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[54] **STRUCTURE WITH VARYING CROSS-SECTIONAL
 MOMENT OF INERTIA**
 12 Claims, 16 Drawing Figs.

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 138/155, 138/172, 166/5

[51] Int. Cl. **E21b 7/12**

[50] Field of Search. **175/7, 5;**
 138/120, 155, 172, 177, 178; 52/788

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ABSTRACT: A structure is described for mounting on a drilling vessel for drilling of submarine wells and the like. A guide horn beneath the conventional drill rig on the ship is in the form of a portion of the surface of a torus. The drill string passes through the guide horn so that any angular misalignment between the drill string at the sea floor and the drill string at the ship due to the ship's roll or the like, is distributed along the surface of the guide horn as a gradual curve over a sufficient length of the drill string that the maximum fiber stress in the drill string is less than the fatigue limit of the drill string. The guide horn has a small entrance aperture at its upper end adjacent the drill rig and flares in a circular arc to an enlarged exit aperture adjacent the bottom of the ship.

For drilling in deep water, a portion of the guide horn is replaced with an elongated tubular member that surrounds the drill string and is fixed to the ship at its upper end as a downwardly extending cantilevered structure. The elongated tubular member has a gradually diminishing cross-sectional moment of inertia so that the drill string within the tubular member is constrained to bend in a substantially circular arc of large radius. In its more rigid portion, the elongated member has a gradually tapering wall thickness. In its more flexible portion, the elongated tubular member comprises a plurality of axially aligned rings in end-to-end relation, surrounded by and substantially flexibly interconnected by a cage. The cage has longitudinally extending ribs with each rib having a gradually tapering cross section.

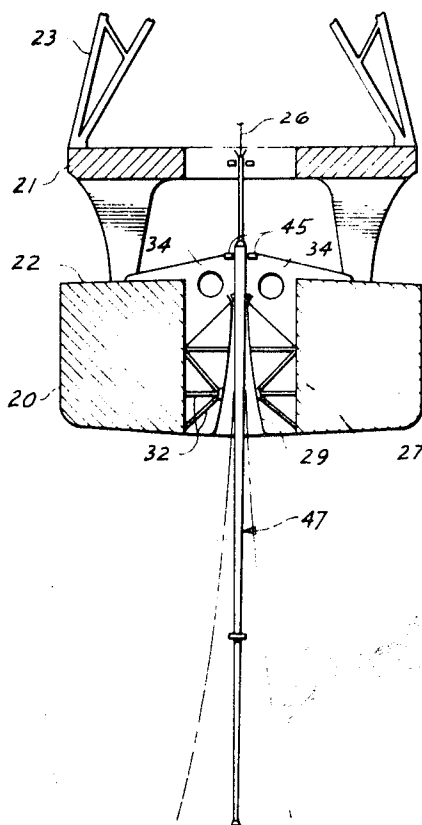


FIG. 1

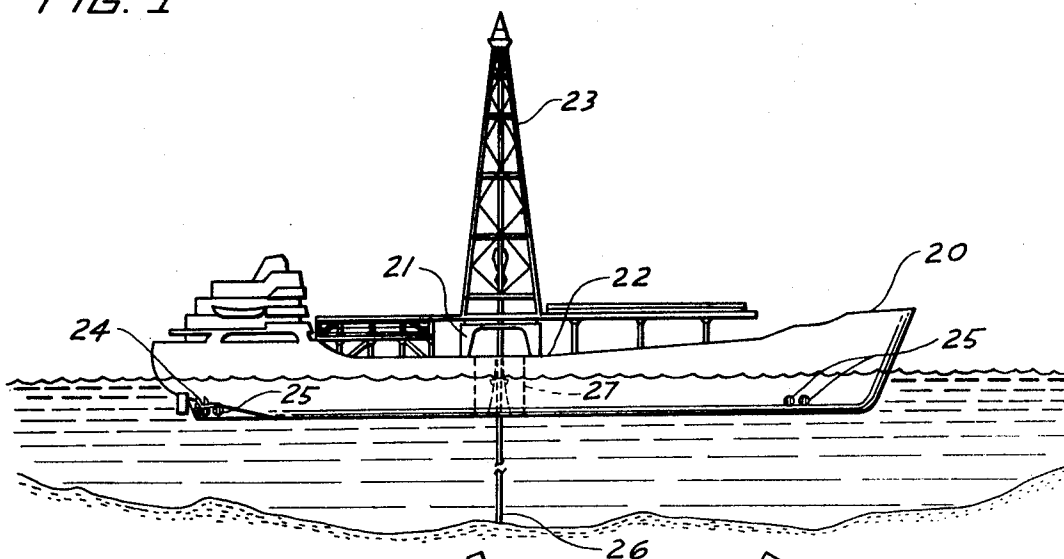
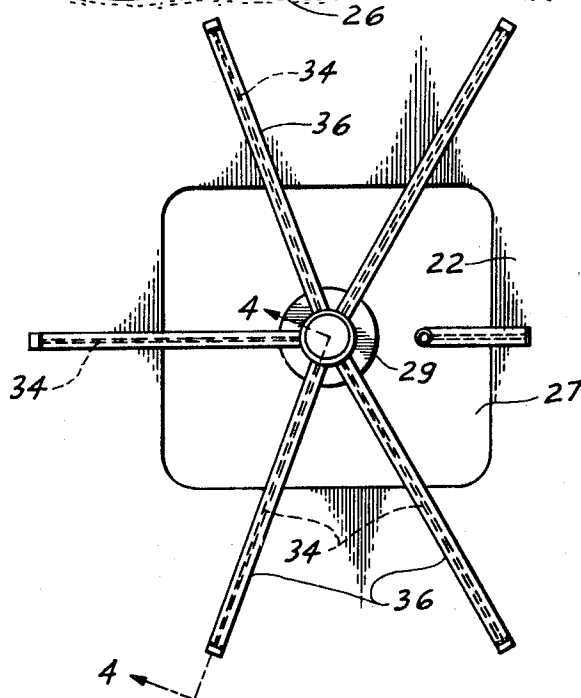


