ANGULAR MEASUREMENT APPARATUS

FIELD AND BACKGROUND OF THE INVENTION

The present invention relates to measurement systems in general and in particular to an apparatus for precise measurement of the angular position of a rotatable element.

It is known to use rotary encoders to convert rotation of a shaft into periodic electrical signals. These signals are then processed to derive position information for display or as an input to control systems. Typically, rotary encoders produce the electrical signals by photoelectric scanning of a graduated disk.

In high precision applications, i.e., where an angular resolution of ± 1 or 2 seconds of arc or less is required, the use of rotary encoders becomes problematic. For such applications, graduated discs having 36,000 lines or more are used, giving a cumulative error of several arcseconds. An example of such a system employing additional reference marks to improve accuracy is disclosed in U.S. Patent No. 4,477,189 to Ernst.

High precision encoders are generally unsuitable for use in calibration of existing rotary tables since the whole encoder assembly is constructed from a complex arrangement of extremely high precision components built into a highly rigid structure. The extremely high precision components are also highly expensive.

Calibration of high-precision rotary platforms or "rotary indexing tables" is typically performed using optical equipment such as a theodolite or a polygon collimator. Use of such equipment is extremely slow, generally requiring between 8 and 16 hours for set-up and calibration.

In order to reduce calibration time, an automated calibration system based on angular interferometry of laser light has been developed. Such a system, disclosed in U.S. Patent No. 5,237,390 to Chaney, is available commercially as the RX10 system from Renishaw plc, U.K. However,

even this very high-cost system typically requires 5-6 hours including the set-up time.

There is therefore a need for an alternative method for precise measurement of the angular position of a rotatable element such as a rotary table. It would also be highly advantageous to have a device which used low cost, relatively low-resolution components to make precise measurements of angular position.

SUMMARY OF THE INVENTION

The present invention is of a device and a method for measuring a precise angular position of an element rotatable relative to a base.

According to the teachings of the present invention there is provided, a method for precise measurement of an angular position of a rotatable element relative to a base, the method comprising the steps of: (a) generating, through rotation of a disk having at least one graduated track: (i) an oscillating reference signal, and (ii) an oscillating measurement signal, the measurement signal being related to the reference signal by a phase shift, the phase shift being a function of the angular position of the rotatable element relative to the base; and (b) measuring the phase shift, wherein a variation of 2π in the phase shift corresponds to a rotation step of less than about 1° of the rotatable element relative to the base.

According to a further feature of the present invention, the phase shift is measured in the range 0-2π thereby indicating the angular position within a rotation step, the method further comprising the step of counting zero crossings of the phase shift from a given starting value, the starting value corresponding to an initial angular position, such that the number of phase shift zero crossings indicates a rotation step within which the angular position lies.

According to a further feature of the present invention, there is also provided a step of identifying the state of the rotatable element as either rotating or stationary.

According to a further feature of the present invention, the phase shift is measured in the range 0-2π thereby indicating the angular position within a rotation step, the method further comprising the step of performing an approximate measurement of the angular position of the rotatable element relative to the base so as to determine a rotation step within which the angular position lies.

According to a further feature of the present invention, the reference signal is generated by measuring optical transmission through a combination of a fixed grid of alternating lines of high and low transparency and the at least one track on the rotating disk.

According to a further feature of the present invention, the measurement signal is generated by measuring optical transmission through a combination of a measuring track of alternating lines of high and low transparency associated with the element and the at least one track on the rotating disk.

There is also provided, according to the teachings of the present invention, a device for measuring a precise angular position of an element rotatable relative to a base, the device comprising: (a) a rotating disk having at least one primary track of alternating lines of high and low transparency, the rotating disk being rotated continuously about the axis of rotation of the element; (b) an optical grid of alternating lines of high and low transparency associated with one of the base and the element, the optical grid being positioned parallel to the rotating disk and opposite at least part of one the primary track; (c) a measuring disk associated with the other of the base and the element, the measuring disk being aligned coaxially with the rotating disk, the measuring disk having a secondary track of alternating lines of high and low transparency, the secondary track

being aligned opposite at least part of one the primary track; (d) a first photoelectric sensor generating a reference signal indicative of variations in optical transmissivity through a combination of one the primary track and the optical grid; (e) a second photoelectric sensor generating a measuring signal indicative of variations in optical transmissivity through a combination of one the primary track and the secondary track; and (f) a processor for processing the reference signal and the measuring signal to calculate information relating to the precise angular position of the element relative to the base.

According to a further feature of the present invention, the processor includes: (a) at least one timer for measuring: (i) a period of a cycle of the reference signal, and (ii) a corresponding phase delay between the reference signal and the measuring signal; (b) a memory for storing a plurality of pairs of the period and the phase delay; and (c) a numerical processor for processing the plurality of pairs so as to calculate a precise representative phase difference.

According to a further feature of the present invention, the processor further includes a counter for counting zero crossings of phase difference between the reference signal and the measuring signal.

According to a further feature of the present invention, there is also provided a ball-and-socket joint associated with the base so as to accommodate a range of orientations of the rotatable element relative to the base.

There is also provided, according to the teachings of the present invention, a method for performing precise measurement of the angular position of an element rotatable relative to a base, the method comprising the steps of: (a) generating a first signal in relation to relative movement between the base and a rotating member, the first signal being approximately periodic; (b) generating a second signal in relation to relative movement between the element and the rotating member, the

second signal being approximately periodic; (c) deriving from the first and second signals a plurality of data pairs (T_i, t_i), where T_i is the period of a cycle of one of the first and second signals, and t_i is the corresponding phase delay between the first and second signals; (d) processing the plurality of data pairs to identify a precise representative phase difference between the first and second signals; and (e) calculating from the representative phase difference information relating to the precise angular position of the rotatable element relative to the base.

According to a further feature of the present invention, the first signal is generated by sensing light transmitted through a combination of a graduated scale associated with the base and a graduated track associated with the rotating member.

According to a further feature of the present invention, the second signal is generated by sensing light transmitted through a combination of a first graduated track associated with the element and a second graduated track associated with the rotating member.

According to a further feature of the present invention, the first and second signals include about 3600 cycles for each rotation of the rotating member.

According to a further feature of the present invention, the step of deriving a plurality of data pairs (T_i, t_i) includes deriving the data pair for consecutive cycles of the first or second signal for N cycles, where N is equal to the number of cycles generated by each rotation of the rotating member.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is herein described, by way of example only, with reference to the accompanying drawings, wherein:

FIG. 1 is a side cross-sectional view of a device, constructed and operative according to the teachings of the present invention, for

measuring a precise angular position of an element rotatable relative to a base;

FIG. 2 is a schematic exploded perspective view showing the alignment of components of the device of Figure 1;

FIG. 3A is a schematic plan view of a part of a measuring disk and an optical grid from the device of Figure 1;

FIG. 3B is a schematic plan view of a part of a rotating disk from the device of Figure 1;

FIG. 4 is a schematic plan view showing the rotating disk of Figure 3B superposed over the measuring disk and optical grid of Figure 3A;

FIG. 5 is a graph showing the variation of transmitted light intensity with time for a reference signal and a measuring signal generated by photoelectric sensors in the device of Figure 1;

FIG. 6 is a block diagram of a processor for use in the device of Figure 1; and

FIG. 7 is a detailed block diagram of an example of a timer for use in the processor of Figure 6.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention is of a device and a method for measuring a precise angular position of an element rotatable relative to a base.

The principles and operation of devices and methods according to the present invention may be better understood with reference to the drawings and the accompanying description.

Referring now to the drawings, Figure 1 shows a device, generally designated **10**, constructed and operative according to the teachings of the present invention, for measuring a precise angular position of a shaft **12** coupled to a rotary table **13** relative to a base **14**. Figure 2 shows, schematically, the alignment of certain components of device **10**.

Generally speaking, device **10** includes a rotating disk **16** having a first track **18** and a second track **20**. Each track **18**, **20** is made up of

alternating lines of high and low transparency, typically with a sinusoidal variation of transmissivity. Rotating disk **16** is rotated continuously about the axis of rotation of shaft **12**. Aligned opposite first track **18** and parallel to rotating disk **16** are two optical grids **22**, each having alternating lines of high and low transparency. Grids **22** are fixed relative to base **14**, typically on opposite sides of the axis of rotation of shaft **12**. A measuring disk **24**, attached to shaft **12**, is aligned coaxially with rotating disk **16**. Measuring disk **24** has a track **26** of alternating lines of high and low transparency, aligned opposite second track **20**.

Device **10** also features photoelectric sensors **28** and **30** which generate signals corresponding to variations in measured optical transmissivity. Photoelectric sensors **28** generate a reference signal corresponding to variations in optical transmissivity through a combination of first track **18** and optical grid **22**. Photoelectric sensors **30** generate a measurement signal corresponding to variations in optical transmissivity through a combination of second track **20** and track **26**. These signals are then processed by a processor **32** to calculate information relating to the precise angular position of shaft **12** relative to base **14**.

It should be noted that the arrangement of device **10** in relation to shaft **12** and base **14** is arbitrary. Hence, device **10** may readily be reversed such that measuring disk **24** is fixed to base **14**, and optical grids **22** are attached shaft **12**, without altering the functionality of device **10**. Similarly, since only relative rotation between shaft **12** and base **14** is to be measured, it is immaterial whether device **10** is arranged to measure rotation of shaft **12** relative to base **14**, or of base **14** relative to shaft **12**.

Device **10** provides a major improvement over the prior art calibration systems by allowing highly precise angular measurement of 360 positions within a total time of 20-30 minutes, including set-up time. Device **10** also utilizes relatively low-precision components, thereby offering considerable cost savings over the prior art systems.

Turning now to the features of device **10** in more detail, rotating disk **16** and measuring disk **24** are typically made from similar materials, and produced by similar techniques, to those used for optical disks in conventional encoders. Typically, rotating disk **16** has a diameter of about 50 mm. Rotating disk **16** and measuring disk **24** are preferably mounted sufficiently close to prevent significant transmission of diffracted light. Typically the spacing between them is of the order of 0.1 mm.

First track **18** and second track **20** of rotating disk **16** feature equal numbers of radial lines at a constant angular spacing. The lines of tracks **18** and **20** are in phase with each other, i.e., each line of first track **18** is collinear with one line of second track **20**. In fact, depending on design considerations, tracks **18** and **20** may be implemented as a single broad track.

