensed magnetic field, such as angular velocity, angular acceleration, angular position, torque, bending moments, twisting moments and other forces exerted on the shaft. Embodiments of the invention are not limited to any particular processor for performing the processing tasks associated with the present invention. The term "processor" as that term is used herein, is intended to denote any machine capable of performing the calculations or computations necessary to perform the tasks associated with the invention. The term is also intended to denote any machine that is capable of accepting a structured input and processing that input according to prescribed rules to produce an output. It should be noted that the phrase "configured to" as used herein means that the processor is equipped with a combination of hardware and software elements for performing the tasks of the invention as understood by those skilled in the art.

[0063] Figure 9 illustrates two magnetically polarized encoded tracks or regions 272 and 274, for example, and a waveform representing the magnetic field flux density, as illustrated in the lower portion of Figure 9, associated with each of the tracks 272 and 274. As can be seen, the flux density is at the zero level approaching the track 272 from the left, and increases until reaching a positive maximum in the middle of the track 272. The flux density declines exiting the track 272, until reaching a negative maximum in the middle of the track 274. The flux density increases upon exiting the track 274 to the right and returns to the zero level as the flux density declines with increasing distance from the track 274. A positive sign to the left of the track 272 and to the right of track 274 indicate that the flux density is increasing in those regions. The negative sign between the two tracks 272 and 274 indicates that the flux density is decreasing in that region. Thus the tracks 272 and 274 (and the tracks 276 and 278 not illustrated) indicate regions of maximum magnetic field flux densities, in particular in the axial direction relative to the shaft 271.

[0064] In Figure 9 (and other Figures in the present application) the location of maximum tangential (or axial) positive magnetic field strength is designated by an open or clear oval. The location of maximum tangential (or axial) negative magnetic field strength is depicted by a blackened oval. In the various presented embodiments, the regions of maximum positive magnetic field strength may be exchanged with the regions of maximum negative field strength without departing from the scope of the present invention. As illustrated with reference to Figure 7, the terms positive and negative reflect the direction of the magnetic field lines, that is, a positive magnetic field strength refers to field lines pointing to the right and a negative magnetic field strength refers to field lines pointing to the left.

[0065] Returning to the electrode array of Figure 7, the encoding current source 309 can typically generate unipolar pulses (either positive-going or negative-going) from a few hundred amperes to a few kiloamperes, with a pulse length of about 0.1-100 msec. In a typical exemplary application the pulse duration is about 1 msec, with a current of about 500 A, and a shaft diameter of about 730 mm. The depth of current penetration and current density in the shaft 271 is controlled by the duration of the current pulses.

[0066] The encoding sources 309 and 310 may comprise a capacitor bank (i.e., discharging a capacitor through a resistor), a pulse generator or a power electronics device that generates the unipolar current pulse waveforms. Because the current pulses are short, they are characterized by their high frequency content.

[0067] In one example the axial distance between the tracks 272 and 274 and between the tracks 276 and 278 is a few millimeters to about one cm. The regions 273 and 277 between the respective tracks 272/274 and 276/278 are sensitive to torque imposed in that region.

[0068] The distance between the electrodes 300 and 306, which is the same as the distance between the electrodes 302 and 308, determines a number of magnetically polarized zones that can be formed before the zones created by the electrodes 300 and 302 are overwritten by the zones created by the electrodes 306 and 308. To avoid this overwriting, after encoding a plurality of magnetic zones for each of the tracks 272 and 274 that span a distance approximately equal to the distance between the electrodes 300 and 306 (or the distance between the electrodes 302 and 308), the electrode array must be circumferentially moved by the distance spanned. This movement prevents overwriting of the previously-written tracks 276 and 278 when writing continues to form additional tracks 272 and 274.

[0069] For example, in one example, the electrodes 300 and 306 (and the electrodes 302and 308) are spaced apart a distance equal to about one-half of the shaft circumference. This shaft may then be encoded during a half rotation of the shaft, i.e., rotation through 180 degrees.

[0070] By cooperative activation of the stepper motor to circumferentially (or axially) move the electrode array support structure, rotation of the shaft 271, and/or multi-axial actuation of the electrode array support structure, arbitrary magnetization patterns within the limits of electrode geometry can be created in the shaft 271.

[0071] For example, if the stepper motor steps the electrode pairs 300/302 and 306/308 in an axial direction along the shaft 271 with no rotation of the shaft about its axis, axial magnetized tracks are formed in the shaft 271as shown in Figure 10. The axial tracks 321 and 324 are formed by the respective electrodes 300 and 302 as the electrodes are stepped axially along the shaft 271. Concurrent with forming the tracks 321 and 324, the tracks 322 and 323 are formed by the respective electrodes 306 and 308. After the four axial tracks 321, 322, 323 and 324 are formed, the shaft 271 is rotated and four more axial tracks are formed in the shaft by again stepping the electrodes 300, 302, 306 and 308 axially across the shaft. If the shaft is rotated through 360 degrees, the shaft is encoded throughout its entire circumference.

[0072] If the electrode pairs 300/302 and 306/308 are stepped circumferentially to create the four tracks (that is, to create the zones that form the four tracks), after which the shaft is rotated or the electrode array is moved circumferentially, four additional tracks can be formed. The process can continue to form tracks completely around the circumference of the shaft 271. See Figure 5.

[0073] In yet another example, the stepper motor can move the electrode array support structure along any of its multi-axes while the shaft 271 is held stationary or the stepper motor can be moved and the shaft 271 rotated to create any desired magnetically polarized or encoded patterns of tracks.

[0074] If the stepper motor is activated and the shaft rotated after each magnetic track is formed, the tracks form an angle relative to the axis of rotation of the shaft 271. Thus the tracks form a spiral pattern, as illustrated in Figures 11 and 12, comprising tracks 326, 327, 328 and 329. These tracks can be formed by appropriate motion of the four-electrode array illustrated in Figure 7 in conjunction with rotation of the shaft 271. Other orientations of tracks and bands can be formed on the shaft by appropriate manipulation of the four-electrode array.

[0075] The waveforms below the shaft 271 in Figure 11 illustrate the various operational parameters that can be determined from the encoded track pattern of Figure

11. The position of the magnetic field positive and negative peaks 350A and 350B, respectively, as determined by an array of fixed (i.e., they do not rotate with the shaft 271) magnetic field sensors 352, indicate the angular shaft position. The speed at which the peaks 350A and 350B move indicates the rotational speed of the shaft 271. The magnetic field detected between the field peaks 350A and 350B (i.e., within the regions 353 on the shaft 271) is proportional to the torque exerted within that shaft region. A waveform 355A indicates that no torque is present in the region 353; a waveform 355B indicates the presence of a torque by the divergence between the no-torque waveform 355A and the torque waveform 355B. When a mechanical torque is applied to the shaft region 353, the magnetic permeability of that region changes, the magnetic field (flux) is altered and the altered magnetic field detected by the magnetic field sensor 352.

[0076] Figure 13 indicates placement of a magnetic field sensor 365 relative to the circumferential magnetically polarized tracks 272, 274, 276 and 278 of the shaft 271. The sensor 365 is disposed in a spaced-apart relation from the shaft 271 and sensitive to axial components of the magnetic field in the region 277. These axial components are identified by the reference character 303 in Figure 8. A sensor 367 is disposed between the tracks 272 and 274 (within the region 273) and sensitive to axial field components within the region 273.

[0077] A force in a first axial direction with the force vector extending from the magnetically polarized track 274 to the track 272 increases the magnetic field within the gap region 273. A force in a second axial direction opposite to the first axial direction has the opposite effect, decreasing the field strength within the gap region 273.

[0078] As in the example illustrated above in conjunction with Figure11, the altered field strengths sensed by the magnetic field sensor 365 are compared with an unaltered field (a map of the unaltered field having been acquired prior to imposition of the torque) to reveal torque or force-induced changes in the magnetic field.

[0079] An approximate numerical measure of the torque can be determined by first calibrating the magnetic field sensor 365 to determine a relationship between various altered magnetic fields and various known imposed torques. When a torque is detected during operation, a value for the torque is determined according to a monotonic relationship (a transfer function) between the detected change in the magnetic field and the torque.

[0080] In one example signals from the sensors 365 and 367 are subtracted to eliminate any common mode effects, such as external magnetic fields. Since stress-related signals from the sensors 365 and 367 have opposite signs, these signals survive the subtraction operation.

[0081] Figure 14 depicts a waveform or signal trace representing a component of an externally measured magnetic field, such as a magnetic field component of the track patterns of Figure 5 or Figure 11. The signal trace may be recorded by moving the magnetic field sensor 365 of Figure 13 in an axial direction through the regions 272/273/274 of Figure 5 (or alternatively through the regions 276/277/278 of Figure 5). Alternatively, the signal trace may be recorded by using an array of individual sensors, such as the sensor array 352 of Figure 11. The Figure 14 trace includes a curve 368 (solid line) that represents an amplitude of the magnetic field through the sensed regions as the sensor is scanned axially across the shaft 271 with no torque present during the scan. A positive peak 369 represents a region on the shaft 271 having the highest magnetic field strength in a first axial direction and a negative peak 370 represents a region on the shaft 271 having a highest magnetic field strength in a second axial direction, the first axial direction opposite to the first axial direction.

[0082] A curve 372 (dashed line) represents the field across the regions 272/273/274. The curve 372 has a perceptible difference from the curve 368 in a torque-sensitive region of the shaft, such as the regions 273 and 277 in Figure 5. This torque-sensitive region is indicated by a circle and a reference character 374 in Figure 14. The difference between the two waveforms represents the altered magnetic field caused by the presence of an axial (i.e., horizontal in the shaft orientation of Figure 5) force component, such as the axial force component of a torque, in the shaft region 273. A axial torque force component pointing in a first direction causes the curve 372 (indicating the presence of a torque force) to fall to the left of the curve 368 in the region of interest 374; a torque force component in a second direction opposite to the first direction causes the curve 354 to fall to the right of the curve 346 in the region of interest 358.

[0083] If the orientation of the encoding regions is altered from the circumferentially-oriented regions illustrated in Figure 5 to axially-oriented regions, such as a magnetically encoded region 400 in Figure 16, the force sensing directionality within the encoded region is changed accordingly. In this latter configuration, if the sensor has not been reoriented from its orientation in Figure 13 (i.e., with the Figure 13 orientation for detecting axial force components) the sensor detects alterations in the magnetic field that have a component in the axial direction in the region 400C between the tracks 400A and 400B. Since the tracks 400A and 400B are axially oriented, the presence of an axial force component may not be associated with a torque imposed on the shaft.

[0084] Figure 16 illustrates an exemplary force imposed in a direction of an arrowhead 404. Any force imposed in any direction on the XY coordinate system of Figure 16 can be resolved into an X-directed force and a Y-directed force. As indicated by the coordinate system depicted in Figure 16, when the magnetically polarized regions are oriented as shown, the sensor exhibits a low sensitivity to force components along the Y-axis and a high sensitivity to force components along the X-axis.

[0085] Returning to Figure 15, it illustrates several different orientations of magnetically-encoded tracks formed in or applied to a shaft 410. The region 400 comprises alternating positive and negative magnetically polarized tracks 400A, 400B, 400C and 400D positioned as shown. A torque sensitive region 403 is disposed between the tracks 400A and 400B and a torque sensitive region 405 is disposed between the tracks 400C and 400D. As shown the tracks 400A and 400C are axially aligned and the tracks 400B and 400D are axially aligned on the shaft 410.

