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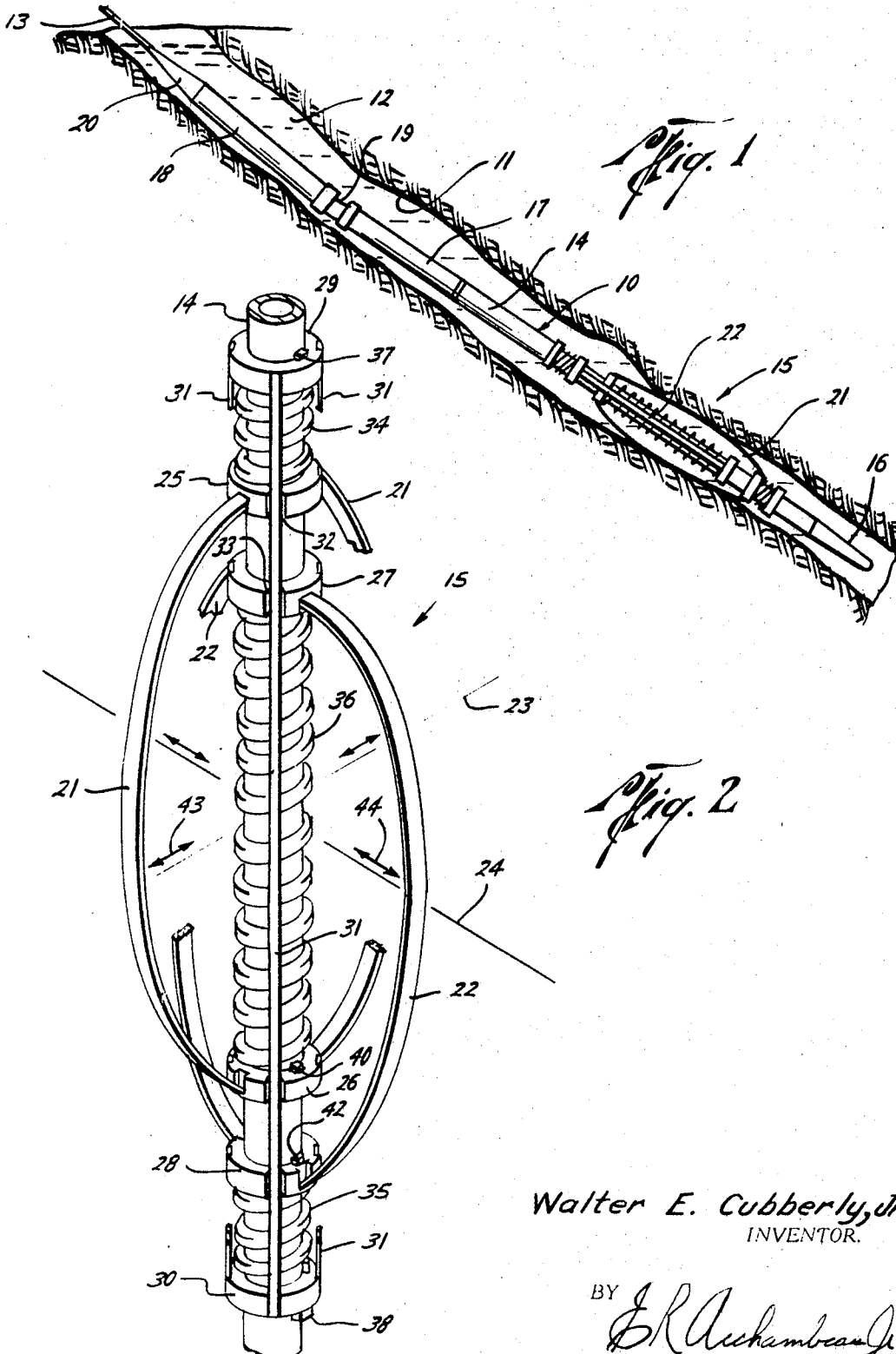
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3,474,541

WELL-CALIPERING APPARATUS

Filed May 27, 1968

3 Sheets-Sheet 1



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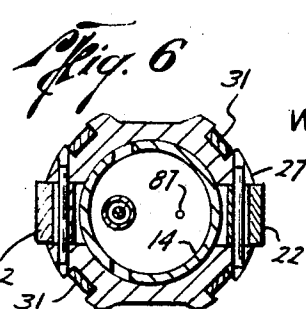
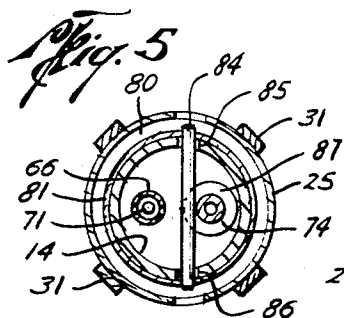
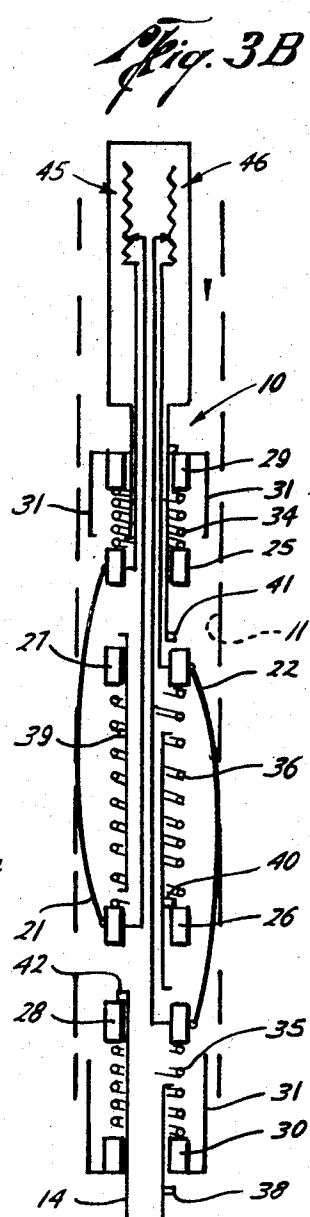
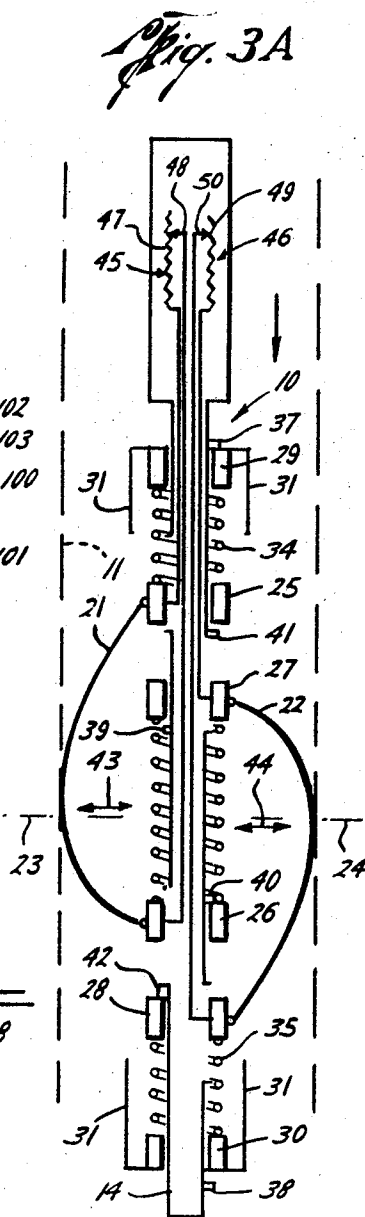
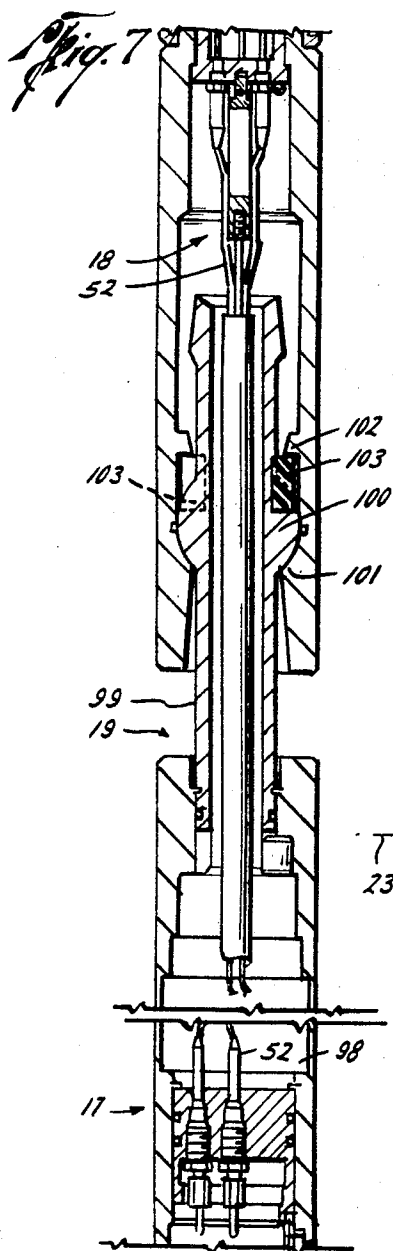
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3,474,541

