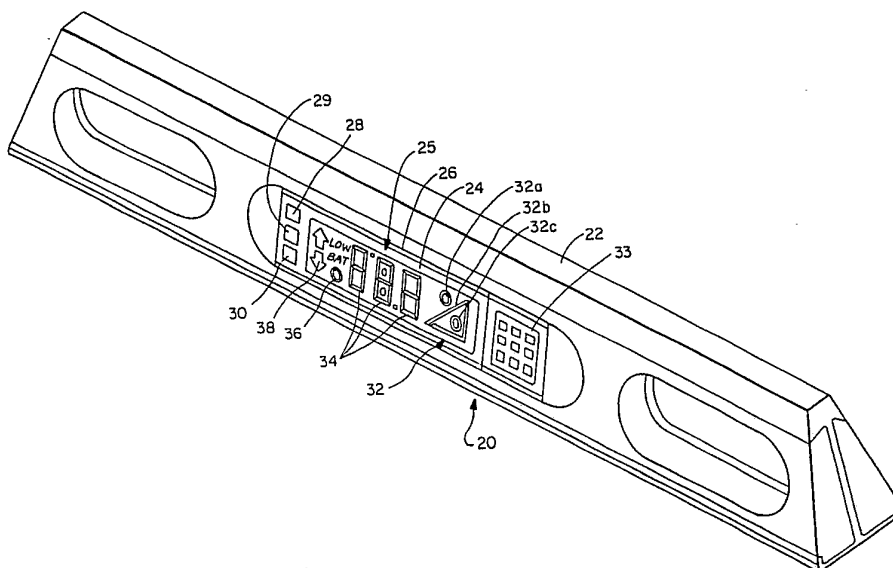




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**(54) Title:** DIGITAL INCLINOMETER**(57) Abstract**

An inclinometer (20) has a sensing unit (40) for providing a varying capacitance signal depending on the orientation of the inclinometer (20). An oscillator circuit unit (82) includes the sensor unit (40) as a capacitive element for providing a signal having a period and a frequency depending on the capacitance of the sensor unit (40). A unit (92) is provided for determining the period of the signal. A look-up table unit (96) stores a predetermined relationship between the period of the signal and the angle of orientation of the inclinometer (20). A comparison unit (94) then compares the period of the signal to the period stored in the look-up table unit (96) and selects the corresponding angle which is the angle of orientation of the inclinometer (20). The angle is then displayed on the inclinometer display (25).

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## DIGITAL INCLINOMETER

### Field of the Invention

The present invention relates to an inclinometer or level and, in particular, to an inclinometer or level with electronic sensing and readout capabilities.

### Background of the Invention

Currently there are a number of electronic inclinometer and level devices disclosed in the prior art. The simpler of these devices in general attempt to apply an electrical circuit to a known device, such as a bubble level, and therefrom directly provide a readout of the orientation of the level. Complicated inclinometers tend to take the same approach but are more bulky and cumbersome to use. In general these prior art inclinometers are difficult to manufacture due to alignment constraints and tolerances required to accurately position the sensing device into the housing. Errors in the manufacture of the sensing device and in the mounting of the sensing device in the housing can only be remedied through a practice of discarding faulty sensors and/or manufacturing the entire

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inclinometer with very exacting and costly procedures. Further, should the inclinometer not be rugged enough, ordinary field use would require that the inclinometer either be discarded when it provides inaccurate readings or sent back to the manufacturer for recalibration.

In addition, the prior art devices provide no compensation nor indication that the device while properly positioned in one plane, for example the pitch plane, could for example have too much of an angle in a perpendicular plane such as the roll plane so as to provide an inaccurate pitch reading. Also the effects of temperature on inclinometers are not accounted for.

Finally, most inclinometers provide for only one or two readout formats requiring additional use of tables and the like for translation into other desired readings.

#### Summary of the Invention

The present invention is directed to overcome the disadvantages of the prior art.

The present inclinometer of the invention is comprised of a sensor for providing at least a varying capacitance depending on the orientation of the inclinometer. The inclinometer further includes an oscillator circuit which includes the sensor as a capacitor element for providing a signal or a plurality of signals, each having a period and a frequency depending on the capacitance of the sensor. The inclinometer further includes a device for determining the period of each signal. A look-up table is provided for storing a relationship

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between the period of each signal and an angle of orientation of the inclinometer. A comparing unit is provided for comparing the period of the signal to a period stored in the look-up table which has a relationship to the angle being measured. Further, a display device is provided for giving selectable digital and analog readouts. The digital readouts can include by way of example angle, rise/run, and percent slope mode readouts.

The sensor for determining the orientation of the inclinometer includes a first plate having a plurality of isolated conducting first sectors which are clustered about an isolated conducting first central hub. The sensor further includes a second plate having a plurality of isolated conducting second sectors which are clustered about an isolated conducting second central hub. The first plate is positioned substantially parallel to the second plate with the sectors and the hubs aligned. A peripheral edge surrounds the aligned first and second plates to form a cavity there between. A fluid partially fills the cavity such that a change in orientation of the inclinometer causes the fluid to shift relative to the sectors and the hubs. Alternatively, the plates and sectors can be misaligned or the plates can be provided in a non-parallel or wedge shaped configuration and fall within the scope of the invention.

In an aspect of the invention, the sensor has three first sectors aligned with three second sectors to form sector pairs, each of which pair is a variable capacitor. The inclinometer provides for determining the period of a signal from each of these sector pairs, at least one of the highest and

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the lowest capacitance values of the sector pairs is for determining the general orientation of the inclinometer with the pair of sectors having a middle capacitance value being used for determining the exact angle. In the several cases where values of the signal pairs cross over each other, as where the highest and middle capacitance values and/or the lowest and middle capacitance are equivalent, either can be used.

In another aspect of the invention, the pair of hubs is provided as a passive element of an oscillator circuit for determining the roll orientation of the inclinometer and warning when there is excessive roll so as to indicate an inaccurate reading. The hubs also eliminate inaccuracies due to roll in an appropriate range before the warning of an inaccurate reading is provided by the inclinometer. It is to be understood that absent the hubs, the capacitance values associated with each sector or plate due to the amount of surface covered by the fluid can also be used to provide a warning and correction for excessive roll and/or yaw.

In another aspect of the invention the display can be a digital display including readouts of angle, slope, or rise to run, as well as an analog display which indicates to which side of level or plumb the inclinometer is positioned.

In another aspect of the invention, the inclinometer includes a field recalibration unit. Should the sensor shift its position relative to the rest of the electrical components or should the entire electrical package shift its position

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relative to the housing, the recalibration unit can be used to correct the readings accordingly.

Further, as the invention provides for the electrical unit to be inserted into one of various housings, each of which has a different length, the inclinometer would be calibrated after insertion into the appropriate length of housing in order to remove any errors due to that mounting.

In yet another aspect of the invention, the inclinometer includes a temperature compensation unit.

In still a further aspect of the invention, the look-up table is provided in permanent semiconductor memory in the inclinometer and is customized in manufacture to the specific sensor used in the inclinometer. Thus, any errors in the manufacture of the sensor or the mounting of the sensor or the manufacture of the inclinometer, generally, are automatically compensated for in an efficient and convenient manner without the expense of exact alignment and discarded unusable parts.

#### Brief Description of the Figures

Figure 1 is a perspective view of an embodiment of the inclinometer of the invention.

Figures 2A through 2C are front views of the analog display of the inclinometer of the invention.

Figure 3 is a sectional view of the sensor of the inclinometer of the invention.

Figure 4A through 4D are front and back views of sensor plates of an embodiment of the invention.

Figure 5 is a side view of an alternate embodiment of a sensor plate of the invention.

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Figures 6A through 6C, 7A and 7B, 8A and 8B, 9A and 9B and 10A through 10C shows representation of the sensor in various orientations.

Figure 11 depicts a representative schematic of a preferred embodiment of the electrical circuitry of the inclinometer.

Figure 12 depicts another preferred embodiment of the circuitry of the inclinometer of the invention.

Figure 13A and 13B show ideal and actual sensor performance.

Figure 14 is a block diagram and schematical flowchart of the methodology and structure for selecting the various modes of an embodiment of the invention.

Figure 15 is a block diagram and schematical flowchart of the methodology and structure for determining an angle.

Figure 16 is a block diagram and schematical flowchart depicting the methodology and structure for determining which sector has the best reading.

Figure 17 is a block diagram and schematical flowchart of the methodology and structure for providing for temperature compensation.

Figure 18 is a block diagram and schematical flow chart of an alternate methodology and structure for determining an angle.

Figure 19 is a block diagram and schematical flow chart of a methodology and structure for a look-up table determination.

Figure 20 is a look-up table determination structure.

Detailed Description of the Preferred Embodiments

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With respect to the Figures, and in particular to Figure 1, a preferred embodiment of the inclinometer is depicted and identified by the number 20. The inclinometer 20 includes one of a number of different lengthed rails such as rail 22 into which is removably inserted an electronic measurement unit 24 which has an outer housing 26. The face of the electronic measuring unit 24 includes a mode selector 28, a recalibration selector 29, and an accuracy range selector 30. The face further includes a combination degree, percentage and rise/run indicator 32, three seven element alphanumeric indicators 34, a low battery indicator 36 and direction indicator 38 which indicates which direction the inclinometer 20 should be moved in order to obtain a level or plumb reading. As will be more fully discussed herein below, the mode selector 28 allows the selection of the display modes which can selectively provide digital displays such as the angle, the rise/run, the percent slope, and also an analog display. The analog display as shown in Figures 2A through 2C includes a level indicator as shown in Figure 2A which comprises two dots. In 2B, the indicator includes three vertical lines located to the right of the dot indicating the right side is high. Figure 2C indicates that the left side is high. The degree that either side is high is indicated by the number of lines to the right or left of the two dots. Thus, three lines to the right of the two dots indicates that the level is higher to the right side than the level would be if only one line were displayed.

The inclinometer 20 includes a sensor unit 40 (Figure 3) which senses the inclination of the

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inclinometer 20 through a full 360 degrees. The sensor 40 consists of two plates 42, 44 which, in a preferred embodiment, are mirror images of each other. The sensor further includes a peripheral edge 46 which hold the plates in a spaced parallel relationship to each other and which defines an internal cavity 48. The peripheral edge 46 is conductive and grounded. Inside and partially filling the cavity is a fluid 50. In a preferred embodiment the plates 42, 44, are divided into three conductive but electrically isolated sectors, or triads, such as wedge shaped sectors 52, 54 and 56 (Figure 4A). These sectors describe an outer circle and are clustered about a central isolated and conducting hub 58. In a preferred embodiment, the sensor plate and the sectors 52, 54 and 56, and hub 58 are coated with a thin layer 60 of a dielectric material such as, for example, Teflon ® and the fluid 50 is conductive.

Plate 44 also has three isolated and electrically conducting sectors 53, 55, and 57 and an isolated and electrically conducting hub 59 coated with a thin layer 61 of dielectric material. Sectors 52, 54 and 56 and hub 58 are parallel to and aligned with sector 53, 55 and 57 and hub 59 respectively to form variable capacitors between each sector or hub and the electrically grounded fluid 50.

It is to be understood that hubs 58, 59 can be eliminated from sensor 40 and still have sensor 70 fall within the scope of the invention. However, for sensor 40 to have the advantageous insensitivity to roll, as discussed below, the sectors would be

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similarly shaped with a semicircle defining the inner border of each sector.

It is also to be understood that roll and yaw compensation can be accomplished with sectors without semicircular inner borders by accounting for the capacitance between each sector and edge 46 individually.

As can be seen in Figure 4B appropriate leads are directed from the back of the plate 42. In the preferred embodiment, the conductive fluid 50 fills half of the cavity so that fifty percent of the area is covered with conductive fluid at any one time. The conductive fluid and the peripheral edge 46 are appropriately grounded. The plates 40, 42, are constructed, in a preferred embodiment, of fiberglass reinforce circuit board material with the edge 46 being made of aluminum. The fluids in a preferred embodiment is a combination of an alkane and a ketone.

It is to be understood that the sensor 40 can also be constructed by having the cavity 48 filled with a dielectric fluid and removing the dielectric layer from plates. The advantage of the initial design using a conductive fluid is that the conductive fluid, in effect, reduces the distance between the pairs of capacitive plates to the thickness of the teflon layer 60, 61 thus allowing a high capacitance sensor 40 to be constructed without the manufacturing problems of placing the plates 42, 44 close to each other.

With the above arrangement, as the sensor unit 40 is moved through rotation, the amount of surface area of the fluid which comes in proximity to the various pairs of sectors varies making the sectors

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variable capacitors. Thus the sensor unit 40 allows for an economical, continuous, sensor output through 360 degrees of rotation.

To achieve continuous sensor output at all angles of inclination, the sensor design requires that the fluid intersect no more than one sensor plate separation line, such as line 62, 64, and 66 (Figure 4A) at any given angle of orientation of the inclinometer. Accordingly, it is highly advantageous that only an odd number of sectors be included in the design of the sensor unit 40. Alternatively, the sectors can have nonlinear plate separations as is shown at 68 in Figure 5. Further there is a high degree of resolution since the electrical circuitry described below allows for the selection of the one pair of adjacent sectors for measuring the capacitance and determining angle which always has a capacitance reading which is not less than 25 percent of the total capacitance of the given pair of sectors.