[0086] Figure 15 also illustrates exemplary tracks 418A, 418B, 418C and 418D comprising alternating positive and negative magnetically polarized regions; the tracks 418A and 418C are circumferentially aligned, as are the tracks 418B and 418D. Regions 419 and 421 are highly sensitive to axial force components in accordance with the force directionality sensitivity map of Figure 16.

[0087] Tracks 424A, 424B, 424C and 424D form an angle of 135 degrees with the positive x-axis of a depicted coordinate system. Force sensitive areas 425 and 426 are located as indicated.

[0088] Tracks 427A, 427B, 427C and 427D are set at an angle of 225 degrees from the x-axis, with force sensitive area 431 and 432 as indicated.

[0089] Other tracks at other orientations can also be formed on the shaft 410 by appropriate manipulation of the electrode pairs 300/302 and 306/308 of Figure 7 and rotation of the shaft 410.

[0090] Arrowheads 440 and 448 in Figure 15 indicate exemplary force directions induced by one or more torque moments (or other forces) applied to the shaft 410. Tensile, compressive, torque and bending loads applied to the shaft 410 are detected by corresponding signals from the magnetic field sensor (or sensor array) that indicate the sensed magnetic field as correspondingly modified by these forces. Thus the various illustrated orientations of the encoded tracks allow detection of forces imposed on the shaft 410 from many different directions.

[0091] Generally, two circumferential bands (e.g., a first band comprising the tracks 418A and 418C and a second band comprising the tracks 418B and 418D) and two axial bands (e.g., a third band comprising the tracks 400A and 400C and a fourth band comprising the tracks 400B and 400D) are required to detect all forces exerted on the shaft 410 in any direction if the first and second bands are perpendicular to the third and fourth bands.

[0092] Three sets of four bands, the sets spaced at 120 degree intervals around the shaft circumference, can resolve both bending and torque moments.

[0093] The tracks 400A, 400B, 400C and 400D are parallel to a rotation axis 411 of the shaft 410. These tracks can detect torque applied to the shaft 410 if a torque vector component passes through the regions 403 or 405 in any direction that is not parallel to the magnetically polarized regions (and is therefore not parallel to the axis of rotation 411). These vector components alter the magnetic field generated by the magnetic domains in the regions 403 and 405 and thus alter the measurable external field above the shaft 410. Further, any torque component that passes through a middle of the regions 403 and 405 (where "middle" is defined as halfway between parallel magnetically polarized regions) produces the largest alteration of the magnetic field.

[0094] Bending moments cannot be detected with the orientation of the tracks 400A, 400B, 400C and 400D since a force exerted by bending moments is parallel to the direction of these magnetically polarized tracks. Referring to Figure 16, such bending moments have a force component parallel to the y-axis (and therefore parallel to the direction of the magnetically polarized tracks) where the magnetically polarized tracks have the lowest sensitivity to forces.

[0095] The tracks 418A, 418B, 418C and 418D are normal to the axis of rotation 410 and reference to Figure 16 indicates that this is an optimum orientation for detecting bending moments with an X-axis component.

[0096] The tracks 424A, 424B, 424C and 424D and the tracks 427A, 427B, 427C and 427D are optimally oriented for detecting both torque and bending forces. A unidirectional torque along an axis 450 alters magnetic domains in the regions 425 and 426, which have a high sensitivity to forces along the axis 450. This torque does not alter or alters only slightly domains in the regions 431 and 432 as domains in this region have a low sensitivity to forces along the axis 450.

[0097] A unidirectional torque along an axis 455 alters the magnetic field in the region 431 and 432 and therefore generates a corresponding signal in the magnetic field sensor. The torque along the axis 455 does not alter the magnetic field produced by the magnetic domains in the region 425 and 426. Generally, any forces along a first axis (either the axis 450 or 455) alter the magnetic field along the first axis with no (or only slight) alteration in the magnetic field along a second axis perpendicular to the first axis..

[0098] Another encoded track or band pattern is illustrated in Figure 17. A stepper motor and an electrode array having four electrodes arranged as illustrated in Figure 7, form tracks 500, 502, 504, and 506 in a shaft 508. A region 509 between the tracks is sensitive to forces imposed on the shaft 508 having force components that pass through the region 509. Figure 16 indicates the directional force sensitivities of the region 509. Gaps 510 and 511 are present between the respective tracks 500/504 and tracks 502/506. The force sensitive region 509 also has a discontinuity or a gap that is aligned with the gaps 510 and 511. That is, gaps 512 are present between the force sensitive regions 509. When one of the gaps 512 faces a magnetic field sensor, the sensor cannot sense the magnetic field and therefore cannot detect forces exerted on the shaft that have a force component within the gap 512.

[0099] To overcome this disadvantage and provide continuous detection of torques and other forces, additional magnetically polarized regions 500A, 502A, 504A and 506A are formed axially displaced from the regions 500, 502, 504, and 506 and shifted circumferentially by about half a track length as illustrated in Figure 17. Thus when a gap 512 is present in the sensing range of the magnetic sensor, one of the force sensitive regions 509A is read by the magnetic field sensor to overcome the inability to sense magnetic fields within the gaps 512. Similarly, when a gap 512A is present in the sensing range of the magnetic sensor, the force-sensitive region 509 is read by the magnetic sensor to overcome the inability to sense magnetic fields within the gap 512A.

[0100] The combined magnetic field signals from the offset regions 509 and 509A provide continuous monitoring of the torque or other forces exerted on the shaft 508.

[0101] Figure 18 illustrates an example where the track lengths are nearly 180 degrees long i.e., spanning one-half of the circumference of a shaft 600. A positive magnetically polarized region 604 and a parallel negative magnetically polarized region 608 are formed or embedded in the shaft 600. The tracks 604 and 608 are circumferentially followed by respective gaps 612 and 614 that are circumferentially followed by positive and negative magnetically polarized regions 624 and 620. The regions 604/608 and the regions 620/624 span about 180 degrees around the shaft 600.

[0102] Additional magnetically polarized regions are formed axially displaced from the tracks 604, 608, 620 and 624. These tracks comprise positive magnetically polarized tracks 634 and 638, and negative magnetically polarized regions 642 and 650. Gaps 650 and 652 between the respective tracks 630/638 and between the tacks 634/ 642 are offset from the gaps 612 and 614. This offset value, which is about 90 degrees in one example, provides for continuous (i.e., around the entire circumference) monitoring of any vector force components exerted on the shaft 600 (except for components that are parallel to the tracks 604, 608, 620, 624, 630, 638, 634 and 652 (i.e., circumferential components). Generally, for large diameter shafts the angular span of the tracks will be less than 180 degrees, but this requires encoding additional tracks on the shaft to form a closed ring that completely circumferentially encircles the shaft.

[0103] It is noted that additional gaps in the tracks 604/620, 608/624, 630/638 and 634/642 are hidden from view in Figure 18.

[0104] The use of four tracks to span 360 degrees (a first positive and negative magnetically polarized track spanning 180 degrees and a second positive and negative magnetically polarized track spanning 180 degrees) as illustrated in Figure 18 is merely exemplary. The tracks can be formed of any arbitrary length to span any angular segment as desired. Gaps in the tracks, which delineate a transition from one polarity to another polarity, are offset to ensure that any force imposed on the shaft can be determined at any circumferential region of the shaft.

[0105] To create the tracks of Figure 18 requires two track forming electrode assemblies, with one such assembly illustrated in Figure 7. The two assemblies (comprising eight electrodes) are axially spaced apart and simultaneously activated to simultaneously create the four tracks, as described herein for a four electrode assembly that simultaneously creates two tracks.

[0106] Generally, when in operation, a magnetic sensor senses the magnetic field from the tracks encoded in the shaft. In one example, the sensor is stationary relative to the rotating shaft and is fixedly mounted to a structure proximate the shaft.

[0107] With only one sensor mounted on one side of the shaft, torque forces imposed in any of the torque sensitive regions of the various presented embodiments cannot be discriminated from bending moments that also impose a similar force (in direction) in that same region. Also, when employing only one sensor, the force sensing system cannot discriminate imposed forces from changes in an environmental magnetic field.

[0108] Figure 19 illustrates a track cluster 702, comprising opposite polarity tracks 706 and 707 aligned with respective tracks 712 and 713. A force sensitive region is located between the tracks 706 and 707 and another force sensitive region is located between the tracks 712 and 713. Two sensors, not illustrated, sense the magnetic field in each of these regions. Figure 20 illustrates a track cluster 704, comprising similar tracks 708, 709, 710 and 711 arranged as shown. A force sensitive region is located between the tracks 708 and 709 and another force sensitive region is located between the tracks 710 and 711. Two sensors, not illustrated, sense the magnetic field in each of these force-sensitive regions.

[0109] In one example, the track arrays 702 and 704 are disposed on opposite sides of a shaft 724 as generally illustrated in Figure 21. In operation, signals representing the magnetic field (i.e., the tangential magnetic field) between tracks 706 and 707, between tracks 713 and 713, between tracks 708 and 709 and between tracks 710 and 711 are generated by magnetic field sensors. Then the signals are subtracted as follows: subtract the signal 706/707 from the signal 712/713 to generate a first resultant signal, and subtract the signal 708/709 from the signal 710/711 to generate a second resultant signal. The sum of the first and second resultant signals represents the torque imposed on the shaft 724. The difference between the first and second resultant signals represents bending moments exerted on the shaft 724.

[0110] It should be noted that the signals generated by the magnetic field between the tracks 706 and 707 is always complementary to the signals generated by the magnetic field between the tracks 712 and 713, given that a stress force vector passes through both force sensitive regions in the same direction.

[0111] In another example, the tracks 706/707 are located on opposite sides of the shaft from the tracks 712/713. In this example the signals from the force sensitive regions have the same sign for bending moments as the stress vectors are of opposite sign on the two sides of the shaft. The signals have the same sign for torque forces.

[0112] Ideally, to obtain the best signals representative of torque and bending moments it is preferred to subtract the two signals as indicated above, although this is not required. However, this subtraction does beneficially reduce the effects of any common mode signals and therefore provides a more accurate result. For example, external magnetic field effects are cancelled using this differential analysis.

[0113] Although the tracks 706, 707, 708, 709, 710, 711, 712 and 713 are illustrated as included relative to a rotational axis of the shaft 724 in Figures 19 and 20, this orientation is not required.

[0114] Relatively short magnetic tracks are illustrated in Figures 19 and 20. However, in another example these tracks can be made longer and may span about one 180 degrees of the shaft circumference, as illustrated in Figure 18.

[0115] Figure 22 depicts a shaft 803 and two oppositely disposed sensors 805 and 807. Bending moments in a plane spanning between the two sensors 805 and 807 and including the shaft's axis generate a signal at each sensor, but the signals are of opposite polarity. Thus combining/adding the two signals effectively subtracts the two signals with a result of zero. For a torque, the two signals from opposite sides of the shaft both increase or decrease in magnitude (depending on the direction of the torque) and combining/adding the two signals yields a positive (or negative) total value. The combined signal can be averaged to determine the average torque exerted on the shaft. Thus at least two sensors are required to discriminate the bending and torque forces. As known by those skilled in the art, these same methods are employed with strain gauge sensors.