WELL-CALIPERING APPARATUS

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3 Sheets-Sheet 2



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3,474,541

WELL-CALIPERING APPARATUS

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U.S. Cl. 33—178

26 Claims

ABSTRACT OF THE DISCLOSURE

The particular embodiment disclosed herein as representative of the present invention is directed to well-calipering apparatus. In particular, the disclosed well-calipering apparatus is comprised of two pairs of outwardly-bowed springs spaced circumferentially around a tool body with their bowed portions being adapted to contact opposed wall portions in a well bore and correspondingly flex laterally inwardly and outwardly as the apparatus encounters diametrical changes in a well bore. These flexural movements of the bowed springs are, in turn, sensed by movement-responsive devices adapted to provide representative indications of these diameters. Where the apparatus is used in a greatly inclined well bore, a buoyant chamber is provided for relieving a significant portion of the apparatus' weight from the bowed springs.

It is, of course, quite common to move a so-called "calipering tool" through a well bore to obtain a record of well bore diameters in relation to depth. Typical of such tools are those shown in Patent Nos. 2,639,512; 2,712,697 and 3,097,433 and which respectively carry a plurality of outwardly-bowed wall-engaging arcuate springs having their ends slidably coupled to an elongated tool body. In this manner, as the calipering tool enters constricted sections of a well bore, the outwardly-bowed intermediate portions of the springs are deflected radially inwardly and their respective end-coupling members are longitudinally shifted apart a distance proportionally related to the particular diameter. Similarly, as the calipering tool encounters an enlarged interval, the springs will flex outwardly and draw the end-coupling members toward one another to new longitudinally-spaced positions related to the enlarged diameter. Thus, as the tool is traversed along a typical well bore, these variations in longitudinal spacings between the end-coupling members are successively translated by one or more suitable electro-mechanical devices on the tool into a meaningful record of well bore diameters.

The calipering tools shown in the above-mentioned patents have been quite successful in those well bores that are substantially vertical. On the other hand, such tools are not usually suited for service in those well bores having substantially deviated or inclined intervals. For example, as noted in the above-mentioned Patent No. 3,097,433 to Walter E. Cubberly, Jr., the forces tending to maintain the springs bowed and in contact with the well bore walls must be relatively minimal to insure sensitivity as well as to not unduly impede movement of the calipering tool. It will be appreciated, of course, that when even the Cubberly tool is used in a greatly inclined well bore, a significant portion of its weight must be carried by those springs engaging the lower wall surfaces; and, in view of these minimal opposing spring forces, the springs will often collapse against the tool body. As a result, it has not heretofore been possible to reliably measure the diameters of those intervals of well bores that deviate more than about 10° from the vertical.

Moreover, irrespective of the orientation of a well bore, those prior-art calipering tools using bowed springs

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have not been particularly suited for simultaneously measuring well bore diameters along multiple axes in a common transverse plane. Thus, heretofore, where more than one diametrical measurement was to be made, it has been necessary to sacrifice the freedom of movement afforded by tools using bowed springs and instead employ tools with multiple wall-engaging arms such as shown in Patent No. 2,680,913, which tools are best suited for only upward movement in a well bore. It will be recognized, of course, that calipering tools of this nature are similarly ineffective in greatly-deviated well bores as well.

Accordingly, it is an object of the present invention to provide new and improved well tools that are capable of providing accurate diametrical measurements of well bores irrespective of their orientation or deviation.

This and other objects of the present invention are attained by arranging on a tool body first and second pairs of arcuately-shaped wall-engaging spring members for independent flexural movements corresponding to various transverse spacings of facing wall-portions of a well bore contacted by the spring members. Means are also included to respond to these flexural movements of the spring members for obtaining indications representative of these transverse spacings. To substantially centralize the spring members in an inclined well bore without imposing either a significant drag on the tool or undue weight on the spring members, a light-weight extension is added to the tool body. Means, such as a buoyant chamber, are included in the extended portion of the tool body for buoyantly supporting at least a significant portion of the tool body.

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 apparatus employing the principles of the invention as illustrated in the accompanying drawings, in which:

FIGURE 1 shows a preferred embodiment of a tool arranged in accordance with the present invention as it might appear while measuring a typical borehole;

FIGURE 2 is an isometric view of a portion of the tool shown in FIGURE 1;

FIGURES 3A and 3B are schematic representations of the tool shown in FIGURE 1 to illustrate the cooperative relation of various elements thereof during the operation of the tool;

FIGURES 4A-4C are cross-sectional elevational views of the more significant portions of the tool shown in FIGURE 1;

FIGURES 5 and 6 are cross-sectional views respectively taken along the lines 5-5 and 6-6 in FIGURE 4A; and

FIGURE 7 is a cross-sectioned partial view of another portion of the tool shown in FIGURE 1.

Turning now to FIGURE 1, a calipering tool 10 arranged in accordance with the principles of the present invention is depicted within a typical well bore, such as a greatly inclined borehole 11, containing a well-control fluid or so-called "mud" 12. As is typical, the upper end of the calipering tool 10 is connected to the surface by a suitable suspension cable 13 having one or more electrical conductors.