FIG. 5



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ATTORNEYS

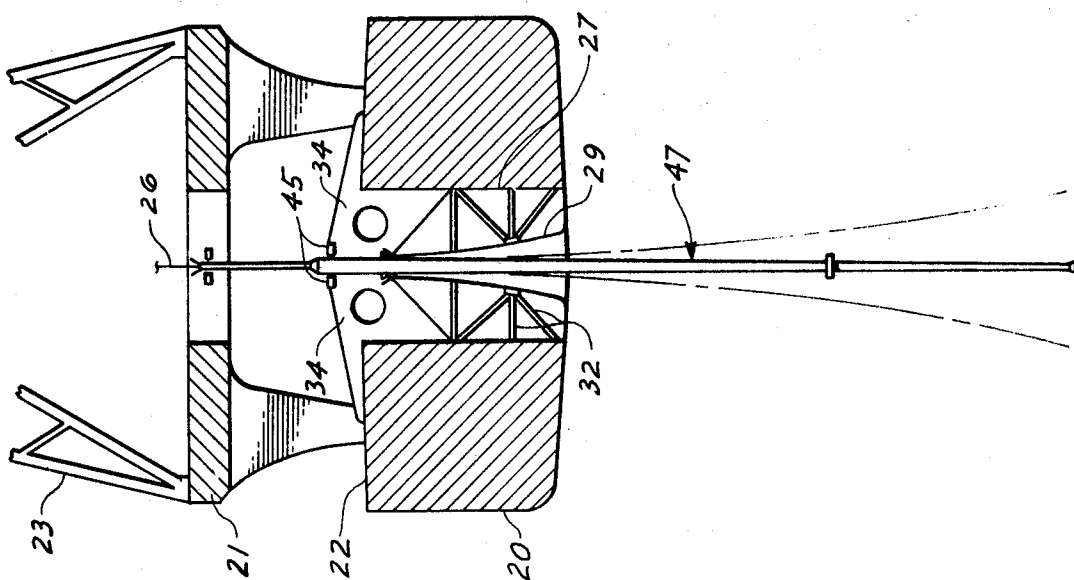


FIG. 3

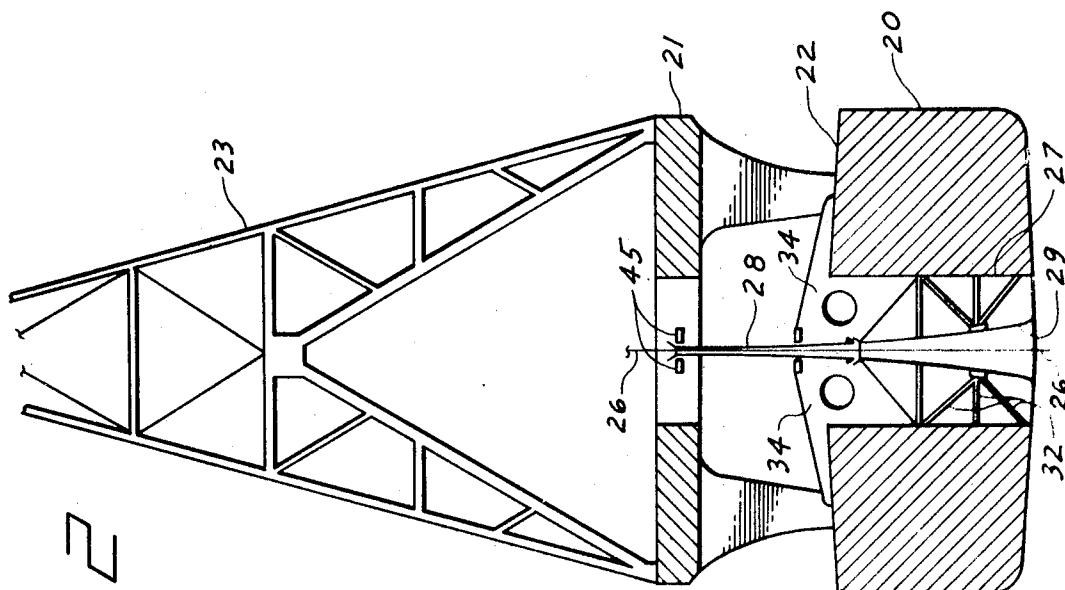


FIG. 2

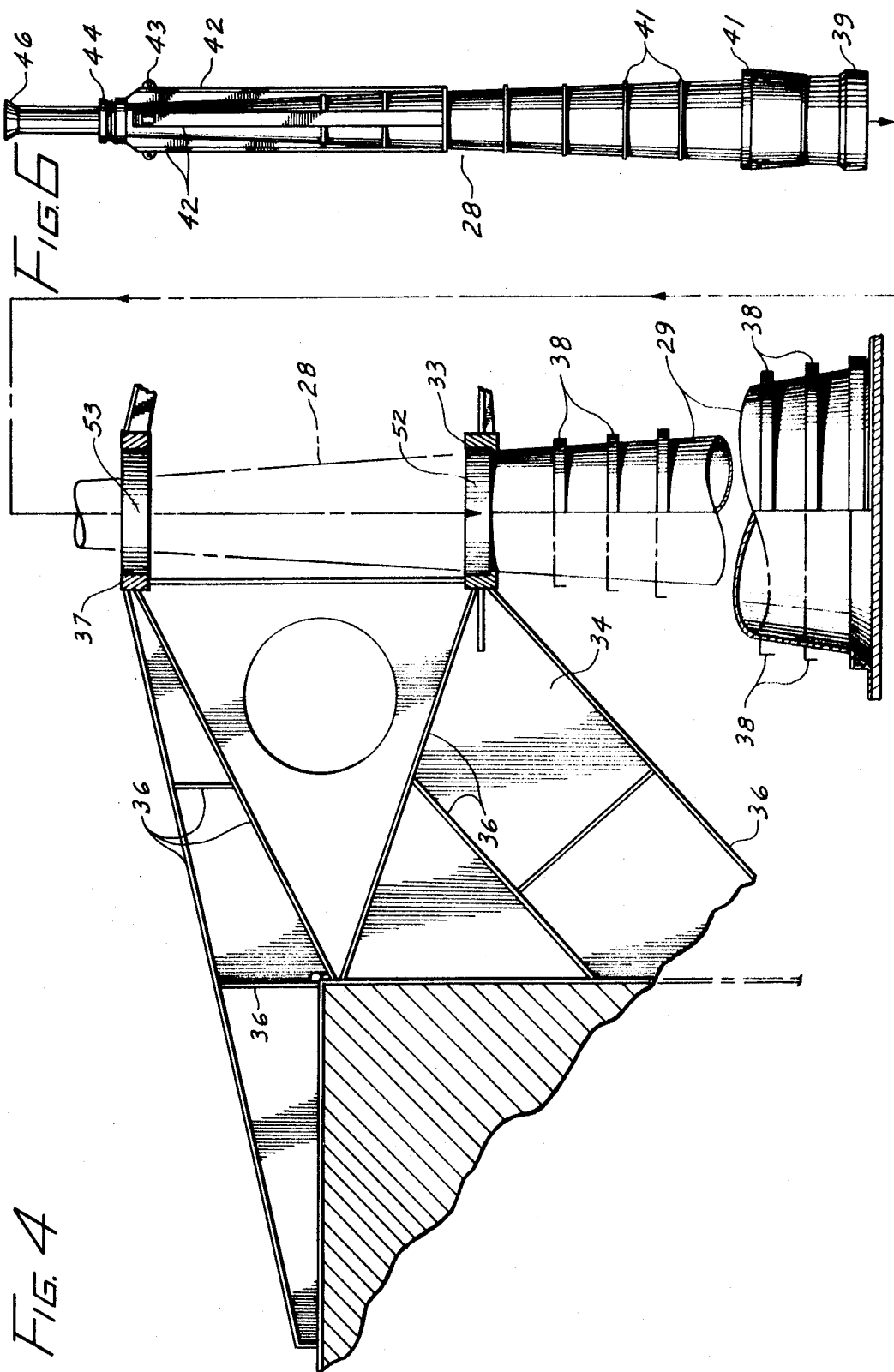


FIG. 7

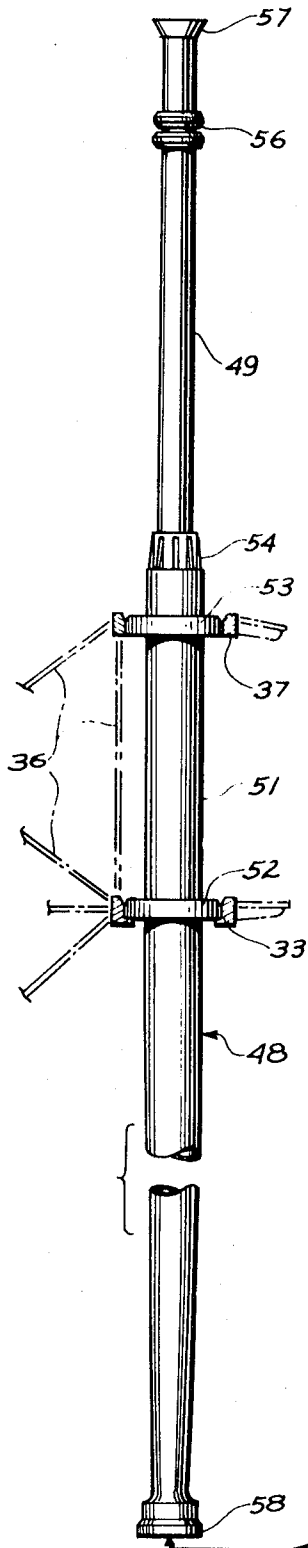


FIG. 8

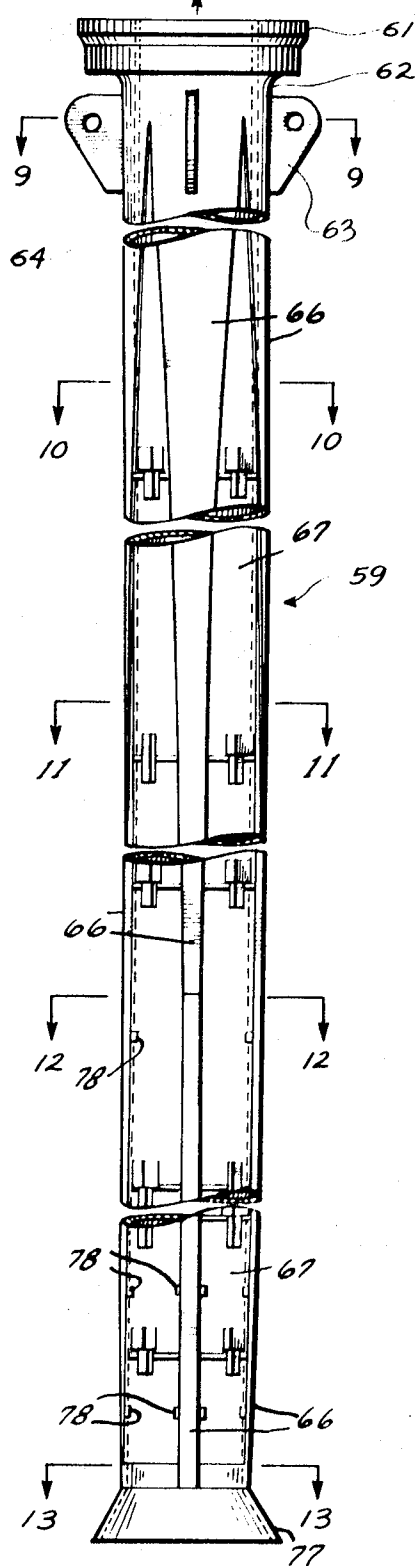


FIG. 14

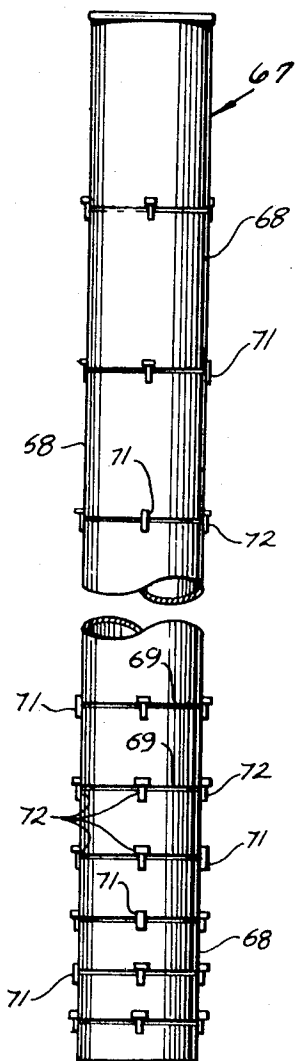


FIG. 9

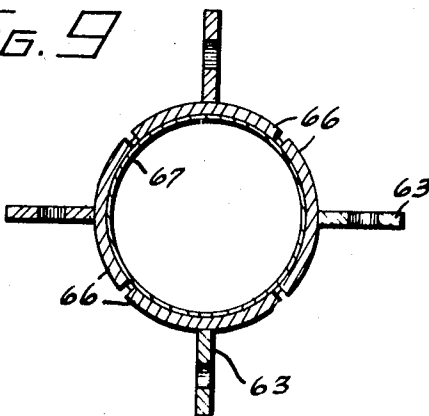


FIG. 10

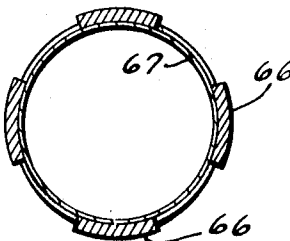


FIG. 11

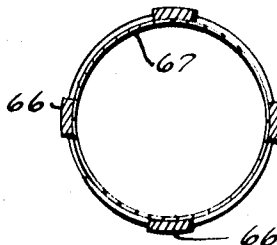


FIG. 12

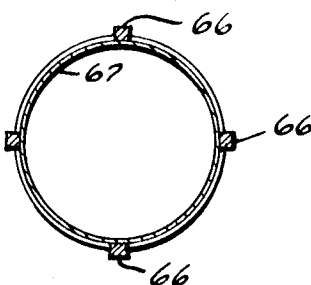


FIG. 13

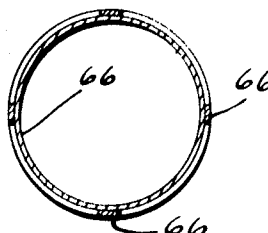


FIG. 15

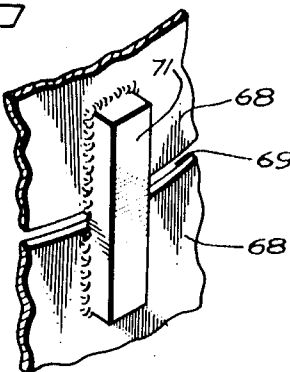
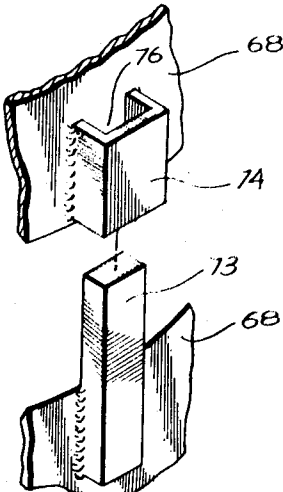


FIG. 16



STRUCTURE WITH VARYING CROSS-SECTIONAL MOMENT OF INERTIA

BACKGROUND

This invention is in the field of underwater drilling from a floating drilling vessel and, in particular, is in the field of providing a structure having a varying cross-sectional moment of inertia along its length for controlling bending of an underwater drill string.

This application is related to copending U.S. Pat. Application Ser. No. 861,018 entitled "Means for Limiting Drill String Bending" by Robert C. Crooke. The copending Pat. Application claims certain aspects of structure described herein. The description herein of the structure claimed in the copending application was derived from the inventor of the subject matter claimed therein.

In recent years it has become desirable to drill oil or gas wells or the like in the sea bed. The drilled wells may be for recovery of oil and gas or may be for the recovery of cores for exploratory and scientific purposes. In either case, the trend has been towards drilling in deeper and deeper waters so that the problems associated with drilling submarine wells have been compounded.

Submarine wells are often drilled from a floating ship having a substantially conventional drilling tower and associated drilling rig mounted over a passage extending vertically through the hull of the ship. When drilling is conducted in the open seas, wind and wave action cause substantial motion of the ship with 6° of freedom in translation and rotation. Modern drilling vessels incorporate various means for minimizing the motions of the ship; however, the forces involved by wind and waves on a ship are so large that substantial motion may still occur. Of greatest concern for purposes of discussion herein is roll of the ship, that is, tilt of the ship about an axis extending in its longitudinal direction.