The pair of hubs 58, 59 define a donut configuration for sensors 40, and serve two functions. First, hubs 58, 59 serve to reduce the sensitivity of the sensor unit 40 to roll and yaw. Second, the hubs and associated circuitry cause the display to blink if there is any unaccepted error due to roll or yaw. As seen in Figure 6A, inclination is measured about the "Y" axis and is described in terms of pitch. Roll and yaw, if not accounted for, tend to add inaccuracies to the sensor as described below. By using the hubs the sensors are made less sensitive to roll and yaw, and in particular when the inclinometer is horizontal or vertical. Further, the hubs, when connected to an oscillator

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circuit as described below, can be used to give an indication that roll and/or yaw is outside of acceptable ranges for accurate readings. The capacitance difference between the first hub and the second hub indicates the roll or yaw is unacceptable. In Figure 6B, the sensor 40 is oriented at a pitch angle of zero degrees. It is clear from Figures 6A, 6B and 6C, that when there is no pitch or roll, that the yaw (rotation about the z axis) will not change the state of the sensor. That is to say that each sector will experience the identical wetted area regardless of yaw. Thus, at zero degrees pitch and roll, the sensor is insensitive to yaw. However, roll does affect the sensor's state at zero degree pitch and yaw. Figure 7B depicts a sensor 40 with a non-zero degree roll angle. As will be discussed herein below, the electronic measuring unit 24 would choose to use the pair of sectors 52, 53 (Figure 6A) for the angle calculation as this pair would give the most accurate value as more surface is wetter in comparison to sections 56, 57, and saturation has not occurred as in Sectors 54, 55.

In Figure 8A, 8B it is evident that the wetted area on each of the two sectors 52, 54 is changed due to the roll. However, due to the hub area which does not contribute to the capacitance measured between the sector 52 and ground, and between the sector 53 and ground, the sum of the two areas of the sectors 52, 53 remains constant. The gain of area 70 by sector 52 is exactly cancelled by the loss of area 72 by sector 53. Thus, using this geometry at roll and pitch of near 0 degrees, the sensor unit 40 is essentially insensitive to roll.

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In Figures 9A and 9B the advantage of the hubs 58, 59 is graphically demonstrated. In these Figures, with no hub section removed, the gain in the wetted area of sector 52, which is area 74 is greater than the loss in the wetted area by sector 53, which is area 76. Thus, the sum of the two wetted areas would not in general be a constant.

An analogous analysis can be done for yaw with the sensor oriented vertically (pitch equal to 90 degrees or 270 degrees) with the similar conclusions regarding yaw insensitivity. Thus it can be understood that there is great advantage to having the variable capacitance part of the sensor resemble a donut defined by an inner and an outer concentric circle.

The radius of the hubs 58, 59, or the inner concentric circle of the sectors, determines how much roll, and also yaw, the sensors can tolerate around zero, ninety, one hundred and eighty, and two hundred and seventy degree pitches without any error. In Figure 10A, the sensor unit 40 has zero degrees pitch and has rolled sufficiently to cause the liquid surface to be a distance of plus or minus  $d$  from the center line. If the distance  $d$  is less than or equal to  $r \sin(\theta)$  where  $r$  is the radius of the hub and  $\theta$  is the angle between the fluid line at zero degrees roll, zero degrees yaw, and the closest sector separation line, the loss in wetted area 78 equals the gain of area 80. Thus as demonstrated before, the total capacitance of the pair of sectors is unchanged. In Figure 10B, the distance  $d$  is greater than  $r \sin(\theta)$ , hence the wetted areas are unequal and error would result in the sensed angle. Thus outside a range of values as

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defined by the above geometry of the sensor 40, sensor 40 is no longer insensitive to roll or yaw. The relationship between  $d$  and the roll angle,  $\phi$ , is a function of the thickness  $t$  of the sensor as demonstrated in Figure 10A, 10B and 10C. Thus, to tolerate a roll angle of  $\phi$  at zero degrees pitch, it is required that:

$$d = (t/2)\tan(\phi) < r\sin(\theta)$$

where  $r$ ,  $\theta$  and  $t$  are properties determined during sensor construction. By setting  $\theta$  equal to 45 degrees, the sensor has an equivalent insensitivity to yaw at 90 degrees pitch as it does to roll at 0 degrees pitch. Therefore,  $t$  and  $r$  can be varied to satisfy the above equation for any reasonable roll or yaw angle. The inclinometer 20 becomes less sensitive to roll and yaw with a decreased  $t$  (thickness) value and an increased  $r_i$  (radius) value. However, as  $r_i$  becomes larger, the maximum capacitive value becomes smaller and the resolution of the inclinometer is reduced.

Each of the variable capacitors formed between the sectors and hubs and the electrically grounded peripheral edge 46, form passive capacitive elements in an oscillator circuit such as the oscillator circuitry 82 in Figure 11. Circuitry 82 in one of the preferred embodiments includes first oscillator 84 which is connected to the variable capacitance defined by sector 52 with the other oscillators so communicating with the other sectors and with the final two oscillators, connected to the hub. The output of each of these oscillators are periodic waves such as square waves which are communicated by OR gate 88 to a microprocessor 90. The frequency and period of the oscillator circuit is thus related

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to the area that a given sector has in contact with a fluid and thus the angle of inclination or pitch of the inclinometer. The period is determined by timing a fixed number of pulses from the given oscillator. In the microprocessor 90 there is a unit 92 for determining the period of the signals coming from the oscillator circuitry 82 and a unit 94 for comparing the determined period with a look-up table contained in PROM 96. During manufacture, each of the sensor units 40 is calibrated and the calibration is stored in the PROM 96 which is part of the electrical measuring unit 24. Thus, any irregularities in the sensor can be accounted for so that the sensor irregularities do not cause errors in the readings which are taken with the inclinometer 20. The PROM 96 stores a look-up table which relates the period of a signal to the pitch angle in degrees. Of course it is understood that other mathematical relationships can be stored so that the appropriate display is created such as the slope, rise to run or analog displays. The microprocessor then drives a display driver 98 which in turns drives the display 25.

As indicated above, having the individual period versus angle relationship stored in the PROM 96 for each sensor allows the sensors to vary due to manufacturing tolerances and still have the readings accurate as the irregularities of each sensor are compensated for by the stored look-up table. Another distinct advantage of the inclinometer is that due to the look-up table it can easily accommodate sensors with nonlinear responses as long as the responses are continuous and repeatable.

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As depicted in Figures 13A and 13B, the performance of the actual sensors vary from that of any ideal sensor. This difference is due to the variation in, for example, dielectric thickness, alignment of the sensor plates, chemical impurities in the fluid conductor, irregularities in the plates, volumetric variations of fluid and surface imperfections in the coatings.

In Figures 13A and 13B lines 100, 102 and 104 correspond respectively to sector pair 52, 53, sector pair 56, 57 and sector pair 54, 55. That is to say, for example, that the capacitance value between sector 52 and ground and sector 53 and ground are summed to produce line 100. Thus, correlating Figures 6A through 6C, with Figure 13A and 13B, it can be seen that at point 106, line 100 is fully saturated giving the highest capacitance reading, line 104 represents the lowest capacitance reading as the sector pair 54, 55 has the least fluid positioned therebetween, and line 102 gives the middle capacitance reading which is the reading used for determining the actual angle as will be discussed hereinbelow. Corresponding curves in Figure 13B are numbered with corresponding prime numbers.

As another example of how an angle is determined it is to be assumed that the inclinometer is pitched to an angle of 30 degrees. It is also to be assumed that the readings has been normalized and temperature compensated so as to behave like the ideal graphs of Figure 13A. Thus, selecting point 109, it is determined from Figure 13A that sector pair 52, 53, line 100, has a normalized capacitance of 1.0, sector pair 56, 57 line 102, has a

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normalized capacitance of 0.125, and sector pair 54, 55, line 104 has a capacitance of 0.375. For simplicity sector pair 52, 53, sector pair 56, 57, and sector pair 54, 55 shall be referred to as pair 1, 2, and 3 respectively. Thus the ordering of the pair from the highest to the lowest capacitance value would be 1, 3, 2. This order uniquely identifies the sextant in which the inclinometer resides. The sextant is one of six 60 degree ranges of pitch. The six non-overlapping sextants can be arranged in the combinations of: 123, 132, 213, 231, 312, and 321. In the 360 degrees of possible pitch angle the sextant of our example is the range from 15 degrees to 75 degrees. It has been found empirically that the most linear readings occur when a sector pairs reading is between that of the other two pairs. A sector pair is associated with two given sextants, and that sector pair is used to determine the angle. Using this criterion, sector pair 54, 55, line 104, is the optimal pair for readings in this example. The microprocessor would use the sextant value (in this case pair 1, highest value, or pair 2, lowest value) to determine which one of six curves in the look-up tables to use. It would then use the pair 3 reading (capacitance = 0.375) to find the angle in the look-up table, interpolating between points in the look-up table, if necessary. It is to be understood that as line 102 is relatively close to line 104 at this angle value, line 104 could also be used to determine the angle with the appropriate algorithm. Further as previously indicated when the lines 100, 102 and 104 cross the value of either line at the crossing point can be used to determine the angle.

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Figure 12 depicts another preferred embodiment of the circuitry of the inclinometer 20 with component similar to the circuitry of Figure 11 having corresponding primed numbers. In Figure 12 the oscillator circuitry 110 includes an analog multiplexing switch 112 which allows the various signals from the capacitor elements to be selectively switched into an oscillator circuit 114 and therefrom directed to the microprocessor 90' in much the same manner as found in the circuitry of Figure 11. One great advantage of the circuitry of Figures 11 and 12 is that there is a interface between the microprocessor 90 and the sensor unit 40, which does not include an analog to digital converter.

The block diagrams of Figures 14 through 17 further describe the invention. In block diagram Figure 14, block 116 determines the mode by the appropriate selection from mode switch 28. The selections are offered by blocks 120 through 126 and include an angle mode, rise/run mode, percent slope mode and analog display mode respectively. Prior to selecting any of the modes, the user can determine the accuracy range by using button 30. Button 30 is associated with blocks 128 and 130. In the preferred embodiment there are a number of accuracy ranges which are determined by the number of places past the decimal point at which the measurements of the period are adjusted by rounding off, truncating and the like.

The calibration mode is exemplified by blocks 132 to 140. It is to be understood that this recalibration can be accomplished in the field at any time. Reasons for recalibrating the

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inclinometer would be that the electrical measurement unit 24 has been inserted into a different rail with different alignment tolerances and thus the sensor would be slightly offset from an ideal position. This offset can be actively accommodated by the recalibration mode. In the recalibration mode, block 132 indicates that the inclinometer is first positioned on a surface and the recalibration button is pressed. This stores the value of this first angle as determined by the determine angle routine of block 134. The determine angle routine is more fully described below with respect to Figure 15. Then the inclinometer is rotated 180 degrees and placed back on the same surface. A second angle measurement is taken and determined as indicated for blocks 136 and 138 and the value stored by touching the recalibration button. The two stored angles are averaged together. In an ideal situation, the average would be zero. Any value greater than or less than zero is used as the offset correction factor in all the other readings from the inclinometer until the inclinometer is again recalibrated.

The angle mode is determined with blocks 142 and 144. Block 142 is the determine angle routine as exemplified by the block diagram of Figure 15 and block 144 is the display angle block. The rise/run mode 122 is determined by first using the determine angle routine of block 146 and the display routine of block 148. The display function is calculated at twelve times the tangent of the angle determined by block 146. This gives the rise to run value of inches per foot.

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The percent slope determination is made at block 124 through blocks 150 and 152. In block 150 the determine angle routine is accomplished and in block 152 the displayed value is the value of the tangent of the angle times 100 to give a percent slope display.

Finally, the analog display as described hereinabove can be selected at block 126. The analog display has predetermined set points whereby above a certain inclination, one line to the right or left of the center line (two dots) is indicated. Above a yet higher value, two lines to the right or left of the center point is indicated. Still above a third higher value, three lines to the right or left of the center line of the display is indicated.

A key pad 33 is included to allow the user to modify and redefine the output provided by blocks 120, 122 and 124. Additionally other outputs can be programmed with key pad 33.

Viewing Figure 15, the determine angle routine is presented through blocks 154 to 174. At block 154 each of the sector pairs, and hub pair is read as previously discussed. The readings are normalized for temperature at block 156 as will be discussed hereinbelow and then the best sector for measuring the angle is determined at block 158. As previously discussed with respect to points 106, 106' and 109 and as discussed with respect to Figure 16 the values from the sector pairs are placed in ascending order, the highest and the lowest capacitance values are excluded and the remaining sector pair is used to determine the angle because it gives the most accurate reading. Again at a cross over point where two of these capacitance values are

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the same, either of the two same values can be selected to determine the angle. At block 160 the angle is determined from the look-up table in the PROM. The value, if not exact, is interpolated between two close values in the look-up table and the value is rounded according to the accuracy setting in block 164. Then a determination is made as to how to energize the display at block 166 to provide the appropriate readings. At block 168, if the angle reading indicates the inclinometer is upside down, the logic of the inclinometer automatically inverts the display at block 170. At block 172, if the roll and/or yaw is outside of acceptable limits, the display blinks indicating to the user that the inclinometer should be repositioned.