In general, the calipering tool 10 is comprised of a tubular body 14 carrying diameter-measuring means 15 arranged in accordance with the principles of the present invention. A resilient nose piece 16 is preferably mounted on the lower end of the body 14 to absorb shocks as well as to facilitate the descent of the tool 10 through the borehole 11. As will subsequently be described, the upper portion of the body 14 is supported by means, such as

an extension body 17 loosely coupled to another body 18, as by an articulated connection 19, which is in turn connected to the cable 13 by a typical cable head 20.

Turning now to FIGURE 2, a somewhat foreshortened isometric view is shown of the diameter-measuring means 15 of the present invention. In general, the diameter-measuring means 15 are comprised of first and second pairs of diametrically-opposed outwardly-bowed leaf springs 21 and 22 mounted on the body 14, with the intermediate or wall-contacting portions of the first pair of springs being arranged for lateral deflection along one transverse axis 23 and the intermediate or wall-contacting portions of the second pair of springs being arranged for lateral deflection along another transverse axis 24 that, preferably, perpendicularly intersects the first axis. To operatively couple the first pair of spring members 21 to the body 14, the upper ends of these springs are pivotally connected on opposite sides of an annular collar 25 that is loosely mounted on the body. Similarly, the lower ends of the springs 21 are pivotally connected to another annular collar 26 loosely mounted on the body 14 well below the collar 25. The second pair of spring members 22 is similarly mounted on the body 14, with the upper ends of these springs being pivotally coupled on opposite sides of a collar 27 just below the collar 25 and the lower ends of these springs being pivotally coupled to a collar 28 just below the collar 26.

Although the collars 25-28 are free to rotate as well as slide in relation to the body 14, means are provided to maintain the collars in angular alignment with one another without hindering their independent longitudinal movement along the body in response to flexural movements of the springs 21 and 22. To accomplish this, annular abutments 29 and 30 are respectively mounted loosely on the body 14 above and below the collars 25 and 28 and co-rotatively secured to one another and maintained at a constant longitudinal spacing by means such as a plurality of circumferentially-spaced longitudinal rigid bars 31 interconnecting the abutments. These alignment bars 31 are preferably arranged at equal circumferential intervals around the tool body 14 and are spaced radially therefrom. Each of the sliding collars 25-28 are in turn co-rotatively secured to the bars 31, as by longitudinal slots (e.g., at 32 and 33) in each collar slidably receiving the bars, in such a manner that longitudinal shifting of the collars in relation to either the body 14 or the abutments 29 and 30 is not hindered. Accordingly, it will be appreciated that the upper and lower abutments 29 and 30 are rigidly interconnected to one another for simultaneous longitudinal shifting as well as free rotation in relation to the tool body 14. On the other hand, although the collars 25-28 are free to shift longitudinally independently of one another in relation to the body 14 as well as to the bars 31 and the abutments 29 and 30, the collars are co-rotatively secured to each other and to the abutments by the alignment bars and the slots as at 32 and 33. Thus, as a result, the first and second pairs of spring members 21 and 22 are always maintained in their respective angular positions but the tool body 14 is free to rotate in relation thereto.

To oppose movements of the first and second pairs of spring members 21 and 22 away from their positions illustrated in FIGURE 2 biasing means are provided such as compression springs 34 and 35 that are respectively disposed between the upper abutment 29 and collar 25 and the lower abutment 30 and collar 28 and a tension spring 36 that is connected between the collars 26 and 27. Stops 37 and 38 are respectively spaced on the tool body 14 just above and just below the abutments 29 and 30. As better illustrated in other drawings, the body stops 37 and 38 are longitudinally separated slightly further than the fixed longitudinal spacing of the abutments 29 and 30 as determined by the length of the rigid alignment bars 31. In this manner, the bars 31 will always be in tension and, at any given time, only one of the two

abutments 29 and 30 will be in contact with its associated body stop 37 or 38. Body stops 39 and 40 (only 40 seen in FIGURE 2) are also provided just below and just above the collars 27 and 26 to establish the minimum longitudinal spacing of these collars. Similarly, body stops 41 and 42 (only 42 seen in FIGURE 2) just below and just above the collars 25 and 28 determine the minimum longitudinal spacing of these collars.

It should be particularly noted that, as shown in FIGURES 2 and 3A, the pairs of bowed spring members 21 and 22 are so arranged that their respective intermediate or wall-engaging portions will contact a well bore wall at circumferentially-spaced points lying in substantially the same transverse plane. Stated another way, the bowed springs 21 and 22 are mounted on the tool body 14 so that their respective wall-contacting surfaces will move laterally along the transverse axes 23 and 24 which intersect one another at a right angle and are each perpendicular to the tool body. To accomplish this, each of the bowed springs 21 and 22 have a substantially rectangular cross-section and are preformed to define a generally semi-elliptical curve. More specifically, each spring 21 and 22 is formed with asymmetrical upper and lower portions of unequal lengths and respectively defining substantially one-fourth of an ellipse. Taking the two springs 21, for example, it will be appreciated that their upper portions (from the axis 23 to the upper collar 25) together substantially define one-half of a first ellipse having a minor axis lying along the transverse axis 23 and a major axis lying along the central axis of the tool body 14 and of a substantial longitudinal dimension. Similarly, the lower portions of the two springs 21 substantially define one-half of a second but slightly smaller ellipse having a minor axis also coinciding with the transverse axis 23 and a dimension equal to the minor dimension of the first ellipse. The major axial dimension of this second ellipse is, however, somewhat shorter than that of the first ellipse. The other bowed springs 22 are identical but are reversely mounted on the tool body 14 in relation to the springs 21 so as to place the shorter partially-elliptical portions thereof above the transverse axis 24 and the lower partially-elliptical portions therebelow. It will be appreciated, therefore, that by making the end portions of the springs 21 and 22 asymmetrical and reversing one pair in relation to the other pair in this manner, the diametrical measurements obtained by the tool 10 will be in a common transverse plane at the same well bore depth and no correction need be made for longitudinal displacement between the axes 23 and 24.

In the preferred embodiment of the caliper tool 10, the springs 34-36 are selected to complement or cooperate with the bowed springs 21 and 22 in such a manner that deflections of the bowed springs are opposed by substantially uniform forces over a wide range of well bore diameters. Taking the bowed springs 21, for example, the tension spring 36 is effective to urge the collar 26 upwardly against the body stop 40 as the compression spring 34 simultaneously urges the upper ends of the bowed springs 21 downwardly. Similarly, the compression spring 35 and tension spring 36 cooperate to simultaneously oppose movements of the ends of the bowed springs 22 away from one another. The fundamental relationships of the coaction between symmetrically-curved leaf springs having their ends yieldably restrained by a single coil spring have been treated in considerable detail in the aforementioned Cubberly patent. By way of analogy with these previously described relationships, it will be appreciated that in the present invention the tension spring 36 is acting on the shorter partially-elliptical portions of the two pairs of bowed springs 21 and 22 in a similar manner as the single tension spring in the aforementioned patent. On the other hand, however, in the present invention, the corresponding upper and lower ends of each pair of the opposed bowed springs 21 and 22 are independently biased by

the compression springs 34 and 35, respectively, so that the coil springs 34-36 cooperate to provide much greater but substantially constant centralizing forces than could possibly be obtained with even the tool shown in the Cubberly patent.

