8-6-74 OR 3,827,294

[11] **3,827,294**

Anderson [45] **Aug. 6, 1974**

[54] WELL BORE FORCE-MEASURING APPARATUS

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[52] **U.S. Cl.** **73/151**
[51] **Int. Cl.** **E21b 47/00**
[58] **Field of Search** ...... 73/151, 141 A; 340/18 LD, 340/18 P; 181/.5 AG; 175/40, 50

[56] **References Cited**

UNITED STATES PATENTS

2,466,034	4/1949	Mathews	73/141 A X
3,488,629	1/1970	Claycomb	73/152 X
3,686,942	8/1972	Chatard et al.	73/151

Primary Examiner—Jerry W. Myracle
Attorney, Agent, or Firm—Ernest R. Archambeau, Jr.; William R. Sherman; Stewart F. Moore

[57] ABSTRACT

In the representative embodiment of the apparatus of the present invention disclosed herein, a pair of force-measuring sleeves are telescoped together and coaxially mounted on a drill string sub with their opposite ends engaged with opposed shoulders on the tubular sub body so that even minor torsional or longitudinal forces acting on the body will cause proportional movement of the sleeve members in relation to one another. To detect these forces, a loop-like deformable member having circumferentially-spaced rings joined together by elongated strips or bars is coaxially disposed on the sub body with the spaced rings tightly clamped between opposed shoulders on the sleeve members. Signaling means are coupled to two or more arrays of strain gages respectively mounted on the rings and bars forming the loop and cooperatively arranged for transmitting signals to the surface which are representative of the longitudinal and torsional forces imposed on the sub body tending to dimensionally distort the loop-like member.

20 Claims, 6 Drawing Figures

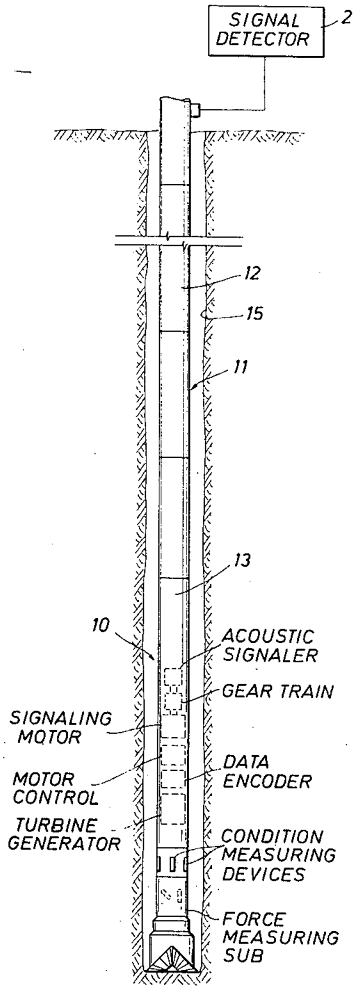
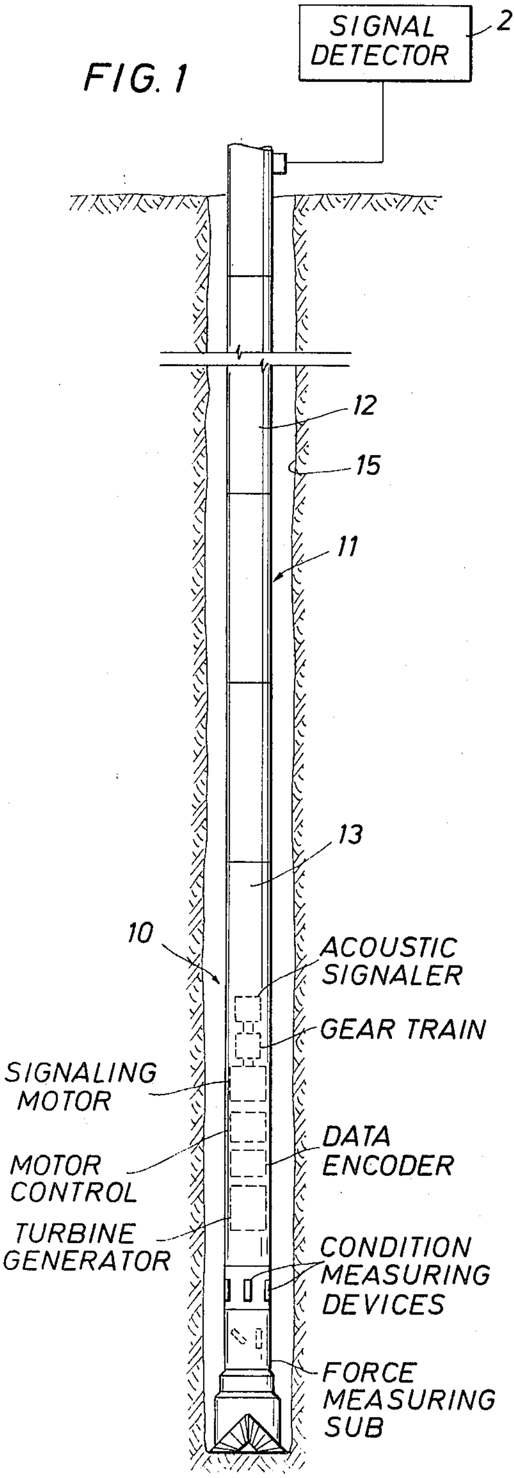


FIG. 1


SIGNAL DETECTOR
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ACOUSTIC SIGNALER
GEAR TRAIN
SIGNALING MOTOR
MOTOR CONTROL
DATA ENCODER
TURBINE GENERATOR
CONDITION MEASURING DEVICES
FORCE MEASURING SUB