In Figure 16, block 176 through 182 determine which sector has the best reading. This is accomplished by determining the sector pair that has the highest capacitance (most often saturation) at block 176 and the sector pair that has the lowest capacitance at block 178. The pairs are ordered and the general orientation of the inclinometer, as previously discussed, is determined at block 180. At block 182 the sector pair which have other than the highest and lowest capacitance configuration is determined. From the value of this pair the angle is determined from the selected look-up table curve as represented in block 160. This determination allows the inclinometer to select one of the several performance curves (Figure 13B) stored in the look-up table.

In Figure 17, the block diagram describe the structure used to normalize the temperature. This

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normalization is accomplished by blocks 186 through 192.

The normalization of the temperature is accomplished beginning at block 186 where reference values have been stored, as previously determined at a specific temperature during manufacture. For temperature normalization,  $Q$  = field measured value for each sector pair and  $C$  = the stored calibration table value of each sector as determined during manufacture. Each of these values  $Q$  and  $C$  is the sum of the capacitance values between adjacent sectors and the ground provided by the edge 46. The reference values stored in the look-up table are  $C_{i, \min}$ , and  $C_{i, \max}$ .

For each pair has a normalization value that is determined according to the formula:

$$\text{Norm} = (Q_i - C_{i, \min}) / (C_{i, \max} - C_{i, \min}).$$

The normalization factor for the total of  $N$  sectors is:

$$\text{Norm}_T = (\text{Norm}_1 + \text{Norm}_2 + \text{Norm}_3 + \dots + \text{Norm}_N).$$

The  $Q_i$  values are determined in block 188. The temperature correction factor as the determined block 190 is:

$$K_T = (N/2) / \text{Norm}_T.$$

In block 192 this temperature correction value is multiplied by the reading from the selected sector pair to compute the value to be used in the look-up table to determine the angle of inclination. In the present example with three sector pairs,  $N=3$ .

An alternate angle determination routine includes a least squares fit between the three measured angles and their values determined during calibration. This would require minimizing the sum

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of the squares of the difference between each of the measured angles and the calibrated values as a function of angle.

Angle theta = the angle to be determined

$$[ (Q_1 - C_1(\theta))^2 + (Q_2 - C_2(\theta))^2 + (Q_3 - C_3(\theta))^2 ]$$

where Q = measured values

C(theta) = calibrated values as a function of angle (either as an expression or in tabular form)

Analytically this minimization can be accomplished by differentiating the function with respect to theta and setting the result equal to zero. The theta that solves this equation is the desired theta.

If the data is in the tabular form a search is performed starting with the assumption that:

$C_1(\theta) = Q_1$  which would give a theta

which would then give  $C_2(\theta)$  and  $C_3(\theta)$  allowing the calculation:

$$[ (Q_1 - C_1(\theta))^2 + (Q_2 - C_2(\theta))^2 + (Q_3 - C_3(\theta))^2 ]$$

This expression is then iteratively evaluated at theta + delta where delta is a predefined small angle. Depending on the effect of delta, delta is modified to result in the minimization of  $[ (Q_1 - C_1(\theta))^2 + (Q_2 - C_2(\theta))^2 + (Q_3 - C_3(\theta))^2 ]$  to within an acceptable range of zero. This is accomplished by block 200 to 208 of Figure 18.

An alternative sensor can use variable resistors 210, 212, 214 (Figure 11) in addition to a variable capacitor (recapacitor). Additionally a variable resistor can be used instead of a variable capacitor.

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A sensor with a variable resistor and a variable capacitor is similar to the embodiments described with respect to Figure 11 and 12, but would not require the dielectric coating on the plates. The fairly low conductance of the fluid allows the fluid to be conceptualized as a capacitor with resistors in parallel and series with it. The oscillator circuit still functions, but in a less linear way, because now, not only is the capacitance of the sensor a function of the wetted area of a given sensor plate, but also the fluid resistance is a function of the wetted area.

A method and structure for determining the look-up table is presented in Figures 19 and 20. In Figure 19 the look-up table routine is presented in blocks 210 through 218. In block 212, the inclinometer 20 is placed on a rotating table such as rotating table 220 in Figure 20. The table is then stepped through 360° as presented in block 214. The position of the rotating table and the electrical signal indicating the angle of the inclinometer are recorded at blocks 216 in Figure 19 and communicated by lines 222, 224 and 226 to storage unit 230 in Figure 20. This information can then be provided to a memory device such as the PROM 96 in Figure 11.

#### Industrial applicability

The inclinometer 20 of the invention is used in the following manner. First an appropriately sized rail, whether 2, 4, 6 or 12 feet long, or of another length, is selected. Then the electrical measuring

-24-

unit 26 is inserted into the rail. The unit is calibrated using the recalibration routine of block 118. Then the range accuracy is selected at selector 30 and the mode selector 28 is used to determine which mode is to be read out. The inclinometer is set in a desired location and an appropriate reading is determined.

From the above, it can be seen that the present inclinometer 20 has significant advantages with respect to ease of construction, ease of use, accuracy and reliability. In addition to the advantages, aspects and objects of the invention as described hereinabove and, in particular, in the summary of the invention, other objects, aspects, and advantages of the invention can be obtained through review of the claims and the figures appended hereto. It is to be understood that although selected embodiments are presented herein, a multitude of other embodiments are possible and within the scope of the invention as claimed. As for example, non-capacitative type sensors or sensors using capacitive as well as other devices can be used and fall within the scope of the invention.

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We Claim:

1. An inclinometer comprising:
  - a sensor means for providing varying capacitance depending on the orientation of the inclinometer;
  - an oscillator circuit means including said sensor means as a capacitive element for providing a signal having period and a frequency dependant on the capacitance of the sensor means;
  - means for determining the period of the signal;
  - look-up table means for storing a relationship between the period of a signal and the orientation of the inclinometer;
  - means for comparing the period of the signal to the periods stored in the look-up table means and for selecting a corresponding orientation;
  - means for displaying the results of the comparing means.
2. The apparatus of Claim 1 wherein the sensor means includes:
  - a first plate having a plurality of isolated, conducting first sectors which first sectors are clustered about an isolated, conducting central first hub;
  - a second plate having a plurality of isolated, conducting second sectors which second sectors are clustered about an isolated, conducting central second hub;
  - said first plate positioned adjacent to said second plate;

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peripheral edge means for defining a cavity between said first and second plates; and  
a fluid partially filling said cavity such that at all orientations of the sensors there is fluid positioned between said first and second hubs.

3. The apparatus of Claim 2 wherein the oscillator circuit means includes means for providing a signal dependant on the capacitance of selected and adjacent pairs of said first and second sectors.

4. The apparatus of Claim 3 wherein said oscillator circuit means include separate oscillator circuits for each of said first and second sectors.

5. The apparatus of Claim 3 wherein said oscillator circuit means includes an analog switch which can select between each of said first and second sectors for providing a signal from any selected sector.

6. The apparatus of Claim 3 wherein said sensor includes three first sectors positioned adjacent three second sectors, wherein said means for determining the period of a signal includes means for ordering at least one of said three first or three second sectors from the highest capacitance configuration to the lowest capacitance configuration.

7. The apparatus of Claim 6 including:

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said ordering means for selecting and using the sector with the highest or the lowest capacitance configuration for determining a range of orientation for the inclinometer and the sector with the middle capacitance configuration to determine the orientation of the inclinometer within said range.

8. The apparatus of Claim 3 including:  
said oscillator circuit means for providing a signal dependant on the capacitance difference between said first hub and said second hub to determine the roll or yaw orientation of the inclinometer, where the pitch orientation is the orientation to be determined by the look-up table.

9. The apparatus of Claim 8 including:  
indicator means for indicating when the roll or yaw orientation of the inclinometer is greater than a preset limit.

10. The apparatus of Claim 2 wherein said first plate has an odd number of first sectors and said second plate has an odd number of second sectors.

11. The apparatus of Claim 6 wherein said means for displaying the results can invert the display of an orientation value of the inclinometer dependant on which pair of sectors has the highest or lowest capacitance.

12. The apparatus of Claim 1 wherein said means for displaying the results include means for

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providing one and more indicators to the left and right of a center line depending on the degree to which the inclinometer is inclined to the right or left.

13. The apparatus of Claim 1 including means for recalibrating, comprising:

means for storing a first representation of an orientation with the inclinometer in a first position;

means for storing a second representation of an orientation with the inclinometer in a second position which is rotated  $180^{\circ}$  from the first position;

means for averaging the first and second representation to determine an offset correction factor; and

means for combining the offset correction factor with further signals representative of the orientation of the inclinometer.

14. The apparatus of Claim 1 including:

means for compensating for a change in temperature.

15. The apparatus of Claim 14 wherein said temperature compensation means includes:

means for storing a reference value for the sensor means;

means for determining a correction factor and applying said correction factor to a value determined by the means for determining the period for the signal.

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16. The apparatus of Claim 2 including a means for compensating for a change in temperature comprising:

means for storing reference values which are minimum and maximum outputs of the period determination means for each pair of sectors of the first and second plates at a preselected temperature;

means for combining the reference values with the current values for each pair to obtain a normalization value where:

$Q_i$  = the current stored calibration value for each pair

$C_{i, \min}$  = the minimum stored calibration value for each pair

$C_{i, \max}$  = the maximum stored calibration value for each pair

Then:

$$\text{Normalization Factor} = \text{Norm}_i = \frac{Q_i - C_{i, \min}}{C_{i, \max} - C_{i, \min}}$$

And:

$$\text{Total Normalization Factor } N_T = \sum_{i=1}^N \text{Norm}_i$$

Where  $N$  = Total number of pairs

And:

$$\text{Correction factor} = K_T = \frac{N/2}{N_T}$$

And, the compensated value to be compared with the look-up table is  $K_T Q_i$ .

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17. The apparatus of Claim 1 including means for recalibrating comprising:

means for storing a first representation of orientation with the inclinometer in a first position;

means for storing a second representation of orientation with the inclinometer in a second position which is rotated  $180^{\circ}$  from the first position;

means for setting the average of the first representation and the second representation to a zero reference signal value.

18. A sensor for determining orientation including:

a first plate having a plurality of isolated conducting first sectors, which first sectors are clustered about an isolated, conducting central first hub;

a first dielectric layer covering said first plate;

a second plate having a plurality of isolated, conducting second sectors, which second sectors are clustered about an isolated, conducting central second hub;

a second dielectric layer covering said second plate;

said first plate positioned substantially parallel to said second plate with the first dielectric layer facing said second dielectric layer;

peripheral edge means for defining a cavity between said first and second plates;

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a conducting fluid partially filling said cavity such that at all orientations of the sensor there is fluid positioned between said first and second hubs.

19. The sensor of Claim 18 wherein said first plate includes an odd number of substantially identically wedge shaped first sectors, the outer edge of which defines a first circle, clustered about the first hub which is substantially circular;

said second plate includes an odd number of substantially identically wedge shaped second sectors, the outer edges of which define a second circle, clustered about the second hub which is substantially circular;

which first sectors are aligned with respect to said second sectors; and

which first hub is aligned with respect to said second hub.

20. The sensor of Claim 18 wherein said conductive fluid is electrically grounded.

21. The sensor of Claim 18 wherein said fluid fills said cavity such that substantially half of each of said first and second plates are covered by the fluid.

22. The sensor of Claim 18 including an odd number of first sectors and an odd number of second sectors.

23. The sensor of Claim 18 wherein each of said first sectors have borders which are

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nonlinear and each of said second sectors have borders which are nonlinear.

24. A sensor for determining orientation including:

a first plate having a plurality of isolated conducting first sectors which first sectors are clustered about an isolated, conducting central first hub;

a second plate having a plurality of isolated, conducting second sectors which second sectors are clustered about an isolated, conducting central second hub;

said first plate positioned substantially parallel to said second plate;

peripheral edge means for defining a cavity between said first and second plates; and

a fluid partially filling said cavity such that at all orientations of the sensor there is fluid positioned between said first and second hubs.

25. The sensor of Claim 24 wherein said fluid is a dielectric.

26. The sensor of Claim 24 wherein said first and second hubs are circular and aligned with each other.

27. The sensor of Claim 24 wherein said first plate includes three substantially identically wedge shaped first sectors, the outer edge of which defines a first circle, clustered about a substantially circular first hub;

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said second plate includes three substantially identically wedge shaped second sectors, the outer edges of which define a second circle, clustered about a substantially circular second hub;

which first sector are aligned with respect to said second sectors; and

which first hub is aligned with respect to said second hub.

28. The sensor of Claim 24 wherein said fluid is electrically grounded.

29. The sensor of Claim 24 wherein said fluid fills said cavity such that substantially half of each of said first and second plates are covered by the fluid.

30. The sensor of Claim 24 including an odd number of first sectors and an odd number of second sectors.

31. The sensor of Claim 24 wherein each of said first sectors have borders which are nonlinear and each of said second sectors have borders which are nonlinear.