Accordingly, each of the bowed springs 21 and 22 is preshaped so that, when relaxed, their respective shorter and longer portions will have partially-elliptical curvatures as defined by Equation 1 of the Cubberly patent with, however, different lengths L being used to calculate the desired curvature for each portion. This requires, therefore, that the simplified forming procedure described in the sentence beginning in col. 6, line 30, of the patent be modified somewhat in the present invention by instead applying a concentrated load at a selected off-centered position so as to achieve the desired asymmetric arcuate configuration.

For the same reasons presented in considerable detail in the Cubberly patent, it is particularly desired that the diameter-measuring means 15 impose a substantially constant (but, of course, greater) centralizing force over a wide range of well-bore diameters. To determine the effective centralizing force F_c required for a particular tool, it must first be realized that as the tool 10 is moving through a well bore such as the borehole 11, the diameter-measuring means 15 will tend to assume a position where the transverse axes 23 and 24 are inclined at an angle of about 45° from the vertical. In other words, since the diameter-measuring means 15 of the present invention will inherently tend to assume a stable angular position in relation to the borehole 11, one of each pair of these bowed springs 21 and 22 will always be equally straddling the lowermost points along the lower half of the borehole wall. Similarly, the diametrically-opposed uppermost ones of the bowed springs 21 and 22 will respectively be running immediately adjacent to opposite sides of the upper half of the borehole wall. Thus, by virtue of this substantially 45° inclination of the transverse axes 23 and 24, the total radial force P_t that must be imposed through each bowed spring to obtain a desired total or minimum centralizing force F_c must be:

$$P_t = \frac{\sqrt{2}F_c}{4} \quad (\text{Eq. A})$$

With the minimum centralizing force F_c , of course, being that portion of the weight of the tool 10 that has been selected to be supported by the diameter-measuring means 15.

Each asymmetric portion of the bowed springs 21 and 22 must, of course, be treated separately in view of their respective differences in length L. Thus, the shorter asymmetric portion of any given bowed spring 21 or 22 will have an end force P_s and its longer portion will have a greater end force P_l , with the summation of these end forces being the total outwardly-acting radial force P_t at the intermediate wall-contacting portion of the bowed spring. With such unequal lengths, these end forces are, of course, respectively equal to:

$$P_s = \frac{P_t \cdot L_s}{L_s + L_l} \quad (\text{Eq. B})$$

$$P_l = \frac{P_t \cdot L_l}{L_s + L_l} \quad (\text{Eq. C})$$

For the same reasons given in the Cubberly patent, it is preferred that the bowed springs 21 and 22 be preshaped so that, when they are relaxed, their respective intermediate wall-contacting portions will be circumscribed by an imaginary circle having a diameter approximately midway between the minimum diameters of those well bores in which the caliper tool 10 of the present invention is intended to be used. Thus, the initial deflection Y_o for each bowed spring 21 and 22 will be determined by selecting an intermediate well-bore diameter.

As was done in the Cubberly patent, the proportionality factor C is defined as being 1.0 at this intermediate well-bore diameter. C is, similarly, set as equal to "zero" at the minimum diameter through which the tool 10 is intended to pass, with all other values of C being linearly related to a corresponding well-bore diameter.

For the same reasons used in deriving Equation 8 in the Cubberly patent, at any given position of the bowed springs 21 and 22, the relationship of the axially-directed spring force Q (respectively supplied by the coil springs 34-36) acting on the free end of each of the asymmetrical spring portions to the outwardly-directed radial force P_s or P_l acting thereon is defined by:

$$P = \frac{3EIY_o(1-C)}{L^3} + \frac{6CY_oQ}{5L} \quad (\text{Eq. D})$$

with the terms in this equation being fully defined in the corresponding discussion in the Cubberly patent.

The design of the bowed springs 21 and 22 is first determined. When the bowed springs 21 and 22 are flattened along the tool body 14 (as where the diameter of the borehole 11 is at a minimum), the bowed springs are, for all practical purposes, supplying all of the outwardly-acting centralizing forces for the tool 10 since the forces of the coil springs 34-36 are now acting directly along the central axes of the bowed springs. At this point, C is "zero" and, by substituting $C=0$ into Equation D for each asymmetric spring portion, Equation D is reduced to:

$$P = \frac{3EIY_o}{L^3} \quad (\text{Eq. E})$$

This equation accordingly defines the significant factors required to select a suitable spring material and the appropriate cross-sectional dimensions for a given Y_o , L_s and L_l of the two asymmetric portions for each of the bowed springs 21 and 22.

On the other hand, it will be appreciated that when the bowed springs 21 and 22 are relaxed (i.e., when the tool 10 is in a borehole having a diameter equal to the aforementioned intermediate diameter used to select Y_o), the total centralizing force F_c must be derived entirely from the coaction of the various coil springs 34-36. In other words, when the tool 10 is in a borehole having an intermediate diameter of this selected magnitude, the bowed springs 21 and 22 are completely relaxed and the portion of weight of the tool that is supported by the diameter-measuring means 15 will be entirely carried by the forces of the coil springs 34-36. Thus, as previously described, at this point $C=1.0$. Using the selected Y_o and a value of 1.0 for C, it will be seen that Equation D for either asymmetric spring portion is reduced to:

$$P = \frac{6Y_oQ}{5L} \quad (\text{Eq. F})$$

Q is, of course, the only unknown factor here and a numerical value of this factor will be obtained for each of the compression springs 34 and 35 as well as for the tension spring 36 by solving Equation F separately for the longer and shorter asymmetric spring portions respectively. Thus, with Equation F being used to find the factor Q_t for the tension spring 36, the appropriate figures for the shorter spring portion are used. Similarly, Q_c is found for each compression spring 34 or 35 by using the appropriate figures for the longer asymmetric spring portion. The two values of Q_t and Q_c obtained as a result are, therefore, the respective spring forces required from the tension spring 36 and from either of the compression springs 34 and 35 when the bowed springs 21 and 22 are fully relaxed.

As already mentioned, the total outwardly-acting force P_t on each of the bowed springs 21 and 22 is equal to the summation of the end forces P_s and P_l acting thereon.

Using Equation D to express each end force, the total force is equal to:

$$P_t = \frac{3EIY_o(l-C)}{L_s^3} + \frac{6CY_oQ_t}{L_s} + \frac{3EIY_o(l-C)}{L_1^3} + \frac{6CY_oQ_o}{L_1} \quad (\text{Eq. G})$$

It will be realized that the summation of the end forces P_s and P_1 when the bowed springs 21 and 22 are fully-flattened is also equal to the total force P_t and that each of these end forces is equal to the expression $(3EIY_o/L^3)$. Accordingly, to simplify Equation G, this expression in the equation is appropriately replaced by P_s and P_1 . Thus Equation G is progressively simplified:

$$P_t = P_s(l-C) + P_1(l-C) + \frac{6}{5}CY_o \left(\frac{Q_t}{L_s} + \frac{Q_o}{L_1} \right) \\ = (P_s + P_1)(l-C) + \frac{6}{5}CY_o \left(\frac{Q_t}{L_s} + \frac{Q_o}{L_1} \right)$$

Since $(P_s + P_1) = P_t$,

$$P_t = P_t(1-C) + \frac{6}{5}CY_o \left(\frac{Q_t}{L_s} + \frac{Q_o}{L_1} \right)$$

and

$$P_t C = \frac{6}{5}Y_o C \left(\frac{Q_t}{L_s} + \frac{Q_o}{L_1} \right)$$

Thus, dividing both sides by C,

$$P_t = \frac{6}{5}Y_o \left(\frac{Q_t}{L_s} + \frac{Q_o}{L_1} \right) = \frac{\sqrt{2}F_o}{4} \quad (\text{Eq. H})$$

It will be seen, therefore, that for any flexural position of the bowed springs 21 and 22, the spring forces Q_t and Q_o for the tension spring 36 and each of the compression springs 34 and 35, respectively, are ideally constant irrespective of the well bore diameter.