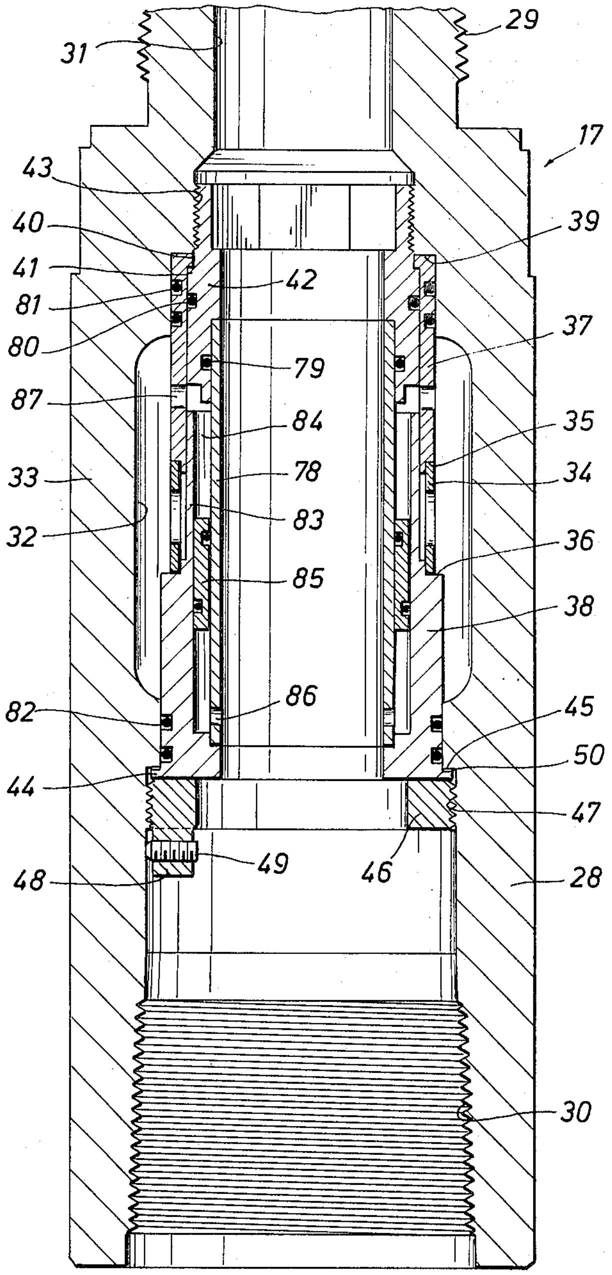
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FIG. 2

FIG. 3

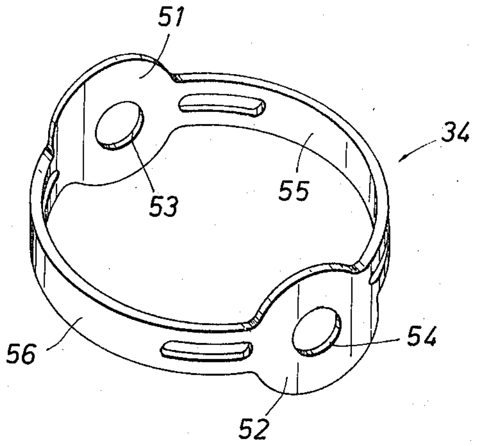


FIG. 4A

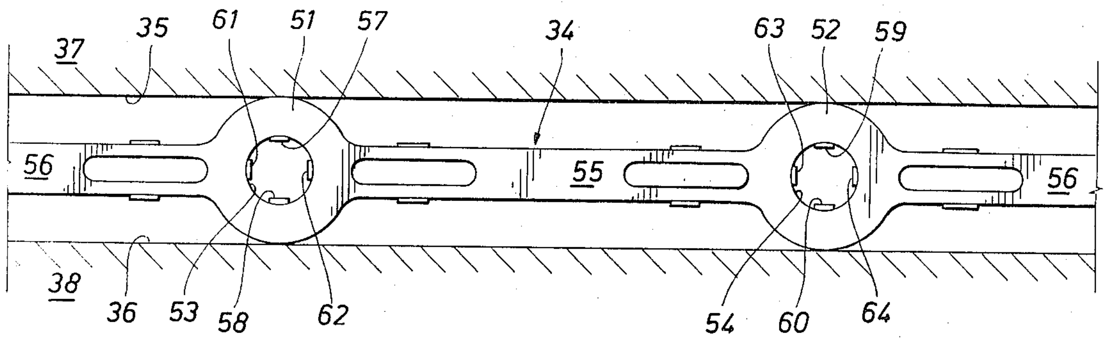
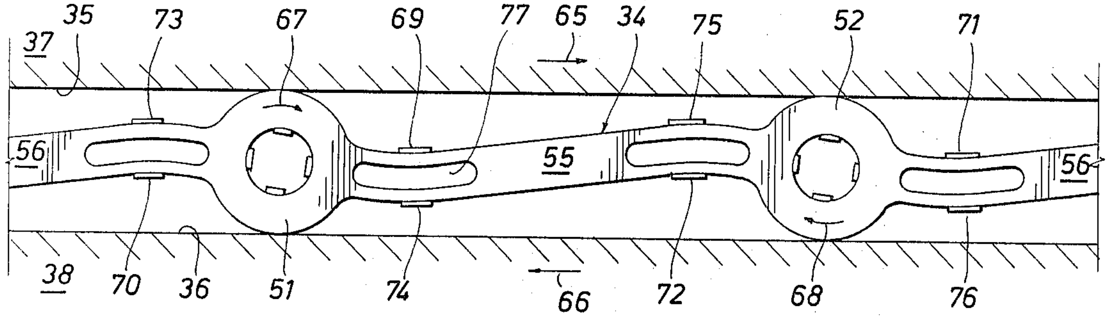


FIG. 4B



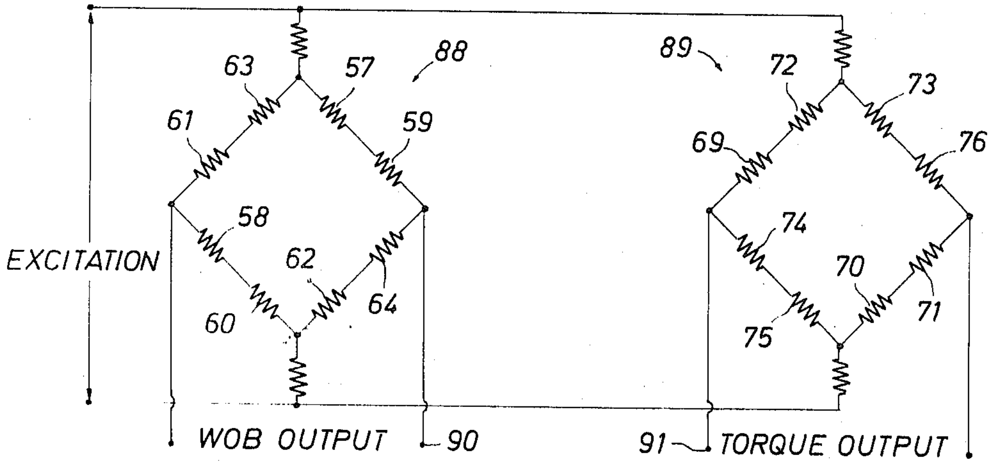


FIG. 5

WELL BORE FORCE-MEASURING APPARATUS

Those skilled in the art will, of course, appreciate that it is of great value to know the axial load as well as the applied torque on the drill bit during the drilling of a well. In addition to being useful in controlling the direction or inclination of the borehole as it is being drilled, such measurements are also of great significance in achieving the most efficient and economical drilling program for that well. For example, it is a common practice to pre-schedule the drilling program for a given well so that the most efficient drilling speeds, bit loads, and drill bits will be used for drilling each of the several formation intervals which are expected to be encountered before the borehole reaches its specified depth. Accordingly, it is widely recognized that knowledge with a fair degree of precision of the actual weight-on-bit and bit torque at any given time during a typical drilling operation is of great value in optimizing the operation.

