



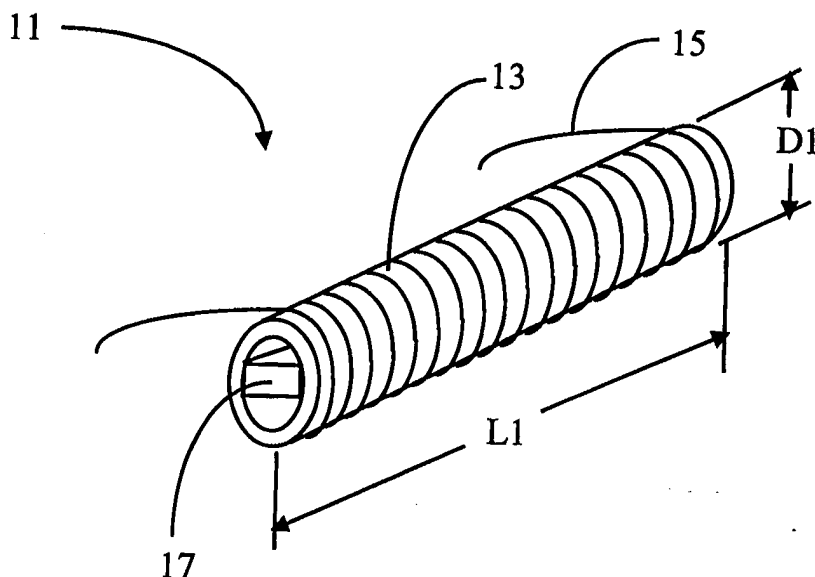
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(54) Title: MAGNETOMETER WITH COIL AND HIGH PERMEABILITY CORE

(57) Abstract

A magnetic field sensor element (11) comprises an elongated core (17) of high-magnetic permeability material having a coil of electrically-conductive wire (15) wound around and along a central axis of the core (17). The sensor, due to inductance of the core (17) which changes with application of a local magnetic field, exhibits a characteristic of delaying an electrical input as a function of the strength of a magnetic field in the direction of the axis of the core, and the delay is measured as a function of the strength of the magnetic field. Appropriate circuitry provides at least one-step function voltage input to the coil such that the resulting delay in current charge-up into the coil creates a voltage across the coil which decays to a known reference value. The time delay for the voltage decaying to the reference value varies as a monotonic function with the strength of the applied magnetic field to be measured.



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MAGNETOMETER WITH COIL AND HIGH PERMEABILITY CORE

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*By Inventors John James and George Hsu***Field of the Invention**

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The present invention is in the area of apparatus and methods for measuring and quantifying magnetic fields, and pertains in preferred embodiments to a weak-field magnetometer useful for navigation instruments such as digitized compasses and the like.

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Background of the Invention

A variety of magnetometers for weak field detection are known in the art. One such is taught in U.S. Patent No. 4,581,775 by Kim et al. The Kim magnetometer is an oscillator whose frequency of oscillation changes as a function of applied magnetic field, and because of this the sampling rate is limited for fast moving magnetic fields. In using the Kim magnetometer, in order to obtain adequate resolution for measuring frequency shifts of an oscillating signal centered around, for example, 50 Khz, one must count up to 300 cycles of the signal waveform against a 5Mhz gating clock in order to obtain 150 nT field resolutions. This limits the ability to sample field changes to only about a 50Hz rate. Furthermore, since multiple cycles must be measured, the sensor circuit becomes an inherent low-pass filter. Although this limitation might be desirable for rejecting unwanted high frequency noise components, such as 60Hz powerline noise, there is no good technique which can be used with this frequency detection scheme to purposely measure higher frequency events.

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The frequency approach in magnetometer technology is also inherently noisy, as a slow comparator is required in order to reject spurious noise from sources such as a microprocessor clock on a power supply in a digitized system. Since a slow comparator moves slowly through the transition range, it is susceptible to frequency modulation (FM) caused by what is known in the art as the Barkhausen effect. This in turn creates noise. This FM limits the bottom of the noise floor to about 15nT.

Power consumption also is relatively high for frequency-based magnetometer systems since such systems must operate on both halves of each oscillator cycle. Typically, in instruments employing this technique, each positive-going cycle must charge up to the positive hysteresis point of a Schmitt trigger as set by a feedback resistor, while each negative cycle must charge down to the negative hysteresis point as well. When the area under the curve is integrated, it can be seen that more power is expended than if only one half of a cycle were used.

What is clearly needed is an apparatus and method for measuring weak magnetic fields, such as the magnetic field of the Earth, which is accurate, relatively inexpensive to manufacture, less noisy than conventional apparatus and techniques, and not inherently bandwidth limited.

Summary of the Invention

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It is an object of the present invention to provide a low cost, temperature-stable, very low-power magnetometer with high sensitivity, very low noise and a sampling rate which allows sampling of low or high intensity magnetic fields from DC to several megahertz. It will be apparent to one skilled in the art of magnetometry that such an invention

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could be applied to a broad variety of uses where making highly accurate low noise weak field measurements is necessary. The invention is especially effective where relatively high sampling rates are required.

It is another object of the invention to provide such a high speed
5 weak field magnetometer in which the field strength as measured along the sensitive axis is determined by the propagation delay time differences of an input signal current through the inductive sensor element.

In a preferred embodiment a sensor for quantifying magnetic field
10 strength is provided, comprising a core of elongated high-magnetic-permeability material having a central long axis; and a multi-turn winding of electrically conducting wire wound on the core along the long axis of the core, and electrically insulated from the core. The sensor in one embodiment further comprises an electrically-insulating,
15 elongated bobbin element having a hollow central axis, wherein the multi-turn winding is wound on the outside of the bobbin and the core is positioned along the hollow central axis of the bobbin. Metglas material is one suitable choice for the core material, and the winding may be provided on the core using a single length of lacquered copper wire
20 having a first end at one end of the bobbin and a second end at the opposite end of the bobbin.