[0116] One example employs three fixed sensors, a sensor at each of 0, 120 and 240 degrees around the circumference of the shaft. Preferably, the shaft is encoded with three track clusters, each cluster comprising four tracks as illustrated in Figures 19 and 20. This embodiment can resolve both bending and torque forces.

[0117] In another example four sensors are employed and mounted at 0, 90, 120 and 270 and four track sections, each section again comprising four tracks as illustrated in Figures 19 and 20. This example simplifies resolution of the signals into the Cartesian coordinate system, provides better cancellation of any external magnetic fields, and improved the ability to distinguish bending moments and torque. In applications where bending moments cannot be exerted along the full length of the shaft (for example, because the drive shaft supports are firmly anchored), one magnetic field array or scanner is sufficient.

[0118] For an example in which the sensors are mounted on the shaft and rotate with the shaft, the orientation of the shaft relative to the stationary mounting system must be determined to transform the rotating shaft's X and Y coordinates to the stationary system's X and Y axis.

[0119] Generally, the angular position of a shaft can be determined by the axial position of one of the two magnetic tracks that span 180 degrees around the shaft. In an example employing a spiral track pattern as in Figure 11 and a fixed sensor, detection of a shaft rotational position can be determined when a peak in the magnetic field (disposed at a predetermined marker location on the spiral track) passes the magnetic field sensor.

[0120] The rotational speed can be determined by the speed of the circumferential movement of distinct track features (e.g., magnetic field markers) or the time between successive passes of these features across the sensor. By using a third non-tilted reference track normal to the shaft axis in a circumferential direction, the axial position of the shaft can also be determined to eliminate any artifacts caused by axial displacement of the shaft. Each of these operational parameters can be determined simultaneously and under both static and dynamic operating conditions, i.e. a rotating shaft or non-rotating shaft.

[0121] The present invention replaces several monitoring instruments commonly applied to rotating machinery with one instrument. As the present invention requires no mechanical alterations to the shaft, implementation of the invention is at a relatively low cost. Further, the present invention offers certain advantages of the sectional magnetic encoding scheme, while also providing shaft position and shaft speed information.

[0122] As described above, using two spiral magnetic encoded regions with gaps in the encoded pattern of the first spiral covered by a second encoded spiral pattern that is shifted relative to the first pattern, a continuous readout of torque can be achieved with two magnetic field sensors targeting the two encoded tracks.

[0123] Because of the sectional encoding scheme of the present invention, the electrical currents, power and voltages needed for the encoding process are independent of the diameter of the shaft. The method of the present invention is therefore suitable for both small diameter shafts, e.g. 60 mm, and large diameter shafts, e.g., a wind turbine low speed shaft with a diameter of about 750 mm.

[0124] By encoding a closely-spaced pattern of axially aligned or tilted encoded sections around the shaft, a virtual magnetic gearwheel can be encoded on the shaft, allowing measurement of the speed of rotation. If two such virtual magnetic gearwheels are encoded spaced a certain distance apart, the phase difference of the acquired signals represents the twisting of the shaft between the two gearwheels being representative of the torque.

[0125] The various described embodiments have all the advantages of the prior art sectional magnetic encoding schemes, but importantly allow continuous readout of torque for large diameter shafts independent of the shaft diameter. The continuous scheme enables continuous readout of torque from DC to high frequencies. In contrast, the prior art sectional encoding schemes provide a continuous torque readout only when a sensor is mounted on the shaft and rotates with the shaft. But this prior art technique, unlike the refinements described in the present invention, requires either a noncontact wireless data and power transmission system or a slip ring. Without these noncontact readout schemes, the prior art system provides a torque readout only each time a section of the shaft passes the stationary sensor. Such a scheme is not considered continuous torque readout and is of limited use for low speed shaft systems that are impacted by higher frequency dynamic affects.

[0126] Although the magnetic regions on the shaft have been represented by elongated areas in the Figures of the present application, in fact a magnetic region of arbitrary shape within the limits of electrode design and laws of physics can be formed according to the present invention. The shape of the region depends on the shape of the electrode array, rotational motion of the shaft or electrode array between the flow of current pulses that encode the shaft, and other factors that affect magnetization of the shaft material.

[0127] While the various embodiments of the invention have been described in what is presently considered to be a preferred embodiment, many variations and modifications will become apparent to those skilled in the art. Accordingly, it is intended that the inventions not be limited to the specific illustrative embodiments but be interpreted within the scope of the appended claims.

[0128] Although described primarily with reference to use in wind turbines, the encoding technique and encoded regions of the present invention can also be employed with shafts used in any large rotating machines, such as electric power turbines, electric power generators, turbomachines, large electric motors, compressors, transportation drives, marine vessel drives, etc.

Claims

1. A method for encoding a shaft (271), according to claim 6, comprising:

   (a) supplying current to a first location on the shaft (271) through a first electrode (300) and withdrawing current from a second location on the shaft (271) through a second electrode (302), the current flowing through the shaft (271) between the first and second electrodes (300,302) forming first and second polarity magnetically polarized zones at the respective first and the second locations (A,B), the first and second electrodes (300,302) circumferentially spaced apart relative to the shaft (271); **characterized by**:

   (b) supplying current to a third location on the shaft (271) through a third electrode (306) and withdrawing current from a fourth location on the shaft (271) through a fourth electrode (308) the current flowing through the shaft (271) between the third and fourth electrodes (306,308) forming first and second polarity magnetically polarized zones at the respective third and fourth locations (C,D), wherein the third and fourth electrodes (306,308) are circumferentially spaced apart relative to the shaft (271), wherein the step of supplying current to the first location (A) is executed concurrently with the step of supplying current to the third location (C);

   (c) wherein the first electrode (300) is axially spaced apart from the fourth electrode (308) and the second electrode (302) is axially spaced apart from the third electrode (306);

   (d) moving the first, second, third and fourth electrodes (300,302,304,306) in unison along the shaft (271) for forming additional magnetically polarized zones, wherein first and second magnetically encoded regions (272,274) are formed on the shaft (271) by merging of respective and adjacent first and second magnetically polarized zones, wherein third and fourth magnetically encoded regions (276,278) are formed on the shaft (271) by merging of respective and adjacent first and second magnetically polarized zones; and

   (e) when the first, second, third and fourth magnetically encoded regions (272,274,276,278) reach a desired length, relocating the first, second, third and fourth electrodes (300,302,304,306) on the shaft (271) and repeating steps (a), (b), (c), and (d) until a plurality of the first, second, third and fourth magnetically encoded regions (272,274,276,278) are formed on the shaft (271).

2. The method of claim 1, wherein each of the second and third electrodes (302,306) comprises a first upright segment (306A) receiving current according to respective steps (a) and (b), each of the first upright segments connected to a first end of a tangential segment (306B), neither the first upright segments nor the tangential segments in contact with the shaft, each of the second and third electrodes (302,306) further comprising a second upright segment (308A) having a first end connected to a second end of the tangential segment and a second end proximate the shaft (271).

3. The method of claim 1 or claim 2, wherein the current comprises current pulses of between about 100 amperes and 6 kiloamperes with a pulse length of between about 0.1 and 100 milliseconds, wherein current pulses are supplied to the first location (A) concurrently with current pulses supplied to the third location (C).

4. The method of any preceding claim, wherein a first distance between the first and the second electrodes (300,302) determines a number of magnetically polarized zones between the first and the second electrodes, and a second distance between the third and

the fourth electrodes (304,306) determines a number of magnetically polarized zones between the third and the fourth electrodes, wherein the first and the second distances are about equal.

5. The method of any preceding claim, wherein the step of relocating the first (300), second (302, third (306) and fourth (308) electrodes comprises at least one of axially moving the first, second, third and fourth electrodes to form axial first, second, third and fourth magnetically encoded regions, and circumferentially moving the first, second, third and fourth electrodes to form circumferential magnetically encoded regions.

6. A magnetically encoded shaft (271), comprising:
a first cluster (702) of magnetically encoded regions comprising first, second, third and fourth magnetically encoded regions (272,274,276,278), the first and fourth magnetically encoded regions (272,278) having a first magnetic polarity and the second and third magnetically encoded regions (274,276) having a second magnetic polarity, the first and third magnetically encoded regions (272,276) defining a first band spaced apart axially from a second band comprising the second and fourth magnetically encoded regions (274,278); **characterized by**:

a second cluster (704) of magnetically encoded regions comprising first, second, third and fourth magnetically encoded regions (272,274,276,278), the first and fourth magnetically encoded regions (272,278) having the first magnetic polarity and the second and third magnetically encoded regions (274,276) having the second magnetic polarity, the first and third magnetically encoded regions (272,276) defining a third band spaced axially apart from a fourth band comprising the second and fourth magnetically encoded regions (272);
a third cluster of magnetically encoded regions comprising first, second, third and fourth magnetically encoded regions (272,274,276,278), the first and fourth magnetically encoded regions (272,278) having the first magnetic polarity and the second and third magnetically encoded regions (274,276) having the second magnetic polarity, the first and third magnetically encoded regions (272,276) defining a fifth band spaced apart axially from a sixth band comprising the second and fourth magnetically encoded regions (274,278);
the first, second and third clusters spaced apart by 120 degrees around a shaft (271) circumference; and
wherein magnetic fields surrounding the first, second and third clusters indicate the presence of bending forces and torque forces on the shaft (271).

7. The magnetically encoded shaft (271) of claim 6, wherein a force-sensitive region (509) between the third and fourth bands is sensitive to force components passing there through, the force components altering the magnetic field associated therewith.

8. The magnetically encoded shaft (271) of claim 6 or claim 7, wherein the first and second bands are inclined at an angle relative to a shaft (271) axis (450) and the third and fourth bands are perpendicular to the shaft (271) axis (450) thereby permitting determination of shaft (271) speed and torque imposed on the shaft (271).

9. The magnetically encoded shaft (271) of any of claims 6 to 8, wherein the first band defines first dead zones (280) between each of the first and second magnetically encoded regions (272,274) aligned with second dead zones (282) between each of the first and the second magnetically encoded regions (274) in the second band, wherein each of the first and the second dead zones (280,282) is axially aligned with a force-sensitive region (509) between the third and fourth bands; and
wherein the third band defines third dead zones between each of the first and second magnetically encoded regions (272,274) axially aligned with fourth dead zones between each of the second and first magnetically encoded regions (272,274) in the fourth band, wherein each of the third and fourth dead zones is axially aligned with the force-sensitive region (509) between the first and second bands.

10. The magnetically encoded shaft (271) of any of claims 6 to 9, the first and second bands disposed at a first axial location on the shaft (271) and the third and fourth bands disposed at a second axial location on the shaft (271), a phase difference between the magnetic field from the force-sensitive region (509) between the first and second bands and the magnetic field from the force-sensitive region (509) between the third and fourth bands indicative of a torque applied to the shaft (271) between the first and second regions (272).

11. The magnetically encoded shaft (271) of any of claims 6 to 10, wherein the force components comprise one or more of torque forces, bending moments, stress forces and strain forces.

12. The magnetically encoded shaft (271) of any of claims 6 to 11, wherein the shaft (271) is disposed in a wind turbine and driven by wind turbine rotor blades in mechanical communication with the shaft (271).

13. The magnetically encoded shaft (271) of any of claims 6 to 12, wherein the shaft (271) is disposed in an electric power turbine or in an electric power generator.