Heretofore, many long-standing techniques have been employed for either estimating or empirically measuring the bit torque and weight-on-bit from the surface. Those skilled in the art will, of course, recognize that any surface measurements which of necessity must be extrapolated to derive an assumed bit torque or weight-on-bit are subject to many potential errors such as those, for example, which arise from such factors as the friction of the drill string against the borehole wall. In more recent years, however, various systems have been proposed for periodically transmitting one or more measurements of various downhole conditions to the surface during the drilling of the borehole. For example, systems such as those shown in U.S. Pat. No. 3,736,558 as well as U.S. Pat. No. 3,764,970, illustrate two of the more-promising downhole signaling systems of current interest which are selectively arranged for developing encoded acoustic data signals which are transmitted to the surface through the circulating mud stream in the drill string.

To obtain measurements representative of the actual weight-on-bit load as well as the bit torque, various measuring devices have been proposed for use with such signaling systems. One of the more common of these devices employs an array of suitable strain gages mounted on one of the several drill collars which are typically connected in the drill string immediately above the drill bit. Suitable circuitry is provided for converting these measurements as required to operate a downhole signaling device arranged in the drill collar. Those skilled in the art will recognize, however, that such arrangements are essentially so insensitive that only major changes in the load conditions will be detected at the surface. Quite simply, the problem is that with the typical heavy-walled drill collars used in present day drilling operations, the amount of deformation experienced thereby in response to changes in torsional or axial loadings are so minute that even the most sophisticated strain gages will simply fail to adequately respond.

To counter these major disadvantages, various proposals have been made for increasing the output response of such strain gages. For example, as shown in FIG. 3 of U.S. Pat. No. 2,422,806, a conventional force-responsive transducer is mounted on an upright post and this assembly is mounted between two opposed shoulders defined by a shallow recess in the drill collar wall to provide output signals representative of the deformations of the slightly-reduced wall section. Although this arrangement offers slightly more sensitivity, the degree of deformation in this wall section which might ordinarily occur during a typical drilling operation is nevertheless so extremely small that the resulting output measurements are still somewhat insensitive to anything short of significant changes in the load conditions on the drill bit.

An alternative proposal is found in U.S. Pat. No. 3,686,942 in which an independent load-bearing member carrying an array of strain gages is cooperatively telescoped within a stronger load-bearing member and arranged to carry all of the axial and torsional loads acting on the drill bit so long as these loads remain within a predetermined range which is well within the useful strength of the weaker transducer-bearing member. Should, however, the loads on the drill bit exceed the maximum design capabilities of the transducer-bearing member, the weaker load-carrying member will be moved into engagement with a cooperative shoulder on the stronger load-carrying member so that the entire load will thereafter be imposed on this paralleling member thereby relieving the weaker member of these potentially-damaging loads. Although this particular arrangement offers many advantages not found heretofore, those skilled in the art will recognize, nevertheless, that since this transducerbearing member must still be capable of supporting significant axial or torsional loads, the strain gages will still be rélatively insensitive to minor load changes.

Accordingly, it is an object of the present invention to provide new and improved apparatus for reliably providing accurate surface measurements of even minor axial or torsional loads which may act on a drill bit during the course of a drilling operation.

This and other objects of the present invention are attained by arranging a force-responsive member having a spaced pair of deformable rings which are joined together by at least one deformable member and clamping the opposite edges of these rings between opposed shoulders on a tubular load-bearing body adapted for coupling in a drill string. Force-responsive transducer means are cooperatively mounted on the force-responsive member. In this manner, upon application of either axial or torsional loads on the load-bearing body, even minute load-inducted deformations of the load-bearing body will induce proprotional deformations in the force-responsive member for producing greatly-increased transducer signals representative of strain for transmission by a signaling system to the surface.

The novel features of the present invention are set forth with particularity in the appended claims. The invention, together with further objects and advantages thereof, may be best understood by way of the following description of exemplary appparatus employing the principles of the present invention as illustrated in the accompanying drawings, in which:

FIG. 1 shows a new and improved well tool arranged in accordance with the present invention as it will appear while coupled in a drill string during the course of a typical drilling operation;

FIG. 2 depicts a preferred embodiment of the force-measuring apparatus employed with the well tool shown in FIG. 1;

FIG. 3 is an isometric view of a preferred embodiment of the force-responsive element used in the new and improved force-measuring apparatus shown in FIG. 2;

FIGS. 4A and 4B are developed views of the force-responsive element of FIG. 3 respectively illustrating its operation in the absence of torsion and under torsional loads; and

FIG. 5 depicts a preferred embodiment of electrical circuitry employed in the tool of the present invention.

Turning now to FIG. 1, a new and improved force-measuring well tool 10 arranged in accordance with the present invention is depicted coupled to the lower end of a typical drill string 11 made up of a plurality of pipe joints 12 and one or more drill collars 13 and having a rotary drill bit 14 dependently coupled thereto for excavating a borehole 15 through various earth formations as at 16. As the drill string 11 is rotated by a typical drilling rig (not shown) at the surface, substantial volumes of the drilling fluid or so-called "mud" are continuously pumped downwardly through the tubular drill string and the tool 10 and discharged from the drill bit 14 for cooling the bit as well as carrying borings removed by the bit to the surface as the mud is returned upwardly along the borehole 15 exterior of the drill string. As is typical, the mud stream is circulated by employing one or more high-pressure mud pumps (not shown) which continuously draw the fluid from a storage pit or surface vessel (not shown) for subsequent recirculation by the mud pumps. It will be appreciated, therefore, that the circulating mud stream flowing through the drill string 11 serves as a transmission medium that is well suited for transmitting acoustic signals to the surface at the speed of sound in the particular drilling fluid.