In order to drill a submarine well, a so-called drill string is suspended from the drill tower on the ship and reaches to the sea floor. The drill string is a conventional element, and for purposes of this description can be considered as an elongated pipe extending from the ship to the sea floor without regard to other structure within the pipe. During drilling operations the drill string is rotated so that the drill bit at the lower end cuts into submarine formations, and the drill string is advanced as the bit sinks into the sea floor. The weight of the drill string between the ship and the sea floor is carried from the ship. When drilling to recover cores for exploratory purposes, a mud riser is not normally employed and drilling fluids are not recovered.

Roll of the drilling vessel can cause excessive stresses in the drill string, particularly in deep water where any stress due to bending is superimposed on the stress due to the weight of the drill string. Bending of the drill string occurs since the lower end at the sea floor is substantially vertical at all times, and the end attached to the drill tower on the ship tilts with the ship as it rolls. Bending must therefore occur at some point between the ends of the drill string. The principal problem occurs near the upper end of the drill string when the roll of the ship is great enough or fast enough that bending in the drill string occurs over a short distance so that the fiber stresses in the drill string are high. This may cause breakage of the drill string with consequent loss of the equipment between the break and the sea floor. Thus it becomes highly desirable to limit the bending that can occur in the drill string.

A curved guide has previously been provided on a drilling vessel for providing a relatively large radius about which a drill string can bend. This guide which was fixed to the ship was useful in relatively shallow water. However, it was not sufficient for relatively deep water drilling since the weight of drill string suspended beneath the ship adds to the bending stress and may cause failure of a drill string bent about a relatively short radius. It is, therefore, desirable to provide a ship with means for controlling the bending in a drill string for both shallow water drilling and deep water drilling.