Selection of the compression and tension springs 34-36 can now, of course, be made in the usual manner. It will be appreciated, however, that these spring forces Q_o that have been determined from Equations F and H must be doubled to obtain the total Q for each of the compression springs 34 or 35 since each compression spring is working on the longer portion of one pair of the bowed springs 21 or 22. Similarly, the Q_t acting on the shorter asymmetrical portions of the springs 21 and 22 must also be doubled to obtain the total Q since each end of the tension spring 36 is alternately working on the shorter portions of one pair of the bowed springs. The ends of the shorter portions of the other pair of bowed springs 21 and 22 is at any given time against one of the inner body stops 39 and 14. Thus, at any given time, the tension spring 36 is functionally cooperating with only one pair of bowed springs.

With a given set of coil springs 34-36 respectively capable of producing the desired forces Q at, for example, the position where the bowed springs 21 and 22 are in their relaxed position (i.e., at $C=1.0$), the coil springs must alternately compress or expand as the bowed springs flex inwardly or outwardly. This, of course, inherently causes the respective spring forces Q to change a corresponding amount. Since this is not desired, it is preferred, therefore, to design the coil springs 34-36 to produce their required force Q but to have a relatively-low spring rate. For example, by selecting appropriate coil springs with a spring rate in the order of only 1.0-lb./inch, as the springs 34-36 change in accordance with flexural movements of the bowed springs 21 and 22 the variations of their respective forces Q will be minimal. This will, therefore, produce a relatively unvarying total centralizing force. It should also be noted that by selecting the coil springs 34-36 to each have the same force Q, the diameter-measuring means 15 will be freer to shift in relation to the tool body 14.

It will, of course, be recognized that the single tension spring could be replaced with two separate springs each

having the same Q_t as the spring 36 and connected to the body 14 and to their respective bowed springs 21 and 22. Thus, in considering the scope of the present invention, it is immaterial whether one or two springs are used for the tension springs.

Contraction of the bowed springs 21 and 22 as by entrance into a well bore will, of course, cause the corresponding upper and lower ends of the bowed springs to move apart, with each pair of bowed springs moving independently of the other pair. Assuming, for example, that (as shown in FIGURE 3A) the tool 10 is moving downwardly through the borehole 11, the frictional drag of the bowed springs 21 and 22 will shift the diameter-measuring means 15 upwardly along the tool body 14 until the upper abutment 29 engages the upper body stop 37. The lower collars 26 and 28 will also be respectively shouldered on their associated body stops 40 and 42. Thus, as the tool 10 continues to move downwardly, diametrical variations in the borehole 11 will cause the bowed springs 21 and 22 to deflect as indicated by the arrows 43 and 44 and correspondingly shift their respective collars 25 and 27 longitudinally along the tool body 14. The longitudinal distance that the collars 25 and 27 respectively shift will, of course, be proportionally related to the lateral deflections of their associated bowed springs 21 and 22 along their respective axes 23 and 24.

It will also be appreciated that the reverse action will be obtained upon upward movement of the tool 10 in a well bore such as the borehole 11. In this instance, the upward travel of the tool 10 will cause the diameter-measuring means 15 to shift downwardly in relation to the tool body 14 until the lower abutment 30 engages the lower body stop 38. The upper collars 25 and 27 will then be abutted on their respective body stops 41 and 39 and it will now be the lower collars 26 and 28 that will independently shift longitudinally in proportion to the deflections of their respective bowed springs 21 and 22 along the transverse axes 23 and 24.

Accordingly, irrespective of the direction of travel of the caliper tool 10 in a well bore, lateral deflections of the bowed springs 21 and 22 will produce independent corresponding shifts of their associated collars 25-28 that are proportionally related to the transverse spacings of the wall-contacting surfaces of the bowed springs. In one manner of translating these independent longitudinal movements of the collars 25-28 into meaningful information, electrical control devices, such as potentiometers 45 and 46, having an electrical characteristic that will be varied in response to movement are operatively coupled to the collars. For example, as seen in FIGURES 3A and 3B, by operatively coupling the resistance element 47 of the potentiometer 45 to the collar 25 and the sliding contact 48 of this potentiometer to the collar 26, flexural movements of the bowed spring 21 as indicated by the arrows 43 will correspondingly vary the relative positions of the sliding contact and the resistance element. Similarly, the resistance element 49 and the sliding contact 50 of the potentiometer 46 are respectively coupled cooperatively to the collars 27 and 28 so that lateral deflections (as at 44) of the bowed springs 22 will also produce corresponding changes in the relative positions of this sliding contact and resistance element. Thus, by means of appropriate electrical circuitry, the changes in the relative positions of the potentiometers 45 and 46 can readily be translated into meaningful electrical indications from which the diametrical spacings of the wall-contacting surfaces of the bowed springs 21 and 22 can be independently determined to continuously measure the diameters of the borehole 11 along the transverse axes 23 and 24 as the tool 10 moves through the borehole.

Turning now to FIGURES 4A-4C, successive cross-sectional views are shown of the more significant portions of a preferred embodiment of the tool 10. As seen there, the tool body 14 is tubular and the various ele-

ments of the tool 10 already described are identified with their respective reference numerals. Inasmuch as the functional relations of these previously described elements have already been brought out, it is believed necessary only to now point out various significant constructional features of the tool 10. Moreover, to clarify the description of the constructional features, various minor features such as joint details have either been omitted or are simplified in some respects. Similarly, the bowed springs 21 have been rotated 90° from their actual positions for purposes of illustration.

Accordingly, as seen in FIGURE 4A, the upper portion of the tool body 14 is preferably arranged to isolate the potentiometers 45 and 46 from well bore fluids 12 and the like by enclosing them in an oil-filled chamber, as at 51, and fluidly sealing around electrical conductors, as at 52, and other elements leaving the chamber. This, of course, makes it necessary to pressure-balance the chamber 51 as well as to arrange the potentiometers 45 and 46 for independent movement therein. In general, therefore, the upper end of the tool body 14 is telescoped into an outer tubular housing 53 and connected thereto by a suitable coupling 54. The upper end of the housing 53 is, in turn, suitably arranged to support an end closure 55 extending downwardly into the outer housing and defining the upper end of the oil chamber 51. A resilient sleeve 56 of elastomer or the like is secured between the end closure 55 and the upper end of the tool body 14 to provide a flexible pressure-transmitting wall for the chamber 51.