In accordance with the principles of the present invention, the new and improved force-measuring well tool 10 includes force-responsive means, as at 17, preferably arranged in the drill string 11 just above the bit 14 and electrically coupled to appropriate measurement encoder means 18 operatively arranged on the tool for producing a series of electrical coded data signals that are representative of the forces being imposed on the drill bit. If desired, the new and improved tool 10 can also include one or more condition-responsive devices, as at 19 and 20, cooperatively arranged on the tool for measuring such other downhole conditions as the pressure, the temperature, or the resistivity or conductivity of either the drilling mud or the adjacent earth formations as well as various formation conditions or characteristics which are typically obtained by various commercial logging tools. These condition-measuring devices 19 and 20 are also cooperatively coupled to the measurement encoder 18 for independently producing electrical signals that are each representative of the particular downhole conditions or formation properties which are being measured. It will be understood, of course, that the measurement encoder 18 will be cooperatively arranged so as to sequentially obtain each of the several desired measurements for independently transmitting a representative encoded signal to the surface. Although a self-contained battery or power supply can be employed, as shown at 21 it is preferred to employ a reaction-type turbine driving a generator for utilizing the circulating mud stream passing through the tool 10 as a motivating source to generate electrical power for operation of the tool.

The preferred embodiment of the new and improved tool 10 further includes acoustic-signaling means 22 such as explained in greater detail in U.S. Pat. No. 3,764,970, incorporated by reference herein and having an electrical motor 23 coupled by control circuitry 24 to the encoder 18 and operatively arranged to respond to its coded output signals for rotatively driving an acoustic signaler 25 by way of a typical gear train 26 to successively interrupt or obstruct the flow of the drilling fluid through the drill string 11. The resulting acoustic signals produced by the acoustic signaler 25 will be successively transmitted to the surface through the mud stream flowing within the drill string 11 as sequential encoded data signals indicative of the force measurements provided by the force-responsive means 17 as well as the one or more downhole conditions or formation characteristics respectively sensed by the condition-measuring devices 19 and 20. As these acoustic data signals are successively transmitted to the surface, they are detected and converted into meaningful indications or records by suitable acoustic signal detecting and recording apparatus 27 such as disclosed in either U.S. Pat. No. 3,309,656, U.S. Pat. No. 3,488,629, U.S. Pat. No. 3,555,504, or U.S. Pat. No. 3,716,830 or U.S. Pat. No. 3,747,059, each of which are incorporated by reference herein. It will, of course, be further recognized that the acoustic signaler 25 could also just as well be the signaler described in either U.S. Pat. No. 3,764,968 or U.S. Pat. No. 3,764,969, and are each incorporated by reference herein. Similarly, the acoustic-signaling means 22 could be any of the new and improved downhole signaling means described in either U.S. Pat. No. 3,309,656, U.S. Pat. No. 3,711,825, U.S. Pat. No. 3,713,089 or U.S. Pat. No. 3,763,558, each of which are incorporated by reference herein.

Turning now to FIG. 2, a cross-sectional elevational view is shown of a preferred embodiment of the force-responsive means 17 of the new and improved force-measuring tool 10. As seen there, the force-responsive means 17 preferably include a thick-walled tubular sub or body 28 which is cooperatively arranged in a typical manner with appropriate end connections, as at 29 and 30, to allow the sub to be tandemly coupled at a desired location in the drill string 11. The sub 28 includes an axial fluid passage 31 for conducting the drilling fluid flowing through the drill string 11 to the drill bit 14 therebelow. For convenience of design, in the preferred embodiment of the force-responsive means 17, the tubular body 28 is arranged to have an external diameter substantially equal to the external diameter of the adjacent body 13, of the tool 10 and the internal bore 31 of the tubular sub is moderately enlarged, as at 32, so as to leave a reduced-thickness central wall portion, as at 33, of sufficient thickness and strength to withstand the rigorous loads normally experienced during the drilling of a typical well bore.

In the preferred embodiment of the new and improved force responsive means 17, a loop-like load-responsive member or circular band 34 such as the one to be subsequently described by reference to FIG. 3 is coaxially disposed in the enlarged body cavity 32 with its opposite edges compressively retained between and frictionally engaged with opposed shoulders 35 and 36 respectively formed around upper and lower sleeve members 37 and 38 coaxially mounted in the internal bore 31 of the body 28. Although other arrangements within the purview of the present invention could just as well be employed, it is preferred to releasably secure the load-bearing sleeves 37 and 38 to the tubular body 28 in such a manner that a selectively-adjustable compressive load can be initially imposed on the load-responsive element 34.

Accordingly, as illustrated in FIG. 2, the upper end of the upper sleeve 37 is firmly abutted against a downwardly-facing shoulder 39 formed in the internal bore 31 of the body 28 just above the enlarged cavity 32. To be certain that the upper sleeve 37 is tightly secured to the body 28 for transmitting downwardly-acting axial or compressive loads as well as torque from the upper portion of the body to the top edge of the load-responsive loop element 34, the upper end of the sleeve is inwardly enlarged, as at 40, and adapted for engagement between the body shoulder 39 and an upwardly-facing outwardly-enlarged shoulder 41 arranged on an annular retainer member 42 which is threadedly secured, as by threads 43, within the internal bore 31 above the enlarged body cavity 32. It will be appreciated, therefore, that by virtue of this arrangement, the retainer 42 can be readily adjusted as required to effectively secure the upper end of the upper sleeve 37 tightly to the sub body 28 without otherwise having to force the sleeve longitudinally into a desired position by imposing a compressive load onto the sleeve through the load-responsive element 34. The significance of this will subsequently be explained.

The lower sleeve 38 is similarly arranged so that it may be adjustably secured tightly to the lower portion of the sub body 28 without imposing an unwanted load onto the load-responsive element 34. To accomplish this, the lower end of the lower sleeve 38 is outwardly enlarged, as at 44, for engagement with a downwardly-facing companion shoulder 45 on the body 28 just below the enlarged body cavity 32. An adjusting nut or annular retainer 46 is threadedly secured, as by threads 47, within the internal bore 31 below the enlarged cavity 32 in the sub body 28. Although a locking or jam nut could just as well be employed, it is preferred to arrange a depending lug 48 on the threaded retainer 46 and have a set screw 49 in the lug adapted to be laterally moved into engagement with the internal wall of the body 28 once the lower retainer is properly positioned.