BRIEF SUMMARY OF THE INVENTION

Thus, in practice of this invention according to a preferred embodiment, there is provided a structure having a gradually changing cross-sectional moment of inertia along its length wherein the change is obtained by a plurality of substantially rigid ringlike sleeves in end-to-end relation along the length of the structure and free to mutually articulate to a limited extent, and a cage surrounding the rings, said cage having a plurality of parallel ribs extending along the length of the structure with each of the ribs having a gradually changing cross-sectional area and being connected at one point to each of the ringlike sleeves. In a preferred embodiment the tubular structure so defined is connected at its upper end to a drilling ship so as to surround a drill string to the sea floor to serve as a drilling guide for subaqueous drilling for limiting the bending of the drill string.

DRAWINGS

The above mentioned and other features and attendant advantages of this invention will be appreciated as the same becomes better understood by reference to the following detailed description of a presently preferred embodiment when considered in connection with the accompanying drawings wherein:

FIG. 1 illustrates a typical drilling vessel incorporating principles of this invention;

FIG. 2 is a transverse cross section of the ship of FIG. 1 with a guide horn;

FIG. 3 is a cross section of the ship of FIG. 1 with an elongated tubular member for controlling bending of a drill string;

FIG. 4 is a detail of a mounting for the guide horn;

FIG. 5 is a top view of the mounting of FIG. 4;

FIG. 6 illustrates an upper portion of the guide horn;

FIG. 7 illustrates an upper portion of the elongated member illustrated in FIG. 3;

FIG. 8 is an elevation view of the lower portion of the elongated member of FIG. 3;

FIGS. 9 through 13 are transverse cross sections through successive portions of the elongated member illustrated in FIG. 8;

FIG. 14 illustrates a liner for the elongated tubular member illustrated in FIG. 8;

FIG. 15 shows in perspective a fixed joint for the liner of FIG. 14; and

FIG. 16 shows in perspective a guide joint for the liner of FIG. 14.

Throughout the drawings like reference numerals refer to like parts.