As previously mentioned, the potentiometers 45 and 46 are free to move in relation to the tool body 14. To accomplish this, a tubular enclosure 57 is coaxially secured at its lower end to the upper end of the tool body 14 and its upper end dependently connected to an axial extension 58 of the end closure member 55. The potentiometers 45 and 46, which are preferably of a type having tubular bodies 58 and 59 carrying helically-wound resistance elements (as at 47 and 49) and axially-movable control rods 60 and 61 carrying the sliding contacts (as at 48 and 50), are movably mounted side-by-side in the tubular enclosure 57. Upright extensions 62 and 63 of the potentiometer bodies 58 and 59 are slidably disposed in appropriately located openings in a transverse guide 64 across the top of the enclosure 57.

Although the control rods 60 and 61 could possibly be passed through fluid seals and directly connected to their respective sliding collars 26 and 28, it is preferred to maintain these typically slender control rods 60 and 61 in tension to avoid any buckling thereof. To accomplish this, depending tubular extensions 65 and 66 are respectively connected to the lower ends of the tubular potentiometer bodies 58 and 59 and slidably passed through annular seals 67 and 68 in complementary openings in a transverse wall 69 extending across the upper portion of the tool body 14. Extension shafts 70 and 71 are suitably connected to the control rods 60 and 61 and extended through their respective tubular body extensions 65 and 66 and slidably passed through annular seals 72 and 73 carried on closure plugs 74 and 75 secured to the lower ends of the body extensions. Compression springs 76 and 77 are coaxially arranged in the body extensions 65 and 66, respectively, and compressed between shoulders 78 and 79 on the shaft extensions 70 and 71 and the end closures 74 and 75. It will be appreciated, therefore, that the seals 67, 68, 72 and 73 and the transverse wall 69 and body extensions 65 and 66 define the lower walls of the oil chamber 51. Moreover, by virtue of the seals 67 and 68, the potentiometer bodies 58 and 59 are independently free to move longitudinally in relation to the oil chamber 51 and tool body 14; and, by virtue of the seals 72 and 73, the potentiometer control rods 60 and 61 are also independently free to move longitudinally relative to the oil chamber 51 and tool body 14 as well. Thus, longitudinal movement in either

direction of the potentiometer bodies 58 and 59 (and their respective resistance elements 47 and 49) is accomplished by movement of their respective closure plugs 74 and 75. Similarly, downward longitudinal movement of the shaft extensions 70 and 71 will correspondingly move the sliding contacts 48 and 50, with upward movement of the sliding contacts being provided by the compression springs 76 and 77 when the shaft extensions are moved upwardly thereby.

As previously described, the longitudinal movements of the sliding collars 25-28 are employed to control the potentiometers 45 and 46. Accordingly, as seen in FIGURES 4B and 4C, the potentiometer body extensions 65 and 66 are respectively connected to the upper sliding collars 25 and 27 and the potentiometer shaft extensions 70 and 71 are respectively connected to the lower sliding collars 26 and 28 to obtain the desired independent movements of the resistance elements 47 and 49 and their associated sliding contacts 48 and 50.

As best seen in FIGURES 4B and 5, the upper sliding collar 25 is slidably mounted on the tool body 14 above the body stop 41 and pivotally connected to the corresponding upper ends of the bowed springs 21. To allow the collar 25 to rotate freely in relation to the tool body 14, an annular recess 80 is formed in the upper end of the collar to receive a ring 81 as well as to provide an upwardly-directed abutment 82 for carrying the lower end of the spring 34. A bearing ring 83 is preferably interposed between the abutment 82 and spring 34 to minimize any friction that might otherwise hinder the free rotation of the collar 25 in relation to the tool body 14 and the ring 81. To connect the ring 81 to the potentiometer body 58, the ends of a transverse pin 84 are passed through longitudinal slots 85 and 86 on opposite sides of the tool body 14 and coupled to the ring, with the central portion of the pin being confined within an adjacent portion of a circumferential groove 87 formed around the end closure plug 74. Thus, irrespective of the angular position of the collar 25 as determined by the rotations of the diameter-measuring means 15, the ring 81 and transverse pin 84 carried thereby will readily follow longitudinal movements of the sliding collar and transfer these movements through the body extension 65 to the resistance element 47 of the potentiometer 45.

To position the sliding contact 48 of the potentiometer 45, the free end of the potentiometer shaft extension 70 is connected, as seen in FIGURES 4B and 4C, to the upper end of a flexible cable 87 by a clevis 88, with the lower end of the cable being connected to a body 89 carrying a transverse pin 90. The free ends of this transverse pin 90 are respectively passed through longitudinal slots, as at 91, in the tool body 14 and connected to a ring 92 slidably mounted on the tool body. The sliding collar 26 carrying the lower ends of the bowed springs 21 is formed with an inwardly-facing annular groove 93 for loosely confining the sliding ring 92 and is secured to the lower end of the tension spring 36. Thus, even though the upper and lower collars 25 and 26 are free to rotate as well as to slide in relation to the tool body 14, their respective sliding rings 81 and 92 are only free to slide longitudinally to respectively position the resistance element 47 and sliding contact 48 of the potentiometer 45 in various positions representative of the relative longitudinal positions of the sliding collars 25 and 26 as the bowed springs 21 flex inwardly and outwardly.

Since the lower sliding collar 28 must similarly carry the upper end of the compression spring 35, this collar is preferably arranged in the same manner as the upper collar 25 except that it is reversely mounted on the tool body 14 and is instead pivotally connected to the corresponding lower ends of the bowed springs 22. The upper collar 27 is similar to the collar 26 except that it is reversed therefrom and is instead connected to the upper end of the tension spring 36 and to the extension 71. Thus, as seen in FIGURES 4B and 4C, corresponding

control of the potentiometer 46 is accomplished as the collars 27 and 28 are moved by the flexural movements of the bowed springs 22. It will be further appreciated that the springs 76 and 77 will cooperably take up any longitudinal play in their respective series of linking connections between the potentiometers 45 and 46 to the collars 25-28.

As best seen in FIGURE 4B, the body stop 41 is preferably arranged to momentarily yield under sudden impacts from the sliding collar 25. To accomplish this, the body stop 41 is comprised of spaced rings 94 and 95 slidably carried on the body 14, with the lower ring having an upwardly-diverging tapered face and being abutted on a stop or snap ring 96 secured on the body. The lower face of the upper ring 94 is downwardly divergent so as to confine one or more resilient rings 97 disposed around the tool body 14 just above the corresponding divergent face of the lower ring 95. Thus, upon sudden downward movements of the sliding collar 25, the sliding collar will strike the upper ring 94 and momentarily compress the resilient rings 97 against the lower sliding collar 95 to absorb the impact shocks. The other body stops 39, 40 and 42 are similarly arranged.