It should be noted at this point that in the preferred embodiment of the force-measuring sub 17 shown in FIG. 2, the upper retainer 42 is cooperatively arranged to tightly engage the upper sleeve 37 against the body 28 as required without imposing any load on the load-responsive element 34. On the other hand, once the upper sleeve 37 is locked into engagement with the body shoulder 39 and the load-responsive element 34 is in position, movement of the lower sleeve 38 into engagement with the body shoulder 44 will tend to compress the load-responsive element. Although it is necessary to compressively load the load-responsive element 34 for securing it against slippage or circumferential movement in relation to the upper and lower sleeves 37 and 38, it is often desired to urge the lower sleeve against its mating body shoulder 45 with more compressive force than is desired to impose on the load-responsive loop element. Accordingly, to allow for such differences, it is often found that by placing one or more flat washers or shims, as at 50, of various selected thicknesses between the outwardly-enlarged sleeve end 44 and the body shoulder 45, the lower retainer 46 can be adjusted so as to adequately clamp the load-responsive element 34 between the two sleeve shoulders 35 and 36 and still urge the lower sleeve 38 and the shim or shims against the body shoulder 45 with sufficient force to secure the lower sleeve against turning with relation to the body 28.

It will be recognized, of course, that as compressive forces are axially applied on the tubular body 28, its overall length will be proportionally shortened in direct relation to the magnitude of the full compressive load. Thus, inasmuch as the thin loop-like element 34 is rigidly clamped at its upper and lower edges to the sleeves 37 and 38 and, by way of the sleeves, to the upper and lower portions of the tubular body 28, any axial deformation of the body will be correspondingly transferred directly to the load-responsive element. In other words, if a given axial load is sufficient to shorten the tubular body 28 by 0.1-inch, for example, the thin-walled loop 34 must also be longitudinally shortened or compressed by 0.1-inch since the large or major portion of any axial deformation acting on the sleeves 37 and 38 will be accommodated by or concentrated on the load-responsive element. Thus, for a given axial force and the resulting longitudinal deformation of the load-bearing tubular body 28, most of the corresponding deformation which must take place between the opposed shoulders 35 and 36 of the upper and lower sleeves 37 and 38 will be concentrated in the relatively short vertical height of the load-responsive element 34. Simple mathematical analysis will, of course, show that the amount of deformation which will be experienced by the thin load-responsive element 34 will be proportional to the ratio of the stiffness of the upper and lower sleeves 37 and 38 to the stiffness of the thinner load-responsive sleeve or loop.

Those skilled in the art will appreciate, of course, that a substantial deformation will be experienced by this thin load-responsive element 34 even under relatively minor axial loads on the tubular body 28 causing only a very minor deformation which must be distributed uniformly along the full length of the tubular body. It may be said, therefore, that this unique arrangement provides a significant amplification of the amount of strain which will be experienced by the thin load-responsive element 34 in comparison to the strain imposed on the body wall 33 thereby causing a much greater sensitivity to longitudinal deformation or movement at this location than will be realized at any other portion of the new and improved force-measuring sub 17. Accordingly, for measuring axial loads on the drill bit 14, as will be subsequently explained, force-responsive transducer means such as a plurality of typical strain gages (not shown in FIG. 2) are mounted at selected locations on the force-responsive element 34 for providing significant output signals in response to even minor axial deformations of the load-bearing sub 17.

Turning now to FIG. 3, an isometric view is shown of a preferred embodiment of the load-responsive element 34. As illustrated, the load-responsive element 34 is preferably formed as an integral band or thin-walled loop of a suitable metal having a pair of generally-circular enlargements 51 and 52 which are perforated, as at 53 and 54, and spaced 180° apart and joined to one another by deformable links such as a pair of semicircular or curved strips **53** and **54** having a width or vertical height somewhat less than the outside diameter of the annular enlargements. By comparing FIGS. **2** and **3** it will, of course, be recognized that it is only the upper and lower tangential points on each edge of the enlarged annular portions **55** and **56** of the load-responsive element **34** which are respectively in contact with the opposed shoulders **35** and **36** on the upper and lower sleeves **37** and **38.** Thus, whenever an axial compressive load is imposed on the tubular body **28,** there will be a proportional load acting on the enlarged annular portions **51** and **52** tending to compress or flatten them.

It will, of course, be appreciated that vertical compressive loads on the enlarged annular portions **51** and **52** will develop proportional tensile stresses or strains on the fibers immediately adjacent to the top and bottom surfaces of each hole **53** and **54.** It will be further recognized that there will be proportional compressive stresses or strains on the fibers immediately adjacent to the side surfaces of the holes **53** and **54** in each annular portion **51** and **52.** Accordingly, in keeping with the objects of the present invention in the preferred embodiment of this invention, tension-responsive strain gages, as at **57–60** in FIG. 4A, are respectively secured at the top and bottom of the holes **53** and **54** in the enlarged portions **51** and **52** and compression-responsive strain gages, as at **61–64,** are respectively secured at the sides of these holes. Thus, each of these several strain gages **57–64** will respectively exhibit a changing or varying electrical characteristic such as resistance which will be proportional to the axial load acting on the force-responsive element **34.** It will, of course, be recognized that all of the strain gages **57–64** will uniformly respond to deformations caused by thermal conditions and other extrinsic forces not related to the axial loads on the drill string **11.** Thus, to compensate for these extrinsic forces, the strain gages **57**– **64** are arranged in an electrical bridge that will subsequently be discussed by reference to FIG. **5.**

Particular recognition should be given to the significant amplification of strain or stress provided by the unique arrangement of the force-responsive element **34.** In addition to the strain amplification previously discussed in relation to the ratio of the strain in the load-responsive member **34** to that in the body wall **33,** the geometry of the rings or annular portions **51** and **52** as such provides a significant additional strain amplification. Considering first of all the stress or strain acting on fibers at the upper and lower surfaces of the holes **53** and **54,** it will be recognized that these surfaces will be subjected to a substantial tensile stress or strain as a compressive load on the tool body **28** tends to flatten the rings **51** and **52.** Similarly, it can also be demonstrated that the fibers along the sides of the holes **53** and **54** will be subjected to a substantial compressive strain in response to a compressive load tending to flatten the rings **51** and **52.** Thus, a still further strain amplification is provided by the new and improved force-responsive element **34** when the tool **10** is subjected to an axial compressive load.