DESCRIPTION

FIG. 1 illustrates a drilling ship 20 such as is employed for drilling submarine oil or gas wells, taking deep water core samples, or the like. A platform 21 above the main deck 22 of the ship supports a conventional drill tower 23 with its associated rotary table and other conventional drilling paraphernalia not further illustrated or described herein. The propulsion for the ship 20 includes conventional propellers 24 and lateral thrusters 25 cross-mounted in the hull. In drilling wells in deep water, it is often impractical to moor the ship to the sea floor, and the ship is maintained over the drilling site by countering the thrust of wind and waves with the propellers 24 and thrusters 25.

A vertically extending passage 27, commonly known as a "moon pool", extends through the hull of the ship from the main deck 22 to the bottom of the hull. During drilling operations, a drill string 26 extends from the drill tower 23 through the "moon pool" 27, and thence to the sea floor. A flaring guide horn extends from the platform 21 to the bottom of the ship 20. The drill string 26 extends from the platform downwardly through the guide horn toward the sea floor.

FIG. 2 illustrates the "moon pool" 27 in a transverse cross section of the ship 20. As seen in this view, the guide horn

comprises a lower section 29 of the guide horn rigidly secured to the sides of the "moon pool" 27 by a truss of I-beams 32. As is more clearly seen in FIGS. 4 and 5, the upper end of the lower guide horn 29 is fixed to a ring 33 which has a slight internal taper to serve as a seat for the bottom end of an upper section of guide horn 28. Five plates 34, with reinforcing fins 36 welded thereon, extend inwardly from the sides of the "moon pool" 27 to support the ring 33 to which the lower part 29 of the guide horn is secured. The plates 34 also support an upper ring 37 which extends around but does not support the upper part of the guide horn 28. (The upper ring 37 provides lateral support for an elongated member hereinafter described.) A plurality of circumferentially extending reinforcing ribs 38 extend around the lower guide horn 29 so that its cross section remains circular even when heavily loaded on one side by a drill string.

The upper part 28 of the guide horn is further illustrated in FIG. 6. At the bottom end of the upper portion 28, a tapered shoulder 39 is provided for seating in the ring 33 to which the lower portion 29 is attached, so that the upper and lower sections of the guide horn are maintained in alignment. A plurality of reinforcing ribs 41 extend around most of the upper section 28 to maintain circularity. Near the top four T-section ribs 42 extend along the length for reinforcement, and also support lifting lugs 43 for installing and removing the upper section of the guide horn. A collar 44, near the top of the upper section of the guide horn, is engaged by conventional centralizing clamps 45 (FIG. 2) for maintaining the upper part of the guide horn in alignment and in a centralized position below the rotary table of the drill rig. A flare 46 at the top of the guide horn assures smooth entry of the drill string into the guide horn.

In a typical embodiment, the opening into the guide horn at the top is about eight inches in diameter. A typical drill string for core drilling in such an embodiment has a 5½-inch outside diameter pipe and so-called "rubbers" (not shown) are spaced at 5-foot intervals along the length of the drill string. The rubbers are hard rubber rings or short sleeves surrounding the drill pipe with an outside diameter of about 7½-inches. The rubbers serve as bearings between the rotating drill string and the inner surface of the guide horn and other equipment associated with the drilling operation. The flare 46 at the top of the upper guide horn section 28 assures that each successive rubber on the drill string enters the top of the guide horn as the drill string is lowered.

The drill bit in a typical embodiment with a 5½-inch diameter drill string would be about 10 inch diameter. The opening in the upper end of the guide horn would typically be about eight inches in diameter to clear the rubbers on the drill string. In order to first install such a drill bit on the end of a drill string the upper section of the guide horn is removed and a section of drill string threaded through the small diameter opening. After the larger diameter drill bit has been connected to the end of the drill string, the upper section of the guide horn is put back in place on the lower section.

The inner surface of the guide horn is substantially continuous between the upper section 28 and the lower section 29, and flares outwardly in a circular arc having a long radius so that the lower end of the guide horn has a large opening. Thus, in a typical embodiment, with a guide horn about 50 feet long, the lower end opening is in excess of 8 feet across, and the radius of the circular arc between the upper and lower ends of the guide horn is in order of 350 feet.

It will be apparent that the inner surface of the guide horn is a portion of the surface of a torus having a cross-sectional radius in the preferred embodiment of about 350 feet. A torus is a three dimensional figure generated when a circle is rotated about an axis in the plane of the circle, and not intersecting the circle (the surface of a doughnut is a torus). A toroid is more general and is the figure generated when any closed curve is rotated about an axis in the plane and not intersecting the curve. In this instance, the axis of the guide horn is the symmetry axis of the torus, and the inner surface of the guide

horn is a portion of the surface of the torus. A tangent to the inner surface of the guide horn at its lower end is at an angle to the axis of the guide horn, greater than the maximum angle of roll of the ship during which drilling operations can otherwise proceed. In a typical embodiment, the angle between a tangent to the guide horn at its lower end and the axis of the guide horn is in the order of about 8°.

In an appropriately sized and stabilized drilling ship, the thrust capacity of the propellers 24 and lateral thrusters 25 (FIG. 1) limit the ability of the ship to stay over the drilling site. With such a ship, the maximum roll encountered for all sea states where the ship could stay over the drilling site would be less than the angle between the axis of the guide horn and a tangent to the guide horn at its lower edge. Stated in another way, when the sea state reaches a level imposing a greater thrust on the ship than can be countered by the propellers, the ship must cease drilling operations and will be driven away from the drilling site. The maximum roll of the ship in such a sea state is less than the angle of a tangent to the bottom edge of the guide horn. For most practical purposes, the drill string extending downwardly from the ship can be considered as substantially vertical; therefore, if the ship rolls less than the angle between the tangent and the axis of the guide horn, the drill string will not contact the side of the guide horn for the full length of the guide horn.

As the ship rolls, the drill string contacts the inner surface of the guide horn and bends to conform approximately to the shape of the inner surface. (The drill string, of course, conforms only approximately to the shape of the inner surface since it contacts the surface only at the rubbers on the pipe and not continuously along the length of the drill string.) If there were no guide horn, large stresses might be imposed on the drill string as the ship rolls, since there will be an angular misalignment between some point on the suspended drill string and the drill rig. In the absence of the guide horn, this angular misalignment may occur in a short length of the drill string so that the fiber stress due to the acute bending, plus the tension stress due to the weight of the suspended drill string, may be excessive. If the roll of the ship were greater than the angle to the tangent at the lower end, the drill string would bend around the lower edge of the guide horn and excessive bending could occur to yield too high a stress level.

The important stress level is not the yield or ultimate strength of the materials forming the drill string, but instead is the fatigue limit of the drill string. This is the case since the drill string in many drilling operations is continually rotating as drilling proceeds, and it may well occur that the drill string will not advance significantly for a period of time while acutely bent so that flexing could occur at substantially the same point for several cycles, thereby causing failure of the drill string. The fatigue limit is the maximum stress below which a material can presumably endure an infinite number of stress cycles without failure. In some drilling operations the drill string is stationary and a higher stress level may be tolerated.