In one embodiment the sensor is utilized in a magnetometer comprising a driver circuit having a voltage-controlled output; a sensor comprising a core of elongated high-magnetic-permeability material
25 having a central long axis and a multi-turn winding of electrically conducting wire wound on the core along the long axis of the core, and electrically insulated from the core, the sensor connected by a first end of the winding to the voltage controlled output of the driver circuit; and a measuring circuit connected to a second end of the winding and
30 adapted to measure time for voltage at the second end to reach a pre-

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selected reference voltage. The driver circuit may have a reset and a comparator may be used to reset the driver when voltage at an output of the sensor reaches a reference voltage, providing thereby an output having a train of pulses having a pulse width proportional to the strength of any magnetic field in the direction of the long axis of the sensor element.

In another aspect of the invention a navigation instrument is provided comprising three sensing units, each sensing unit comprising a sensor for quantifying magnetic field strength, the sensor comprising a core of elongated high-magnetic-permeability material having a central long axis, and a multi-turn winding of electrically conducting wire wound on the core along the long axis of the core, and electrically insulated from the core;

three driver circuits each having a voltage-controlled output and connected one each to a first end of the multi-turn winding of one of the sensors; and a measuring circuit connected to a second end of each of the multi-turn windings and adapted to measure time for voltage at the second end of each of the windings to reach a pre-selected reference voltage. In this instrument the central long axes of the cores of the three sensors are arranged mutually orthogonally. In other embodiments there may be two sensor units at right angles for those situations where measurements in two dimensions will suffice.

In a preferred embodiment the navigation instrument described above further comprises processing and display circuitry coupled to the measuring circuitry, and adapted for processing measurement data reported by the measuring circuitry and displaying processed data to a user. The navigational instrument can be a digital compass, wherein the processed data displayed indicates direction.

In another aspect of the invention a digital compass is provided comprising multiple sensing units, each sensing unit comprising a sensor

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for quantifying magnetic field strength, the sensor comprising a core of elongated high-magnetic-permeability material having a central long axis, and a multi-turn winding of electrically conducting wire wound on the core along the long axis of the core, and electrically insulated from the core; multiple driver circuits each having a voltage-controlled output and connected one each to a first end of the multi-turn winding of one of the sensors; and a measuring circuit connected to a second end of each of the multi-turn windings and adapted to measure time for voltage at the second end of each of the windings to reach a pre-selected reference voltage. In this digital compass the central long axes of the cores of the three sensors are arranged in different directions. In other embodiments there may be sensors on two axes rather than three.

In other aspects methods for practicing the present invention are provided.

15

Brief Description of the Drawing Figures

Fig. 1 is an isometric view of an inductive sensor element according to an embodiment of the present invention.

20 Fig. 2 is a simplified electrical diagram illustrating use of the sensor element of Fig. 1 with other elements to measure magnetic field strength Y

Fig. 3 is a permeability curve representative of the permeability of a core material useful for sensors according to embodiments of the present invention.

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Fig. 4 is a graph illustrating a voltage step function used to drive a sensor in an embodiment of the present invention.

Fig. 5 is a graph illustrating a voltage decay function for a sensor according to an embodiment of the present invention.

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Fig. 6 is a graph similar to the graph of Fig. 5, but showing voltage decay to a reference voltage for a single sensor effected by two different strength magnetic fields.

Fig. 7 is an electrical diagram of a circuit for driving a sensor
5 according to a preferred embodiment of the present invention.

Figs. 8A-8C are square-wave diagrams illustrating pulse width produced for two different fields under conditions of two different input frequencies for the circuit of Fig. 7.

Fig. 9 is a block diagram illustrating elements in an instrument
10 utilizing a sensing circuit according to an embodiment of the present invention.

Fig. 10 is a block diagram illustrating an instrument utilizing sensing circuitry according to an embodiment of the present invention, wherein multiple sensors are arranged to provide data relative to field
15 direction as well as field strength.

Description of the Preferred Embodiments

20 The present invention in its several aspects is based on a novel high-sensitivity, weak-field magnetometer device using an inductive sensor element whose reactance is effected by an applied magnetic field and causes a variable output delay to any given input driving signal.. In a preferred embodiment this feature enables a methodology wherein
25 timed input pulses cause output pulses whose width, and not frequency or duty cycle, varies monotonically in proportion to any given magnetic field applied externally along the sensitive axis of the sensor element. Such pulses, whose width varies, can be easily measured in many different ways known to those skilled in the art, such as by pulse width
30 detection or integration by a simple capacitive integrator. The

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measurement of output pulse width, properly calibrated, may be converted to a direct current analog voltage level which can be subsequently converted into a digital input for use by a processing circuit.

5 A field measuring device as described above can be used in a broad variety of applications, such as Earth field sensing for the purpose of providing heading information for a digital compass or for the purpose of linear or angular position or rate sensing either by proximity or encoder sensing as well as many other traditionally difficult and
10 costly uses for measuring weak DC magnetic fields.

Fig. 1 is an isometric view of an inductive sensor element 11 according to an embodiment of the present invention, useful in circuitry for measuring magnetic fields. Sensor element 11 comprises a plastic bobbin 13 of length L1 and diameter D1 having a winding of N1 turns of
15 electrically conductive wire 15. An elongated core 17 of high-direct-current-permeability material is arranged along the central axis of bobbin 13. In preferred embodiments of the present invention voltage across the coil is monitored by connection to the ends of coil wire 15, and variations in voltage are processed as an indication of the strength of
20 any magnetic field in the direction of the axis of bobbin 13.

In a preferred embodiment, diameter D1 is about 0.15 inches and L1 is about 0.8 inches. High-permeability core 17 in this embodiment is a strip of No. 2705M Metglas made by Allied Signal Corporation fashioned to dimensions of about 0.60 inches in length by about 0.35
25 inches width by about .001 inches thickness. The wire in this embodiment is 41 gauge lacquer-insulated copper magnet wire, wrapped to 1400 turns on the plastic bobbin. It will be apparent to those with skill in the art that these dimensions and materials are convenient and not necessarily limiting to the invention. There are many other materials

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and geometries that may be used within the spirit and scope of the invention.

Fig. 2 is a simplified electrical diagram illustrating a use of the sensing coil with other elements to measure magnetic field strength. In Fig. 2 a voltage source 19, a switch 21, a current source 23, and sensor 11 are wired in series and in a loop. That is, one side of the sensor element is connected to one side of the voltage source, and the other side of the sensor element is wired in series through the current source and the switch back to the opposite side of the voltage source.