As previously mentioned, it is also of considerable importance to know the actual torque being applied to the drill bit **14** during the course of a typical drilling operation. It will be recognized, therefore, that when the drill bit **14** is set on the bottom of the borehole **15** and a torsional force is applied to the drill string **11,** the upper portion of the body **28** above its enlarged cavity **32** will be angularly advanced or twisted about the longitudinal axis of the body so as to move the upper body portion in relation to the lower portion of the body below the cavity through an angle that is proportional to the magnitude of the applied torque. Thus, since the sleeves **37** and **38** are tightly engaged with the body **28,** the upper sleeve will tend to rotate in relation to the lower sleeve as torque is applied through the drill string **11** and the tool **10** to the drill bit **14.**

As illustrated in the exaggerated developed view in FIG. 4B, therfore, torque will cause the upper sleeve shoulder **35** to be moved in relation to the lower sleeve shoulder **36** as represented by the arrows **65** and **66.** Accordingly, as shown by the arrows **67** and **68,** this relative angular movement between the upper and lower sleeves **37** and **38** caused by torsional loads will tend to roll each of the enlarged annular portions **51** and **52** respectively about an axis perpendicular to and passing through the center of each of the holes **53** and **54.** The extent of this rotation will, of course, be directly related to torque. This tendency of the enlarged portions **51** and **52** to roll will, however, be resisted by their interlinking strips **55** and **56** so that these strips will be distorted in a manner similar to that illustrated in the exaggerated developed view of the force-responsive element **34** shown in FIG. **4B.** Thus, it is preferred to make the links **55** and **56** relatively flexible so that they will readily deflect and impose only a minimum restraint on the rotation of the rings **52** and **53.** It will be recognized, of course, that any resistance to rotation of the rings **52** and **53** will impose counteracting stresses which will be undesirably sensed by the transducers **57–64.**

Various techniques may be provided for relating the rotation of the rings **52** and **53** to the magnitude of the torque on the drill string **11** causing this rotation. However, those skilled in the art will appreciate that the magnitude of the deflection or distortion of the strips or links **55** and **56** is directly related to the magnitude of any torsional forces and that this deflection of the strips will be most pronounced at about their respective "one-quarter" and "three-quarter" points. Moreover, in keeping with accepted strain analysis techniques, where, for example, the rotation of the drill string **11** results in a downward bowing at the "one-quarter" point and an upward bowing at the "three-quarter" point of the interlinking strips **55** and **56,** the fibers lying along the convex edges of each bulge will be proportionally tensioned and the fibers running along the concave edges of each bulge will be proportionally compressed. The opposite result would, of course, occur should the usual rotation of the bit **14** be in the opposite direction.

Accordingly, to measure these compressive forces for the usual direction of bit rotation, one or more compression-responsive strain gages, as at **69–72,** are respectively placed on the appropriate edges of the interlinking strips **55** and **56** at about their respective one-quarter and three-quarter points. Similarly, one or more typical tension-responsive strain gages, as at **73–76,** are respectively mounted on the upper and lower edges of the interlinking strips **55** and **56** opposite each of the compression-responsive gages **69–72.** Thus, upon application of torque to the drill string **11,** those of the tension-responsive strain gages **73–76** which are subjected to tensile forces will exhibit a corresponding change in their respective electrical characteristic which is proportional to the deflection of the strips **55** and **56** and, therefore, to the amount of torque. In a like manner, the characteristic of the compression-responsive strain gages **69–72** will also change in proportion to the torque. It should be noted in passing that by drilling either a reduced-diameter hole or elongated slots, as at **77**, in the strips **55** and **56** at about their respective one-quarter and three-quarter points, the resistance to deflection of these strips at these points will be greatly reduced and the strain in those portions of the strips adjacent to these slots will be greatly accentuated so as to provide an amplified output from the transducers **69–76.** In this manner, the output signals provided by the torque-responsive strain gages **69–76** will be greatly increased over what would otherwise be provided if it were not for the particular unique arrangement of the present invention.

The various devices used heretofore for measuring torque and weight-on-bit have typically either ignored or taken less than adequate measures for limiting or avoiding the effects of pressure differentials which must otherwise affect the accuracy of the force measurements. Those skilled in the art will, of course, appreciate that there is normally a substantial pressure differential between the drilling fluid flowing through the drill string **11** and the fluid in the borehole **15** exterior of the drill string. Where there are downhole signaling devices such as those previously described herein for transmitting acoustic signals to the surface, the additional pressure pulses produced by these signaling devices will also increase the pressure differential acting across the force-measuring tool **10.** Thus, if no preventative measures are taken for protecting or isolating the force-responsive element **34,** an increased pressure in the longitudinal bore **31** will tend to circumferentially enlarge as well as elongate the tubular body **28** and thereby impose a corresponding deformation on the force-responsive element.

Accordingly, to at least minimize this unwanted deformation, as shown in FIG. **2** a thick-walled tube **78** is coaxially extended between the upper retainer member and the lower sleeve and slidably fitted within each member so as to not be compressively loaded as the sleeves **37** and **38** and the retainer members **42** and **46** are being positioned during the assembly of the force-responsive sub **17.** A fluid seal, as at **79,** is mounted around the tube **78** so as to fluidly seal its upper end in relation to the upper retainer **42.** Fluid seals, as at **80** and **81,** are also arranged to fluidly seal the upper sleeve **37** in relation to the upper retainer **42** and to the upper portion of the body **28.** Since it is necessary to seal the lower sleeve **38** in relation to only the lower portion of the body **28,** a single seal, as at **82,** is sufficient to achieve the objects of the present invention.

The lower sleeve **38** is extended, as at **83,** so as to be telescopically fitted within the upper sleeve **37** and thereby define an annular space **84** between the sleeves and the elongated tube **78.** To maintain the body cavity **32** at a pressure which will sufficiently minimize elongation and circumferential expansion of the tubular body **28** due to pressure differentials, the cavity is filled with a suitable hydraulic fluid, such as oil, and pressure-balancing means, such as an annular piston **85** mounted in the annular space **84** and coupled by a passage **86** in the tube **78,** are provided for communicating the pressure of the drilling mud flowing through the internal bore **31** to the body cavity. To allow the oil filling the upper end of the annular space **84** above the piston **85** to communicate with the body cavity **32,** one or more ports **87** are formed in the upper sleeve **37.** In this manner, it will be appreciated that the oil filling the upper end of the annular space **84** and the body cavity **32** will be maintained at a pressure equal to that of the drilling fluid flowing through the longitudinal bore **31.**

It will, of course, be recognized that various types of electrical circuits may be arranged to measure the respective changes in the electrical characteristics of the several transducers **57–64** and **69–76.** However, as shown in FIG. **5,** in the preferred embodiment of the present invention, it is preferred to arrange these transducers **57–64** and **69–76** into two typical bridge circuits as shown generally at **88** and **89.** It will be appreciated, therefore, from a comparison of FIG. **5** with FIGS. **4A** and **4B** that the bridge circuits **88** and **89** are arranged to produce separate output signals at **90** and **91** which are respectively representative of the applied axial loads on the body **28** as well as the torque applied thereto.