With the guide horn in place, the angular misalignment between the suspended drill string and the portion of the drill string connected to the drill rig is distributed over an appreciable length of the drill string against the inner surface of the guide horn. Some bending may also occur over a substantial distance below the guide horn, but this is gradual and involves no tight bends. The drill string therefore has a gradual curve of sufficient length and long enough radius that the curvature at any point contributes a maximum fiber stress which, when superimposed on the stress due to the weight of the suspended drill string, is still less than the fatigue limit of the drill string. Thus the guide horn serves to prevent sharp bends in the drill string by distributing the bending over a substantial length of the drill string, and forcing the bending to occur along the inner surface of the guide horn which has a long radius of curvature.

The drill string goes substantially vertically from the upper end of the guide horn and therefore is in a direction tangent to the inner surface thereof. When bent into a curve against the

inner surface of the guide horn, its lower end leaves the inner surface in the direction of a tangent to the surface at the point where it leaves. The point at which the drill string leaves the inner surface of the guide horn on its way toward the sea floor depends on the angle of roll of the ship at the moment. Since the tangent to the surface of the guide horn at its lower end is greater than the maximum angle of roll of the ship at the sea state that would force cessation of drilling operations, the full angular misalignment occurring in the drill string is within the guide horn. This misalignment is distributed and stresses on the drill string are thereby minimized. Another way of viewing this is that the drill string always leaves the lower end of the guide horn away from the edge of the horn. The lowest point where the drill string is in engagement with the guide horn is above the lower edge of the guide horn.

When drilling is conducted in deeper waters, the weight of drill string suspended from the ship is increased and the allowable curvature of the drill string to stay below the fatigue limit may be decreased below the amount afforded by the guide horn. That is, the radius of curvature of the drill string should be longer than the radius provided by a drill string bearing on the guide horn when a greater weight of drill string is employed.

Therefore, in order to distribute the angular misalignment of the drill string over a still greater length with more gradual curvature, the upper portion 28 of the guide horn is removed from the lower portion and it is replaced by an elongated tubular member 47 through which the drill string passes, as seen in FIG. 3. The elongated tubular member 47 extends from the platform 21, supporting the drill tower and associated drilling equipment, to a point substantially below the bottom of the ship. In a typical embodiment the total length of the elongated member may be in the order of 100 feet, and the internal diameter may be in the order of 1 foot.

In this way the elongated tubular member 47 cooperates with the guide horn for controlling bending of a drill string in deep and shallow water drilling respectively. The lower portion of the guide horn is permanently fixed to the ship and serves to guide the drill string in shallow water drilling. The lower portion serves as a support for the upper portion of the guide horn and also for the tubular member so that no modification of the ship is required to adapt it to either shallow or deep water drilling.

The elongated tubular member 47 in a preferred embodiment is divided into three end-to-end segments. The center segment 48 of the elongated tubular member and the upper segment 49 are illustrated in FIG. 7. As illustrated therein, the center segment 48 has a cylindrical portion 51 between a lower flange 52 and an upper flange 53. The lower flange 52 has a slight taper thereon so as to fit into the lower ring 33 to which the lower portion 29 of the guide horn is connected. The upper flange 53 fits within the upper ring 37 so as to transmit lateral loads. The flange 52 supports the principal weight of the elongated tubular member and both flanges 52 and 53 transmit lateral loads between the elongated tubular member and the ship. Thus any bending moments applied to the elongated tubular member are carried by the flanges 52 and 53 to the rings 33 and 37 which are secured to the ship as hereinabove described. Since the lower end of the tubular member is free and the upper end is fixed against bending moments it is a cantilevered structure and can be analyzed in the same manner as a cantilever beam.

On top of the cylindrical section 51 is an open collar or sleeve 54 in which the upper segment 49 of the tubular member is inserted. A collar 56 on this upper segment is centered beneath the drill rig by the same centralizing clamps 45 (FIG. 3) employed for centering the upper segment of the guide horn. A flared end 57 on the top of the upper segment 49 assures entry of the drill string and rubbers on the drill string into the elongated tubular member. The upper segment 49 is merely a lightweight cylindrical guide since no substantial lateral loads are applied thereto by the drill string.

Below the lower flange 52, the center segment 48 of the elongated member comprises an elongated tapered tube, having a substantially constant inside diameter and a larger outside diameter at its upper end than at its lower end. Thus in a typical embodiment the wall thickness may be about 3.8 inches at the upper end and a little over 1 inch at the lower end. A shoulder 58 at the bottom end of the center segment 48 permits attachment of a lower segment 59 (FIG. 8) of the elongated member by a conventional clamp (not shown).

Since the wall thickness of the tapered tubular portion of the center segment 48 varies continuously from one end to the other, the moment of inertia of the cross section of such tapered tubular portion about the neutral axis diminishes with increasing distance from the lower flange supporting 52. As is well known, the bending or flexure of a beam varies with the cross-sectional moment of inertia, all other factors being equal. In the tapered tubes, the distance to the outermost fiber of the tube varies and this plus the change in cross-sectional area of the tube, vary its cross-sectional moment of inertia as a function of length. The tapered tube, with its varying cross-sectional moment of inertia, has the drill string passing therethrough, and the drill string has a substantially constant moment of inertia along its length. When there is an angular misalignment along the length of the drill string, a bending load is applied to the tapered tube, and the combined tapered tube and drill string bend together throughout the length of the tapered tube. With a properly selected variation in combined moment of inertia, the combined cantilevered structure bends in a substantially circular path having a long radius, the magnitude of which can be made any desired value by selecting wall thicknesses and diameters for the desired curvature. Any other desired curvature can be obtained with suitable variation in cross-sectional moment of inertia, the type of curve being readily determined by well known beam bending formulas. Since the tapered tube has at all points a circular cross section, it bends with equal facility in any direction, so that with a given bending force, the combined tapered tube and drill string bend into a position lying on the surface of a large radius torus, the axis of which is the neutral position of the drill string and elongated tube. In a typical embodiment the radius of the circular cross section of the torus may be about 700 feet, that is, the minimum bending radius of the drill string is about 700 feet.

It is desirable to continue the gradually diminishing moment of inertia along the length of the drill string to a point where the moment of inertia contribution of the surrounding elongated tubular member 47 is appreciably less than the cross-sectional moment of inertia of the drill string alone. This assures that no sharp bend occurs in the drill string at its exit from the elongated tubular member. A difficulty is encountered, however, in fabricating a tapered tube with sufficiently thin wall to have a very low moment of inertia, both from the point of view of manufacturing technology and also because of the difficulty of maintaining the circularity of a large diameter thin walled tube with low moment of inertia. Therefore, a lower segment 59, as illustrated in FIGS. 8 through 13, is fabricated to have a gradually changing cross-sectional moment of inertia for controlling bending of the drill string and still have adequate strength to remain circular.