In the circuit of Fig. 2, closing switch 21 supplies a step function to sensor 11. At the instant of closing switch 21, the circuit, because of the reactance of sensor 11, appears to be an open circuit, and essentially the full voltage of the voltage source appears across sensor element 11. As time passes, the apparent resistance of the sensor element diminishes, until, at steady state, the sensor appears as a short circuit, displaying very small voltage drop across the sensor, due to the inherent, steady state resistance of the winding wire over the length of the wire forming the winding on the bobbin. The nature of the sensor element is such that the time constant for voltage decay across the sensor element is a function of the strength of any magnetic field along the length of the sensor element.

In an alternative implementation a resistor may be placed in series with the sensor element, and the voltage across the resistor is measured instead of the voltage across the sensor element. In this alternative, the voltage variation is from zero at the instant the switch is closed, and the voltage rises until the full voltage appears across the resistor at the time that the voltage drop across the sensor element reaches zero. The time constant for voltage increase across the resistor in this alternative is a monotonic function of the strength of any magnetic field along the long axis of the sensor element.

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It will be apparent to those with skill in the art that a sudden step function is only one way a signal can be provided to the circuit of Fig. 2. In the case of a step function, the step is repeated periodically, so the input is substantially a square waveform, but essentially any other sort of waveform may be used.

Fig. 3 is a typical permeability curve for a high-permeability material such as the Metglas material used in embodiment of the invention herein described. Because the permeability of the Metglas core material is a monotonic function of an applied magnetic field H, the inductance of the sensor is directly proportional to the externally applied magnetic field.

Fig. 4 is a simple graph illustrating instantaneous current in the circuit of Fig. 2 as a result of closing switch 21. When the step function current (Fig. 3) is applied to the sensor coil a voltage develops across the coil whose e^{-kt} decay is proportional to the externally applied magnetic field. The general form of the voltage decay curve is illustrated as Fig. 5. The time (tau) required for voltage across the sensor coil to decay from the initially applied voltage (V_0) to an arbitrary reference voltage (V_{ref}) is determined by the time constant as determined by the sensor coil's inductance. This inductance is primarily dominated by the inductance of the sensor's high permeability core.

The time tau shown in Fig. 5 will differ with different values of time constant according to different values of magnetic field strength H along the axis of the sensor coil. The difference in time interval for this measurable voltage change is temperature stable, and varies proportionally to the applied magnetic field.

The voltage across the sensor coil in the circuit of Fig. 2 may be expressed mathematically as follows:

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Equation 1 $v(t) = L \frac{di}{dt} + Ri$

Solving Equation 1 for i in the particular instance of a step function such as provided by closing switch 21 in Fig. 1 yields the following

5 solution for i :

Equation 3 $i = \frac{1}{R}(1 - e^{-\frac{t}{L/R}}) + ce^{-\frac{t}{L/R}}$

It may be seen that the time constant for current into the sensor is simply

equal to $\frac{L}{R}$

10

for small changes in field, $L = \mu_0 n^2 V \left(\frac{dB}{dH} \right)$

where μ_0 is the permeability of free space, n is the number of turns of

15 the sensor, V is the volume of the core material, and $\frac{dB}{dH}$ is the slope of the B versus H curve at any particular point.

Substituting $\mu(H) = \frac{dB}{dH}$

20 then $L = \mu_0 n^2 V \mu(H)$

Referring to the $\mu(H)$ versus H curve of Figure 3, along the linear portions of the right or left half of the curve $\mu(H) = kH$. In other words, $\mu(H)$ is a linear function of H and k is the slope of that part of the

25 curve.

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So, along these linear portions of the curve of Fig. 3 the time constant is

$$\frac{\mu_0 n^2 V k H}{R}$$

5 As can be seen from the mathematical derivation then, the time constant of the inductive sensor element is a linear function of H , which is the externally applied magnetic field to be measured. So as stated previously, the time it takes to reach any given reference voltage across the sensor or resistor is a linear function of the applied magnetic field we
10 are trying to measure and is temperature stable.

Fig. 6 is a graph similar to that of Fig. 5, but exhibiting voltage decay across a sensor element under conditions of two different applied fields of strength H_1 and H_2 . Under the influence of the field of strength H_1 the time to reach the reference voltage is τ_1 , and under the
15 influence of the field of strength H_2 the time to reach the reference voltage is τ_2 .

Fig. 7 is a generalized electrical diagram of an embodiment of the present invention wherein a triggered flip-flop circuit 25 drives a sensor 11 with a repeating square wave of magnitude V_{CC} . When a
20 rising edge of an input trigger is input into the D flip-flop, V_{CC} is output to Q (pin 5). As the voltage initially appearing across sensor 11 decays, the voltage at point 27 on the far side of sensor element 11 from Q will rise from ground potential toward V_{CC} as a result of resistor R2.

A comparator 29 having a preset trip point value is provided
25 connected by pin 2 to point 27. Once the voltage at point 27 (at pin 2 of the comparator) reaches the pre-set trip point value, the comparator will fire low, which, by virtue of line 31 will clear the D flip-flop and cause the output Q to go low.

In the circuit of Fig. 7, the period of the input trigger function is
30 deliberately selected to be longer than any expected time for voltage at

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pin 2 of the comparator to reach the reference voltage for the highest value of field strength H expected to be measured. Because the comparator fires each time the voltage at pin 2 reaches a pre-set trip value, resetting the flip-flop, and because this time will be less than the period of the input trigger function, the output at Q will be a square wave of magnitude V_{cc} wherein the pulse width is determined by the strength of any magnetic field along the axis of sensor element 11. This output pulse train appears on line 23, and may be connected to suitable circuitry for measuring the pulse width as a function of the magnetic field strength.

An advantage of this particular circuit is that it can be gated once for one output pulse, or as many times as is necessary for adequate resolution to be obtained. If the circuit is gated with a clock signal, it will output a train of pulses where each pulse width is determined by the strength of an externally applied magnetic field. It can, of course, be gated with a clock whose frequency is as fast or as slow as desired thereby obtaining high sampling rates with a fast clock, or for saving power and obtaining high resolution with fewer pulses with a slow gating clock.