Patentansprüche

1. Verfahren zum Kodieren einer Welle (271), gemäß Anspruch 6, umfassend:

(a) Zuführen von Strom an eine erste Stelle auf der Welle (271) durch eine erste Elektrode (300) und Entnehmen von Strom von einer zweiten Stelle auf der Welle (271) durch eine zweite Elektrode (302), wobei der Strom zwischen der ersten und zweiten Elektrode (300, 302) durch die Welle (271) fließt, erste und zweite Polarität magnetisch polarisierter Zonen an der entsprechenden ersten und zweiten Stelle (A, B) bildend, wobei die erste und zweite Elektrode (300, 302) relativ zu der Welle (271) in Umfangsrichtung beabstandet sind; **gekennzeichnet durch:**
(b) Zuführen von Strom an eine dritte Stelle auf der Welle (271) durch eine dritte Elektrode (306) und Entnehmen von Strom von einer vierten Stelle auf der Welle (271) durch eine vierte Elektrode (308), wobei der Strom zwischen der dritten und vierten Elektrode (306, 308) durch die Welle (271) fließt, erste und zweite Polarität magnetisch polarisierter Zonen an der entsprechenden dritten und vierten Stelle (C, D) bildend, wobei die dritte und vierte Elektrode (306, 308) relativ zu der Welle (271) in Umfangsrichtung beabstandet sind, wobei der Schritt des Zuführens von Strom an die erste Stelle (A) gleichzeitig mit dem Schritt des Zuführens von Strom an die dritte Stelle (C) ausgeführt wird;
(c) wobei die erste Elektrode (300) axial von der vierten Elektrode (308) beabstandet ist und die zweite Elektrode (302) axial von der dritten Elektrode (306) beabstandet ist;
(d) Bewegen der ersten, zweiten, dritten und vierten Elektrode (300, 302, 304, 306) gemeinsam entlang der Welle (271) zum Bilden zusätzlicher magnetisch polarisierter Zonen, wobei durch Zusammenführen von entsprechenden und benachbarten ersten und zweiten magnetisch polarisierten Zonen erste und zweite magnetisch kodierte Bereiche (272, 274) auf der Welle (271) gebildet werden, wobei dritte und vierte magnetisch kodierte Bereiche (276, 278) durch Zusammenführen von entsprechenden und benachbarten ersten und zweiten magnetisch polarisierten Zonen auf der Welle (271) gebildet werden; und
(e) wenn die ersten, zweiten, dritten und vierten magnetisch kodierten Bereiche (272, 274, 276, 278) eine gewünschte Länge erreichen, Verschieben der ersten, zweiten, dritten und vierten Elektrode (300, 302, 304, 306) auf der Welle (271) und Wiederholen der Schritte (a), (b), (c) und (d), bis eine Vielzahl der ersten, zweiten, dritten und vierten magnetisch kodierten Bereiche (272, 274, 276, 278) auf der Welle (271) gebildet sind.

2. Verfahren nach Anspruch 1, wobei jede der zweiten und dritten Elektrode (302, 306) ein erstes aufrechtes Segment (306A) umfasst, das gemäß den entsprechenden Schritten (a) und (b) Strom aufnimmt, wobei jedes der aufrechten Segmente mit einem ersten Ende eines tangentialen Segments (306B) verbunden wird, weder die ersten aufrechten Segmente noch die tangentialen Segmente mit der Welle in Kontakt sind, wobei jede der zweiten und dritten Elektrode (302, 306) ferner ein zweites aufrechtes Segment (308A) mit einem ersten Ende, das mit einem zweiten Ende des tangentialen Segments verbunden ist, und einem zweiten Ende in der Nähe der Welle (271), umfasst.

3. Verfahren nach Anspruch 1 oder Anspruch 2, wobei der Strom Strompulse von zwischen etwa 100 Ampere und 6 Kiloampere mit einer Pulslänge von zwischen etwa 0,1 und 100 Millisekunden umfasst, wobei die Strompulse der ersten Stelle (A) gleichzeitig zugeführt werden mit Strompulsen, die der dritten Stelle (C) zugeführt werden.

4. Verfahren nach einem vorstehenden Anspruch, wobei ein erster Abstand zwischen der ersten und der zweiten Elektrode (300, 302) eine Anzahl von magnetisch polarisierten Zonen zwischen der ersten und der zweiten Elektrode bestimmt, und ein zweiter Abstand zwischen der dritten und der vierten Elektrode (304, 306) eine Anzahl von magnetisch polarisierten Zonen zwischen der dritten und der vierten Elektrode bestimmt, wobei der erste und der zweite Abstand etwa gleich sind.

5. Verfahren nach einem vorstehenden Anspruch, wobei der Schritt des Verschiebens der ersten (300), zweiten (302, dritten (306) und vierten (308) Elektrode mindestens eines von axialem Bewegen der ersten, zweiten, dritten und vierten Elektrode, um axiale erste, zweite, dritte und vierte magnetisch kodierte Bereiche zu bilden, und das Bewegen der ersten, zweiten, dritten und vierten Elektrode in Umfangsrichtung umfasst, um umlaufende magnetisch kodierte Bereiche zu bilden.

6. Magnetisch kodierte Welle (271), umfassend:
einen ersten Cluster (702) magnetisch kodierter Bereiche, umfassend erste, zweite, dritte und vierte ma-

gnetisch kodierte Bereiche (272, 274, 276, 278), wobei die ersten und vierten magnetisch kodierten Bereiche (272, 278) eine erste magnetische Polarität aufweisen und die zweiten und dritten magnetisch kodierten Bereiche (274, 276) eine zweite magnetische Polarität aufweisen, wobei die ersten und dritten magnetisch kodierten Bereiche (272, 276) ein erstes Band definieren, das von einem zweiten Band, das die zweiten und vierten magnetisch kodierten Bereiche (274, 278) umfasst, axial beabstandet ist; **gekennzeichnet durch:**

einen zweiten Cluster (704) magnetisch kodierter Bereiche, umfassend erste, zweite, dritte und vierte magnetisch kodierte Bereiche (272, 274, 276, 278), wobei die ersten und vierten magnetisch kodierten Bereiche (272, 278) die erste magnetische Polarität aufweisen und die zweiten und dritten magnetisch kodierten Bereiche (274, 276) die zweite magnetische Polarität aufweisen, wobei die ersten und dritten magnetisch kodierten Bereiche (272, 276) ein drittes Band definieren, das von einem vierten Band, das die zweiten und vierten magnetisch kodierten Bereiche (272) umfasst, axial beabstandet ist;
einen dritten Cluster magnetisch kodierter Bereiche, umfassend erste, zweite, dritte und vierte magnetisch kodierte Bereiche (272, 274, 276, 278), wobei die ersten und vierten magnetisch kodierten Bereiche (272, 278) die erste magnetische Polarität aufweisen und die zweiten und dritten magnetisch kodierten Bereiche (274, 276) die zweite magnetische Polarität aufweisen, wobei die ersten und dritten magnetisch kodierten Bereiche (272, 276) ein fünftes Band definieren, das von einem sechsten Band, das die zweiten und vierten magnetisch kodierten Bereiche (274, 278) umfasst, axial beabstandet ist;
wobei die ersten, zweiten und dritten Cluster um 120 Grad um einen Umfang einer Welle (271) herum beabstandet sind; und
wobei magnetische Felder, die die ersten, zweiten und dritten Cluster umgeben, die Anwesenheit von Biegekräften und Torsionskräften auf der Welle (271) anzeigen.

7. Magnetisch kodierte Welle (271) nach Anspruch 6, wobei ein kraftempfindlicher Bereich (509) zwischen dem dritten und dem vierten Band empfindlich gegenüber durch ihn hindurchtretenden Kraftkomponenten ist, wobei die Kraftkomponenten das damit assoziierte Magnetfeld ändern.

8. Magnetisch kodierte Welle (271) nach Anspruch 6 oder Anspruch 7, wobei das erste und zweite Band relativ zu einer Achse (450) einer Welle (271) in einem Winkel geneigt sind, und das dritte und vierte Band senkrecht zu der Achse (450) der Welle (271) sind, wodurch das Bestimmen von auf die Welle (271) auferlegter Geschwindigkeit und auferlegtem Drehmoment der Welle (271) gestattet wird.

9. Magnetisch kodierte Welle (271) nach einem der Ansprüche 6 bis 8, wobei das erste Band erste Totzonen (280) zwischen jedem der ersten und zweiten magnetisch kodierten Bereiche (272, 274) definiert, die mit zweiten Totzonen (282) zwischen jedem der ersten und zweiten magnetisch kodierten Bereiche (274) in dem zweiten Band ausgerichtet sind, wobei jede der ersten und zweiten Totzonen (280, 282) mit einem kraftempfindlichen Bereich (509) zwischen dem dritten und vierten Band axial ausgerichtet ist; und
wobei das dritte Band dritte Totzonen zwischen jedem der ersten und zweiten magnetisch kodierten Bereiche (272, 274) definiert, die mit vierten Totzonen zwischen jedem der zweiten und ersten magnetisch kodierten Bereiche (272, 274) in dem vierten Band axial ausgerichtet sind, wobei jede der dritten und vierten Totzonen mit dem kraftempfindlichen Bereich (509) zwischen dem ersten und zweiten Band axial ausgerichtet ist.

10. Magnetisch kodierte Welle (271) nach einem der Ansprüche 6 bis 9, wobei das erste und zweite Band an einer ersten axialen Stelle der Welle (271) angeordnet sind und das dritte und vierte Band an einer zweiten axialen Stelle auf der Welle (271) angeordnet sind, wobei eine Phasendifferenz zwischen dem magnetischen Feld von dem kraftempfindlichen Bereich (509) zwischen dem ersten und zweiten Band und dem magnetischen Feld von dem kraftempfindlichen Bereich (509) zwischen dem dritten und vierten Band indikativ ist für ein zwischen den ersten und zweiten Bereichen (272) auf die Welle (271) angelegtes Drehmoment.

11. Magnetisch kodierte Welle (271) nach einem der Ansprüche 6 bis 10, wobei die Kraftkomponenten eins oder mehrere von Drehmomentkräften, Biegemomenten, Spannkräften und Dehnungskräften umfassen.

12. Magnetisch kodierte Welle (271) nach einem der Ansprüche 6 bis 11, wobei die Welle (271) in einer Windturbine angeordnet ist und durch Windturbinenrotorblätter in mechanischer Verbindung mit der Welle (271) angetrieben wird.

13. Magnetisch kodierte Welle (271) nach einem der Ansprüche 6 bis 12, wobei die Welle (271) in einer elektrischen Leistungsturbine oder in einem Generator für elektrische Leistung angeordnet ist.