Since the bridge circuit **88** is typical and is well known to those skilled in the art, it is believed necessary only to point out that the weight-responsive strain gages **57–64** comprising this bridge are arranged in an additive fashion for providing a maximum output in response to deformation of the load-responsive element **34** caused by direct or actual axial loads on the body **28.** Similarly, as various ones of the torque-responsive transducers **69–76** change in response to changes in the torsional loads on the body **28,** a correspondingly enhanced output signal will be produced at the output **91** of the bridge circuit **89.**

Accordingly, it will be appreciated that the new and improved force-measuring tool **10** of the present invention is particularly responsive to both axial and torsional forces for producing much-greater output signals than has been possible heretofore. By arranging the force-responsive element **34** to be particularly susceptible to pronounced or magnified deformation at the very location of the several strain-measuring devices **57–64** and **69–76,** the typically-low outputs of these devices will be greatly accentuated so as to provide a much wider proportional band or response than would otherwise be possible. Moreover, by arranging the force-responsive element **34** as previously described, there is no concern that this weak force-responsive element will be damaged by even extreme axial or torsional loads. Additionally, by arranging the force-measuring sub **17** to be pressure balanced, the effects of changes in temperature or pressure that would otherwise tend to limit the reliability and accuracy of the force measurements are significantly minimized.

While only a particular embodiment of the present invention has been shown and described, it is apparent that changes and modifications may be made without departing from this invention in its broader aspects; and, therefore, the aim in the appended claims is to cover all such changes and modifications as fall within the true spirit and scope of this invention.

What is claimed is:

1. Apparatus adapted for measuring downhole load conditions while drilling a borehole and comprising:

a drill string having a borehole-drilling device dependently coupled to the lower end thereof and defining a fluid passage for circulating drilling fluids between the surface end of said drill string and said borehole-drilling device;

a deformable load-responsive member having upper and lower portions respectively secured between longitudinally-spaced portions of said drill string and an unrestrained intermediate portion adapted to deform in response to increases and decreases in axial loads imposed on said drill bit tending to move said spaced drill string portions longitudinally in relation to one another and to tilt in relation to a normal upright position in response to torsional loads imposed on said drill bit tending to move said spaced drill string portions angularly in relation to one another;

first transducer means coupled to said load-responsive member and having a measurable characteristic adapted to vary in response to deformation of said load-responsive member occurring upon relative longitudinal movement between said spaced drill string portions;

torque-responsive means including second transducer means coupled to said load-responsive member and having a measurable characteristic adapted to vary in response to tilting movements of said load-responsive member away from its said normal position occurring upon relative angular movement between said spaced drill string portions;

acoustic-signaling means on said drill string operatively coupled to said first and second transducer means and cooperatively arranged for producing acoustic signals in drilling fluids flowing through said drill string representative of variations in said measurable characteristics; and

acoustic signal-detecting means operatively coupled to said surface end of said drill string and cooperatively arranged for detecting said acoustic signals.

2. The load-measuring apparatus of claim **1** wherein at least one of said measurable characteristics is an electrical property; and said first tranducer means include at least one strain gage mounted on said intermediate porion of said load-responsive member and exhibiting a varying range of said electrical property in response to strain variations occurring upon the deformation of said load-responsive member which are representative of the axial loads on said drill bit.

3. The load-measuring apparatus of claim **2** wherein said torque-responsive means include a deformable member projecting laterally from said intermediate portion of said load-responsive member and cooperatively arranged to deform in response to tilting movements of said load-responsive member, and said second transducer means include at least one strain gage mounted on said lateral member and exhibiting a varying range of said electrical property in response to strain variations occurring upon the deformation of said lateral member which are representative of the torsional loads on said drill bit.

4. The load-measuring apparatus of claim **1** wherein said load-responsive member is interior of said drill string; and further including:

a sleeve member cooperatively arranged within said load-responsive meber and having upper and lower end portions respectively extending above and below said load-responsive member to said spaced portions of said drill string;

first and second means respectively arranged between said upper and lower end portions of said sleeve member and said spaced portions of said drill string for defining an enclosed chamber around said load-responsive member; and

pressure-regulating means cooperatively arranged on said drill string and adapted for maintaining said enclosed chamber at an elevated pressure about equal to the pressure of drilling fluids flowing through said drill string.

5. Apparatus adapted for measuring downhole load conditions while drilling a borehole and comprising:

a multi-sectional drill string having a borehole-drilling device dependently coupled to the lower end thereof and defining a fluid passage for circulating drilling fluids between the surface end of said drill string and said borehole-drilling device;

a tubular load-bearing body tandemly coupled between one of said drill string sections and said drill bit and having a longitudinal bore for conducting drilling fluids between said drill string sections and said drill bit;

a load-responsive member having axially-spaced opposite portions respectively secured between longitudinally-spaced portions of said load-bearing body for normally maintaining said load-responsive member in an upright position and an unrestrained non-linear intermediate portion cooperatively arranged to deflect in response to axial loads imposed on said drill bit through said load-bearing body tending to move one of said spaced body portions longitudinally in relation to the other of said spaced body portions as well as to shift away from said upright position in response to torsional loads imposed on said drill bit through said load-bearing body tending to move one of said spaced body portions angularly in relation to the other of said spaced body portions;

first means coupled to said intermediate portion of said load-responsive member and cooperatively arranged for providing a first output signal proportional to deflections of said intermediate portion of said load-responsive member occurring upon relative longitudinal movement between said spaced body portions caused by application of an axial load on said drill bit;

second means coupled to said intermediate portion of said load-responsive member and cooperatively arranged for providing a second output signal proportional to the extent of movement of said load-responsive member away from its said upright position occurring upon relative angular movements between said spaced body portions caused by application of torque on said drill bit; intermediate proportional

acoustic-signaling means on said drill string operatively coupled to said first and second means and cooperatively arranged for producing first and second acoustic signals in drilling fluids flowing through said drill string representative of said first and second output signals;

acoustic signal-detecting means operatively coupled to said surface end of said drill string and cooperatively arranged for detecting said first and second acoustic signals to provide surface indications of axial and torsional loads imposed on said drill bit through said drill string.