First track **18** and second track **20** typically feature between about 1000 and about 10000 lines. Preferably, a value of about 3600 lines, i.e., an angular spacing of 0.1°, is sufficient to provide very high accuracy without requiring highly expensive production techniques. The lines are preferably opaque, or near-opaque, lines on a relatively transparent background, and are preferably sufficiently broad to cover about 50% of the functional area of each track. However, any arrangement of equally spaced radially-extending regions of relatively higher transparency alternating with equally spaced radially-extending regions of relatively lower transparency will be functional. Thus, the various options for the pattern of regions in tracks **18** and **20** will be referred to herein generally as alternating lines of high and low transparency.

Rotating disk **16** is mounted on a rotating hub **34** which is driven continuously through a flexible coupling **35** by a motor **36**. Motor **36** is preferably of a type which does not produce significant vibration. Coupling **35** prevents slight eccentricity of motor **36** from effecting alignment of rotating disk **16**. The speed of rotation of motor **36** is not

critical, but should be significantly greater than the anticipated speed of rotation of rotary table **13**. Motor **36** is attached to a casing **38** which provides a rigid structure and protective cover for device **10**.

For the purposes of calibrating an existing rotary table **13**, base **14** must be fixed to some rigid structure which provides a fixed relation to the basis of rotor table **13**. In the implementation shown here, one side of casing **38** is attached to base **14** though a ball-and-socket joint **40**, and shaft **12** is rotatably mounted through bearings **42** in the opposite side of casing **38**. This configuration allows convenient accommodation of different positions or attitudes of base **14** relative to rotary table **13** without interfering with operation of device **10**. An additional flexible coupling **37** is provided between shaft **12** and rotary table **13** thereby making device **10** less sensitive to eccentric mounting of shaft **12** relative to rotary table **13**.

Measuring disk **24** is mounted near the end of shaft **12** parallel to rotating disk **16** and in a common plane with optical grids **22**. Measuring disk **24** is generally equivalent to rotating disk **16** cut down such that its radius lies between that of first track **18** and second track **20**. Track **26** features a number of lines equal to that of tracks **18** and **20**. The lines of track **26** are preferably opaque, or near-opaque, lines on a relatively transparent background, and are preferably sufficiently broad to provide about 50% coverage of the operative area of track **26**.

One of optical grids **22** and one of each of photoelectric sensors **28** and **30** are typically set in a U-shaped bracket **46** attached to the inside of casing **38** such that it extends over the faces of rotating disk **16** and measuring disk **24**. In a basic embodiment of the present invention, a single U-shaped bracket **46**, with a single set of one of optical grids **22** and one of each of photoelectric sensors **28** and **30**, would be sufficient. Preferably, however, two such assemblies are provided opposite to each other, i.e., one rotated from the other by 180° around the axis of rotation

of shaft 12. The second pair of photoelectric sensors are designated, respectively, 29 and 31. The outputs from the two assemblies are processed by processor 32 to reduce the effects of cumulative error and shaft eccentricity. The details of this processing will be described below.

Optical grids 22 are typically equivalent to a small section of first track 18 with its lines aligned towards the axis of rotation of shaft 12, i.e., "radially". The lines of optical grids 22 are "angularly spaced" at the same angular spacing as the lines of tracks 18, 20 and 26 relative to the axis of rotation of shaft 12. However, since the area of optical grids 22 is generally small in relation to the diameter of first track 18, the required pattern may be adequately approximated by a similar grid of equidistant parallel lines.

Photoelectric sensors 28 and 30 each include a light emitter 48, such as, for example, an infrared LED or a bulb, and a light sensor 50 of any conventional type, such as, for example, a photodiode or phototransistor. A single light emitter 48 may be common to adjacent photoelectric sensors 28 and 30.

The two parts of photoelectric sensor 28 are in fixed alignment with optical grid 22 and aligned in a manner such that a beam of light from light emitter 48 passes through both optical grid 22 and first track 18 before reaching light sensor 50. Photoelectric sensor 28 thus produces an output signal, referred to herein as the "reference signal", corresponding to the transmissivity of the superposition of optical grid 22 and first track 18 at any given instant. As will be explained below, this reference signal is an oscillating signal. The output signals are typically of approximately sinusoidal form.

The two parts of photoelectric sensor 30 are aligned in a manner such that light from light emitter 48 passes through both second track 20 and track 26 of measuring disk 24 before reaching light sensor 50. Photoelectric sensor 30 thus produces an output signal, referred to herein

as the "measuring signal", corresponding to the transmissivity of the superposition of track **26** and second track **20** at any given instant. This measuring signal is also an oscillating signal, differing only in phase from the reference signal, as will be explained below.

The reference and measuring signals are transferred through electrical connections **52** to processor **32**. The details of processor **32** will be described below with reference to Figures 6-7.

Turning now to the operation of device **10**, this will be described with reference to Figures 3-5. Figure 3A shows, schematically, a portion of measuring disk **24** with track **26**, and optical grid **22**. In this example, measuring disk **24** is in a rotational position such that the lines of track **26** are out of alignment with the lines of optical grid **22** by about a quarter of the angular separation between the lines. Figure 3B shows, schematically, a portion of rotating disk **16** with first track **18** and second track **20**, here broadened to form a single broad track **54**. In both Figures 3A and 3B, the operative areas of photoelectric sensors **28** and **30** are indicated by dashed lines.

Figure 4 illustrates the effect of superposing rotating disk **16** as shown in Figure 3B over measuring disk **24** and optical grid **22** as shown in Figure 3A. The rotation of rotating disk **16** causes the lines of tracks **18** and **20** to pass over the lines of optical grid **22** and track **26**, respectively, thereby producing a cyclic variation of the amount of overlap of lines of low transparency over the operative areas of photoelectric sensors **28** and **30**. This, in turn, causes cyclic variation of the transmission measured by photoelectric sensors **28** and **30**, generating oscillating output signals.

Figure 5 shows the variations in the reference signal, designated **56**, produced by photoelectric sensor **28**, and in the measuring signal, designated **58**, produced by photoelectric sensor **30**. The values corresponding to successive positions of rotating disk **16** are denoted by

capitals A-D. The period of the oscillations measured, for example, from peak to peak is denoted **T**. The time lag of measuring signal **58** after reference signal **56** is denoted Δt. A normalized phase shift $\Delta\phi$ between the signals is then defined by:

(1) $$\Delta\phi = 2\pi\Delta t/T$$

It will readily be appreciated that calculation of the normalized phase shift $\Delta\phi$ determines extremely accurately the angular position of measuring disk **24** relative to optical grid **22**, and hence of shaft **12** and rotary table **13** relative to base **14**, within a certain rotation step. Expressed algebraically, if measuring track **26** has a total of N lines so that the angular step between them is given by $\Delta\theta=360°/N$, the angular position θ of rotary table **13** relative to base **14** measured from some arbitrary initialization position may be written as:

(2) $$\theta = n\Delta\theta + \Delta\phi\Delta\theta/2\pi$$

where n is an integer. In other words, if, by way of example, track **26** and optical grid **22** are ruled with lines at an angular spacing of $\Delta\theta=0.1°$ (N=3600 lines per rotation), phase shift $\Delta\phi/2\pi$ corresponds to the angular position of rotary table **13** within a 0.1° step, expressed as a fraction. Thus, device **10** transforms a rotation of 0.1° to a phase shift of 2π, thereby providing much higher accuracy of angular measurement than is conventionally achieved using components of a given angular spacing or resolution.

In principle, a single measurement of phase shift is sufficient to determine the angular position of rotary table **13** within a given rotation step, and the only additional information required is low-resolution information to determine within which rotation step the rotary table currently lies. However, it is a particular feature of a preferred embodiment of the present invention that extremely accurate measurement of angular position may be taken using low precision components. This is achieved by collecting large amounts of data in a manner such as to

minimize systematic errors and then performing statistical analysis on the data, as will now be described with reference to Figures 6-7.

Figure 6 shows a possible structure of processor **32**. Processor **32** typically includes a signal processor **60**, a mode switch **62**, a zero-crossing counter **64**, a timer **66**, a memory **68** and a microprocessor **70**. Processor **32** typically also includes a display **72**, a standard computer communications port **74** and a control panel or other input device **76**.

Signal processor **60** receives a pair of reference and measuring signals through electrical connections **52**. Signal processor **60** generally converts the oscillatory reference and measuring signals to a pulse or square-wave form to allow use of digital processing techniques. For convenience, these wave forms will be referred to collectively as "pulse signal". Devices and methods for performing this signal processing are well known in the art. In a preferred embodiment in which two photoelectric sensor assemblies are used, signal processor **60** receives a pair of signals from each assembly, i.e., a total of four signals. In this case, signal processor also includes a switching system operative under the control of microprocessor **70** to select one pair of inputs. Typically, one pair of inputs remains in use continuously except for a short period when precise angular measurement is being made, as will be described below.

From signal processor **60**, two pulse signals corresponding to a pair of reference and measuring signals are transferred to mode switch **62**. Mode switch **62** sets the mode of processor **32** according to the state of shaft **12** as either rotating or stationary. Preferably, mode switch **62** is automatic, functioning by identifying significant shifts in phase between the two signals. The sensitivity of mode switch **62** is set so as to disregard variations which are within the range of tolerance of the components used. When shaft **12** is rotating, mode switch **62** switches to pass the signals to phase shift zero-crossing counter **64** for coarse measurement of angular position. When shaft **12** is stationary, mode switch **62** switches to pass the

signals to timer **66** for precise measurement of angular position. Signal processor **60**, may provide somewhat different signal forms for of zero-crossing counter **64** and timer **66** as appropriate for the processing to be performed by each. Alternatively, mode switch **62** may be replaced by any other type of movement sensor or a simple manual switch operated by a user when precise measurement is required.

Phase shift zero-crossing counter **64** maintains a cumulative count of zero crossings of the phase shift between the reference signal and the measuring signal. By way of example only, this may be done simply by counting pulses, i.e., adding one to a counter for each signal pulse which arrives and subtracting one for each reference pulse. The number reached then corresponds to the number of rotation steps moved through by shaft **12** relative to base **14** from some given initialization position. This number is passed on to microprocessor **70** for use in determining the overall angular position of rotary table **13**.