Figs. 8A through 8D illustrate several output pulse trains produced as a result of input trains of two different gating clock frequencies and for two different values of magnetic field to be measured.

The external magnetic field strength H_1 is common for Fig. 8A and Fig. 8B, but the driving signal clock frequency 1 for Fig. 8A is slower than clock frequency 2 for Fig. 8B. The result is that the output pulse is of constant width, independent of clock frequency. Fig. 8C and Fig. 8D repeat this illustration for a different magnetic field strength but the same clock frequencies used for Figs. 8A and 8B. It is only necessary that the input pulse width be longer than the output pulse

width, which is a simple matter to preset by calculation, and to adjust empirically if necessary.

There are many uses in the art for the magnetic field strength measuring apparatus according to embodiments of the present invention.

5 The output pulse train on line 23 of Fig. 7, for example, can be fed into a simple voltage integrator to produce a fast-moving DC voltage signal which will be proportional to the applied magnetic field, providing highly accurate, low-noise magnetic field measurements. Alternatively, the pulse width can be measured directly with any variety of counting
10 and timing schemes for use by a microprocessor without necessitating any analog to digital conversion.

For high speed magnetic encoder applications, the gated clocking is especially useful, since a trip level on the pulse width can be set and a reference one-shot can be generated by the clock signal and fed into an
15 AND gate for high speed determination as to whether a variable field being measured has reached a certain threshold value. When a preset magnetic field strength threshold has been reached, the AND gate will output a stream of pulses for as long as the magnetic field strength stays above the threshold level. Conversely the AND gate will output nothing
20 when the magnetic field is below the threshold. Circuits to accomplish the purposes described herein using the output pulse train from the apparatus with a unique sensor according to an embodiment of this invention may be provided by skilled persons from known circuitry of the sort, without undue experimentation, and are therefore not presented
25 here in detail.

By strategically selecting a comparator trip point and a clocking frequency for different purposes, a variety of speed, sensitivity, resolution, and power savings can be achieved with any given sensor coil and core geometry. As an example, power consumption using a
30 sensor according to an embodiment of the present invention with

circuitry described herein and made by Precision Navigation, Inc. has been measured to be as low as 90 microamps at 3 volts, by using a slow 30Hz driving signal. The Earth's magnetic field was still measured effectively at full resolution in this low-power operating mode.

5 A very advantageous feature of the new technology taught herein is that the sensor geometry can be provided to complement specific circuit parameters, thereby customizing a magnetometer for optimal performance for any particular magnetic sensing application. Another advantage is that the noise floor is extremely low. This is because the magnetometer always operates in one or the other of either a chargeup or
10 in a decay mode, and is not a mix of the two. This, in effect, minimizes the contribution of noise from the well-known Barkhausen effect as the transition of the core material through the permeability curve is always in one direction and is always done in a consistent manner during any
15 one period of the signal and clocking pulse.

 The technique taught herein also minimizes noise caused by any residual hysteresis which the high permeability material might exhibit, thereby eliminating any ambiguity which is caused by the effect of retentivity which manifests itself in the B versus H curve of the core
20 material, causing the classical looping curve path during the demagnetization of the material by the method of reversals [pp 242, Fundamentals of Electricity and Magnetism, Loeb, by John Wiley and Sons, 3rd Edition]. Additionally, a fast comparator can be used without injecting noise, since the sole function of the comparator is that of a
25 voltage level detector. This allows quick transition and substantially reduced FM noise from any ambiguity caused by the hysteresis voltage levels of a Schmitt trigger.

 Another source of noise and non-linear response in the prior art is that the permeability of Metglas is also a function of frequency. Since
30 some prior art devices change frequency for different applied magnetic

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field strength, the permeability of a sensor is changing as a direct result of the frequency shift alone. The invention described here has the advantage of always operating at a fixed frequency dependent upon the clocking signal, which in practical application will always remain fixed

5 As a result of the improvements described, the noise floor of the system in an embodiment of the present invention has been measured at well below 1 nanoTesla, and may with further development possibly be in the 1 picoTesla range. The sensitivity of the device has been observed to match that of laboratory-grade reference magnetometers, but
10 implemented with less than one dollar's worth of components.

It is the material property of the high permeability Metglas material or any equivalent substance which is key to enabling this invention to work as described. Without the high permeabilities of the Metglas materials, the change in pulse widths would not be present or
15 measurable, as the weak Earth field and other fields like it would not be able to cause any Barkhausen alignment of the magnetic domains of those other core substances such as iron. Additionally, low-hysteresis exhibited by the Metglas materials also allows the invention to operate within the linear regions of the permeability curve and does not
20 necessitate the operation of the device by driving the core into saturation in order to circumvent the wandering effect caused by retentivity. This is the case with almost all of the magnetometer inventions based on saturable core devices which preceed this present invention.

Another aspect of the present approach which should be
25 discussed is that the step function driving signal, which was described earlier, contains a natural DC bias which biases the operating point of the sensor core material to the desired operating region on its permeability curve. This not only provides for optimal operating sensitivity, but it can also be seen that by structuring the electronics to
30 electrically reverse the sensor coil within the circuit, that a forward and a

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reverse reading can be obtained, which if subtracted from each other will provide a reading value which will be independent of drifts due to temperature, age, or manufacturing defects of the sensors. The inventors use an operating circuit topology which is a cycle by cycle differencing integrator, which puts out a zero drift-corrected DC voltage for input
5 into a volt meter or an analog to digital converter. This differencing integrator actually does the forward and backward biasing and sums up the voltage difference between the two and contributes that value to the integrated DC voltage.

10 Another extremely advantageous feature in embodiments of the present invention is that there is no perceptible drift in the operation of the sensor due to temperature. The only circuit parameter which changes with temperature in a significant fashion for temperatures less than the Curie point is the series resistance of the copper wire used in the
15 windings. The time constant change due to this circumstance remains constant, because as the resistance in the wire moves up or down, the inductance of the coil also moves up or down in a manner which tracks the resistance change. This keeps the overall time constant at the same value for a given magnetic field. Since the input of the excitation signal
20 is a step function at the rail value for the comparator, the DC bias component to the sensor core is constant over temperature and does not drift, unlike other biasing schemes used in other prior art magnetometer circuits. This creates a temperature-stable magnetometer.