Broadly, the lower segment 59 of the elongated tubular member comprises a plurality of end-to-end circular sleeves interconnected by a surrounding cage extending along the length of the sleeves. The sleeves provide hoop strength for maintaining circularity and articulation is provided between the sleeves so that most of the cross-sectional moment of inertia is contributed by the surrounding cage. The cross-sectional moment of inertia of the surrounding cage is, therefore, varied as a function of length by tapering the ribs or bars of the cage.

Specifically, the lower segment 59, as illustrated in FIG. 8, has a shoulder 61 at its upper end for clamping to the shoulder 58 at the lower end of the middle segment 48 (FIG. 7). A short tubular portion 62 adjacent the shoulder 61 supports four lifting lugs 63. Extending further along the length of the lower

segment from the shoulder 61, the tubular section is interrupted by four longitudinally extending tapered slits 64 to leave four gradually tapering ribs 66 extending along the length of the lower segment. The manner in which the ribs 66 taper can be seen in the transverse cross sections of FIGS. 9, 10, 11 and 12, which show that the ribs have a constant radial thickness and become progressively narrower circumferentially as a function of distance from the upper end of the lower segment towards the lower end of the lower segment. At the point where the section 12—12 is taken in FIG. 8, the arcuate width of the ribs 66 reaches a minimum and the width of the ribs continues to be constant to substantially the bottom of the lower segment. From the point where the section 12—12 is taken in FIG. 8 to the bottom of the lower segment where the section 13—13 is taken, the radial thickness of the ribs is gradually diminished. The decreasing thickness of the ribs can be seen in FIGS. 12 and 13.

It will be apparent that since the cross-sectional area of the ribs 66 varies along the length of the lower segment, that the moment of inertia of the cross section also varies along the length. By choosing an appropriate thickness and rate of change of width and thickness of the ribs 66, a variation in moment of inertia as a direct continuation of the moment of inertia of the center segment 48 can readily be provided.

If one merely had an open cage of ribs 66 in the lower segment, the drill string could slip between the ribs and no bending control would be provided. If the drill string did not slip between the ribs but instead bore on one or two of the ribs, only these would contribute to bending control, and too large a curvature would be obtained. Abrasion of rubbers on the drill string against the separated ribs would be prohibitive. There is, therefore, provided a substantially flexible cylindrical liner 67 within the cage of ribs 66.

The liner 67 which is illustrated separately in FIG. 14 and in place in FIG. 8, is formed of a plurality of sleeves or rings 68 connected end-to-end to form a hollow tube. A short space 69 is provided between adjacent rings 68 in the liner to permit articulation. Adjacent rings in the liner are connected together by one fixed joint comprising a square bar 71, having an end welded to each of the adjacent rings, as illustrated in FIG. 15. One such fixed bar 71 is provided between each adjacent pair of rings 68.

In addition to the bar 71 interconnecting adjacent rings or sleeves, a longitudinally movable guide joint 72 is provided between adjacent rings at three points around the circumference so as to span the space 69 between adjacent rings. A typical guide joint 72 is illustrated in FIG. 16 which shows a square bar 73 welded at one end to a ring 68 so that the other end of the bar extends beyond the end of the ring. A guide sleeve 74 is welded to an adjacent ring 68 so that the guide bar 73 is free to slide in an open slot 76 through the guide sleeve 74.

Thus each pair of adjacent rings or sleeves 68 is interconnected by a fixed joint 71 and three guide joints 72, each spaced about 90° from the adjacent joints. The fixed joints 71 interconnect a first pair of sleeves at one point on the circumference and interconnect the next pair of adjacent sleeves at a point on the circumference 90° from the fixed interconnection between the first pair of rings. The fixed interconnection between a third pair of rings is 90° further around the circumference than the second interconnection, or 180° from the first fixed interconnection. In this manner, the fixed interconnections between adjacent pairs of rings or sleeves progresses in the general manner of a helix along the length of the liner, as illustrated in FIG. 14. Since the rings of the liner are interconnected by a few helically disposed fixed joints and the plurality of longitudinally slidable guide joints 72, the inner liner is substantially flexible in bending about the interfaces 69 between adjacent sleeves or rings. The rings themselves are substantially rigid and the joints 71 and 72 between adjacent rings along the length maintain the ends of the rings in alignment. The joints serve to transmit shear and torsion loads between adjacent rings to maintain the lower segment in align-

ment. These loads are normally rather small and readily accommodated by four one-half inch square bars at the four joints respectively.

The inner liner 67 is fitted within the cage of ribs 66 as illustrated in FIG. 8, and also seen in the transverse cross sections of FIGS. 9 through 13. The lowermost sleeve 68 in the liner is welded at its lower end to the lowest end of the ribs 66, and a flare 77 is provided on the bottom end of the lower segment 59 for guiding the rubbers on the drill string into the interior. In addition, each of the rings 68 is welded at its midpoint to each of the ribs 66 by a weld 78. The guide joints 71 and 72 are about midway in the slits between the ribs so that the ribs are substantially flush with the outside of the liner.

Thus the four ribs are interconnected intermittently by the circumferentially extending sleeves 68. Likewise, adjacent sleeves or rings are interconnected longitudinally between their midpoints by welds 78 to the ribs 66. This interconnection of the rings along the length of the lower segment has no substantial contribution to the rigidity of the lower segment since the inner liner 67 is still quite flexible as compared with the flexibility of the ribs. The sleeves 68 maintain circularity of the lower segment throughout its length, and provide a means for transmitting transverse or bending loads between the drill string within the lower segment and the ribs 66.

It will be noted in FIG. 14 that the length of each sleeve 68 along the length of the lower segment differs from the adjacent sleeves, with relatively shorter sleeves being employed at the lower, more flexible end and longer sleeves being employed at the upper, more rigid end. There are two reasons for varying the length of the rings along the length of the lower segment. Since the ribs 66 are more flexible near their lower end, it is desirable to insure circularity of the ribs at more frequent intervals in this region. Of greater interest are the dynamic characteristics of the elongated tubular member under transient loading. Under steady state conditions, the elongated tubular member having a changing cross-sectional area, and hence a varying cross-sectional moment of inertia, will bend in a substantially circular arc when loaded by a drill string therein which also has a substantial cross-sectional moment of inertia. The same is not necessarily true in a dynamic situation. When some transient influence varies the angular misalignment between the drill string below the ship and the drill string connected to the drilling tower, some time is required to reach an equilibrium bending, and during that time a greater degree of bending may occur in the lowermost end of the elongated tubular member. It is, therefore, desirable that the sleeves have a relatively shorter length near the bottom end to accommodate a somewhat greater degree of bending as compared with longer sleeves near the upper end, which may not bend as sharply.