Turning now to timer **66**, this functions to derive a plurality of data pairs (T_i, t_i) from the pulse signals corresponding to the reference and measuring signals. Within each data pair, T_i is the period of a cycle of the reference signal, i.e., the time between adjacent pulses or wave-fronts, and t_i is the corresponding phase delay of the measuring signal relative to the reference signal, i.e., the time between the first of the adjacent pulses of the reference signal and the measuring signal pulse which follows it.

An example of a structure for timer **66** is shown in Figure 7. Thus, according to this example, timer **66** features a high-frequency counter **78** driven by a high frequency generator **80**. Typically, generator **80** operates at a frequency of some tens of MHz, and preferably about 45 MHz. Counter **78** is typically a two-byte counter, but a larger counter may be used if required. A first buffer **82** is provided for measuring t_i and a second buffer **84** is provided for measuring T_i.

Arrival of a pulse from the signal corresponding to the reference signal causes writing of the value from counter **78** to second buffer **84** and then, after a very short delay caused by delay **86**, resetting of counter **78**. The delay is solely for the purpose of allowing reading of the counter before resetting and is of the order of a nanosecond, thereby having no measurable effect on the precision of the device. When a pulse from the signal corresponding to the measuring signal arrives, it causes writing of the value from counter **78** to first buffer **82**, thereby recording t_i, the number of generator cycles corresponding to the phase delay between the reference and measuring signals. Arrival of the subsequent reference signal pulse causes writing to second buffer **84** of the corresponding T_i, the number of generator cycles corresponding to the period of the reference signal within which t_i was measured. Counter **78** is then reset in preparation to measure the next data pair (T_{i+1}, t_{i+1}) while (T_i, t_i) is stored in memory **68**.

Microprocessor **70** then processes the data pairs stored in memory **68** to identify a precise representative phase difference between the reference signal and the measuring signal. This is typically done by calculating the normalized phase difference:

$$\Delta\phi_i = 2\pi t_i/T_i$$

and then using standard statistical methods to determine a precise representative value. This value may be a simple mean value, or may be determined by more complex methods. In particular, it is valuable to check for ranges of measured phase differences which overlap a zero-crossing. In such a case, a correction factor of $\pm 2\pi$ must be added to certain phase measurements to form a single contiguous range of data before statistical analysis is performed. A corresponding correction of ± 1 to the figure from counter **64** may be required. This allows accurate measurement in any angular position over a continuous range of 360°.

out. Each data pair is used to calculate a position measurement and statistical analysis is performed on the results.

As a further technique for reducing systematic errors, after collection of data pairs corresponding to a rotation of rotating disk **16** using signals from one set of photoelectric sensors, microprocessor **70** actuates temporary switching of signal processor **60** to the signals from the second set of photoelectric sensors. Memory **68** then accumulates an additional set of data pairs corresponding to substantially a full rotation of rotating disk **16**. In this way, processor **32** utilizes 2N data pairs where N is the number of lines on each graduated disk. The total time for measurement and processing at each position is typically a few seconds corresponding to an almost-real-time measurement system.

If required, the measuring cycle may be repeated one or more times, thereby providing multiples of 2N (2kN: k=1,2,3...). Since this corresponds to a very large number of measurements taken in a manner minimizing systematic errors, statistical analysis yields a very high degree of precision.

In a preferred example in which rotating disk **16** features about 3600 lines per rotation, use of a single full set of data pairs from each set of photoelectric sensors yields 7200 data pairs. Analysis of this data provides angular precision of better than ½ arcsecond, thereby representing a profound improvement over the precision achieved with components of similar tolerances in the prior art.

It will be appreciated that the above descriptions are intended only to serve as examples, and that many other embodiments are possible within the spirit and the scope of the present invention. For example, while the present invention has been described in an embodiment particularly suited to calibration of existing rotary tables or platforms, it may readily be adapted for inclusion in a rotary platform assembly to be used as part of the control system.

WHAT IS CLAIMED IS:

1. A method for precise measurement of an angular position of a rotatable element relative to a base, the method comprising the steps of:

(a) generating, through rotation of a disk having at least one graduated track:

(i) an oscillating reference signal, and

(ii) an oscillating measurement signal,

said measurement signal being related to said reference signal by a phase shift, said phase shift being a function of the angular position of the rotatable element relative to the base; and

(b) measuring said phase shift,

wherein a variation of 2π in said phase shift corresponds to a rotation step of less than about 1° of the rotatable element relative to the base.

2. The method of claim 1, wherein said phase shift is measured in the range 0-2π thereby indicating the angular position within a rotation step, the method further comprising the step of counting zero crossings of said phase shift from a given starting value, said starting value corresponding to an initial angular position, such that the number of phase shift zero crossings indicates a rotation step within which the angular position lies.

3. The method of claim 2, further comprising the step of identifying the state of the rotatable element as either rotating or stationary.

4. The method of claim 1, wherein said phase shift is measured in the range 0-2π thereby indicating the angular position within a rotation

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step, the method further comprising the step of performing an approximate measurement of the angular position of the rotatable element relative to the base so as to determine a rotation step within which the angular position lies.

5. The method of claim 1, wherein said reference signal is generated by measuring optical transmission through a combination of a fixed grid of alternating lines of high and low transparency and said at least one track on said rotating disk.

6. The method of claim 1, wherein said measurement signal is generated by measuring optical transmission through a combination of a measuring track of alternating lines of high and low transparency associated with the element and said at least one track on said rotating disk.

7. A device for measuring a precise angular position of an element rotatable relative to a base, the device comprising:

(a) a rotating disk having at least one primary track of alternating lines of high and low transparency, said at least one primary track providing a first track portion and a second track portion, said rotating disk being rotated continuously about the axis of rotation of the element;

(b) an optical grid of alternating lines of high and low transparency associated with one of the base and the element, said optical grid being positioned parallel to said rotating disk and opposite said first track portion;

(c) a measuring disk associated with the other of the base and the element, said measuring disk being aligned coaxially with said rotating disk, said measuring disk having a secondary

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track of alternating lines of high and low transparency, said secondary track being aligned opposite said second track portion;

(d) a first photoelectric sensor generating a reference signal indicative of variations in optical transmissivity through a combination of said first track portion [one said primary track] and said optical grid;a first photoelectric sensor generating a reference signal indicative of variations in optical transmissivity through a combination of said first track portion and said optical grid;

(e) a second photoelectric sensor generating a measuring signal indicative of variations in optical transmissivity through a combination of said second track portion and said secondary track; and

(f) a processor for processing said reference signal and said measuring signal to calculate information relating to the precise angular position of the element relative to the base,

wherein said first track portion, said second track portion, said optical grid and said secondary track all have a substantially equal effective angular line spacing.

8. A device as in claim 7, wherein said processor includes:

(a) at least one timer for measuring:

(i) a period of a cycle of said reference signal, and

(ii) a corresponding phase delay between said reference signal and said measuring signal;

(b) a memory for storing a plurality of pairs of said period and said phase delay; and

(c) a numerical processor for processing said plurality of pairs so as to calculate a precise representative phase difference.

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9. A device as in claim 8, wherein said processor further includes a counter for counting zero crossings of phase difference between said reference signal and said measuring signal.

10. A device as in claim 7, further comprising a ball-and-socket joint associated with the base so as to accommodate a range of orientations of the rotatable element relative to the base.

11. A method for performing precise measurement of the angular position of an element rotatable relative to a base, the method comprising the steps of:

(a) generating a first signal in relation to relative movement between the base and a rotating member, said first signal being approximately periodic;

(b) generating a second signal in relation to relative movement between the element and said rotating member, said second signal being approximately periodic;

(c) deriving from said first and second signals a plurality of data pairs (T_i, t_i), where T_i is the period of a cycle of one of said first and second signals, and t_i is the corresponding phase delay between said first and second signals;

(d) processing said plurality of data pairs to identify a precise representative phase difference between said first and second signals; and

(e) calculating from said representative phase difference information relating to the precise angular position of the rotatable element relative to the base.

12. A method as in claim 11, wherein said first signal is generated by sensing light transmitted through a combination of a

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graduated scale associated with said base and a graduated track associated with said rotating member.

13. A method as in claim 11, wherein said second signal is generated by sensing light transmitted through a combination of a first graduated track associated with said element and a second graduated track associated with said rotating member.

14. A method as in claim 11, wherein said first and second signals include about 3600 cycles for each rotation of said rotating member.

15. A method as in claim 11, wherein said step of deriving a plurality of data pairs (T_i, t_i) includes deriving said data pair for consecutive cycles of said first or second signal for N cycles, where N is equal to the number of cycles generated by each rotation of said rotating member.