Revendications

1. Procédé de codage d'un arbre (271), selon la revendication 6, comprenant :

(a) la fourniture d'un courant à un premier emplacement sur l'arbre (271) à travers une première électrode (300) et le retrait d'un courant d'un deuxième emplacement sur l'arbre (271) à travers une deuxième électrode (302), le courant circulant à travers l'arbre (271) entre les première et deuxième électrodes (300, 302) formant des première et deuxième zones polarisées magnétiquement de polarité au niveau des premier et deuxième emplacements respectifs (A, B), les première et deuxième électrodes (300, 302) espacées circonférentiellement par rapport à l'arbre (271) ; **caractérisé par** :
(b) la fourniture d'un courant à un troisième emplacement sur l'arbre (271) à travers une troisième électrode (306) et le retrait d'un courant d'un quatrième emplacement sur l'arbre (271) à travers une quatrième électrode (308) le courant circulant à travers l'arbre (271) entre les troisième et quatrième électrodes (306, 308) formant des première et deuxième zones polarisées magnétiquement de polarité au niveau des troisième et quatrième emplacements respectifs (C, D), dans lequel les troisième et quatrième électrodes (306, 308) sont espacées circonférentiellement par rapport à l'arbre (271), dans lequel l'étape consistant à fournir un courant au premier emplacement (A) est réalisée simultanément à l'étape consistant à fournir un courant au troisième emplacement (C) ;
(c) dans lequel la première électrode (300) est espacée axialement de la quatrième électrode (308) et la deuxième électrode (302) est espacée axialement de la troisième électrode (306) ;
(d) le déplacement des première, deuxième, troisième et quatrième électrodes (300, 302, 304, 306) à l'unisson le long de l'arbre (271) pour former des zones polarisées magnétiquement supplémentaires, dans lequel les première et deuxième régions codées magnétiquement (272, 274) sont formées sur l'arbre (271) par fusion de première et deuxième zones polarisées magnétiquement adjacentes et respectives, dans lequel les troisième et quatrième régions codées magnétiquement (276, 278) sont formées sur l'arbre (271) par fusion de première et deuxième zones polarisées magnétiquement respectives et adjacentes ; et
(e) lorsque les première, deuxième, troisième et quatrième régions codées magnétiquement (272, 274, 276, 278) atteignent une longueur souhaitée, le replacement des première, deuxième, troisième et quatrième électrodes (300, 302, 304, 306) sur l'arbre (271) et la répétition des étapes (a), (b), (c), et (d) jusqu'à ce qu'une pluralité des première, deuxième, troisième et quatrième régions codées magnétiquement (272, 274, 276, 278) soient formées sur l'arbre (271).

2. Procédé selon la revendication 1, dans lequel chacune des deuxième et troisième électrodes (302, 306) comprend un premier segment vertical (306A) recevant du courant selon les étapes respectives (a) et (b), chacun des premiers segments verticaux relié à une première extrémité d'un segment tangentiel (306B), ni les premiers segments verticaux ni les segments tangentiels en contact avec l'arbre, chacune des deuxième et troisième électrodes (302, 306) comprenant en outre un deuxième segment vertical (308A) ayant une première extrémité reliée à une deuxième extrémité du segment tangentiel et une deuxième extrémité proche de l'arbre (271).

3. Procédé selon la revendication 1 ou la revendication 2, dans lequel le courant comprend des impulsions de courant comprises entre environ 100 ampères et 6 kiloampères avec une longueur d'impulsion comprise entre environ 0,1 et 100 millisecondes, dans lequel des impulsions de courant sont fournies au premier emplacement (A) simultanément à des impulsions de courant fournies au troisième emplacement (C).

4. Procédé selon l'une quelconque des revendications précédentes, dans lequel une première distance entre les première et deuxième électrodes (300, 302) détermine un nombre de zones polarisées magnétiquement entre les première et deuxième électrodes, et une deuxième distance entre les troisième et quatrième électrodes (304, 306) détermine un nombre de zones polarisées magnétiquement entre les troisième et quatrième électrodes, dans lequel les première et deuxième distances sont environ égales.

5. Procédé selon l'une quelconque des revendications précédentes, dans lequel l'étape de replacement des première (300), deuxième (302, troisième (306) et quatrième (308) électrodes comprend au moins l'un du déplacement axial des première, deuxième, troisième et quatrième électrodes pour former des première, deuxième, troisième et quatrième régions codées magnétiquement axiales, et du déplacement circonférentiel des première, deuxième, troisième et quatrième électrodes pour former des régions codées magnétiquement circonférentielles.

6. Arbre codé magnétiquement (271), comprenant :
un premier groupe (702) de régions codées magnétiquement comprenant des première, deuxième, troi-

sième et quatrième régions codées magnétiquement (272, 274, 276, 278), les première et quatrième régions codées magnétiquement (272, 278) ayant une première polarité magnétique et les deuxième et troisième régions codées magnétiquement (274, 276) ayant une deuxième polarité magnétique, les première et troisième régions codées magnétiquement (272, 276) définissant une première bande espacée axialement d'une deuxième bande comprenant les deuxième et quatrième régions codées magnétiquement (274, 278) ; **caractérisé par** :

un deuxième groupe (704) de régions codées magnétiquement comprenant des première, deuxième, troisième et quatrième régions codées magnétiquement (272, 274, 276, 278), les première et quatrième régions codées magnétiquement (272, 278) ayant la première polarité magnétique et les deuxième et troisième régions codées magnétiquement (274, 276) ayant la deuxième polarité magnétique, les première et troisième régions codées magnétiquement (272, 276) définissant une troisième bande espacée axialement d'une quatrième bande comprenant les deuxième et quatrième régions codées magnétiquement (272) ;
un troisième groupe de régions codées magnétiquement comprenant des première, deuxième, troisième et quatrième régions codées magnétiquement (272, 274, 276, 278), les première et quatrième régions codées magnétiquement (272, 278) ayant la première polarité magnétique et les deuxième et troisième régions codées magnétiquement (274, 276) ayant la deuxième polarité magnétique, les première et troisième régions codées magnétiquement (272, 276) définissant une cinquième bande espacée axialement d'une sixième bande comprenant les deuxième et quatrième régions codées magnétiquement (274, 278) ;
les premier, deuxième et troisième groupes étant espacés de 120 degrés autour d'une circonférence d'arbre (271) ; et
dans lequel des champs magnétiques entourant les premier, deuxième et troisième groupes indiquent la présence de forces de flexion et de forces de couple sur l'arbre (271).

7. Arbre codé magnétiquement (271) selon la revendication 6, dans lequel une région sensible à la force (509) entre les troisième et quatrième bandes est sensible à des composantes de force qui le traversent, les composantes de force modifiant le champ magnétique qui lui est associé.

8. Arbre codé magnétiquement (271) selon la revendication 6 ou la revendication 7, dans lequel les première et deuxième bandes sont inclinées selon un angle par rapport à un axe (450) d'arbre (271) et les troisième et quatrième bandes sont perpendiculaires à l'axe (450) d'arbre (271) permettant ainsi la détermination de la vitesse et du couple d'arbre (271) imposés sur l'arbre (271).

9. Arbre codé magnétiquement (271) selon l'une quelconque des revendications 6 à 8, dans lequel la première bande définit des premières zones mortes (280) entre chacune des première et deuxième régions codées magnétiquement (272, 274) alignées avec des deuxièmes zones mortes (282) entre chacune des première et deuxième régions codées magnétiquement (274) dans la deuxième bande, dans lequel chacune des première et deuxième zones mortes (280, 282) est alignée axialement avec une région sensible à la force (509) entre les troisième et quatrième bandes ; et
dans lequel la troisième bande définit des troisièmes zones mortes entre chacune des première et deuxième régions codées magnétiquement (272, 274) alignées axialement avec des quatrièmes zones mortes entre chacune des deuxième et première régions codées magnétiquement (272, 274) dans la quatrième bande, dans lequel chacune des troisième et quatrième zones mortes est alignée axialement avec la région sensible à la force (509) entre les première et deuxième bandes.

10. Arbre codé magnétiquement (271) selon l'une quelconque des revendications 6 à 9, les première et deuxième bandes disposées au niveau d'un premier emplacement axial sur l'arbre (271) et les troisième et quatrième bandes disposées au niveau d'un deuxième emplacement axial sur l'arbre (271), une différence de phase entre le champ magnétique de la région sensible à la force (509) entre les première et deuxième bandes et le champ magnétique de la région sensible à la force (509) entre les troisième et quatrième bandes indicative d'un couple appliqué à l'arbre (271) entre les première et deuxième régions (272).

11. Arbre codé magnétiquement (271) selon l'une quelconque des revendications 6 à 10, dans lequel les composantes de force comprennent un ou plusieurs de forces de couple, de moments de flexion, de forces de tension et de forces de contrainte.

12. Arbre codé magnétiquement (271) selon l'une quelconque des revendications 6 à 11, dans lequel l'arbre (271) est disposé dans une éolienne et entraîné par des aubes de rotor d'éolienne en communication mécanique avec l'arbre (271).

13. Arbre codé magnétiquement (271) selon l'une quelconque des revendications 6 à 12, dans lequel l'arbre (271) est disposé dans une turbine d'énergie électrique ou dans un générateur d'énergie électrique.

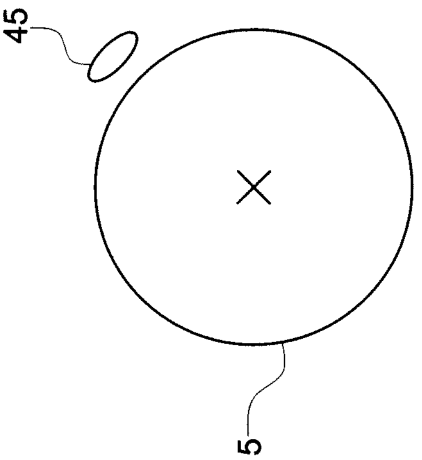

FIG. 2
(Prior Art)

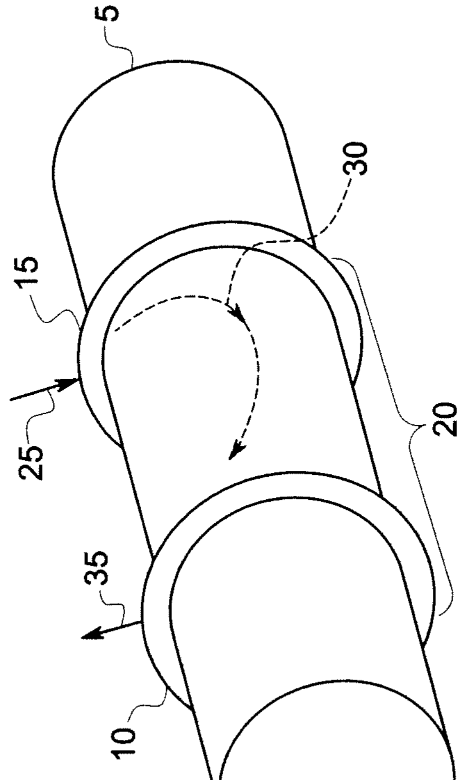

FIG. 1
(Prior Art)

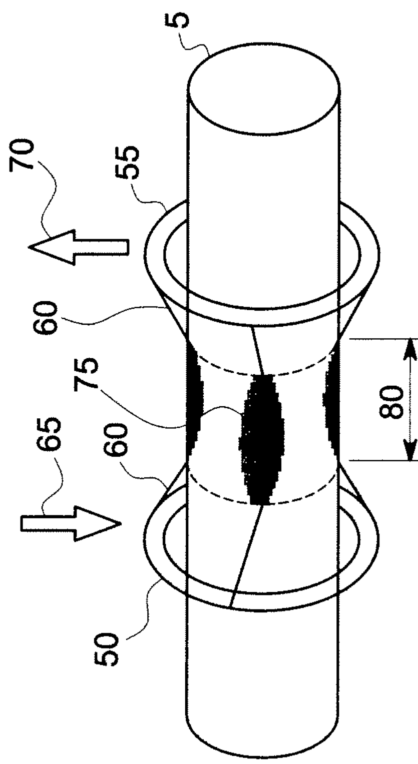

FIG. 3
(Prior Art)