32. The apparatus of Claim 1 wherein the sensor means includes:

a first plate having a plurality of isolated, conducting first sectors, which first sectors have an inner curved border defining a first center, generally circular, area;

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a second plate having a plurality of isolated, conducting second sectors, which second sectors have an inner curved border defining a second central, generally circular area;

said first plate positioned substantially parallel to said second plate;

peripheral edge means for defining a cavity between said first and second plates; and

a fluid partially filling said cavity such that at all orientations of the sensors there is fluid positioned between said first and second central areas.

33. A sensor for determining orientation including:

a first plate having a plurality of isolated conducting first sectors, which first sectors have an inner curved border defining a first central, generally circular, areas;

a first dielectric layer covering said first plate;

a second plate having a plurality of isolated, conducting second sectors, which second sectors have an inner curved border defining a second central, generally circular, area;

a second dielectric layer covering said second plate;

said first plate positioned substantially parallel to said second plate with the first dielectric layer facing said second dielectric layer;

peripheral edge means for defining a cavity between said first and second plates;

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a conductive fluid partially filling said cavity such that at all orientations of the sensor there is fluid positioned between said first and second central areas.

34. A sensor for determining orientation including:

a first plate having a plurality of isolated conducting first sectors, which first sectors have an inner curved border defining a first central, generally circular, area;

a second plate having a plurality of isolated, conducting second sectors which second sectors have an inner curved border defining a second central, generally circular, area;

said first plate positioned substantially parallel to said second plate;

peripheral edge means for defining a cavity between said first and second plates; and

a fluid partially filling said cavity such that at all orientations of the sensor there is fluid positioned between said first and second central areas.

35. The apparatus of Claim 6 which two of said pairs of sectors can have the same capacitance configuration, which same capacitance configuration can be the highest capacitance configuration or the lowest capacitance configuration.

36. The apparatus of Claim 7 wherein the middle capacitance configuration can be equal to the highest capacitance configuration or to the lowest capacitance configuration.

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37. The apparatus of Claim 8 including:  
indicator means for indicating when  
the roll or yaw orientation of the inclinometer is  
greater than a preset limitation, said limitation is  
defined as follows:

with:

$r$  = the radius of the first  
and the second hubs

$t$  = the thickness of the  
sensor means

$\phi$  = the roll angle

$\phi$  is such that:

$r > \frac{1}{2}t \tan(\phi)$

38. The apparatus of Claim 1 which said  
means for displaying the results can invert the  
display of an orientation value dependent on the  
apparatus orientation.

39. The apparatus of Claim 2 wherein the  
first plate is parallel to the second plate.

40. A method for determining and indicat-  
ing inclinations with an inclinometer comprising:

generating an electrical signal  
having a signal property which varies with respect  
to the inclination of the inclinometer;

identifying and storing said signal  
property;

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converting said signal property into  
an inclination value;

displaying said inclination value.

41. The method of claim 40 including a  
recalibration step of:

storing a first representation of a  
signal property of a first position of an  
inclinometer;

storing a second representation of a  
signal property of a second position of an  
inclinometer with the inclinometer rotated 180° from  
the first position;

setting the average of the first  
representation and the second representation to a  
reference signal value.

42. The method of Claim 40 including the  
initial calibration steps of placing the  
inclinometer upon a rotating table;

stepping the table through  
substantially 360°;

simultaneously storing a plurality of  
electrical signals and the position of the table.

43. The method of Claim 42 including the  
step of simultaneously recording the temperature.

44. The method of Claim 40 including:

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selectively inverting the displayed angle reading dependent on the position of the inclinometer.

45. The method of Claim 40 including:

selectively displaying the angle reading as one of (a) degree of inclination, (b) percent slope and (c) rise to run.

46. The method of Claim 40 including:

providing an analog display of inclination.

47. The method of Claim 40 including:

providing a user definable display mode.

48. The method of Claim 40 including:

providing for temperature compensation.

49. The method of Claim 48 including:

storing reference temperature values; determining a correction factor based on the reference temperature values, and actual values;

applying said correction factor to the actual values.

50. The method of Claim 40 including:

-39-

adjusting the accuracy of the display.

51. The method of Claim 40 wherein said converting step includes applying a least squares formula between measured angle values and angle values determined during calibration.

52. The method of Claim 51 wherein said converting step includes:

with  $C_i(\text{theta})$  = calibrated angle value;

$Q_i$  = measured angle values;

and the least squares formula =

$$[ (Q_1 - C_1(\text{theta}))^2 + (Q_2 - C_2(\text{theta}))^2 + (Q_3 - C_3(\text{theta}))^2 + \dots + (Q_N - C_N(\text{theta}))^2 ]$$

then differentiating the least squares formula;

setting the result equal to zero;

determining theta.

53. The method of Claim 40 wherein said generating step includes:

providing an electrical signal that varies with capacitance.

54. The method of Claim 40 wherein said generating step includes:

providing an electrical signal that varies with resistance.

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55. The method of Claim 40 wherein said generating step includes:

providing an electrical signal that varies with capacitance and resistance.

56. The method of Claim 40 including the steps of providing temperature compensation by:

measuring and storing a signal property at a calibration temperature,

measuring and storing a signal property at an actual temperature;

normalizing the signal property at the actual temperature based on the signal property at the calibration temperature.

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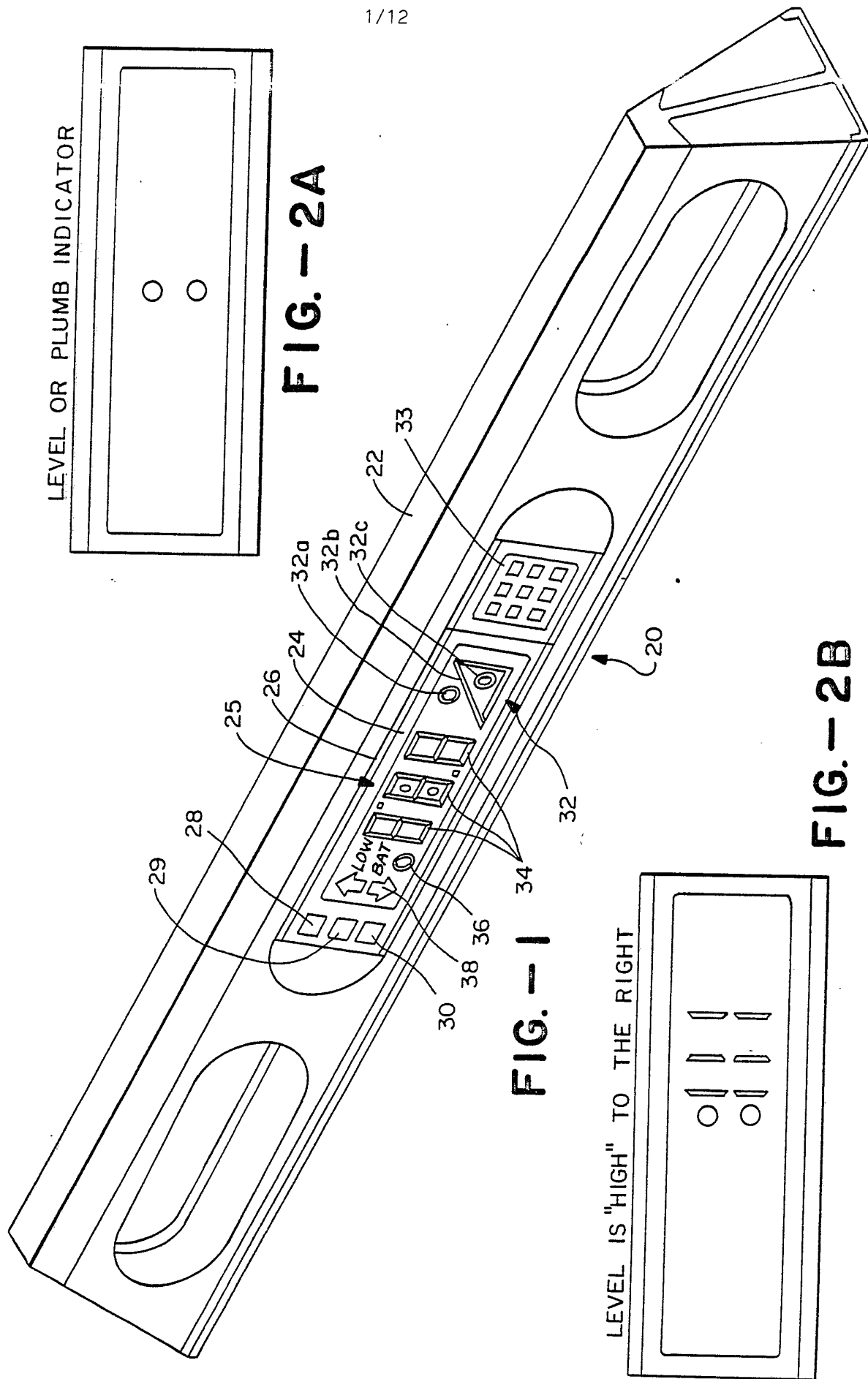