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FIG. 1

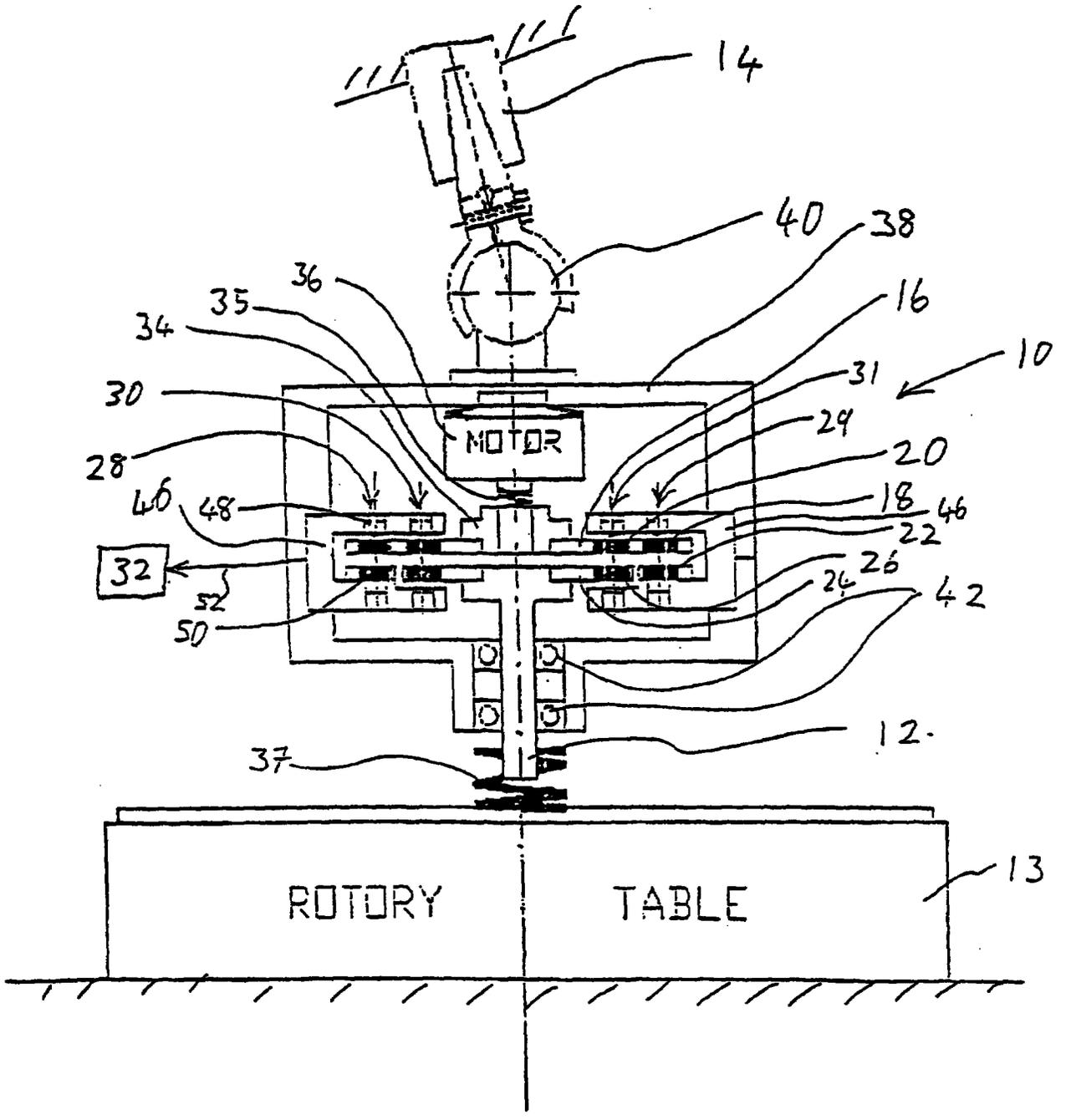

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FIG. 2

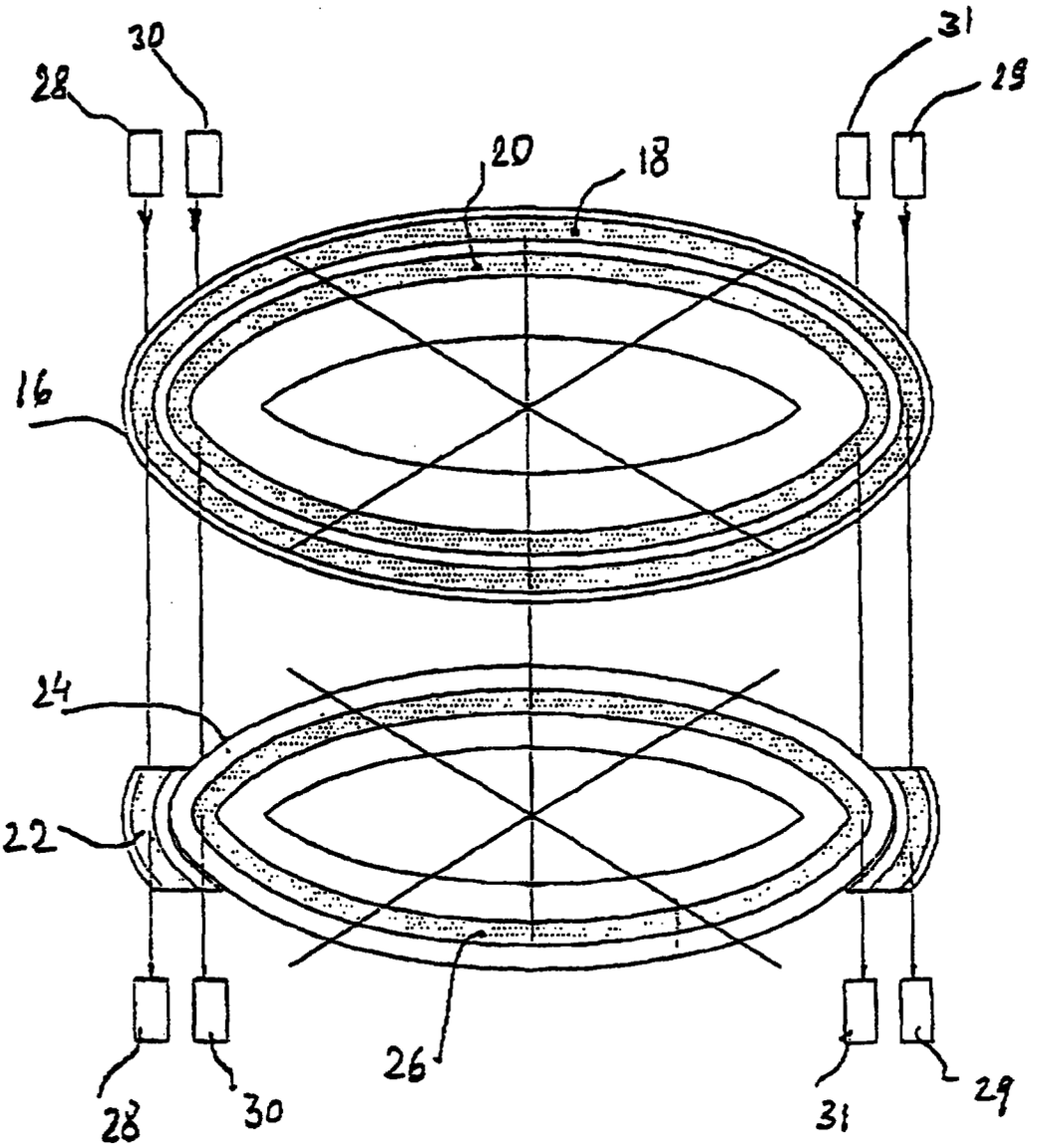

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FIG. 3A

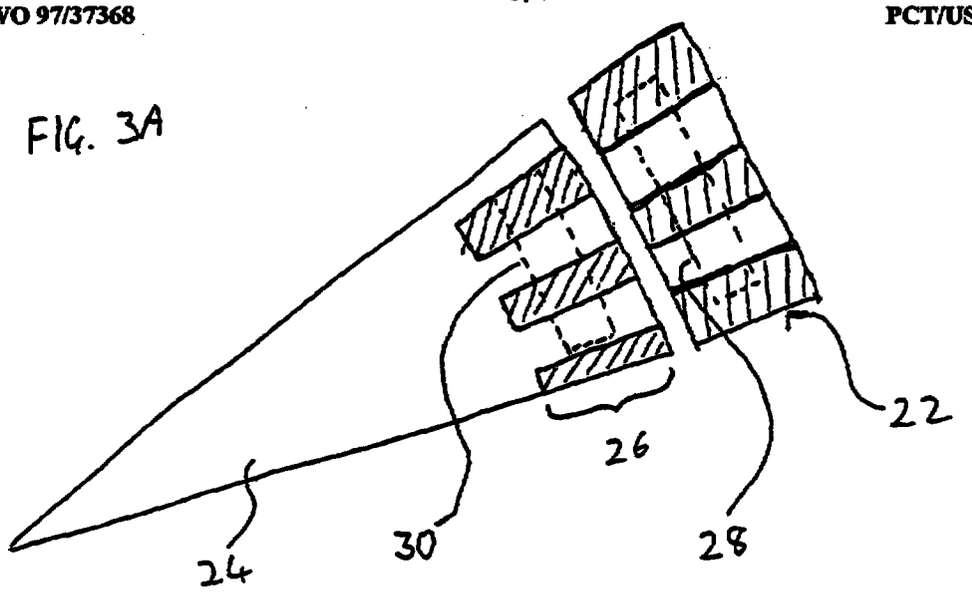
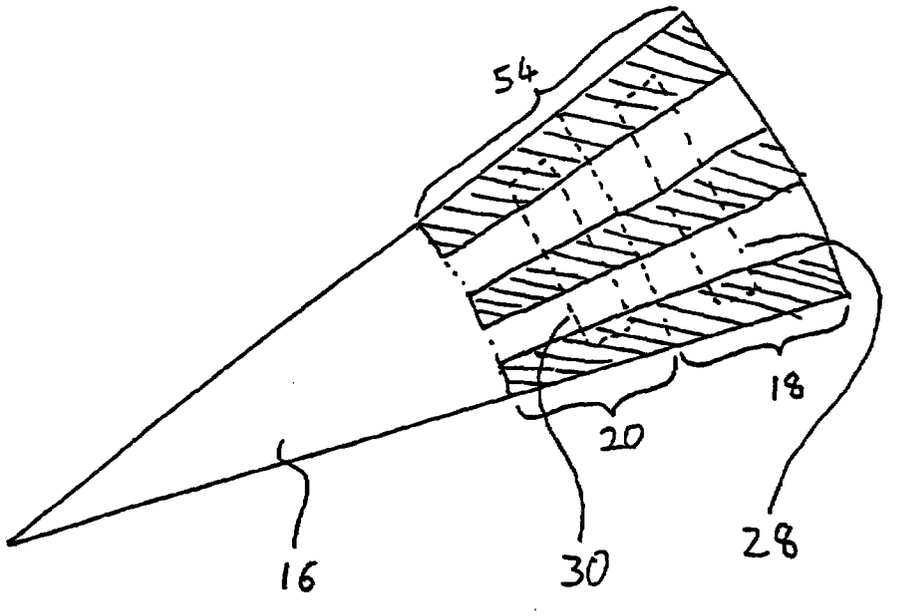