6. The load-measuring apparatus of claim 5 wherein said load-responsive member is interior of said load-bearing body.

7. The load-measuring apparatus of claim 6 further including:

a sleeve member cooperatively arranged within said load-responsive member;

first and second means respectively arranged between the upper and lower end portions of said sleeve member and said load-bearing body above and below said load-responsive member for defining an enclosed chamber therearound; and

pressure-equalizing means on said load-bearing body and cooperatively arranged for maintaining said enclosed chamber at an elevated pressure at least about equal to the pressure of drilling fluids flowing through said longitudinal bore.

8. The load-sensing apparatus of claim 5 wherein said second means include a laterally-oriented deformable member secured between said load-bearing body and said intermediate portion of said load-responsive member and cooperatively arranged to deform upon movement of said load-responsive member away from its said upright position, and transducer means including at least one strain gage cooperatively arranged on said deformable member and exhibiting a variable electrical characteristic which is proportional to the strain developed in said deformable member by deformation thereof upon application of torque to said drill bit.

9. The load-sensing apparatus of claim 5 wherein said intermediate portion of said load-responsive member is symmetrically curved away from an axis passing through said axially-spaced portions of said load-responsive member for producing a concentrated strain at about the mid-point of said intermediate portion upon deflection thereof; and said first means include at least one strain gage mounted on about said mid-point of said intermeidate portion and exhibiting a variable electrical characteristic which is proportortional to the strain developed in said mid-point of said intermediate portion n upon application of an axial load on said drill bit.

10. The load-sensing apparatus of claim 9 wherein said second means include a laterally-deformable member secured between said load-bearing body and said intermediate portion of said load-responsive member and cooperatively arranged to deform upon movement of said load-responsive member away from its said upright position, and transducer means including at least a second strain gage cooperatively arranged on said deformable member and exhibiting a variable electrical characteristic which is proportional to the strain developed in said deformable member by deformation thereof upon application of torque to said drill bit.

11. Apparatus adapted for measuring downhole load conditions while drilling a borehole and comprising:

a multi-sectional drill string having a borehole-drilling device dependently coupled to the lower end thereof and defining a fluid passage for circulating drilling fluids between the surface end of said drill string and said borehole-drilling device;

a tubular load-bearing body tandemly coupled between said drill bit and one of said drill string sections and having a longitudinal bore for conducting drilling fluids between said one drill string section and said drill bit;

load-responsive means cooperatively arranged between upper and lower portions of said load-bearing body and adapted for selectively responding to compressional loads imposed on said drill bit through said load-bearing body tending to move said upper and lower body portions longitudinally in relation to one another and to torsional loads imposed on said drill bit through said load-bearing body tending to turn said upper and lower body portions angularly in relation to one another, said load-responsive means including a deformable loop coaxially arranged around an intermediate portion of said load-bearing body and divided into at least a first substantially-rounded compressible segment and at least a first elongated strip-like bendable segment having one end coupled to one side of said first rounded segment and extending laterally therefrom around said intermediate body portion, first and second means respectively securing the upper and lower edges of said first rounded segment to said upper and lower body portions for alternatively compressing said first rounded segment upon longitudinal movement of said upper and lower body portions toward one another and rolling said first rounded segment to an inclined position upon relative angular movement between said upper and lower body portions so as to correspondingly bend said first strip-like segment;

first electrical transducer means cooperatively arranged on at least said first rounded segment and adapted for exhibiting a varying first electrical characteristic proportional to the magnitude of compressional forces applied to said first rounded segment upon application of an axial load through said load-bearing body onto said drill bit;

second electrical transducer means cooperatively arranged on at least said first strip-like segment and adapted for exhibiting a varying second electrical characteristic proportional to the magnitude of the turning forces applied to said first rounded segment upon application of a torsional load through said load-bearing body onto said drill bit;

acoustic-signaling means on said drill string operatively coupled to said first and second transducer means and cooperatively arranged for producing first and second acoustic signals in drilling fluids flowing through said drill string respectively representative of the variations in said first and second electrical characteristics; and

acoustic signal-detecting means operatively coupled to said surface end of said drill string and cooperatively arranged for detecting said first and second acoustic signals to provide surface indications of the axial and torsional loads imposed on said drill bit through said drill string.

12. The load-measuring apparatus of claim 11 wherein said deformable loop is interior of said load-bearing body.

13. The load-measuring apparatus of claim 12 further including:

a sleeve member cooperatively arranged within said deformable loop and having upper and lower end portions extending above and below said deformable loop;

means cooperative with said upper and lower end portions of said sleeve member for defining an enclosed chamber around said deformable loop; and

pressure-equalizing means on said load-bearing body and cooperatively arranged for maintaining said enclosed chamber at an elevated pressure at least about equal to the pressure of drilling fluids in said longitudinal bore.

14. The load-measuring apparatus of claim **11** wherein said first rounded segment is annular so that compressional forces imposed thereon will develop enhanced strains at selected positions thereon; and said first transducer means include at least one strain gage mounted on one of said selected positions and cooperatively arranged for responding to such enhanced strains.

15. The load-measuring apparatus of claim **11** wherein the other end of said first strip-like segment is secured against vertical movement so that torsional forces imposed on said first rounded segment tending to tilt said first strip-like segment will develop enhanced strains at selected positions thereon; and said second transducer means include at least one strain gage mounted on one of said selected positions and coooperatively arranged for responding to such enhanced strains.

16. The load-measuring apparatus of claim **11** wherein said deformable loop further includes a second substantially-rounded compressible segment circumferentially spaced from said first rounded segment and having one side coupled to the other end of said first strip-like segment, and a second elongated strip-like bendable segment coupled between the other sides of each of said first and second rounded segments.

17. The load-measuring apparatus of claim **16** wherein said first and second rounded segments are on opposite sides of said intermediate body portion.

18. The load-measuring apparatus of claim **16** wherein said first and second rounded segments are annular so that compressional forces imposed thereon will develop enhanced strains at selected positions on each of said rounded segments; and said first transducer means include a strain gage mounted on each of said selected positions and cooperatively arranged for responding to such enhanced strains upon application of axial loads through said load-bearing body onto said drill bit.

19. The load-measuring apparatus of claim **18** wherein said second transducer means include at least one strain gage mounted on each of said strip-like segments at a position thereon expected to experience maximum distortion and, therefore, enhanced strains upon application of torsional loads through said load-bearing body onto said drill bit.

20. The load-measuring apparatus of claim **11** wherein at least one of said first and second means respectively securing said upper and lower edges of said first rounded segment include a sleeve member defining a shoulder adapted to be securely engaged with one of said upper and lower edges, and sleeve-positioning means cooperatively arranged for securing said sleeve member to said load-bearing body in a selected position for securely engaging said sleeve shoulder with said one edge of said first rounded segment.

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