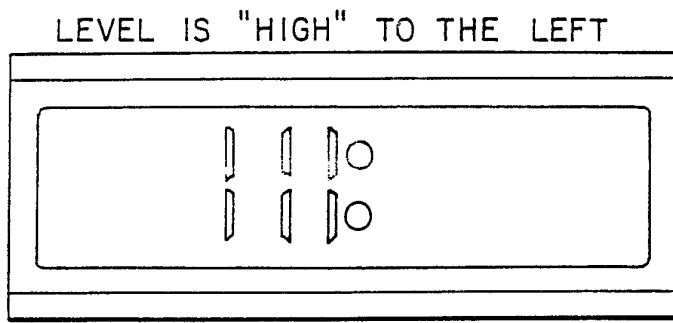
FIG. - 2A

FIG. - 1

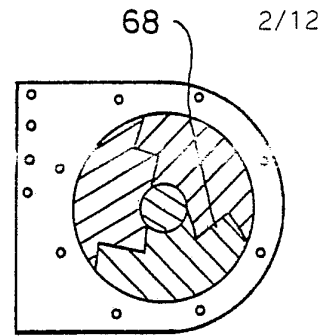
FIG. - 2B

LEVEL IS "HIGH" TO THE RIGHT

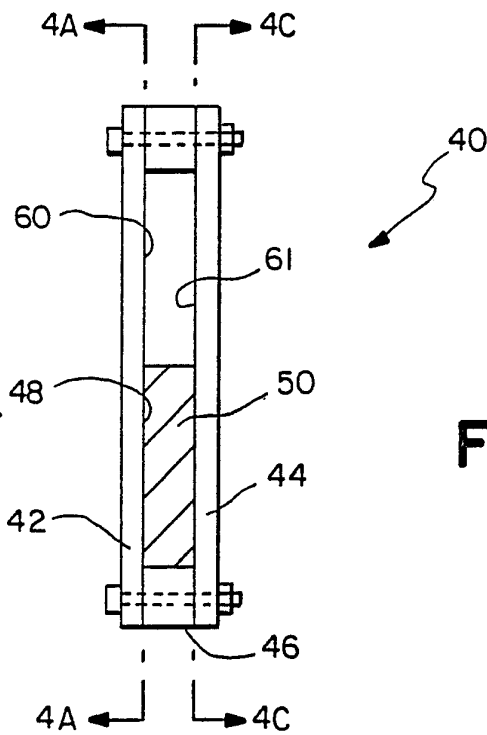
LEVEL OR PLUMB INDICATOR



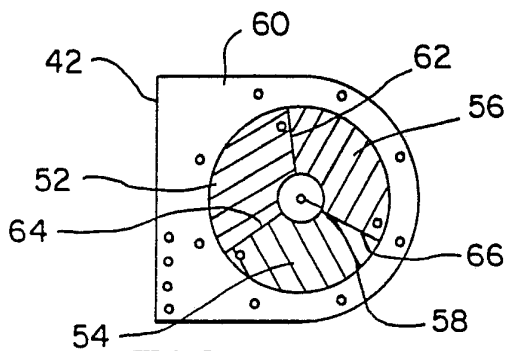
**FIG. - 2C**



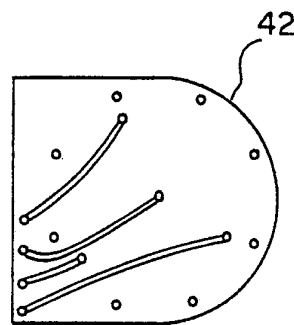
**FIG. - 5**



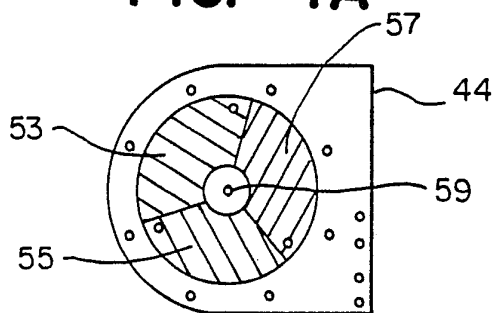
**FIG. - 3**



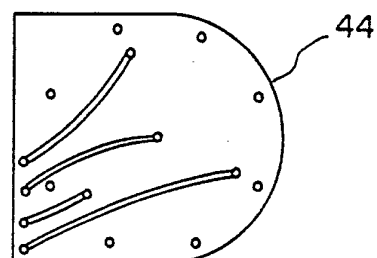
**FIG. - 4A**



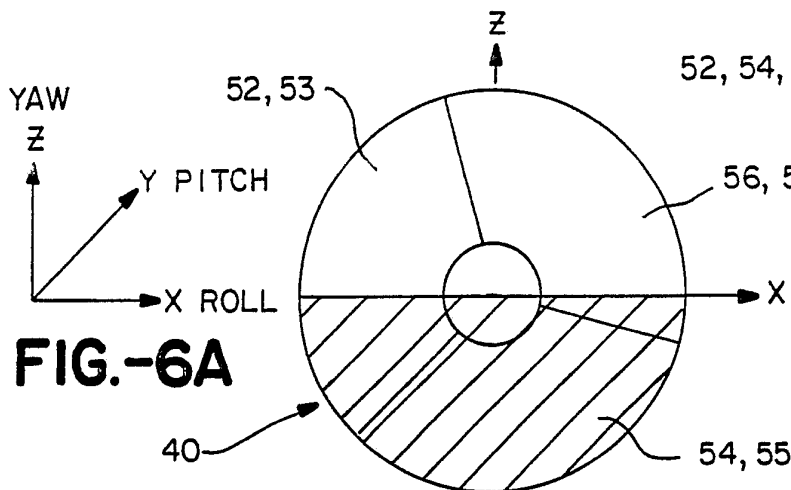
**FIG. - 4B**



**FIG. - 4C**

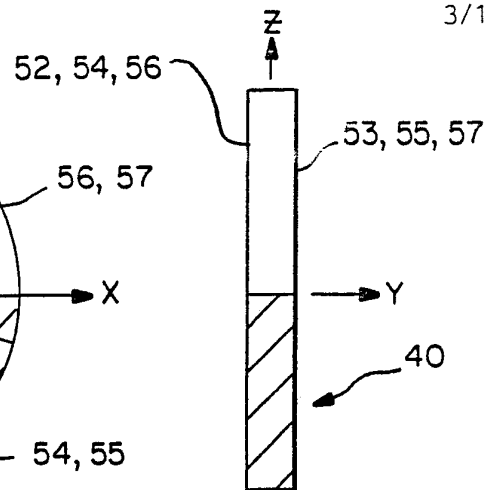


**FIG. - 4D**

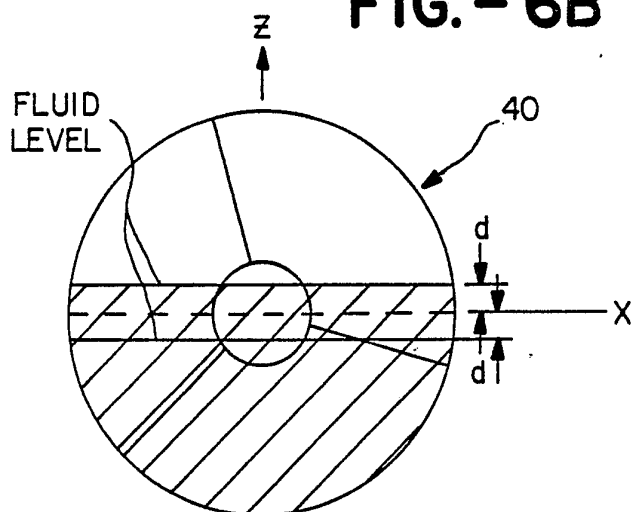


**FIG.-6A**

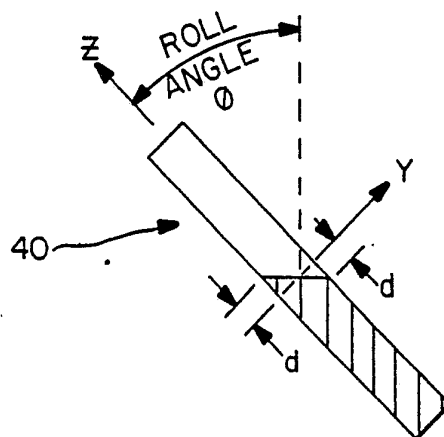
**FIG. - 6B**



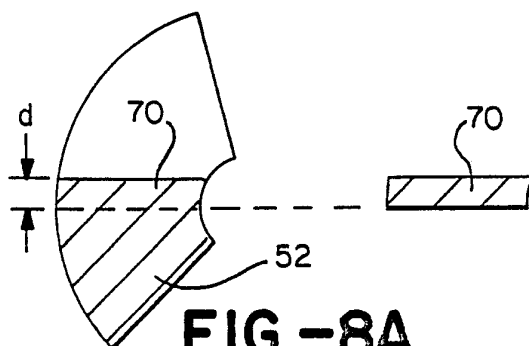
**FIG.-6C**



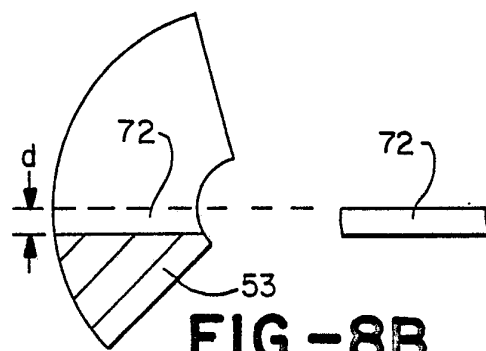
**FIG. - 7A**



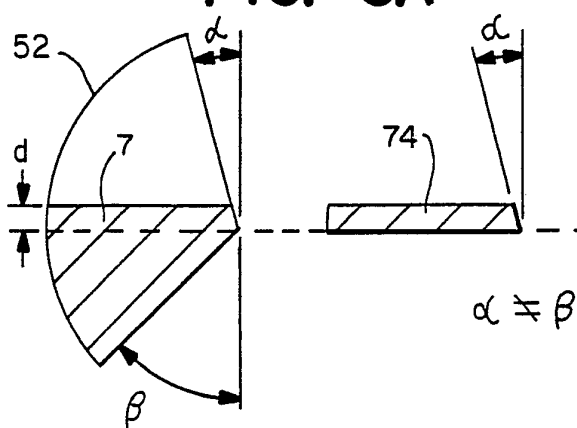
**FIG.-7B**



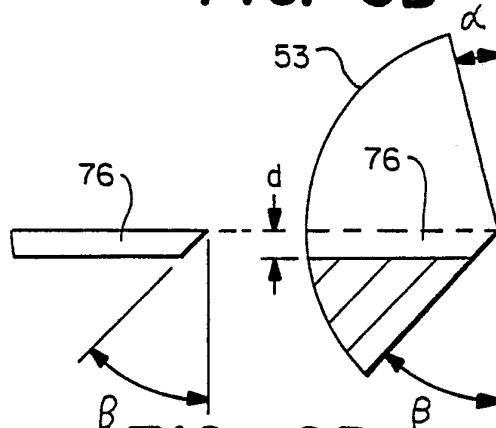
**FIG.-8A**



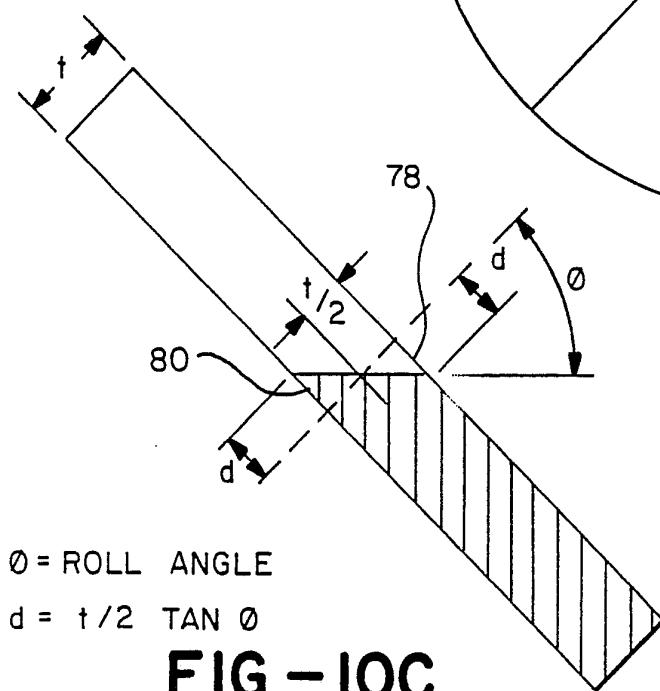
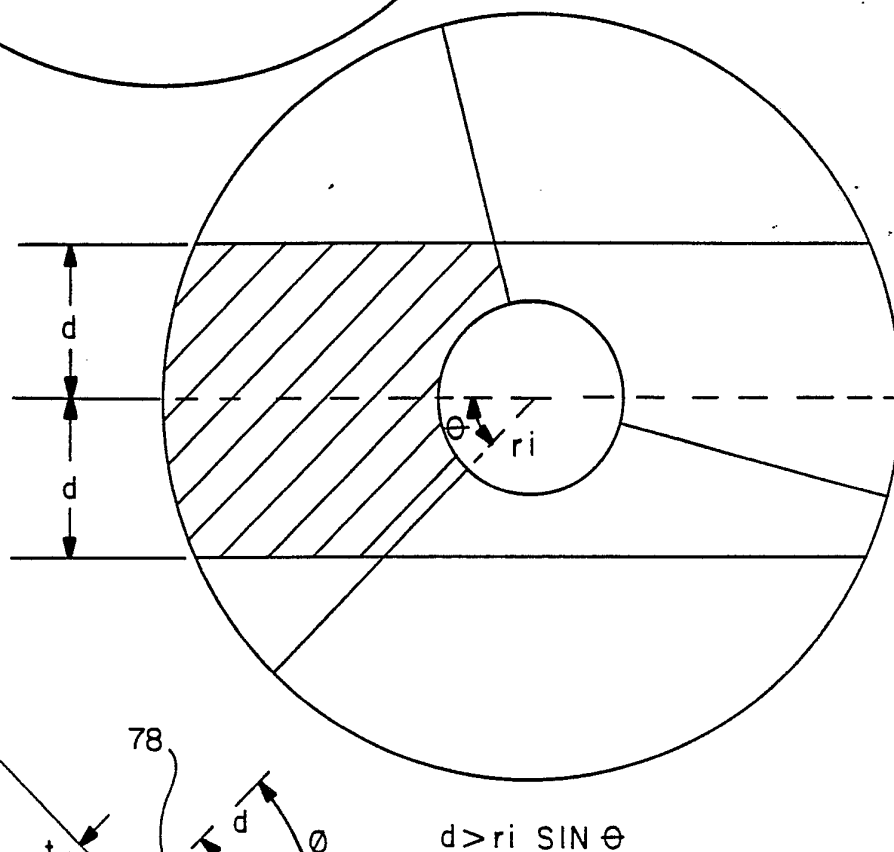
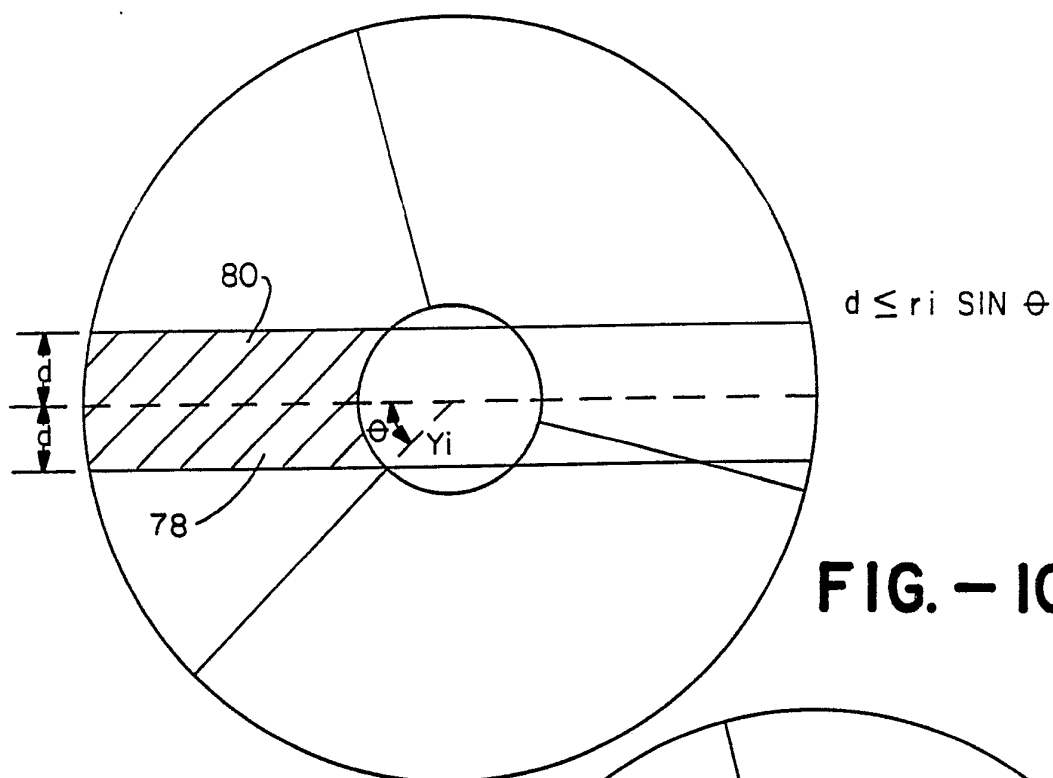
**FIG.-8B**