FIG. 3B



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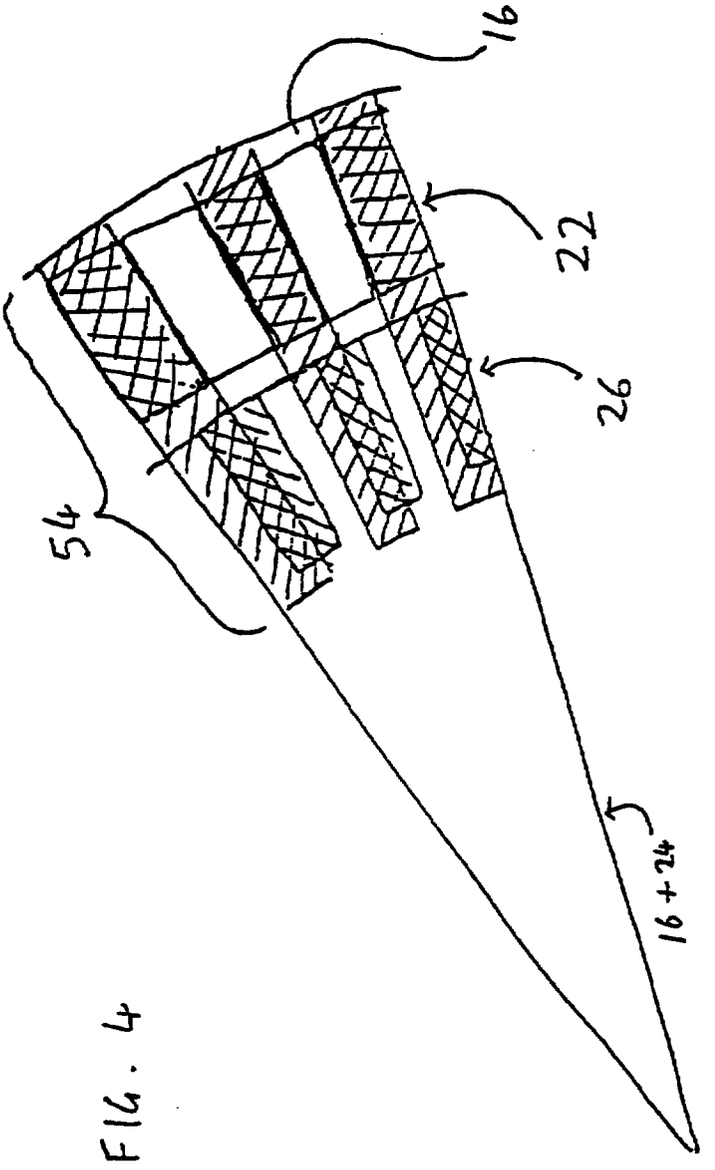

FIG. 4

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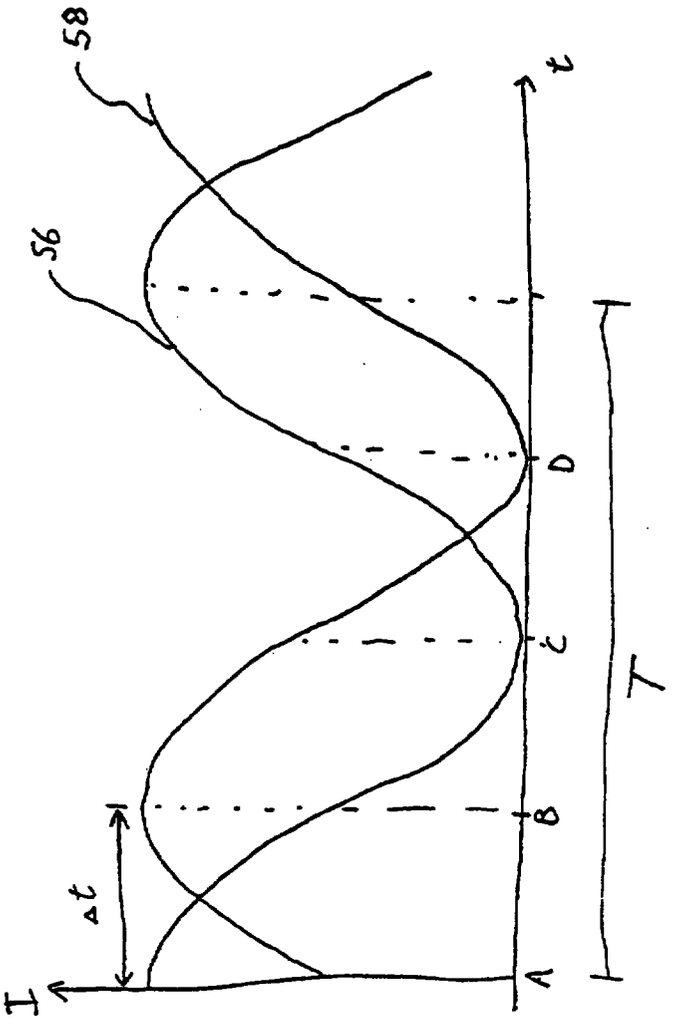

FIG. 5

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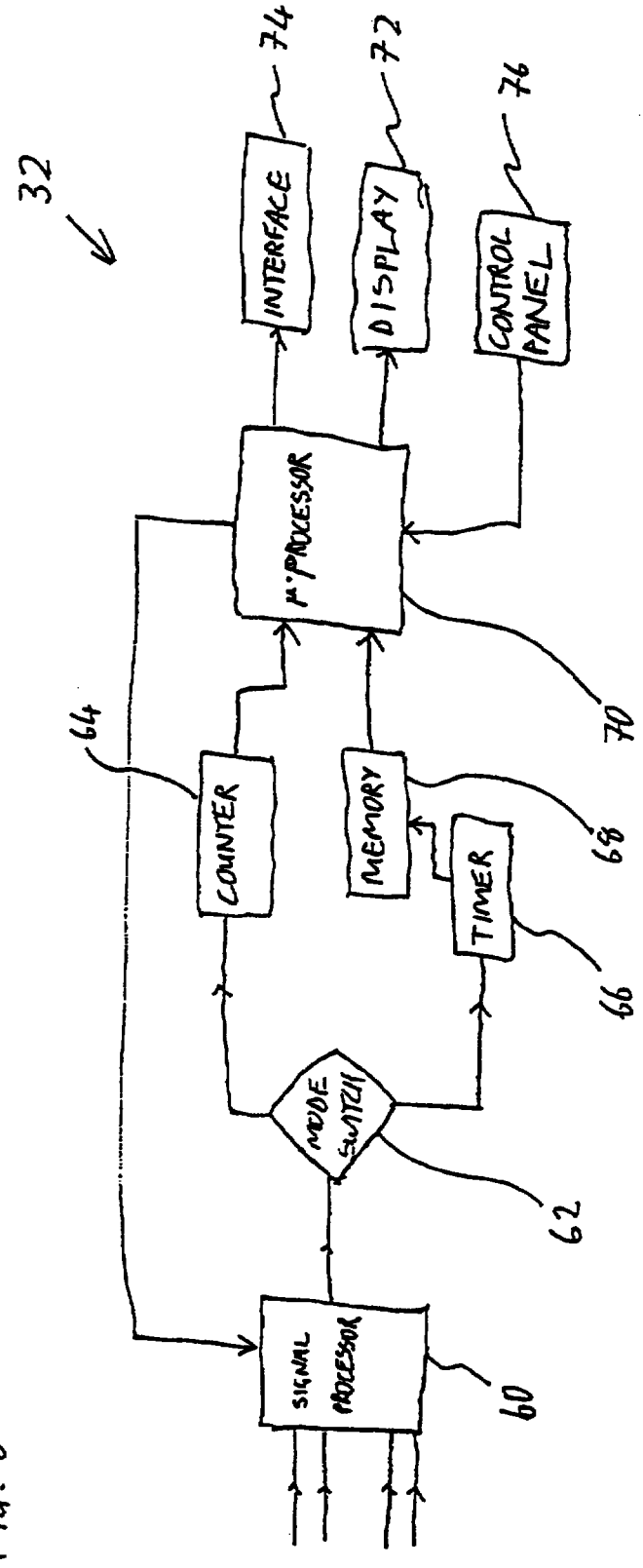

FIG. 6

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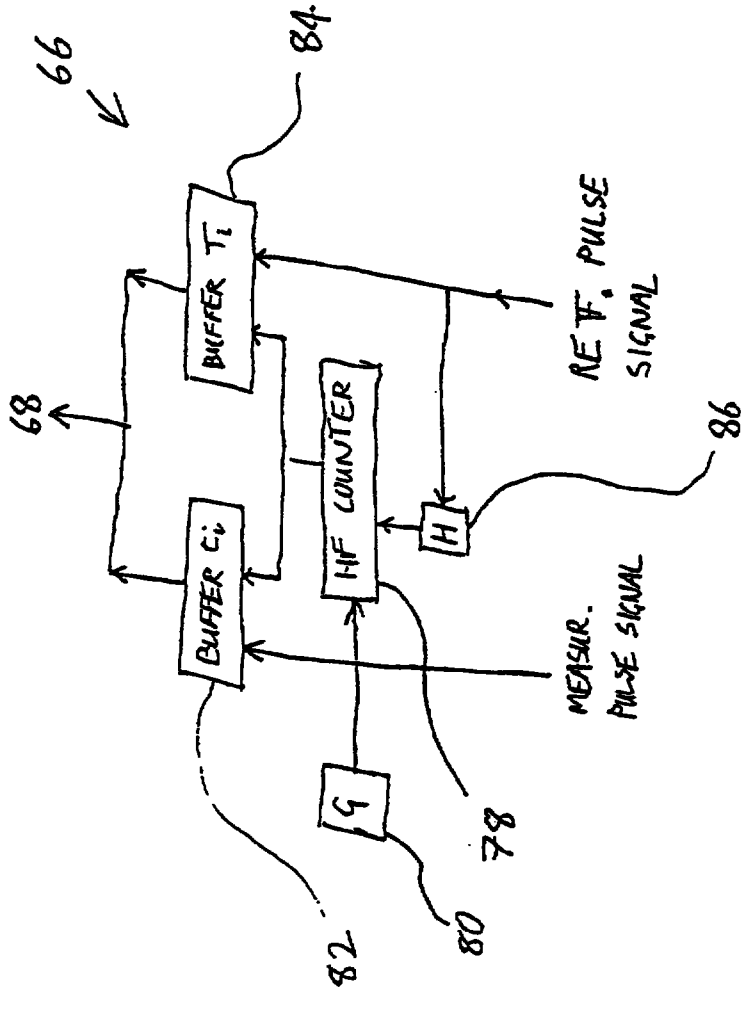

FIG. 7

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WHAT IS CLAIMED IS:

1. A method for precise measurement of an angular position of a rotatable element relative to a base, the method comprising the steps of:

(a) generating, through rotation of a disk having at least one graduated track:

(i) an oscillating reference signal, and

(ii) an oscillating measurement signal,

said measurement signal being related to said reference signal by a phase shift, said phase shift being a function of the angular position of the rotatable element relative to the base; and

(b) measuring said phase shift,

wherein a variation of 2π in said phase shift corresponds to a rotation step of less than about 1° of the rotatable element relative to the base.