In a typical embodiment the inside diameter of the elongated member is about 10½ inches and the diameter of the rubbers on the drill string is about 7½ inches. The drill string is therefore "loose" within the elongated tube and is not in contact with the inner wall throughout the length. When there is a small angular misalignment, the drill string contacts the inside of the tubular member at the lower, more flexible end. As the misalignment becomes larger the forces between the drill string and the surrounding tube increased. Initially a small bending occurs and the drill string lies along a short portion of the bent tube. The drill string below the tube extends in a direction substantially tangent to the lower end of the tube. At the point where the drill string leaves the inner surface of the tube above the region of contact it also proceeds substantially along a tangent to the surface.

Thus in both the guide horn and the elongated tube the length of drill string contacting the surface in bending is proportional to the angular misalignment accommodated. The angular misalignment of the drill string is therefore distributed over a gradual curve of substantial length. In both the guide horn and the elongated tube, the drill string leaves the surface about which it bends in a direction substantially along a tangent to the surface. That is, there is no substantial bending of

the drill string at the point where it leaves the surface, the angular misalignment having been accommodated substantially completely in the portion in contact with the surface. Some bending will occur in the drill string beyond the lower end of the elongated tubular member in approximately the form of the curve of a cantilevered beam of invariant moment of inertia.

In a preferred embodiment in both the guide horn and the elongated tube, the drill string bends about a curve that is a portion of the surface of a torus, that is, it follows a circular arc. In the case of the guide horn the torus is fixed relative to the ship. In the case of the tubular guide, the torus has no fixed spatial relation except that its axis lies along an axis through the top of the tube and aligned with the drill rig. It should also be noted that the bending of the drill string in the tubular guide can be around other than a circular arc depending on the variation of cross-sectional moment of inertia chosen and therefore this bending may be about a portion of the surface of a toroid.

Although only one embodiment of a structure with varying cross-sectional moment of inertia has been described and illustrated herein, many modifications and variations will be apparent to one skilled in the art. Thus, for example, the lower segment can be provided with five, six or more ribs instead of the four ribs illustrated herein. It will also be apparent that such a structure can be employed in many situations other than for subaqueous drilling, such as, for example, in the laying of underwater pipe lines where the pipe passes through the "moon pool" to be layed on the bottom or where the pipe line is deployed from a "stinger" on the aft end of the vessel. Such a structure may also be useful in deploying other conduits or in other environments where a substantial tension exists in a cylindrical member and relative motion between the two ends of the member must be accommodated.

What is claimed is:

1. An elongated structure having a gradually changing cross-sectional moment of inertia along its length comprising:

a plurality of substantially rigid ringlike sleeves in end-to-end relation along the length of the structure; and

a cage surrounding the rings having a plurality of parallel ribs extending along the length of the structure, each of the ribs being connected at one point to each of the sleeves, each of the ribs having a gradually changing cross-sectional area.

2. An elongated structure as defined in claim 1, wherein each of the sleeves has a shorter length than the previous sleeve along the length of the structure.

3. A structure as defined in claim 1, further comprising:

means between each pair of sleeves for enabling a limited longitudinal translation and for preventing substantial relative rotation of adjacent sleeves about the longitudinal axis of the structure.

4. A structure as defined in claim 1, wherein the ribs are interconnected circumferentially at each end of the elongated structure, and each rib has an arcuate cross section having a concave side adjacent the exterior of the sleeves, the arc length gradually decreasing along the length of the structure.

5. A structure as defined in Claim 4, wherein each of the sleeves has a shorter length than the previous sleeve along the length of the structure, the relatively longer sleeve being nearer the greater cross-sectional area of the ribs and the relatively shorter sleeve being nearer the smaller cross-sectional area of the rib and further comprising:

means between each pair of sleeves for enabling a limited longitudinal translation and for preventing substantial relative rotation of adjacent sleeves.

6. Apparatus for improved control of bending of a drill

string extending between a drilling rig fixed on a floating drilling ship and the sea floor, said apparatus comprising:

an elongated tubular member connected at its upper end to the ship in alignment with the drilling rig for passing the drill string therethrough and extending to a free lower end, said elongated tubular member having a gradually varying cross-sectional moment of inertia along its length with a relatively larger cross-sectional moment of inertia at the end connected to the ship and a relatively smaller cross-sectional moment of inertia at the free end, said tubular member comprising:

at least a portion having a plurality of parallel tapered ribs extending longitudinally along the tubular member to form a cage; and

a plurality of ringlike segments within the cage substantially freely articulatable relative to each other.

7. Apparatus as defined in Claim 6, wherein the ringlike segments are connected intermittently to the ribs in end-to-end relation to form a tubular member.

8. Apparatus as defined in Claim 7, further comprising means for interconnecting ends of adjacent ringlike segments for preventing substantial relative rotation of adjacent sleeves about the longitudinal axis of the tubular member.

9. A drilling guide for a floating drilling vessel comprising:

an elongated tubular member having a cylindrical bore sufficiently large to accommodate a drill string;

means on the tubular member for aligning an end of the member with the drilling vessel;

means on the tubular member for varying the cross-sectional moment of inertia of the tubular member as a function of its length with a relatively larger cross-sectional moment of inertia adjacent to the end aligned with the drilling vessel and a relatively smaller cross-sectional moment of inertia adjacent to the opposite end, said means for varying comprising at least in part:

a plurality of tapered ribs extending longitudinally along the tubular member to form a cage; and wherein

the tubular member comprises a plurality of ringlike segments in end-to-end alignment within the cage and intermittently connected to the tapered ribs and otherwise substantially free to mutually articulate in a direction to accommodate bending of the tubular member.

10. A drilling guide as defined in Claim 9, wherein the length of adjacent ringlike segments differs with a segment having a relatively shorter length relatively closer to the smaller end of the tapered ribs and a segment having a relatively longer length relatively closer to the larger end of the tapered ribs.

11. A drilling guide as defined in Claim 10, further comprising:

means interconnecting adjacent ringlike segments for conveying shear and torsion loads therebetween and for permitting limited longitudinal articulation.

12. A drilling guide as defined in Claim 10, wherein the means for varying the cross-sectional moment of inertia further comprises:

a tubular section having a higher cross-sectional moment of inertia than the section including the ribs and segments and having a gradually decreasing outside diameter with increasing distance from the means for aligning, the end of the tubular section having the relatively lower cross-sectional moment of inertia connected in end-to-end relation with the end of the rib section having the relatively higher cross-sectional moment of inertia so that the variation in cross-sectional moment of inertia with increasing distance from the means for aligning is substantially continuous.