**FIG.-9A**



**FIG.-9B**



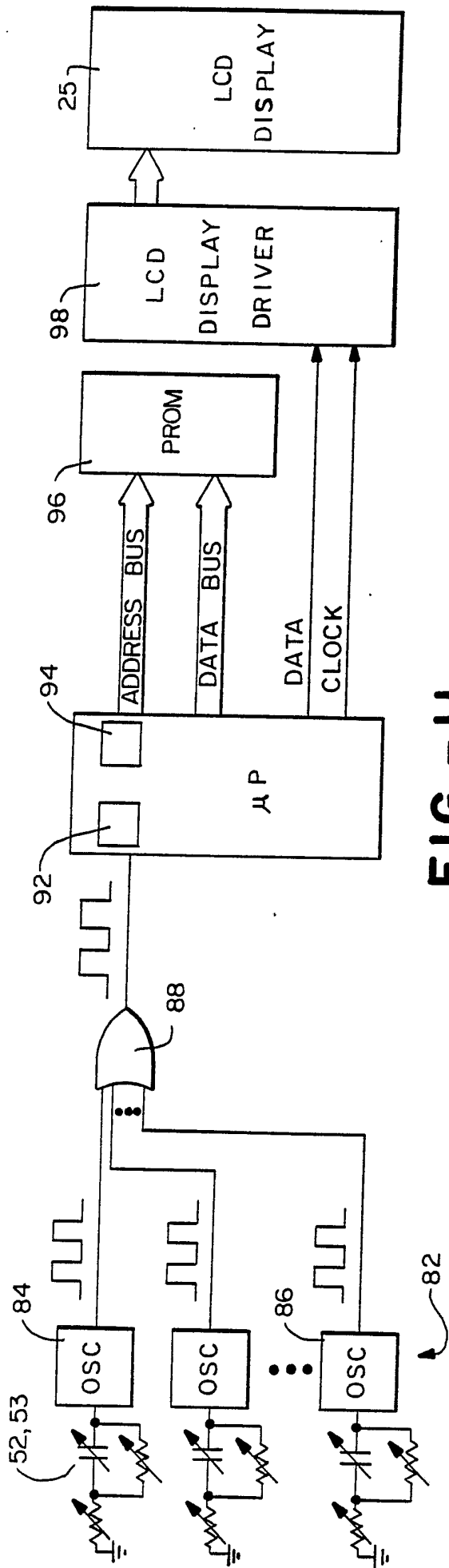


FIG. -11

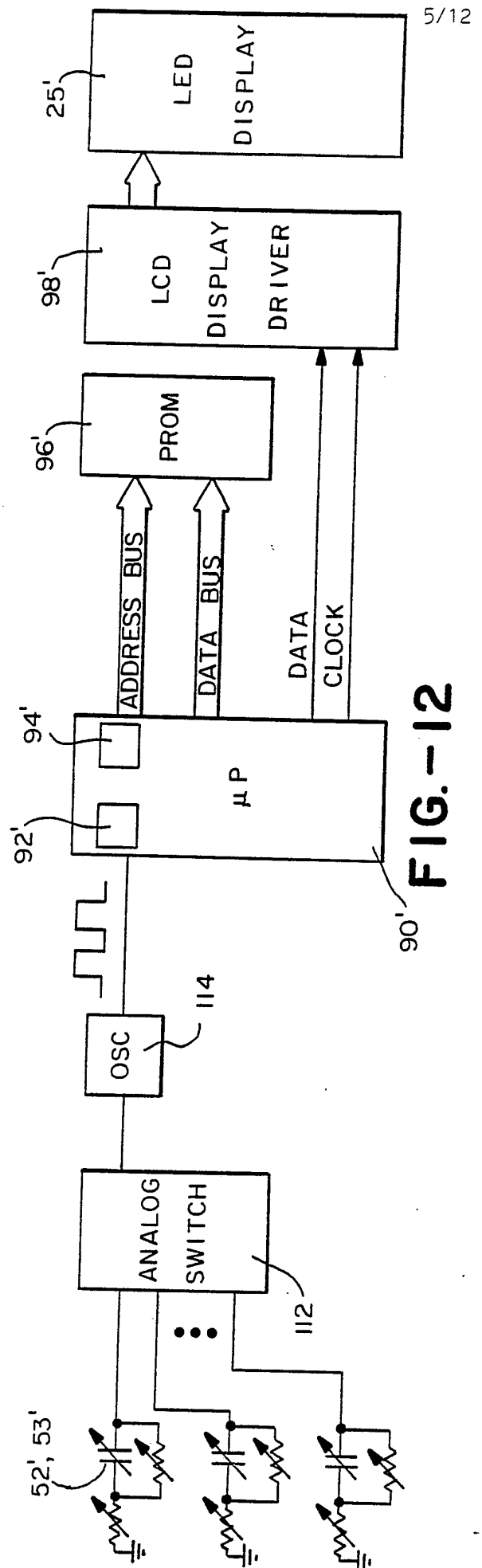
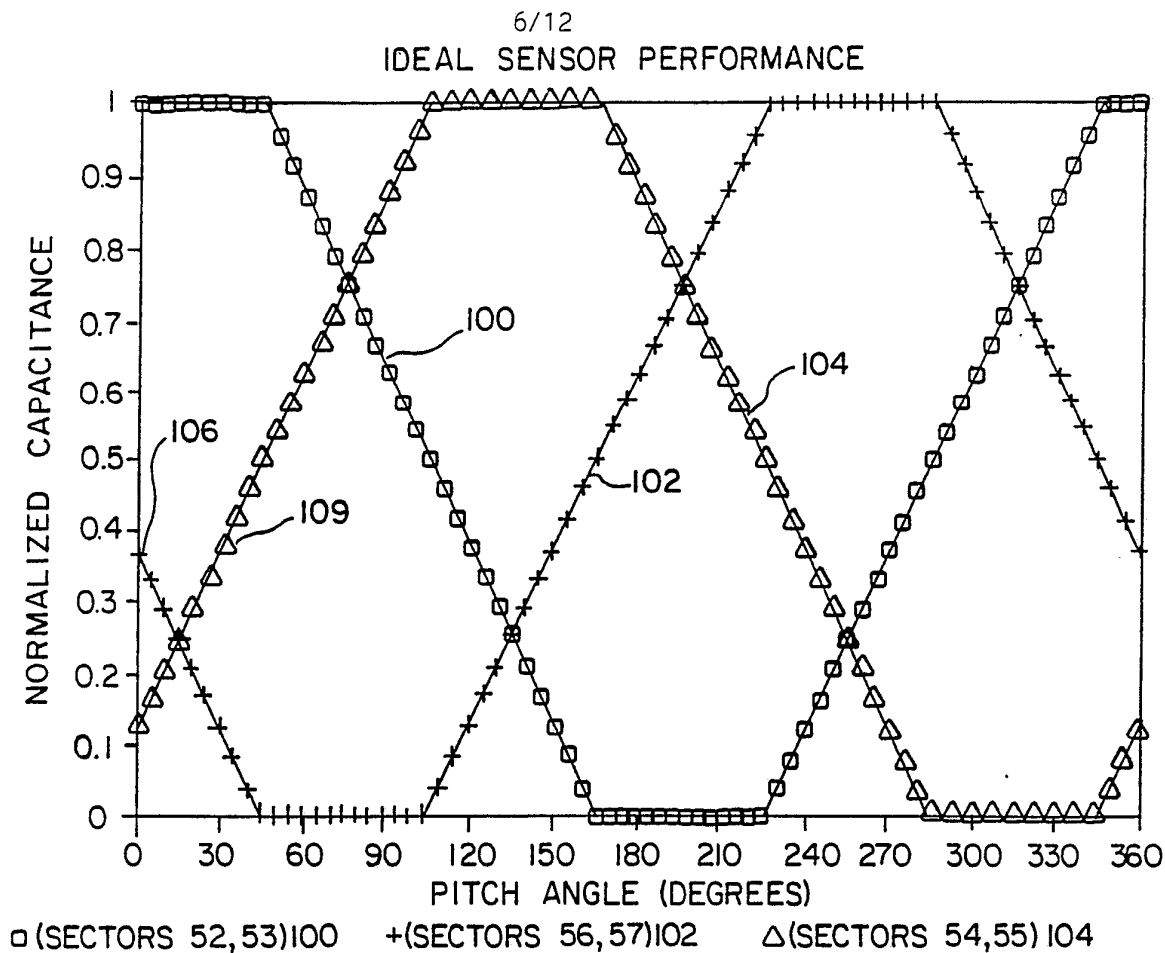
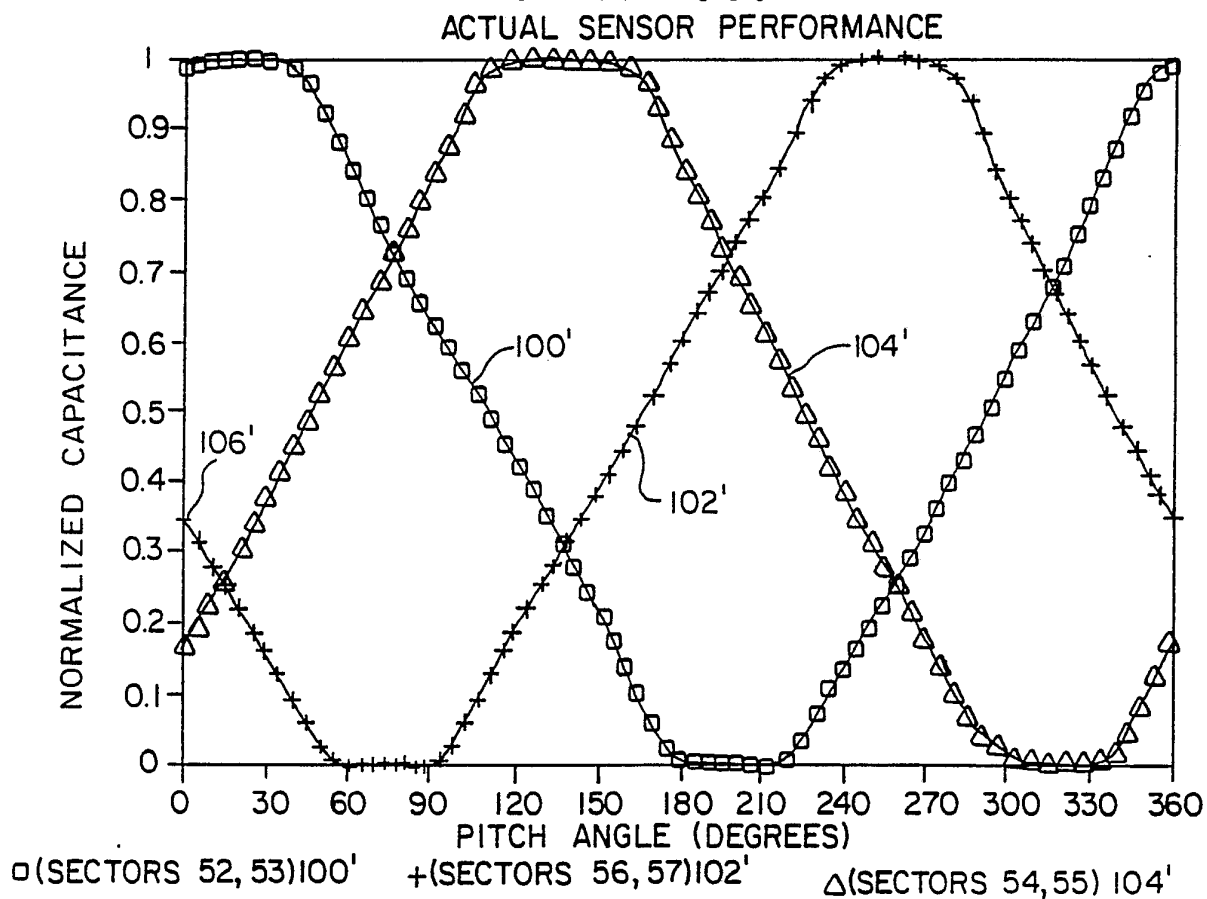