2. The method of claim 1, wherein said phase shift is measured in the range $0\text{-}2\pi$ thereby indicating the angular position within a rotation step, the method further comprising the step of counting zero crossings of said phase shift from a given starting value, said starting value corresponding to an initial angular position, such that the number of phase shift zero crossings indicates a rotation step within which the angular position lies.

3. The method of claim 2, further comprising the step of identifying the state of the rotatable element as either rotating or stationary.

4. The method of claim 1, wherein said phase shift is measured in the range $0\text{-}2\pi$ thereby indicating the angular position within a rotation step, the method further comprising the step of performing an approximate measurement of the angular position of the rotatable element relative to the base so as to determine a rotation step within which the angular position lies.

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5. The method of claim 1, wherein said reference signal is generated by measuring optical transmission through a combination of a fixed grid of alternating lines of high and low transparency and said at least one track on said rotating disk.

6. The method of claim 1, wherein said measurement signal is generated by measuring optical transmission through a combination of a measuring track of alternating lines of high and low transparency associated with the element and said at least one track on said rotating disk.

7. A device for measuring a precise angular position of an element rotatable relative to a base, the device comprising:

(a) a rotating disk having at least one primary track of alternating lines of high and low transparency, track said at least one primary providing a first track portion and a second track portion, said rotating disk being rotated continuously about the axis of rotation of the element;

(b) an optical grid of alternating lines of high and low transparency associated with one of the base and the element, said optical grid being positioned parallel to said rotating disk and opposite said first track portion;

(c) a measuring disk associated with the other of the base and the element, said measuring disk being aligned coaxially with said rotating disk, said measuring disk having a secondary track of alternating lines of high and low transparency, said secondary track being aligned opposite said second track portion;

(d) a first photoelectric sensor generating a reference signal indicative of variations in optical transmissivity through a combination of said first track portion and said optical grid;

(e) a second photoelectric sensor generating a measuring signal indicative of variations in optical transmissivity through a combination of said second track portion and said secondary track; and

(f) a processor for processing said reference signal and said measuring signal to calculate information relating to the precise angular position of the element relative to the base.

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wherein said first track portion, said second track portion, said optical grid and said secondary track all have a substantially equal effective angular line spacing.

8. A device as in claim 7, wherein said processor includes:

(a) at least one timer for measuring:

(i) a period of a cycle of said reference signal, and

(ii) a corresponding phase delay between said reference signal and said measuring signal;

(b) a memory for storing a plurality of pairs of said period and said phase delay; and

(c) a numerical processor for processing said plurality of pairs so as to calculate a precise representative phase difference.

9. A device as in claim 8, wherein said processor further includes a counter for counting zero crossings of phase difference between said reference signal and said measuring signal.

10. A device as in claim 7, further comprising a ball-and-socket joint associated with the base so as to accommodate a range of orientations of the rotatable element relative to the base.

11. A method for performing precise measurement of the angular position of an element rotatable relative to a base, the method comprising the steps of:

(a) generating a first signal in relation to relative movement between the base and a rotating member, said first signal being approximately periodic;

(b) generating a second signal in relation to relative movement between the element and said rotating member, said second signal being approximately periodic;

(c) deriving from said first and second signals a plurality of data pairs (T_i, t_i), where T_i is the period of a cycle of one of said first and second signals, and t_i is the corresponding phase delay between said first and second signals;

(d) processing said plurality of data pairs to identify a precise representative phase difference between said first and second signals; and

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* C L M S *

(e) calculating from said representative phase difference information relating to the precise angular position of the rotatable element relative to the base.

12. A method as in claim 11, wherein said first signal is generated by sensing light transmitted through a combination of a graduated scale associated with said base and a graduated track associated with said rotating member.

13. A method as in claim 11, wherein said second signal is generated by sensing light transmitted through a combination of a first graduated track associated with said element and a second graduated track associated with said rotating member.

14. A method as in claim 11, wherein said first and second signals include about 3600 cycles for each rotation of said rotating member.

15. A method as in claim 11, wherein said step of deriving a plurality of data pairs (T_i, t_i) includes deriving said data pair for consecutive cycles of said first or second signal for N cycles, where N is equal to the number of cycles generated by each rotation of said rotating member.