In the preferred embodiment described with reference to Fig. 7,
25 the magnetometer is constructed of the following: 1) a plastic bobbin with diameter of 0.15" and overall length of 0.8"; 2) a Metglas core of Allied Signal Corp. 2705M cut to the dimensions of 0.600" x 0.35" x 0.001" and placed in the center of the bobbin of item 1 above; 3) 1400 turns of 41 gauge lacquer-insulated copper magnet wire available from

[7]

which is almost layer wound onto the bobbin of item 1 above with the core of item 2 above in the center of the unit.

Electrical connection is made to this sensor coil as shown in Fig.

7. D-Flip Flop 25 in this embodiment is an AC74 available from many
5 manufacturers, such as National Semiconductor Corp. The analog
comparator can be any comparator, but the one used for this example is a
model TLC3702 from Texas Instruments. Vcc can be almost any
voltage, though a nominal voltage of 3 volts has been used preferentially
in experiments connected with the present invention. Pulldown resistor
10 R_6 in input to the D Flip-Flop is nominally 100Kohms, although the
specific value will not seriously effect the operation of the device. The
series resistors R1 and R2 to the sensor coil are chosen to bias the sensor
to the desired area of operation on the permeability curve and in this
example are 330 ohms each. The comparator reference voltage biasing
15 resistors R3 , R4, and R5 are 68Kohm (R3), 10Kohm (R4) and 22Kohm
(R5).

Fig. 9 is a block diagram illustrating elements in an instrument
utilizing a sensing circuit 33 according to an embodiment of the present
invention. Sensing circuit 33 may be of the architecture of that circuit
20 shown in Fig. 7, or some elements for driving and measuring the sensor
element may be different but drawn from circuitry known in the art. In
the instrument of Fig. 9 delayed output of input to sensing circuitry 35 is
received by processing circuitry 37, processed to yield field information,
and the field information is further processed to be displayed on a
25 display 39. Instruments of this sort utilizing single sensing elements
may be used for applications wherein field direction is known and field
strength measurement is needed.

Fig. 10 is a block diagram of an instrument 41 utilizing sensing
circuitry 43, 45, and 47 according to an embodiment of the present
30 invention, wherein multiple sensors are arranged with axes in different

directions to provide data relative to field direction as well as field strength. In one embodiment sensors may be arranged mutually orthogonally (X, Y, Z) and suitable algorithms employed by processing circuitry 49 providing display data to a display apparatus 51. This
5 architecture may be utilized for a digital compass, for example.

It will be apparent to those skilled in the art that many alterations in form and details of the embodiments of the invention described herein may be made without departing from the spirit and scope of the invention, and in various embodiments inventive elements from the
10 teaching herein may be adapted to instruments and functions of many sorts. Many such alterations have already been described above. There are many others. For example, there are other materials than the specific Metglas used in the embodiments described which may be useful in other embodiments. There is a broad range of sizes of sensor element
15 components which may be used as well. There are similarly many applications to which embodiments of the invention may be put, such as navigational equipment (mentioned previously). For example, since the sensor is sensitive to the component of any applied field which lies along the long axis of the sensor, two different sensors at different
20 angles can determine field direction in a plane, and three different sensors physically arranged mutually at known angles (right angles for Cartesian analysis) to one another and connected to suitable circuitry may measure both the strength and three-dimensional direction of an applied magnetic field. The polarity of a field may be similarly
25 determined. It is intended that such changes be included within the spirit and scope of the invention, and the scope of the invention is limited only by the claims below

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What is claimed is:

1. A sensor for quantifying magnetic field strength, comprising:
 - 5 a core of elongated high-magnetic-permeability material having a central long axis; and
 - a multi-turn winding of electrically conducting wire wound on the core along the long axis of the core, and electrically insulated from the core.
- 10 2. The sensor of claim 1 further comprising an electrically-insulating, elongated bobbin element having a hollow central axis, wherein the multi-turn winding is wound on the outside of the bobbin and the core is positioned along the hollow central axis of the bobbin.
- 15 3. The sensor of claim 1 wherein the core comprises an elongated strip of Metglas material.
4. The sensor of claim 1 wherein the multi-turn winding is formed from
 - 20 a single length of lacquered copper wire having a first end at one end of the bobbin and a second end at the opposite end of the bobbin.
5. A magnetometer comprising:
 - a driver circuit having a voltage-controlled output;
 - 25 a sensor comprising a core of elongated high-magnetic-permeability material having a central long axis and a multi-turn winding of electrically conducting wire wound on the core along the long axis of the core, and electrically insulated from the core, the sensor connected by a first end of the winding to the voltage controlled output
 - 30 of the driver circuit; and

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a measuring circuit connected to a second end of the winding and adapted to measure time for voltage at the second end to reach a pre-selected reference voltage.

- 5 6. The magnetometer of claim 5 further comprising an electrically-insulating, elongated bobbin element having a hollow central axis, wherein the multi-turn winding is wound on the outside of the bobbin and the core is positioned along the hollow central axis of the bobbin.
- 10 7. The magnetometer of claim 5 wherein the core comprises an elongated strip of Metglas material.
8. The magnetometer of claim 5 wherein the multi-turn winding is formed from a single length of lacquered copper wire having a first end
15 at one end of the bobbin and a second end at the opposite end of the bobbin.
9. A magnetometer comprising:
 - a driver circuit having a voltage-controlled output and a reset;
 - 20 a sensor comprising a core of elongated high-magnetic-permeability material having a central long axis and a multi-turn winding of electrically conducting wire wound on the core along the long axis of the core, and electrically insulated from the core, the sensor connected by a first end of the winding to the voltage controlled output
25 of the driver circuit; and
 - a comparator circuit having a voltage reference, an input connected to a second end of the winding and an output connected to the reset of the driver circuit;

wherein the driver circuit provides a voltage to the sensor and the comparator output fires, resetting the driver circuit, when the voltage at the comparator input equals the reference voltage.