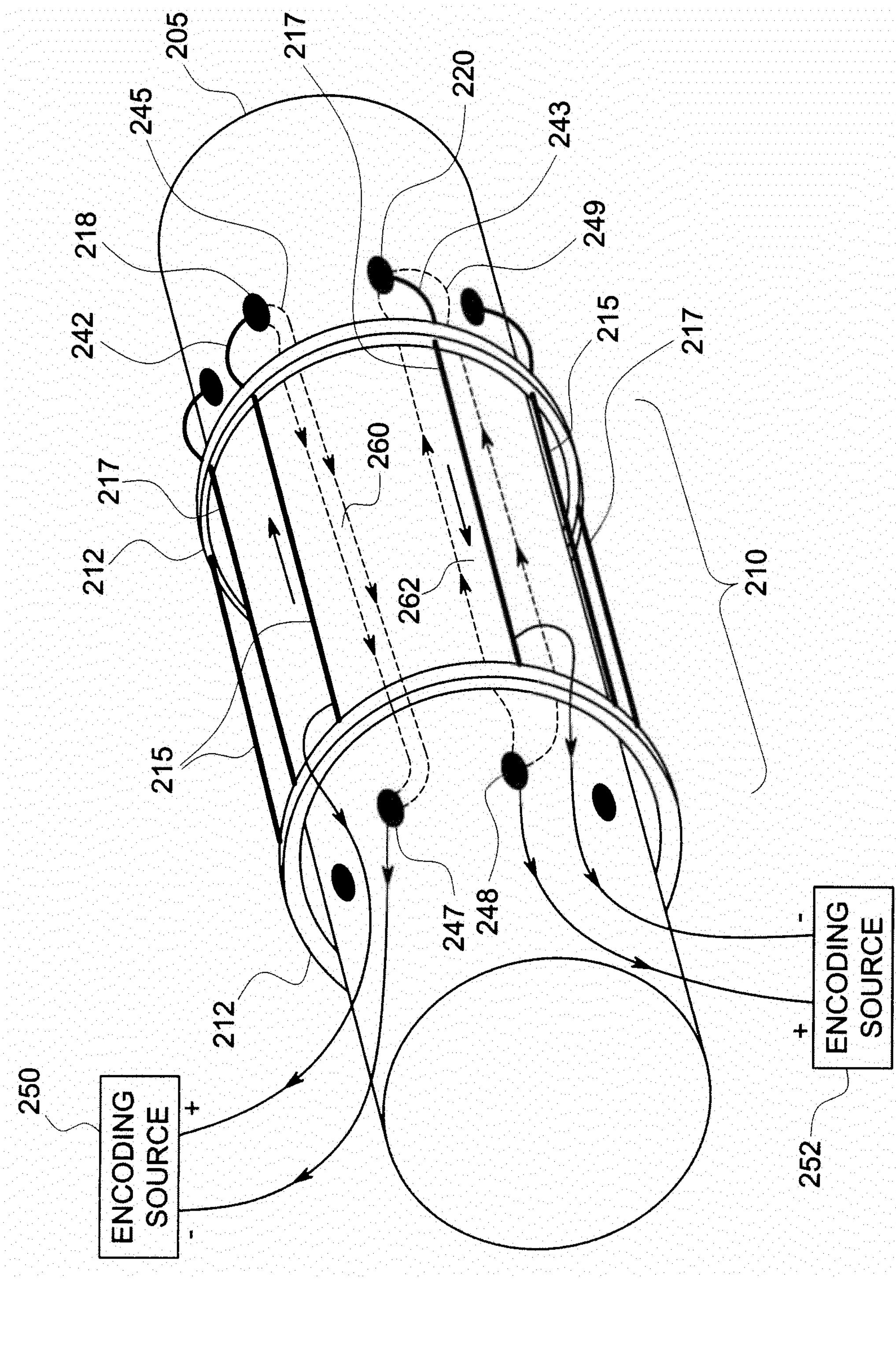

FIG. 4
(Prior Art)