FIG. -12

**FIG.-13A****FIG.-13B**

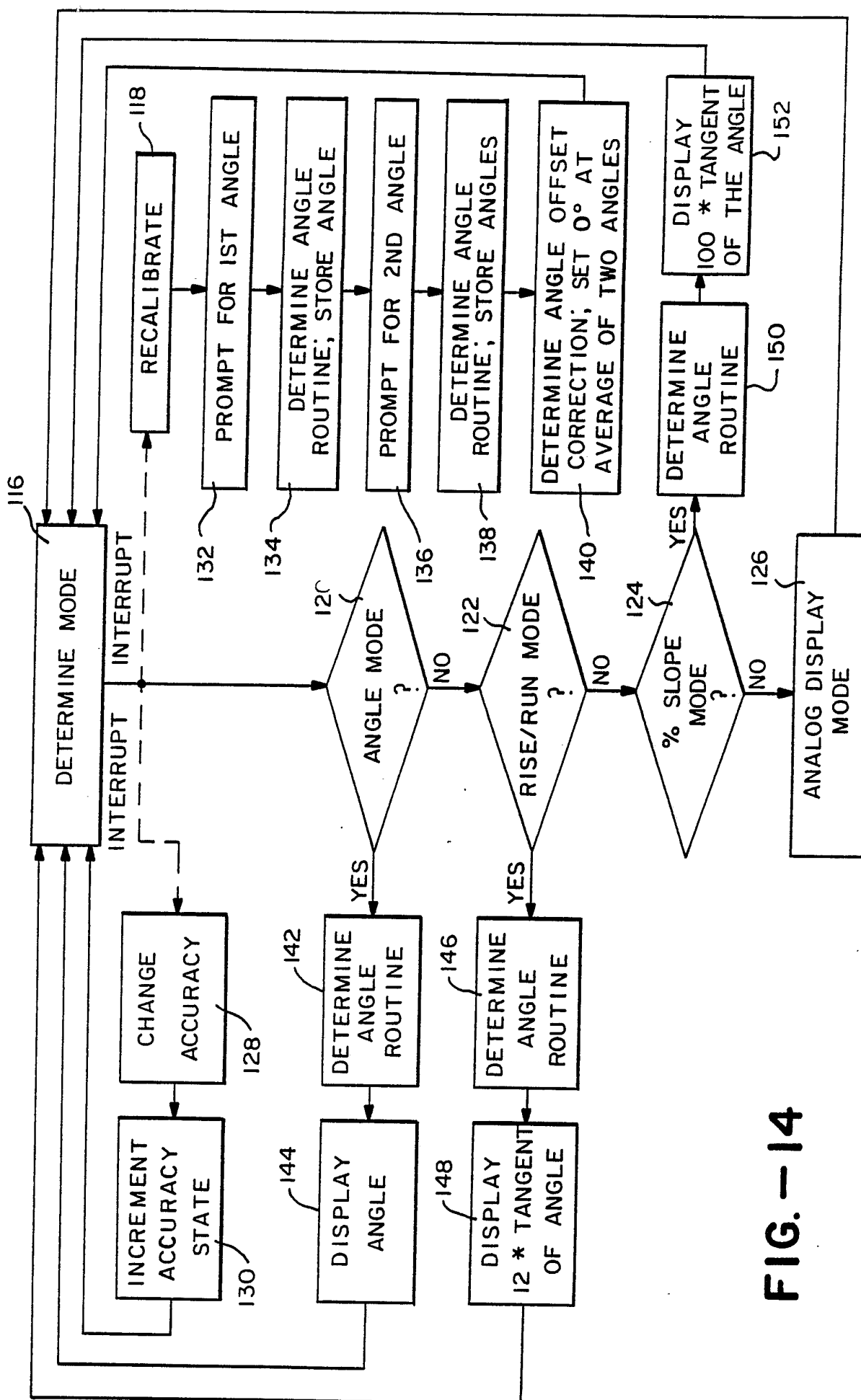
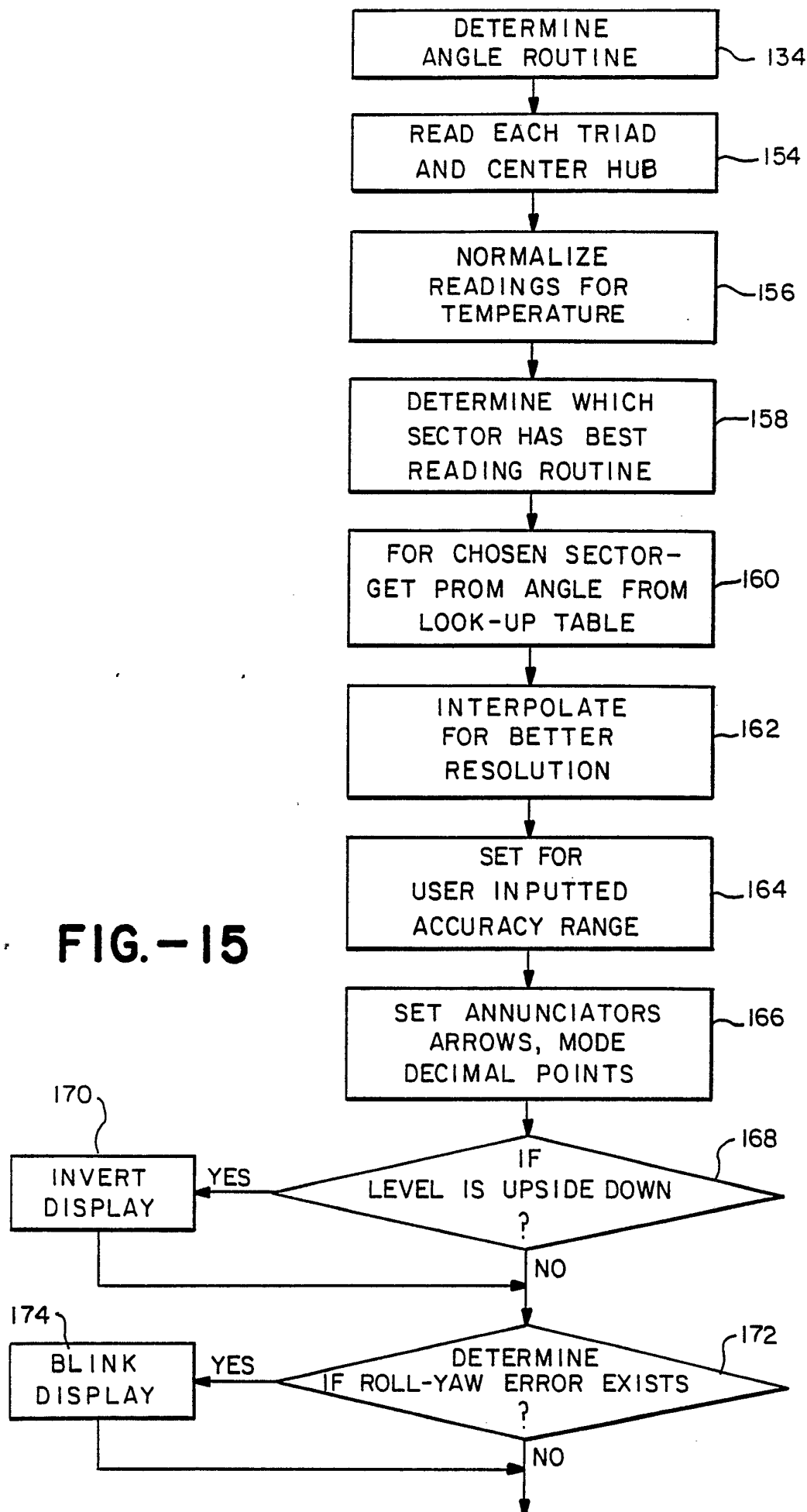
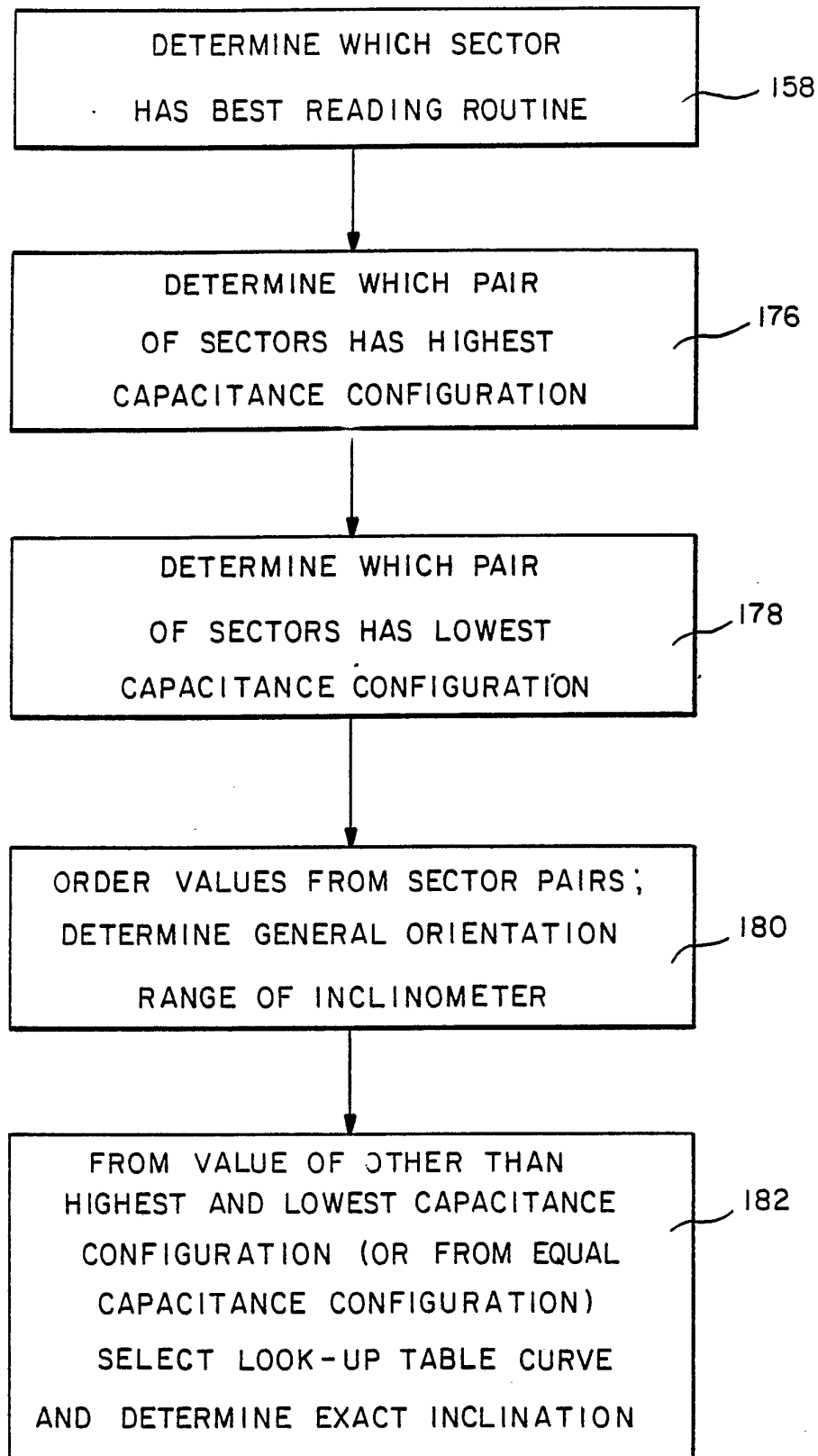