- 5 10. The magnetometer of claim 9 further comprising an electrically-insulating, elongated bobbin element having a hollow central axis, wherein the multi-turn winding is wound on the outside of the bobbin and the core is positioned along the hollow central axis of the bobbin.
- 10 11. The magnetometer of claim 9 wherein the core comprises an elongated strip of Metglas material.
12. The magnetometer of claim 9 wherein the multi-turn winding is formed from a single length of lacquered copper wire having a first end
15 at one end of the bobbin and a second end at the opposite end of the bobbin.
13. The magnetometer of claim 9 wherein the driver circuit comprises a flip-flop circuit driven by a clock signal.
- 20 14. The magnetometer of claim 9 wherein the output of the flip-flop circuit is connected to measuring circuitry adapted to measure pulse width of output pulses.
- 25 15. A navigation instrument comprising:
three sensing units, each sensing unit comprising a sensor for quantifying magnetic field strength, the sensor comprising a core of elongated high-magnetic-permeability material having a central long axis, and a multi-turn winding of electrically conducting wire wound on

2.2.

the core along the long axis of the core, and electrically insulated from the core;

three driver circuits each having a voltage-controlled output and connected one each to a first end of the multi-turn winding of one of the sensors; and

a measuring circuit connected to a second end of each of the multi-turn windings and adapted to measure time for voltage at the second end of each of the windings to reach a pre-selected reference voltage;

wherein the central long axes of the cores of the three sensors are arranged mutually orthogonally.

16. The navigation instrument of claim 15 further comprising processing and display circuitry coupled to the measuring circuitry, and adapted for processing measurement data reported by the measuring circuitry and displaying processed data to a user.

17. The navigation instrument of claim 16 wherein the navigation instrument comprises a digital compass, and the processed data displayed indicates direction.

18. A digital compass comprising:
multiple sensing units, each sensing unit comprising a sensor for quantifying magnetic field strength, the sensor comprising a core of elongated high-magnetic-permeability material having a central long axis, and a multi-turn winding of electrically conducting wire wound on the core along the long axis of the core, and electrically insulated from the core;

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multiple driver circuits each having a voltage-controlled output and connected one each to a first end of the multi-turn winding of one of the sensors; and

5 a measuring circuit connected to a second end of each of the multi-turn windings and adapted to measure time for voltage at the second end of each of the windings to reach a pre-selected reference voltage;

wherein the central long axes of the cores of the three sensors are arranged in different directions.

10

19. A method for measuring strength of a magnetic field, comprising steps of:

(a) wrapping a coil of electrically conductive wire on an elongated core comprising high-magnetic-permeability material, the core
15 having a central axis;

(b) driving the coil with a known electrical input to a first end of the coil;

(c) measuring electrical characteristics at a second end of the coil; and

20

(d) processing the measured electrical characteristics to provide information about strength of a magnetic field along the direction of the central axis.

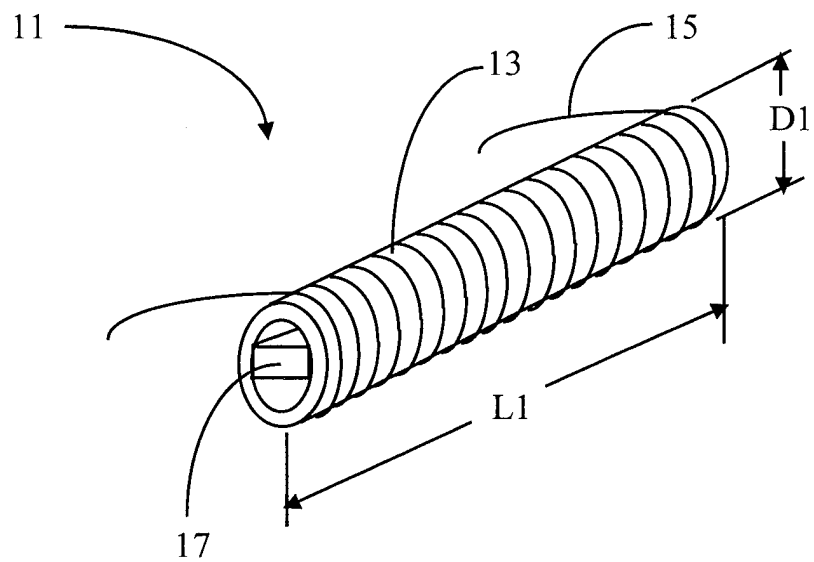
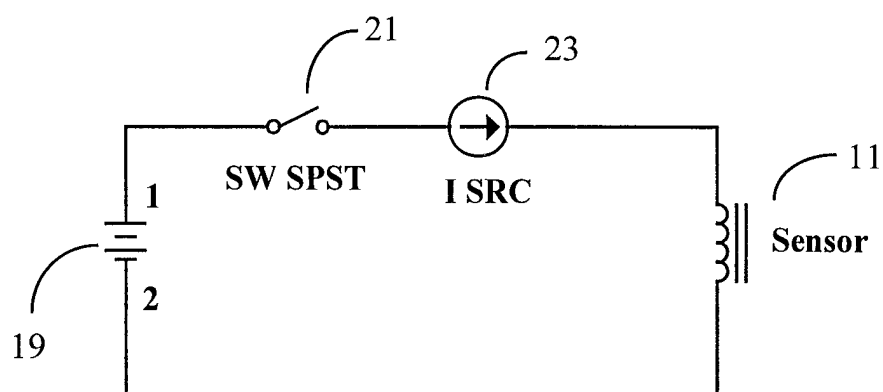