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FIG.1

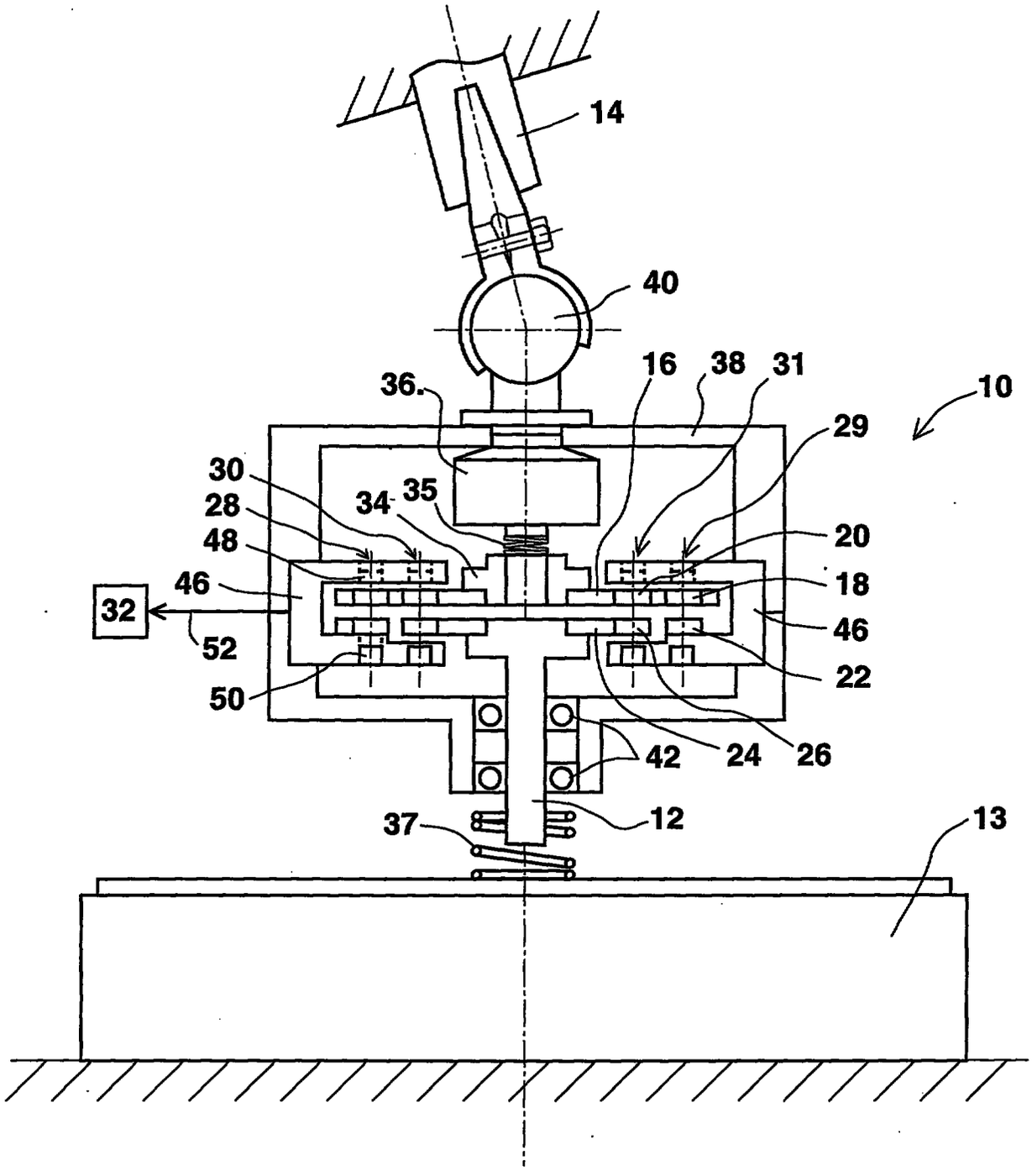

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FIG. 2

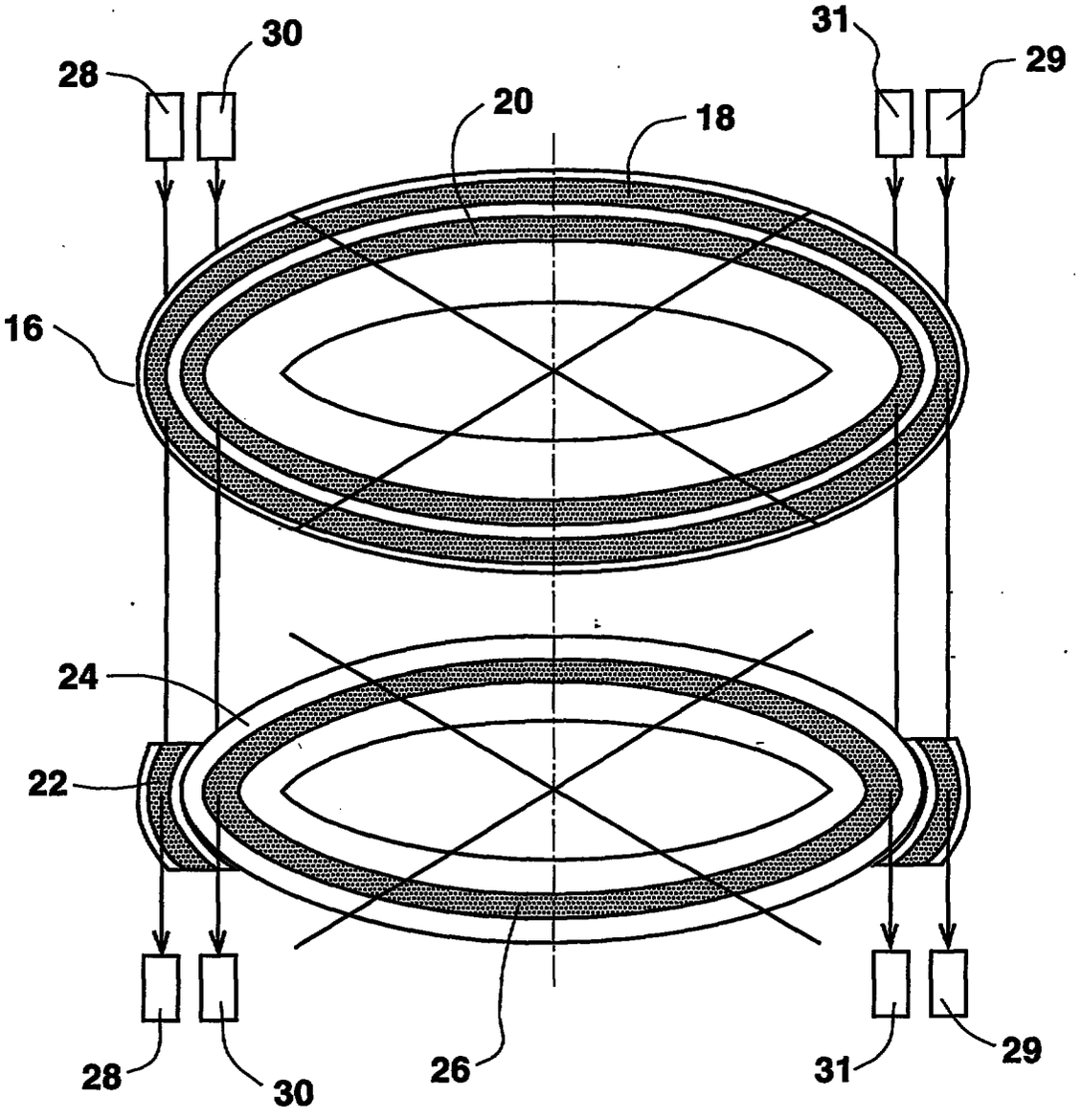

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FIG. 3a

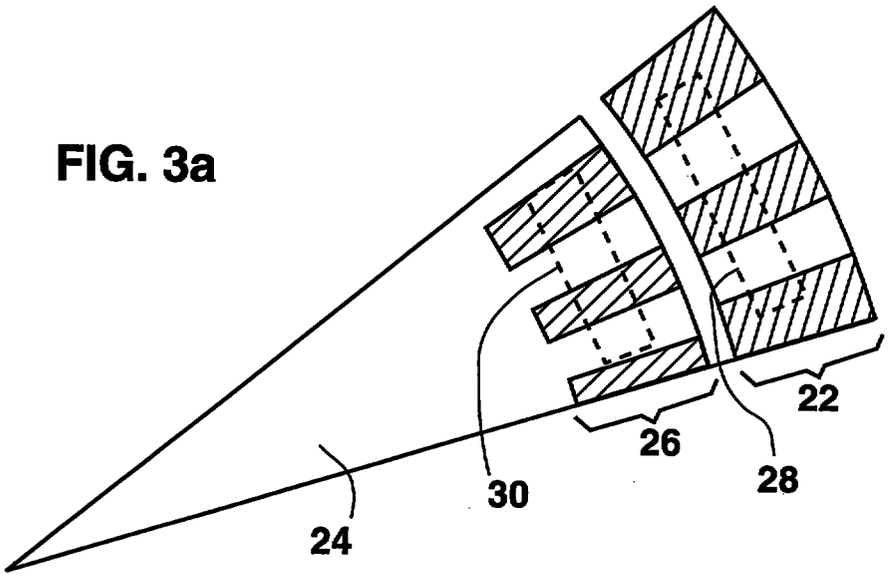

FIG. 3b

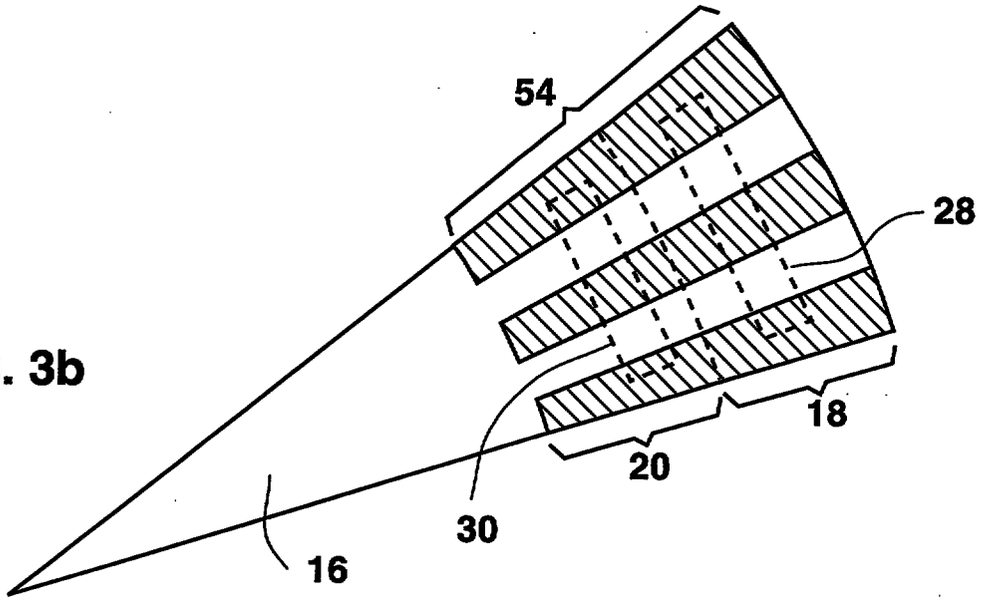

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FIG. 4

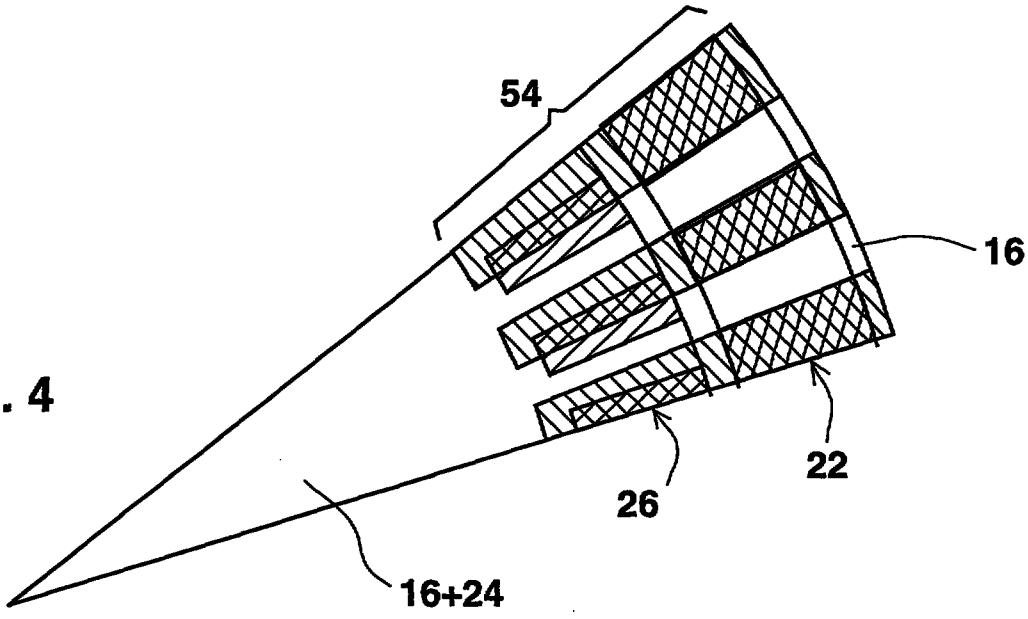

FIG. 5

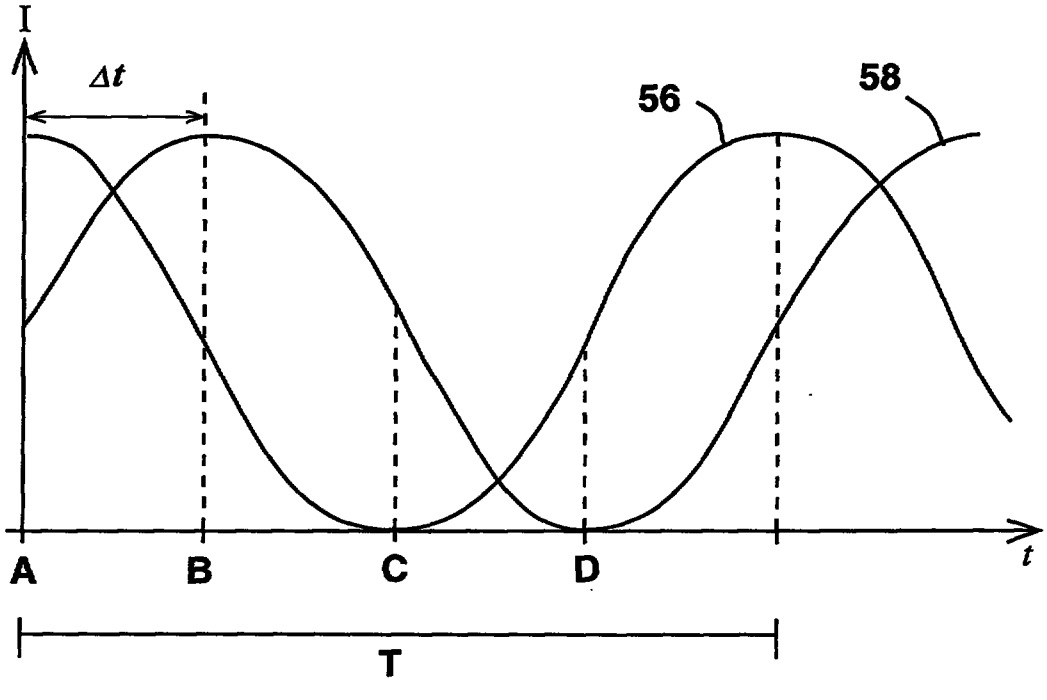

FIG. 6

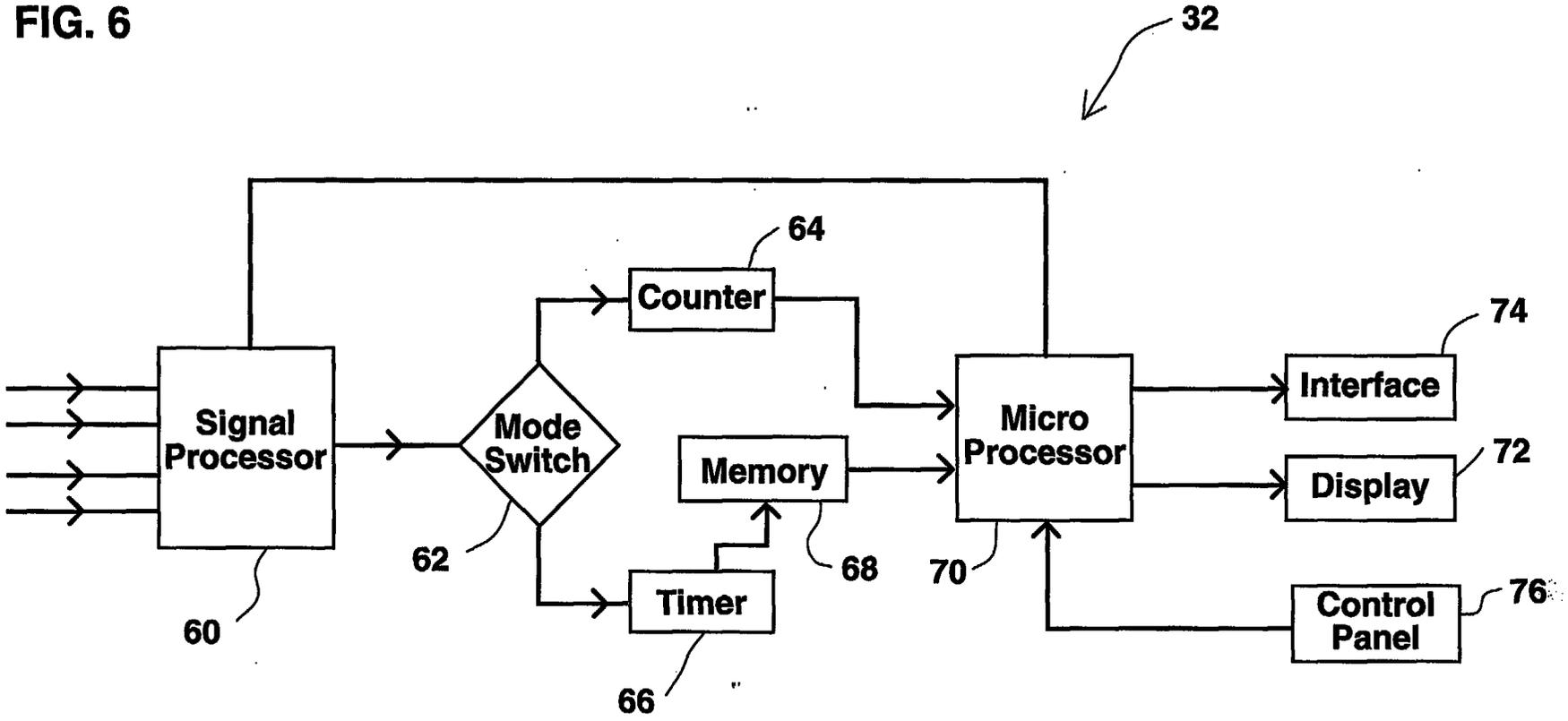

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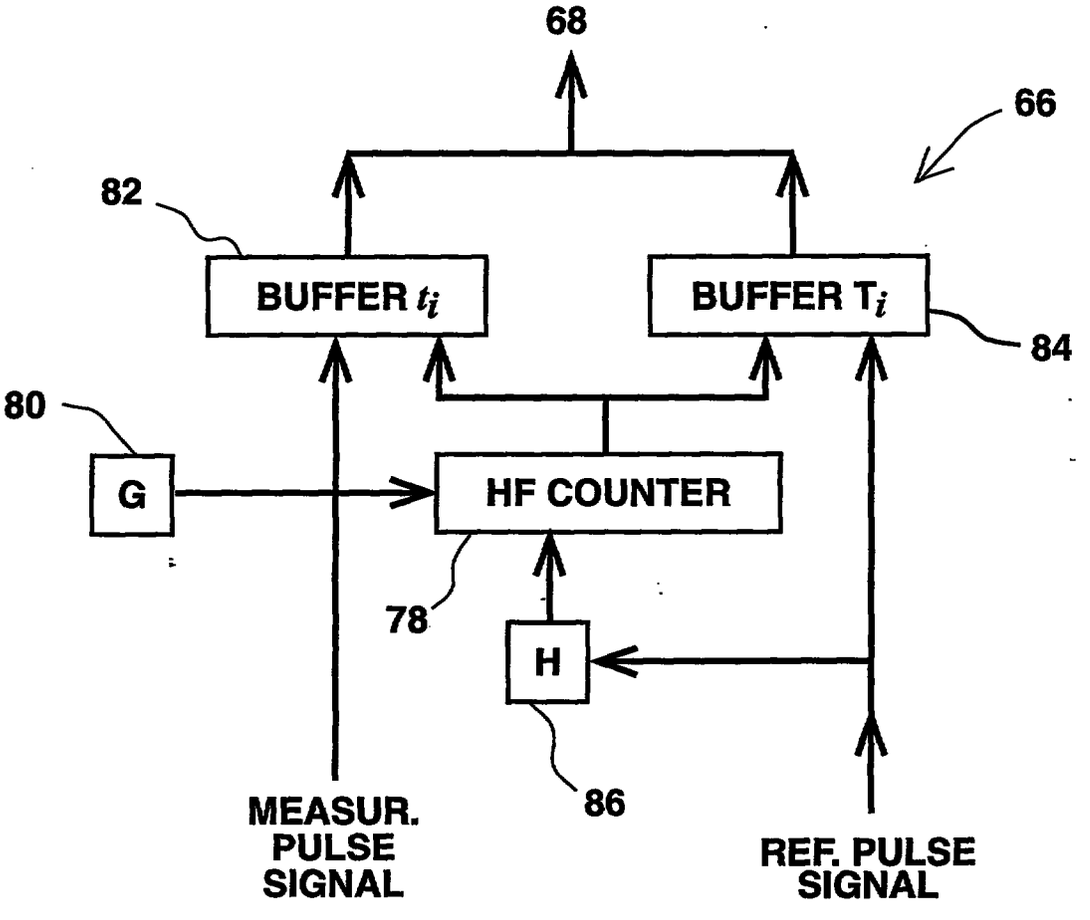
FIG. 7



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(71) Applicant *(for all designated States except US)*: PLACA LTD. [IL/IL]; Building 3, Kiryat Weizmann Science Park, 70400 Ness Ziona (IL).

(71) Applicant *(for TJ only)*: FRIEDMAN, Mark, M. [US/IL]; 1 Alharizi Street, 43406 Raanana (IL).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: PESCHANSKY, Boris [IL/IL]; Apartment 6, 37 Ben-Gurion, 76390 Rehovot (IL). KRAITMAN, Lev [IL/IL]; 55 Yaron Street, 12900 Katzrin (IL). KRAITMAN, Shimon [IL/IL]; 103/9 Etzel Street, 74014 Ness Ziona (IL).

(74) Common Representative: FRIEDMAN, Mark, M.; c/o Robert Sheinbein, 2940 Birchtree Lane, Silver Spring, MD 20906 (US).

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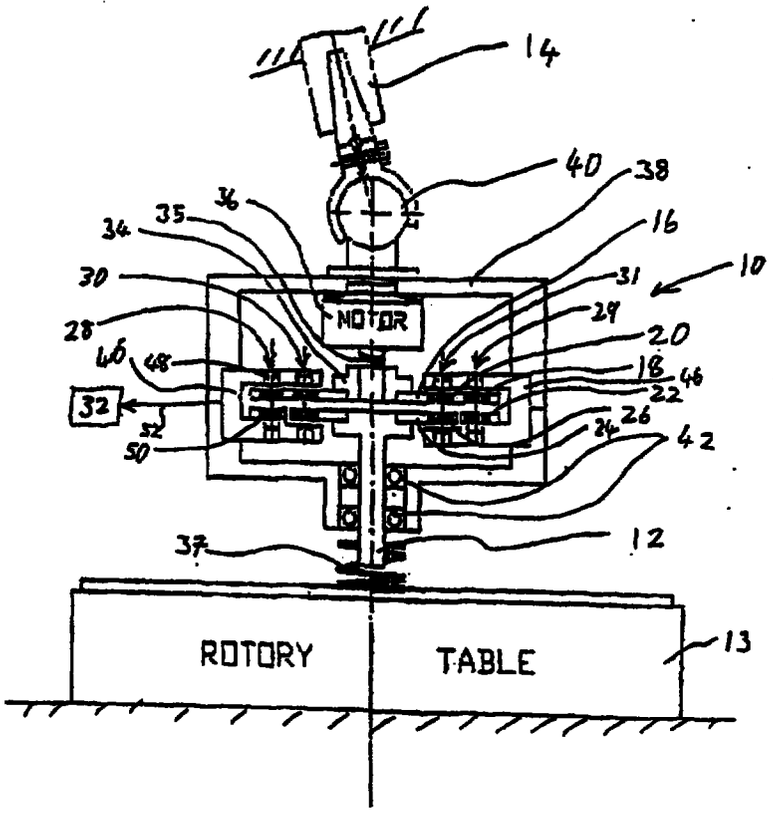
(54) Title: ANGULAR MEASUREMENT APPARATUS

(57) Abstract

A device and method for measuring a precise angular position of an element rotatable (13) relative to a base (14). The device includes a rotating disk (16) having a first track (18) and a second track (20), each track being made up of alternating lines of high and low transparency. The rotating disk is rotated continuously about the axis of rotation of the element. Aligned opposite the first track and parallel to the rotating disk is an optical grid (22) fixed relative to the base, having alternation lines of high and low transparency. A measuring disk (24) attached to the element is aligned coaxially with the rotating disk. The device also features two photoelectric sensors (28 and 30) and which generate signals corresponding to variations in measured optical transmissivity. One photoelectric sensor generates a reference signal (56) corresponding to variations in optical transmissivity through a combination of the first track and the optical grid. The other photoelectric sensor generates a measuring signal (58) corresponding to variations in optical transmissivity through a combination of the second track and the track of the measuring disk. These signals are then processed by a processor to calculate information relating to the precise angular position of the element relative to base.