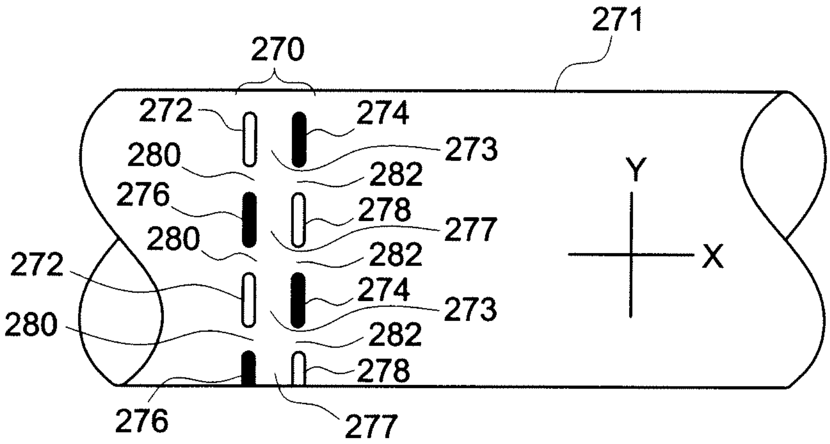

FIG. 5

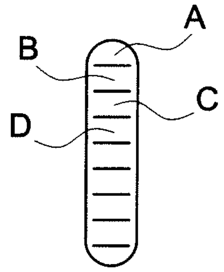

FIG. 6

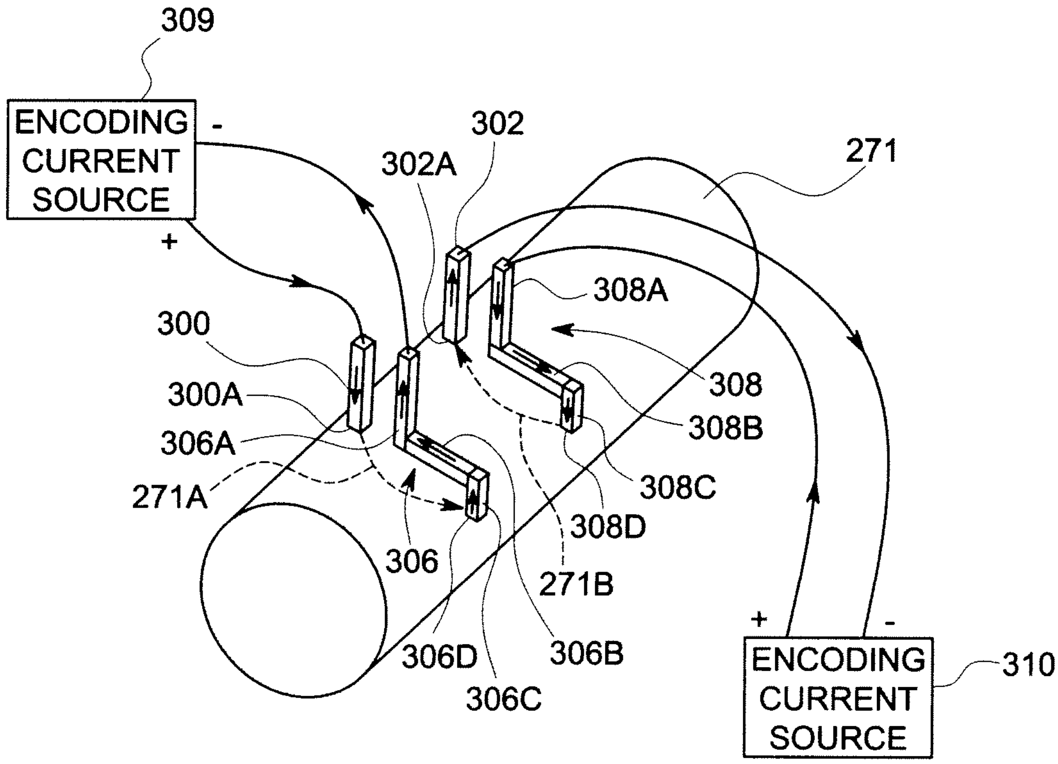

FIG. 7

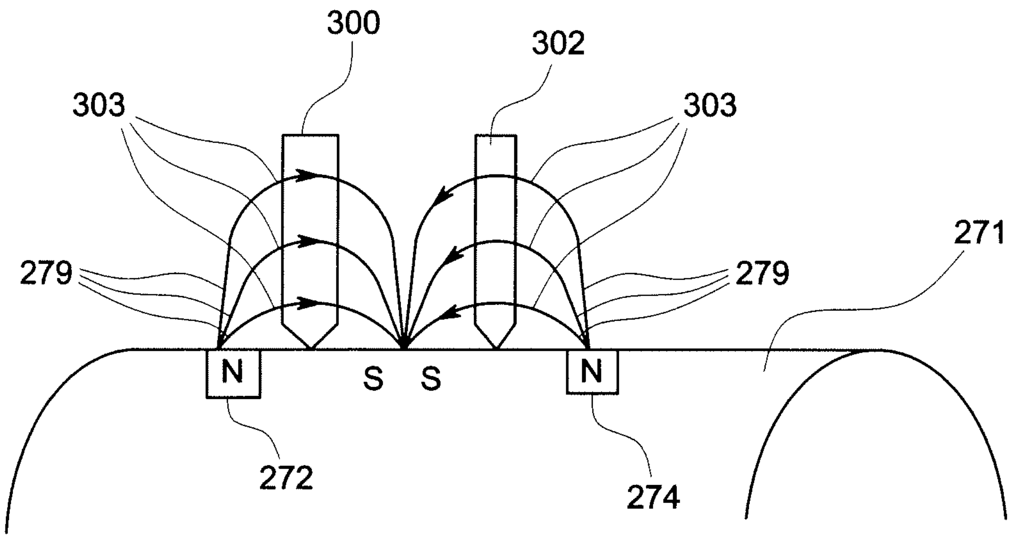

FIG. 8

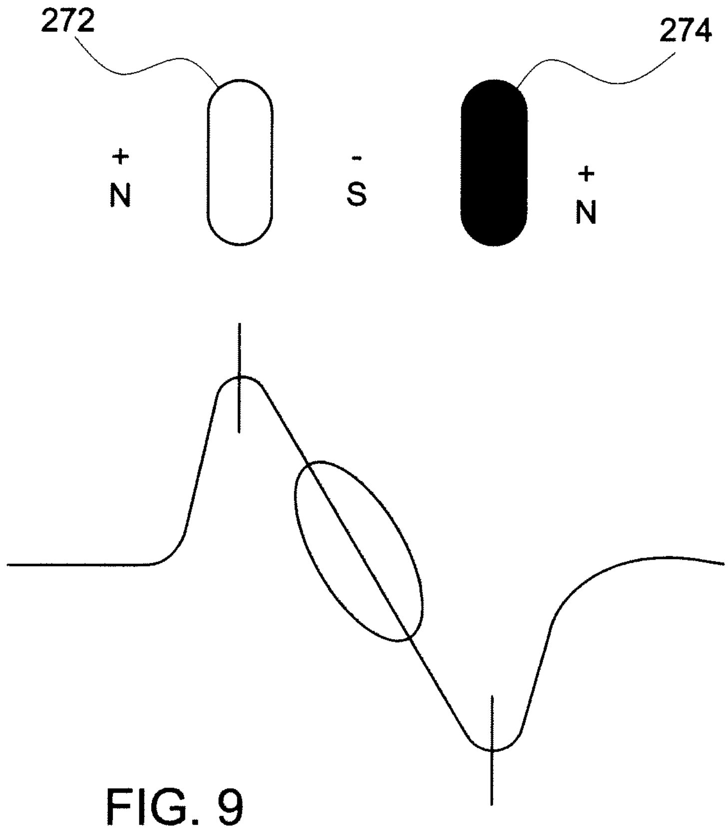

FIG. 9

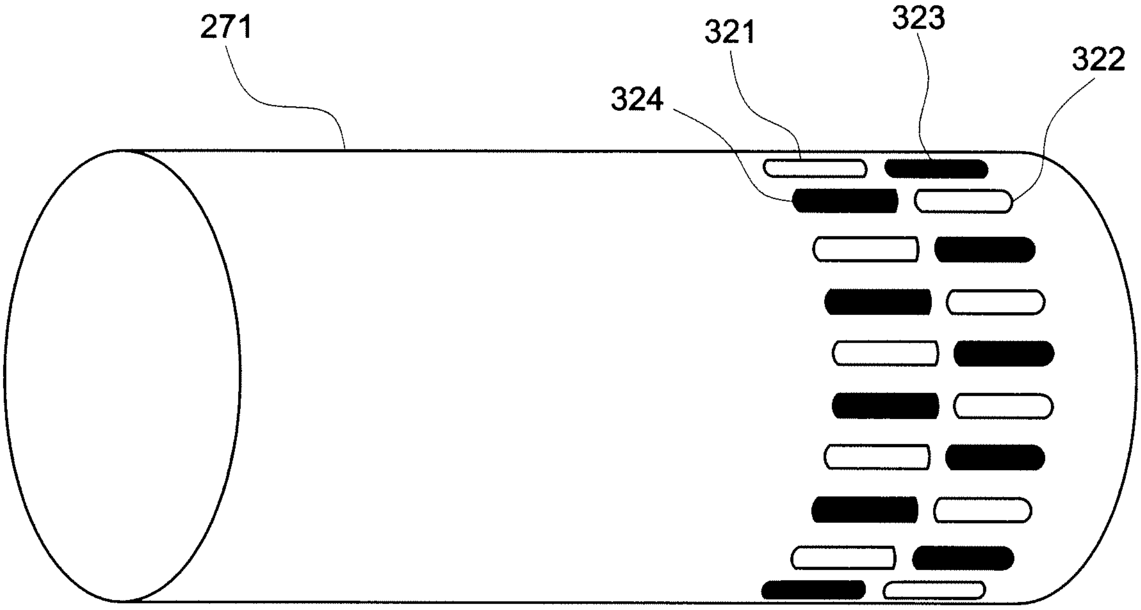

FIG. 10

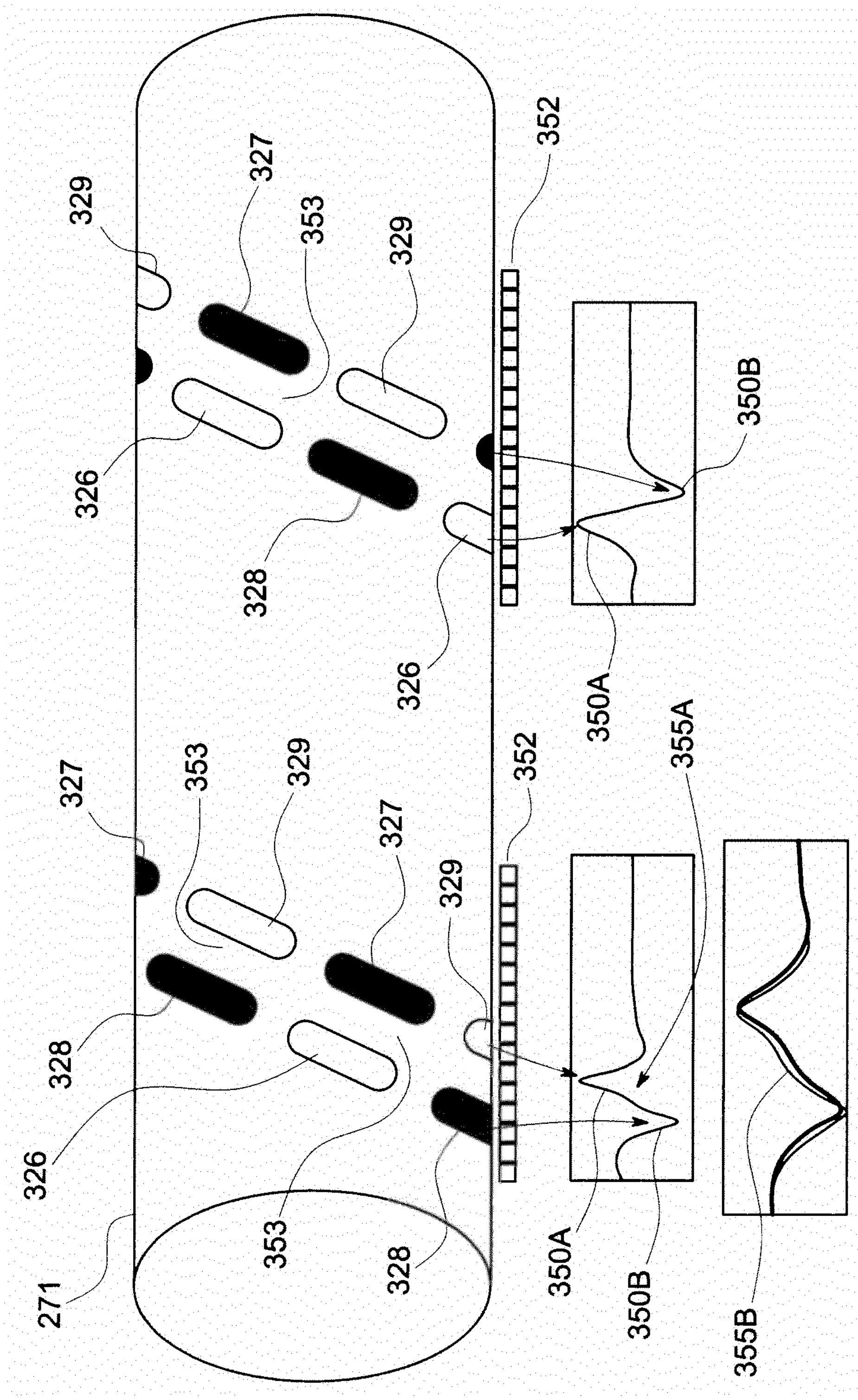
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FIG. 11

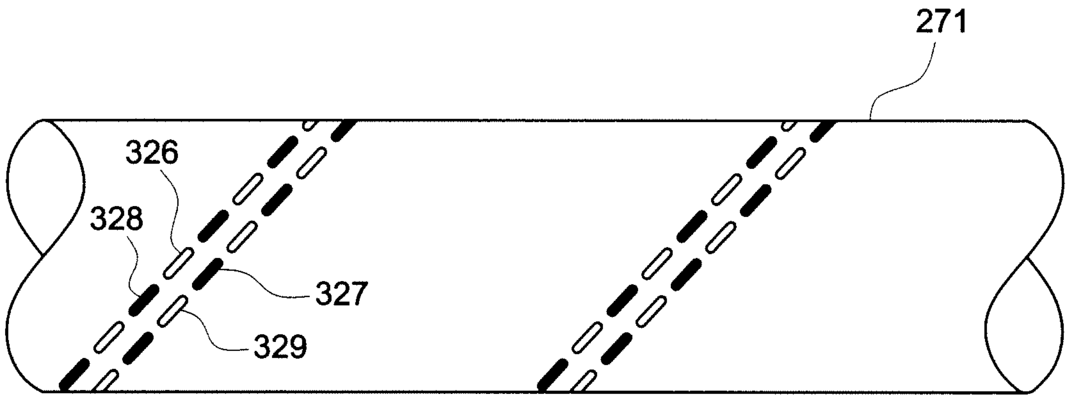

FIG. 12

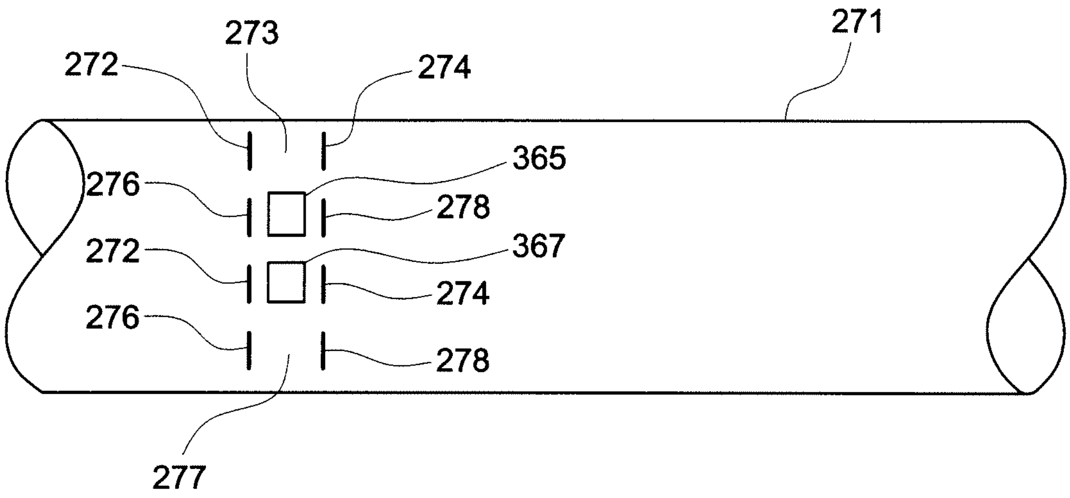
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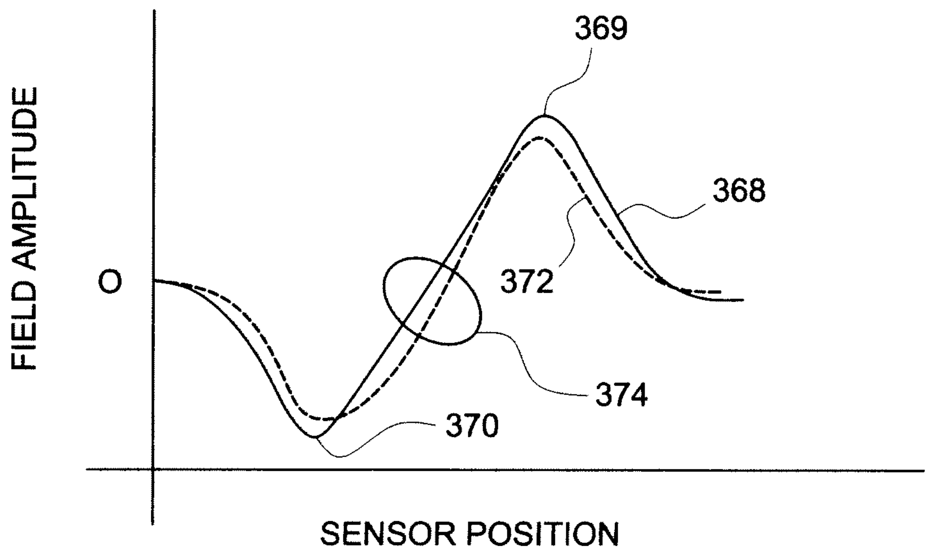
FIG. 13