Referring again to FIGURE 1, it will be appreciated that downward movement of the caliper tool 10 through the borehole 11 will be directly related to the weight of the tool and the frictional restraint imposed by the bowed springs 21 and 22 and other portions of the tool in contact with the borehole walls. As previously described, it is necessary to keep the tool 10 fairly well centralized in the borehole 11 as well as to impose a relatively constant, but minimum, centralizing force with the bowed springs 21 and 22. As previously discussed, the centralizing force of the bowed springs 21 and 22 (as supplemented by the coil springs 34-36) is directly related to the amount of tool weight that must be carried by the diameter-measuring means 15. It will be appreciated from FIGURES 4A-4C that the tool body 14 and all parts carried thereby are relatively light. However, to keep the longitudinal axis of the tool body 14 in relatively-close axial alignment within the borehole 11 as well as to support some of the tool weight, it is preferred to extend the tool body, as by the body 17, a sufficient distance so that when the upper end of the body 17 is resting on the lower borehole wall the tool body will be fairly well aligned in the borehole. It will be appreciated, however, that the longer the bodies 14 and 17 are made to improve their alignment with the axis of the borehole 11, the weight that must be carried by the diameter-measuring means 15 will be correspondingly increased.

Accordingly, to permit at least a substantial portion of the additional weight of the tool body 17 to be offset, the body 17 is arranged for selective use as an enclosed buoyancy chamber that is adapted to be filled with a light oil or such to prevent collapse of the preferably-thin chamber walls. As seen, therefore, in FIGURE 7, the body 17 is suitably arranged to provide an enclosed chamber 98 that is connected to the upper end of the tool body 14. The electrical conductors 52 are passed through the chamber 98 and fluidly sealed where they leave the upper and lower ends of the body 17.

To couple the upper end of the body 17 to the tool body 18 and cable head 20 thereabove, the articulated connection 19 is arranged between the two bodies. As seen in FIGURE 7, the articulated connection 19 is comprised of a tubular member 99 rigidly connected to the tool body 17 and having a partially-spherical enlarged portion 100 adapted for reception between opposed complementary upper and lower annular seats 101 and 102 mounted in the lower end of the body 18. A plurality of rigid or resilient keys, as at 103, are loosely fitted into opposed longitudinal slots circumferentially spaced around the spherical head 100 and upper seat 102 to co-rotatively secure the body 18 to the tubular member 99 without unduly limiting their omnidirectional articula-

tion. The electrical conductors 52 are conveniently passed through the tubular member 99.

It will be appreciated, therefore, where the chamber 98 is filled with a light oil, the body 17 will be at least partially buoyant and its added length will add little weight to that of the relatively-light body 14 which must be supported by the diameter-measuring means 15. This added length of the body 17 will, however, aid significantly in keeping the body 14 well-centralized in the borehole 11 to improve the accuracy of the diametrical measurements of the tool 10.

It will be appreciated as well that by employing the non-rotating articulated connection 19 as an intermediate coupling in the tool 10, substantial weight can be added, as in the body 18 or other bodies (not shown) connected thereabove, to facilitate the downward movement of the caliper tool in even highly-deviated boreholes as at 11. None of this extra weight will have to be carried by the diameter-measuring means but the added weight will still be effective to act through the articulated connection 19 for moving the tool 10 down the borehole 11.

Accordingly, by employing the tool 10 of the present invention, accurate diametrical measurements can be made along at least two transverse axes of even highly-deviated well bores. The new and improved caliper tool 10 of the invention will be maintained in fairly close alignment in a well bore by the added length of the body 17 without, by virtue of the buoyancy chamber 98 therein, adding any significant amount of weight that must also be carried by the bowed springs 21 and 22. Moreover, by employing the articulated connection 19, other tool bodies, as at 18, can be carried thereabove without adding extra weight that must be supported by the diameter-measuring means.

While 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.

What is claimed is:

1. A well tool adapted for measuring the spacing between opposed wall-portions of a well bore and comprising: a support; first and second pairs of opposed arcuately-curved spring members circumferentially spaced around said support, each of said spring members having an upper and a lower end portion longitudinally spaced along said support and an outwardly-bowed intermediate portion laterally spaced from said support and adapted for engagement with a wall portion of a well bore; first and second means respectively coupling said upper end-portions of said first pair of spring members and said lower end-portions of said second pair of spring members to said support for independent longitudinal movement in relation thereto; third means coupling said lower end-portions of said first pair of spring members and said upper end-portions of said second pair of spring members to one another and to said support; first and second biasing means between said support and said first and second coupling means respectively and independently urging said first and second coupling means toward one another; and first and second means independently responsive to respective longitudinal movements of said first and second coupling means along said support for providing first and second indications representative of the transverse spacings of opposed wall-portions of a well bore respectively engaged by said first and second pairs of spring members.

2. The well tool of claim 1 wherein said third coupling means are between said first and second coupling means.

3. The well tool of claim 1 wherein said end portions of each of said spring members are of unequal lengths and have a partially-elliptical curvature asymmetric to the curvature of the adjoining end portion thereof.

4. The well tool of claim 3 wherein said third coupling means are between said first and second coupling means, and said upper portions of said first pair of spring mem-

bers are longer than said lower portions thereof and said lower portions of said second pair of spring members are longer than said upper portions thereof so that said intermediate portions of said first and second pairs of spring members are substantially located in a common transverse plane.

5. The well tool of claim 1 wherein said spring members are adjacent to one end of said support and further including: means on the other end of said support and defining a buoyancy chamber for at least offsetting a portion of the weight of said well tool in well bore liquids.

6. The well tool of claim 1 wherein said first and second movement-responsive means respectively include first and second variable electrical control devices on said tool with each having an electrical characteristic variable over a selected range and further including: a tool-supporting cable connected to said well tool and adapted for supporting said well tool in a well bore, said cable having electrical conductor means connected to said first and second electrical control devices; and first and second indicating means connected to said electrical conductor means and respectively adapted for measuring variations in said electrical characteristics of said electrical control devices produced by corresponding transverse spacings of opposed wall-portions of a well bore engaged by said first and second pairs of spring members.

7. The well tool of claim 1 wherein each of said spring members have a normal arcuate curvature when relaxed and said first and second biasing means are operative to impose substantially constant forces irrespective of the transverse spacings of opposed wall-portions of a well bore respectively engaged by said spring members.

8. A well tool adapted for measuring the spacing between opposed wall-portions of a well bore and comprising: a support; first and second pairs of opposed outwardly-curved spring members circumferentially spaced around said support with the upper and lower corresponding ends of each pair of said spring members longitudinally spaced along said support, each of said spring members having upper and lower portions respectively extending above and below an intermediate wall-engaging portion thereof adapted for lateral deflection in relation to said support; means respectively coupling said corresponding ends of said spring members to said support for independent longitudinal movements therealong in response to lateral deflections of their respective wall-engaging portions; first biasing means operatively urging said upper ends of said first pair of spring members and said lower ends of said second pair of spring members toward one another; second biasing means operatively urging said upper ends of said second pair of spring members and said lower ends of said first pair of spring members toward one another; and first and second indicating means respectively coupled to said first and second pairs of said spring members and independently responsive to lateral deflections thereof for providing first and second indications representative of such deflections.

9. The well tool of claim 8 wherein said upper and lower portions of each of said spring members are of unequal lengths and have a partially-elliptical curvature asymmetric to the curvature of the adjoining portion thereof.

10. The well tool of claim 9 wherein said upper portions of said first pair of spring members are longer than said lower portions thereof and said lower portions of said second pair of spring members are longer than said upper portions thereof so that said wall-engaging portions of said first and second pairs of spring members are substantially in a common transverse plane.

11. The well tool of claim 9 wherein said first biasing means include first and second coil springs respectively urging said upper ends of said first pair of spring members downwardly and said lower ends of said second pair of spring members upwardly.