FIG. -14



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**FIG. -16**

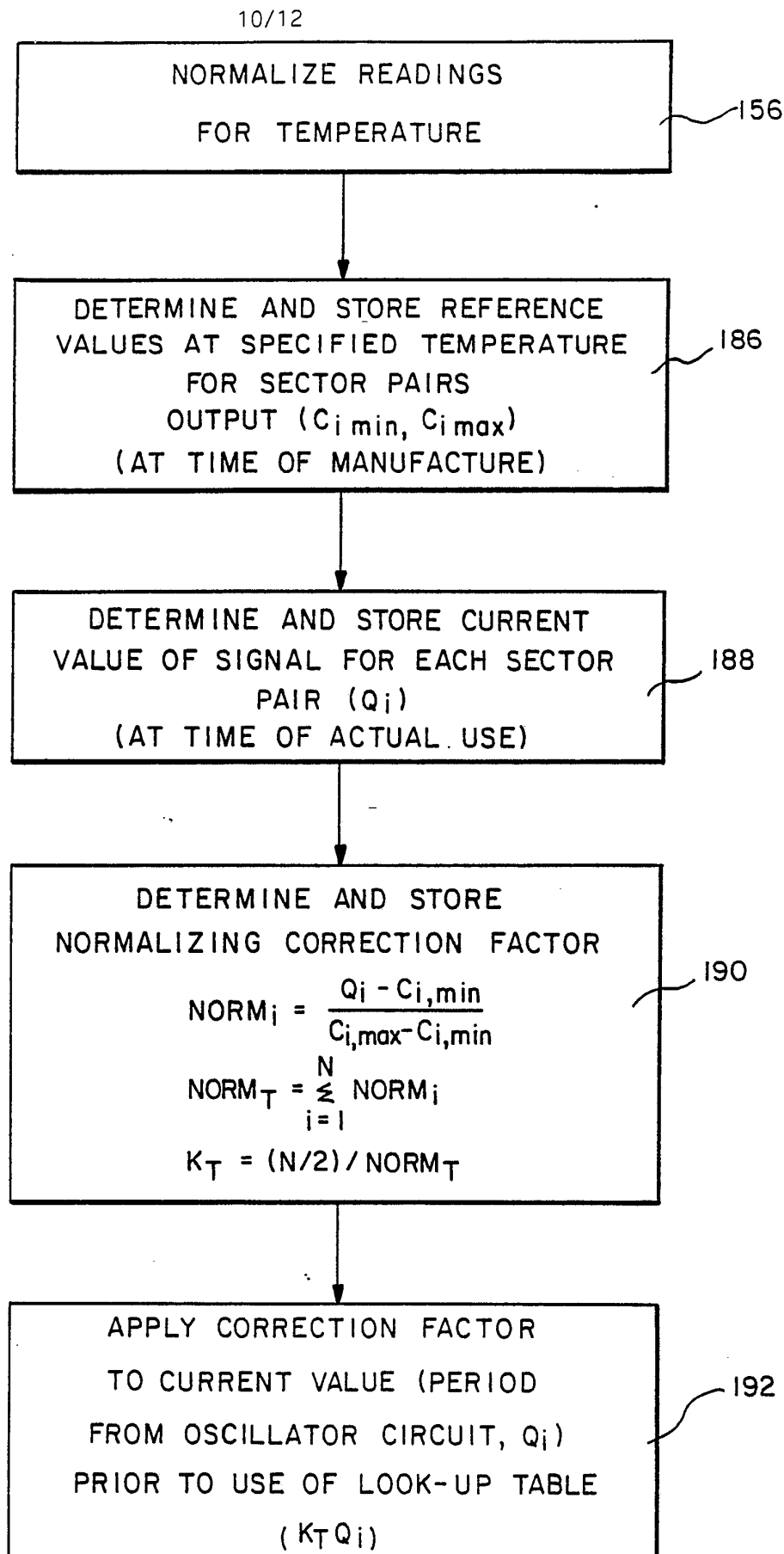


FIG. -17

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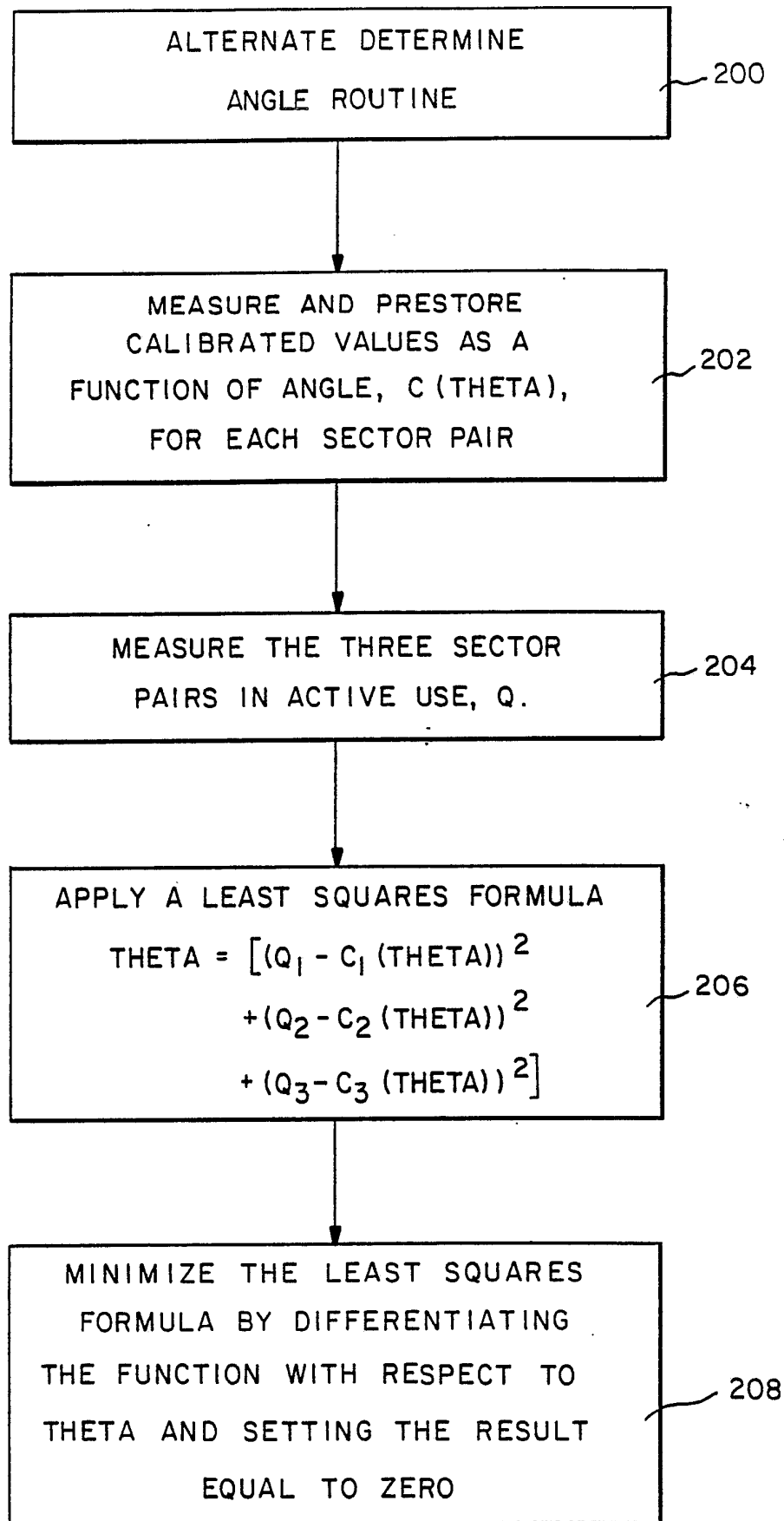
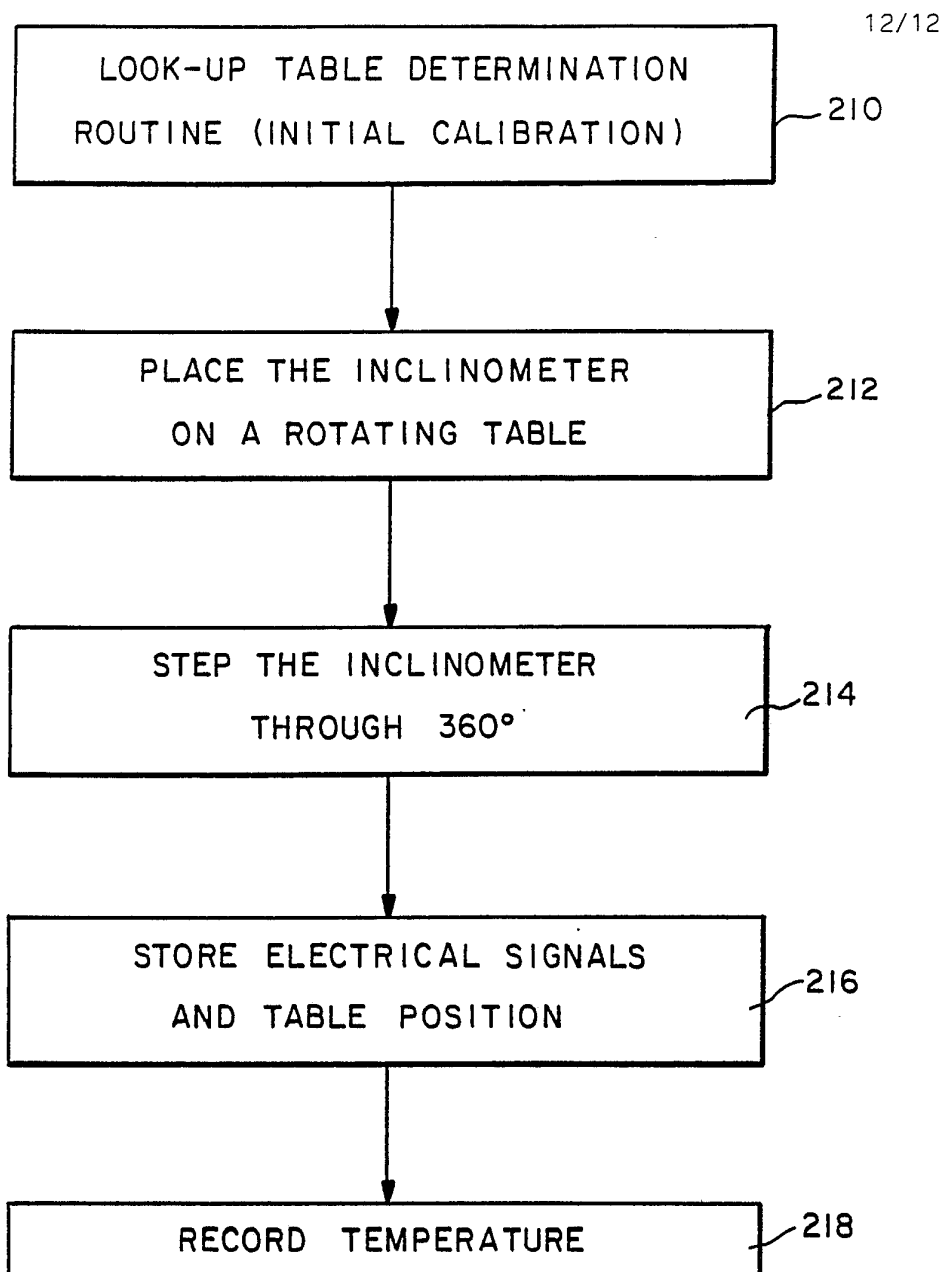
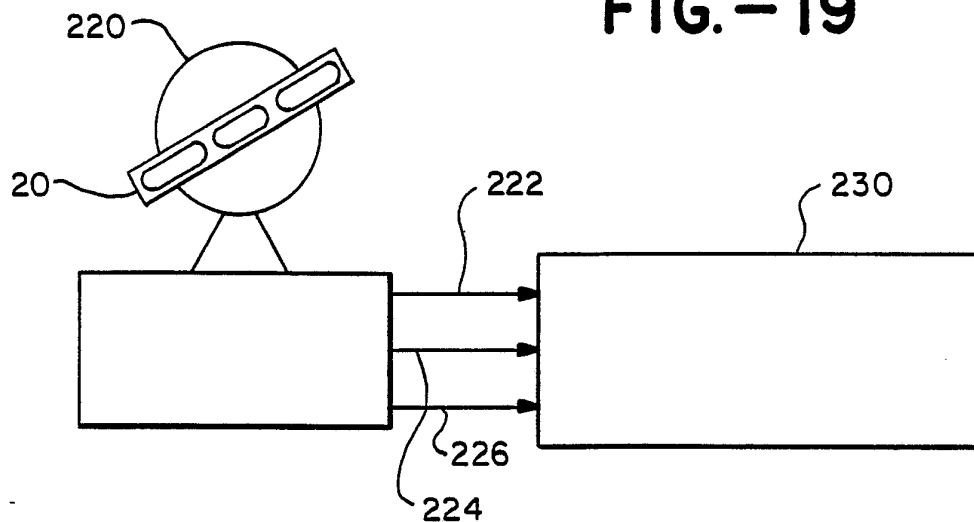


FIG. - 18

**FIG. - 19****FIG. - 20**

# INTERNATIONAL SEARCH REPORT

International Application No. PCT/US88/02149

## I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) <sup>6</sup>

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC(4): G01C 9/06

U.S. CL.: 364/559; 33/366; 73/1E

## II. FIELDS SEARCHED

Minimum Documentation Searched <sup>7</sup>

Classification System	Classification Symbols
U.S.	364/550, 556, 570, 571; 73/1E, 517R, 189; 33/366, 377, 346; 340/870.37, 870.23, 870.32, 689; 324/61R

Documentation Searched other than Minimum Documentation  
to the Extent that such Documents are Included in the Fields Searched <sup>8</sup>

Automated Patent Search (APS): L1: S Inclinator; L2: S Level; L3: S L1 Or L2; L4: S L3 And Capacitance; L5: S L4 And (Computer Or Processor Or Microprocessor); L6: S L5 And Oscillator

## III. DOCUMENTS CONSIDERED TO BE RELEVANT <sup>9</sup>

Category *	Citation of Document, <sup>11</sup> with indication, where appropriate, of the relevant passages <sup>12</sup>	Relevant to Claim No. <sup>13</sup>
Y	US, A, 4,660,290 (HORI ET AL.) 28 April 1987 See the entire document.	1, 5, 13, 17, and 39
<u>Y</u> X	US, A, 4,549,277 (BRUNSON ET AL.) 22 October 1985 See the entire document.	1, 13, and 17 40-43, 47, 50, and 53-55
Y	US, A, 4,528,760 (PLUMMER) 16 July 1985 See Figure 1.	2-4, and 18-34
Y	US, A, 4,551,921 (PUYO ET AL.) 12 November 1985 See Figure 2, Element 16.	12, 38, and 44-46
Y	BARKER ET AL., "Intelligent Inclinator," Published April 1980, By Central Electricity Generating Board (London), See Pages 1-4.	14-15, 48-49, and 56
A, P	US, A, 4,676,103 (NAKAJIMA) 30 June 1987 See the entire document.	
A, P	US, A, 4,707,927 (HIYAMA) 24 November 1987 See the entire document.	

\* Special categories of cited documents: <sup>10</sup>

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

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## IV. CERTIFICATION

Date of the Actual Completion of the International Search

01 AUGUST 1988

International Searching Authority

ISA/US

Date of Mailing of this International Search Report

26 SEP 1988

Signature of Authorized Officer

David Goldman  
DAVID GOLDMAN