Fig. 1

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*Fig. 2*

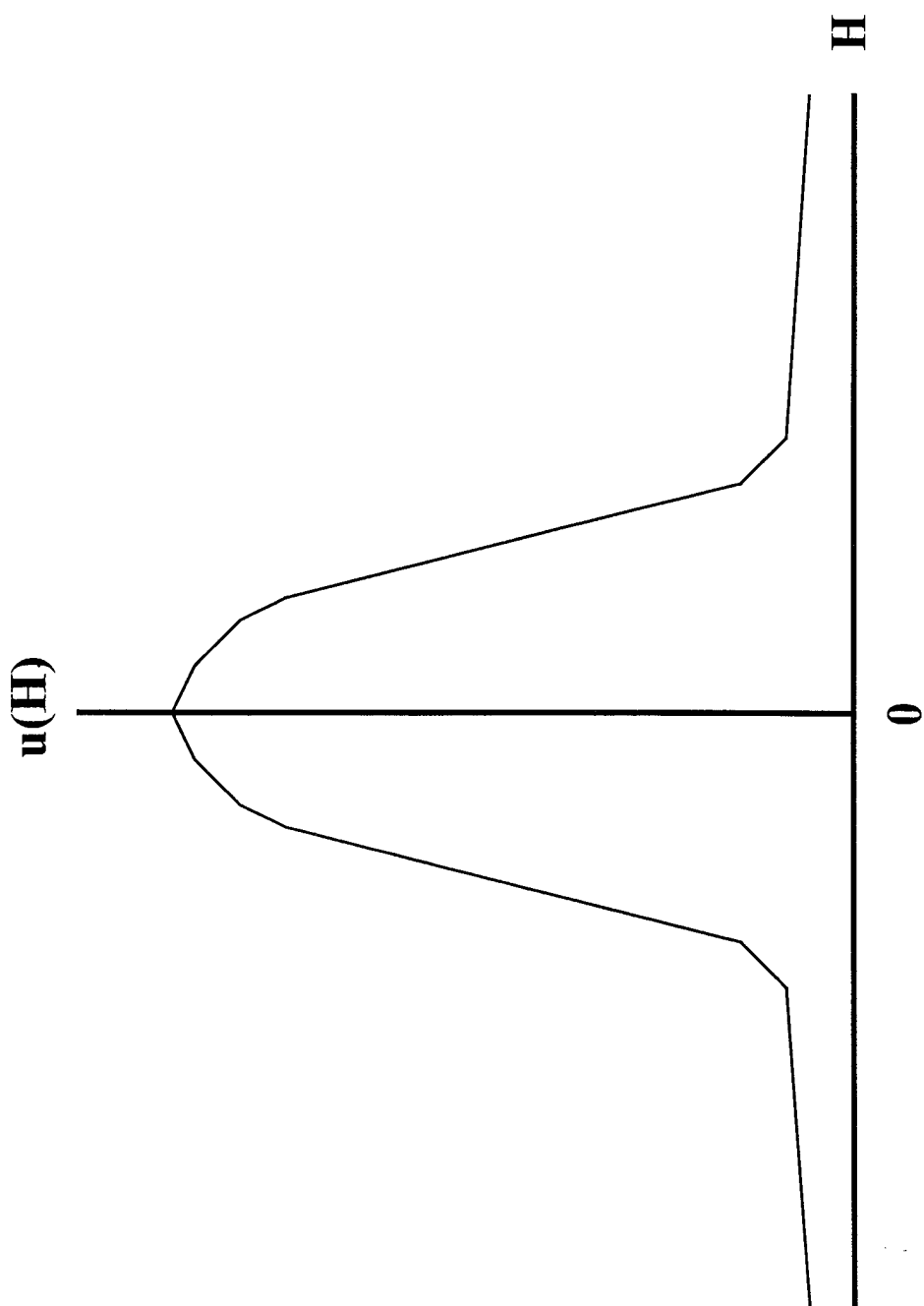
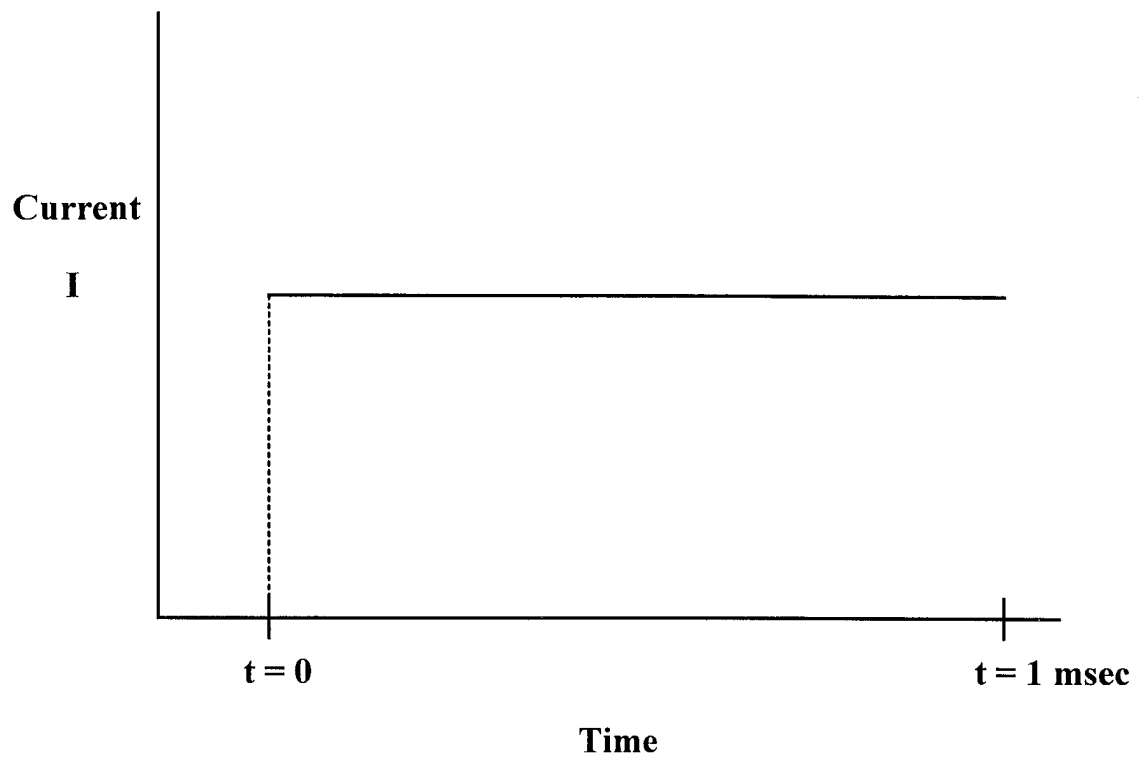
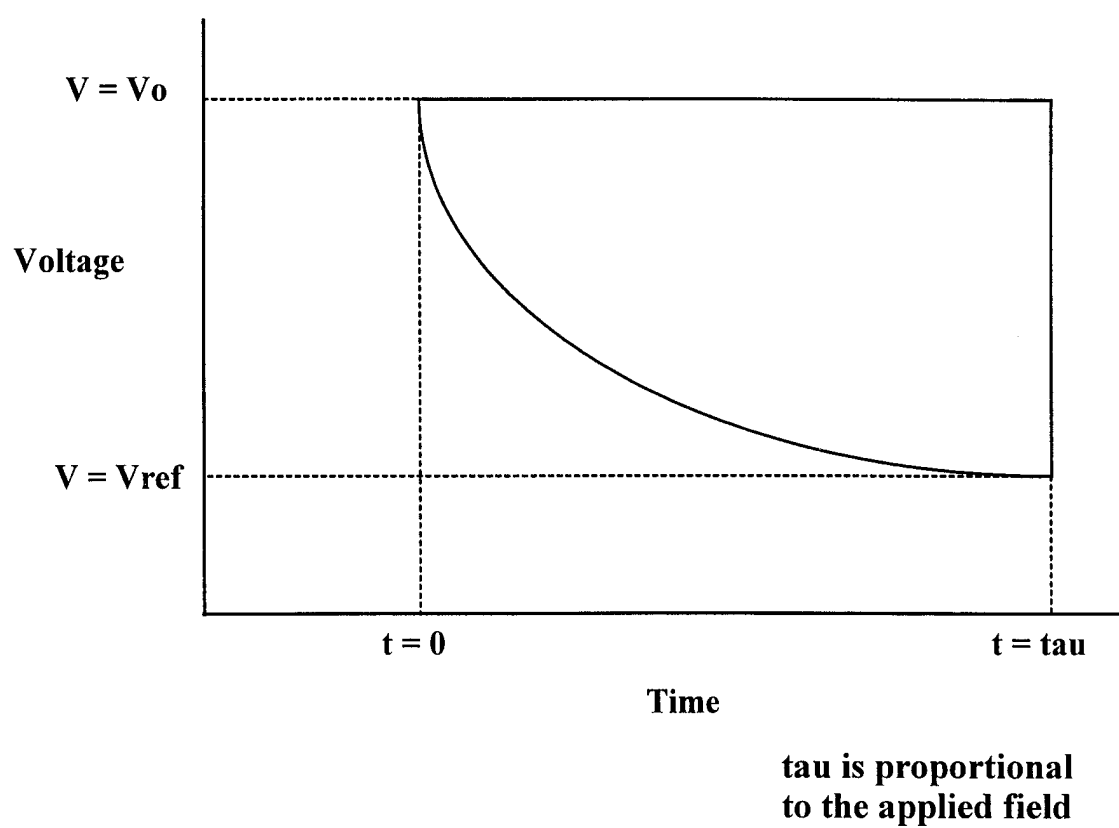