FIELD AMPLITUDE
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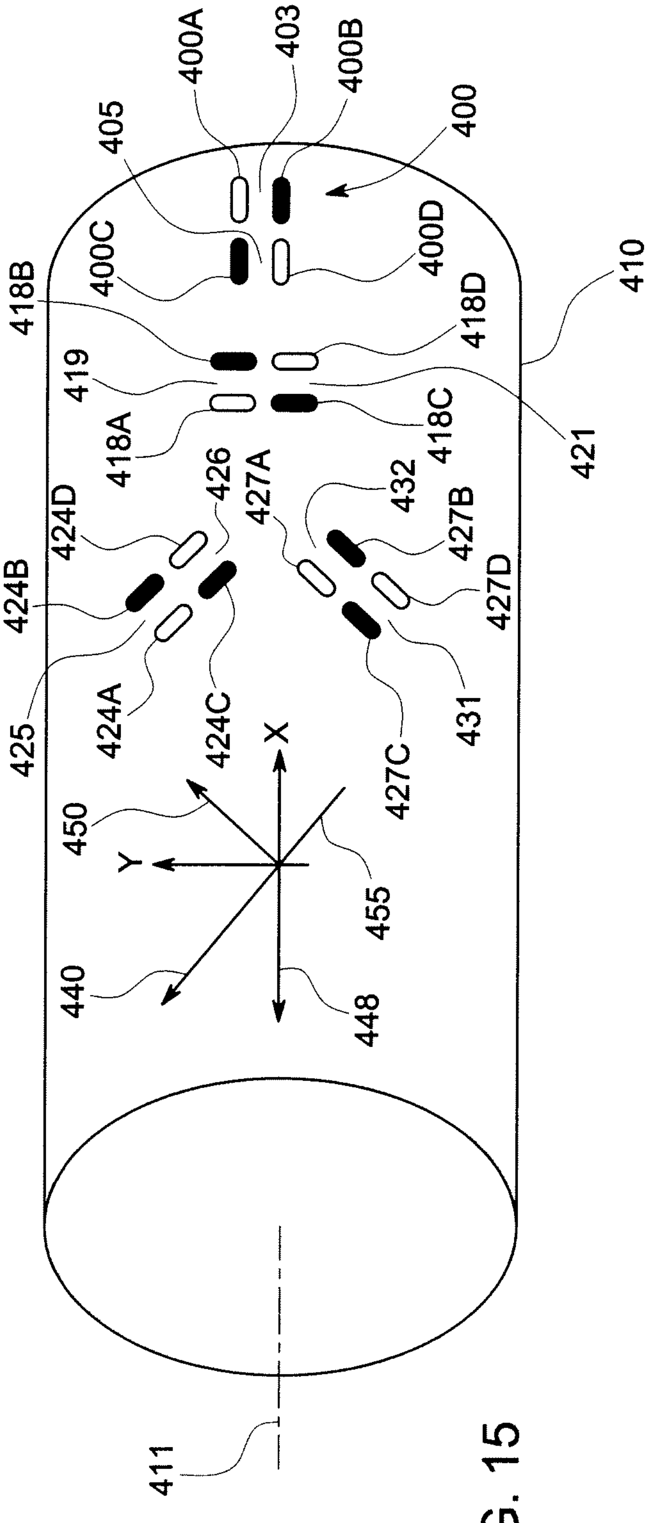
SENSOR POSITION

FIG. 14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427A
432
427B
427D
424B
425
424A
424C
427C
431
X
Y
450
455
440
448
411

FIG. 15

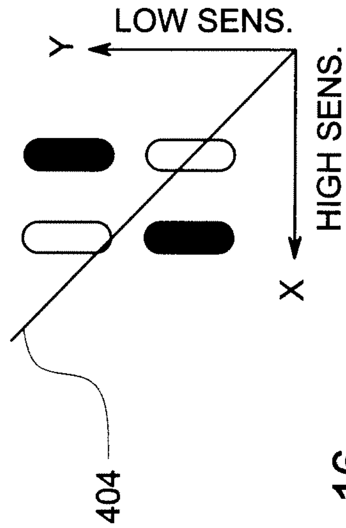

LOW SENS.
Y
HIGH SENS.
X
404

FIG. 16

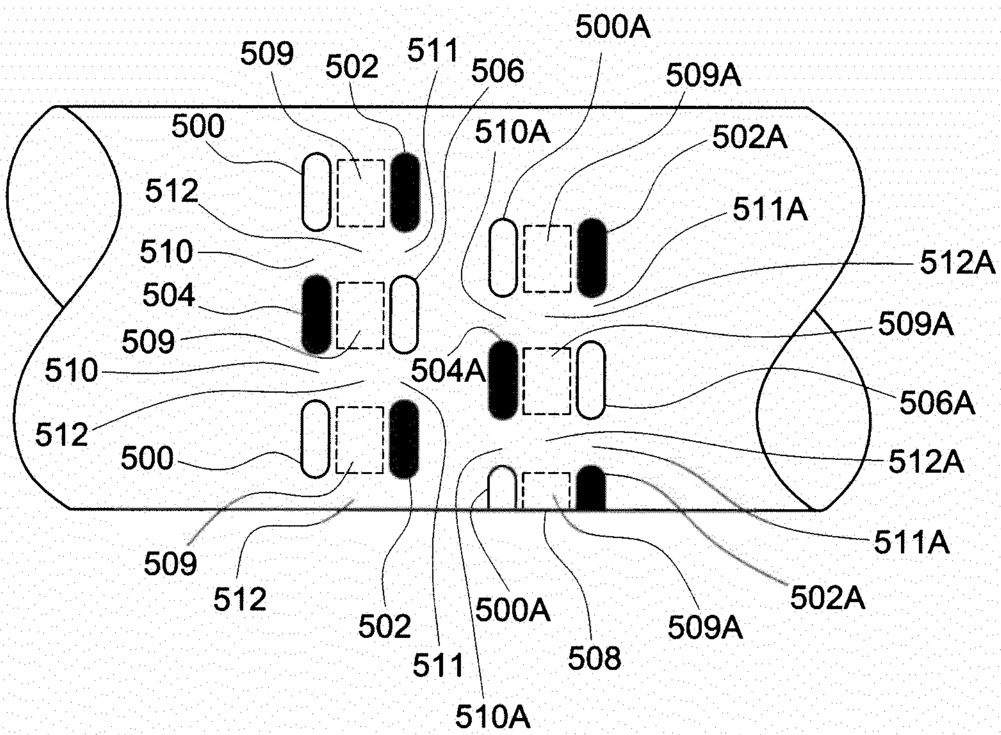


FIG. 17

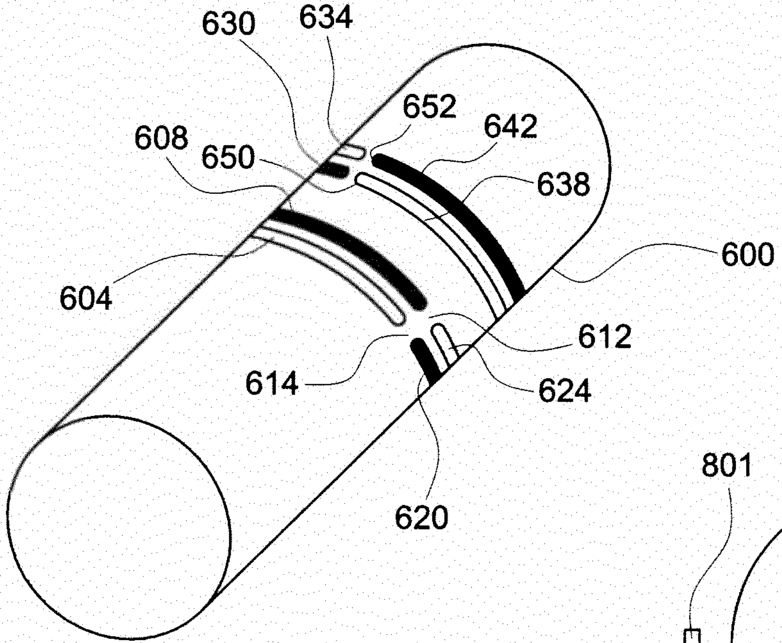
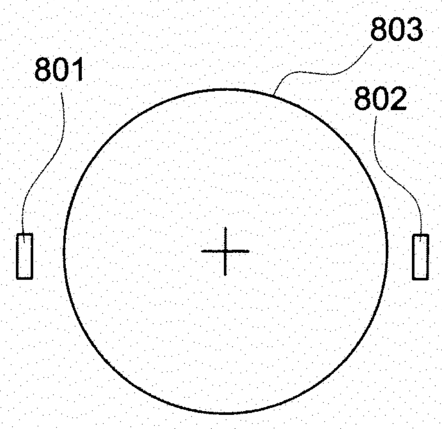


FIG. 18

FIG. 22



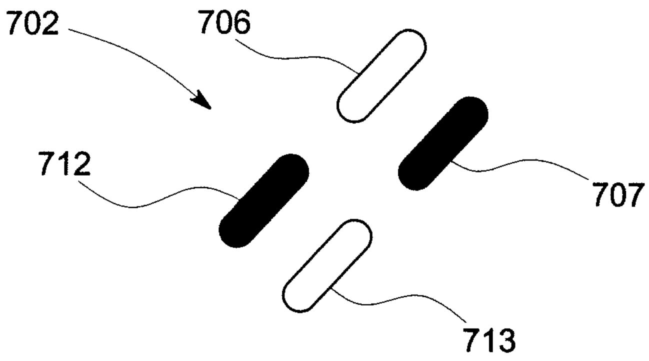


FIG. 19

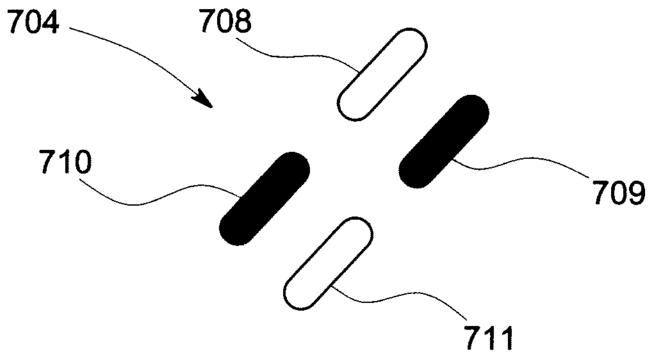


FIG. 20

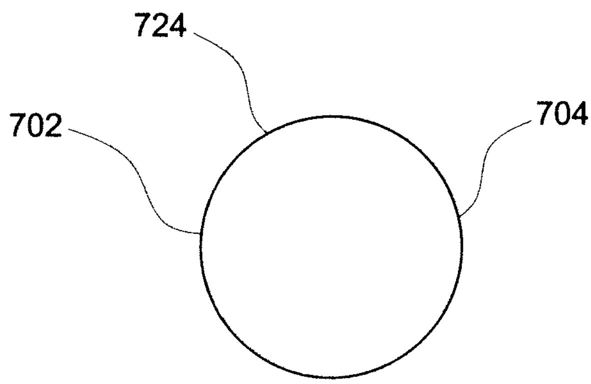


FIG. 21

REFERENCES CITED IN THE DESCRIPTION

Patent documents cited in the description

- WO 0057150 A **[0001]**
- WO 20090301223 A **[0035]**
- WO 12134689 A **[0035]**