12. The well tool of claim 11 wherein said second biasing means include at least a third coil spring urging said upper ends of said second pair of spring members downwardly and said lower ends of said first pair of spring member upwardly.

13. The well tool of claim 9 wherein said upper and lower portions of said first and second pairs of spring members each have a length L_1 longer than the respective lengths L_s of said lower and upper portions thereof with each of said spring members being normally bowed when relaxed and having a normal lateral deflection Y_0 so that said wall-engaging portions of said first and second pairs of spring members are substantially in a common transverse plane and equally spaced laterally away from said support.

14. The well tool of claim 13 wherein said first biasing means include first and second coil springs respectively urging said upper ends of said first pair of spring members downwardly and said lower ends of said second pair of spring members upwardly with a force Q_1 acting longitudinally on the associated end of each of said spring members; and said second biasing means include a third coil spring interconnecting and urging said upper ends of said second pair of spring members downwardly and said lower ends of said first pair of spring members upwardly with a force Q_2 acting longitudinally on the associated end of each of said spring members so that the net outwardly-directed force along said transverse plane provided by each of said spring members is equal to:

$$\frac{6}{5} Y_0 \left[\frac{Q_1}{L_1} + \frac{Q_2}{L_s} \right]$$

15. A well tool adapted for measuring the spacing between opposed wall-portions of a well bore and comprising: a support; first and second pairs of opposed leaf spring members having a normally outwardly-curved shape circumferentially spaced around said support with the upper and lower corresponding ends of each pair of said spring members longitudinally spaced along said support, each of said spring members having upper and lower portions of unequal lengths L_1 and L_s respectively extending above and below an intermediate wall-engaging portion thereof adapted for lateral deflection inwardly and outwardly from a normal deflection Y_0 in relation to said support; means respectively coupling said corresponding ends of said spring members to said support for independent longitudinal movements therealong in response to lateral deflections of their respective wall-engaging portions; first biasing means operatively urging said upper ends of said first pair of spring members and said lower ends of said second pair of spring members toward one another with a force Q_1 acting longitudinally on the associated end of each of said spring members; second biasing means operatively urging said upper ends of said second pair of spring members of said lower ends of said first pair of spring members toward one another with a force Q_2 acting longitudinally on the associated end of each of said spring members so that the net outwardly-directed radial centralizing force from each of said spring members is equal to:

$$\frac{6}{5} Y_0 \left[\frac{Q_1}{L_1} + \frac{Q_2}{L_s} \right]$$

and first and second indicating means respectively coupled to said first and second pairs of said spring members and independently responsive to lateral deflections thereof for providing first and second indications representative of such deflections.

16. The well tool of claim 15 wherein said forces Q_1 and Q_2 are substantially constant irrespective of the lateral deflections of said spring members.

17. The well tool of claim 15 wherein said first pair of spring members are reversely directed in relation to said second pair of spring members to position said wall-engaging portions of each of said spring members in a

common transverse plane in which said centralizing forces will be acting.

18. The well tool of claim 15 wherein each of said spring members has a rectangular cross-section having a moment of inertia I about its bending axis and a modulus of elasticity E sufficient to develop an outwardly-directed spring force when lying substantially parallel to said support of:

$$3EIY_0 \left[\frac{1}{(L_s)^3} + \frac{1}{(L_1)^3} \right]$$

19. The well tool of claim 15 wherein said indicating means include first and second electrical devices respectively having an electrical characteristic and selectively-operable actuating means adapted to vary said electrical characteristic upon movement of said actuating means, and first and second means operatively interconnecting said actuating means respectively to said coupling means for said first pair of spring members and to said coupling means for said second pair of spring members.

20. The well tool of claim 19 further including: a tool-supporting cable connected to said well tool and adapted for supporting said well tool in a well bore, said cable having first and second electrical conductors respectively connected to said first and second electrical devices.

21. A well tool adapted for movement between opposed wall-portions of a well bore and comprising: an elongated support; upper and lower abutments loosely mounted on said support and longitudinally spaced apart; four couplings loosely mounted on said support and successively spaced therealong at longitudinally-spaced intervals between said abutments; means for maintaining said abutments at a fixed longitudinal spacing including a plurality of elongated members spaced around said support and interconnecting said abutments to one another; means for angularly aligning said couplings with one another and said abutments including guide means on each of said couplings slidably engaged with at least one of said interconnecting members and co-rotatively securing that coupling thereto for only longitudinal movement therealong; first and second pairs of opposed outwardly-bowed spring members circumferentially spaced around said support between said abutments, each of said spring members having upper and lower portions respectively extending above and below an intermediate wall-engaging portion thereof adapted to deflect laterally in relation to said support; means pivotally connecting the corresponding upper and lower ends of said first pair of spring members respectively to the uppermost one of said couplings and to an intermediate one of said couplings so that flexural movements of said first pair of spring members will independently move said uppermost and one intermediate couplings longitudinally in relation to said abutments and support; means pivotally connecting the corresponding lower and upper ends of said second pair of spring members respectively to the lowermost one of said couplings and to the other intermediate coupling so that flexural movements of said second pair of spring members will independently move said lowermost and other intermediate couplings in relation to said abutments and support; first and second springs means respectively arranged between said upper abutment and uppermost coupling and between

said lower abutment and lowermost coupling for independently urging said upper ends of said first pair of spring members downwardly and said lower ends of said second pair of spring members upwardly; and third spring means operative on said intermediate couplings for independently urging said lower ends of said first pair of spring members upwardly and said upper ends of said second pair of spring members downwardly respectively.

22. The well tool of claim 21 wherein said upper and lower portions of each of said spring members are of unequal length and have a partially-elliptical curvature asymmetric to the adjoining portion thereof, said one intermediate coupling being below said other intermediate coupling with said shorter portions of said first and second pairs of spring members being arranged between said intermediate couplings to position said wall-engaging portion of each of said spring members in a substantially common transverse plane intersecting said support.

23. The well tool of claim 22 further including: an elongated body having a lower end adapted for connection to the upper end of said support and an upper end adapted to engage a wall-portion of a well bore at a distance from said wall-engaging spring portions and maintain said common transverse plane about perpendicular to the central axis of such a well bore.

24. The well tool of claim 23 further including: means on said elongated body defining an enclosed chamber adapted to be sealed for providing buoyancy to said elongated body when said well tool is in well bore liquids.

25. The well tool of claim 22 wherein said spring members are normally bowed when relaxed and respectively have a normal lateral deflection Y_0 , said first and second spring means respectively acting longitudinally on the associated end of each of said spring members with a force of Q_1 , and said third spring means acting longitudinally on the associated end of each of said spring members with a force of Q_2 so that the net outwardly-acting force directed along said common transverse plane provided by each of said spring members is equal to:

$$\frac{6}{5} Y_0 \left[\frac{Q_1}{L_1} + \frac{Q_2}{L_s} \right]$$

where L_1 and L_s are respectively equal to the lengths of said longer and shorter spring portions.

26. The well tool of claim 25 further including: first and second variable electrical control means respectively connected between said upper and said one intermediate couplings and between said lower and said other intermediate couplings and adapted for independently providing first and second indications representative of flexural movements of said first and second pairs of spring members.

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