Fig. 3

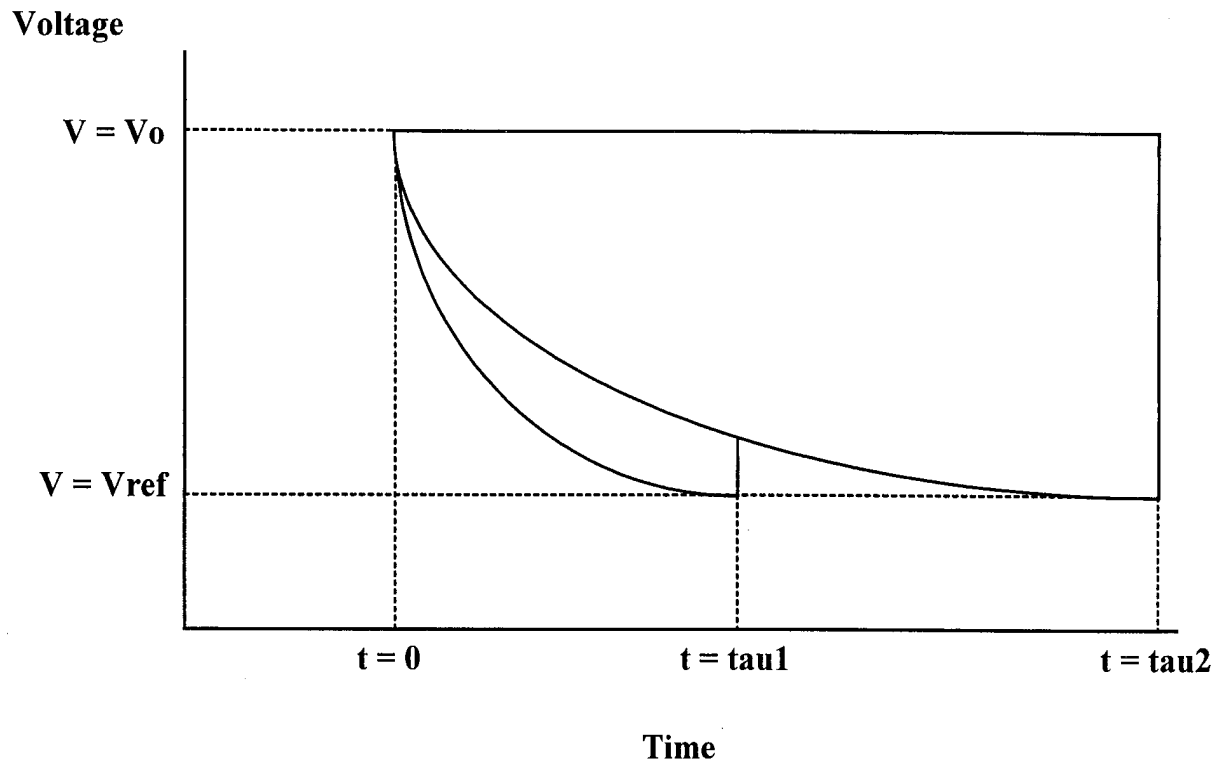
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***Fig. 4***

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*Fig. 5*

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τ_1 is proportional
to the applied field H_1

τ_2 is proportional
to the applied field H_2

Fig. 6

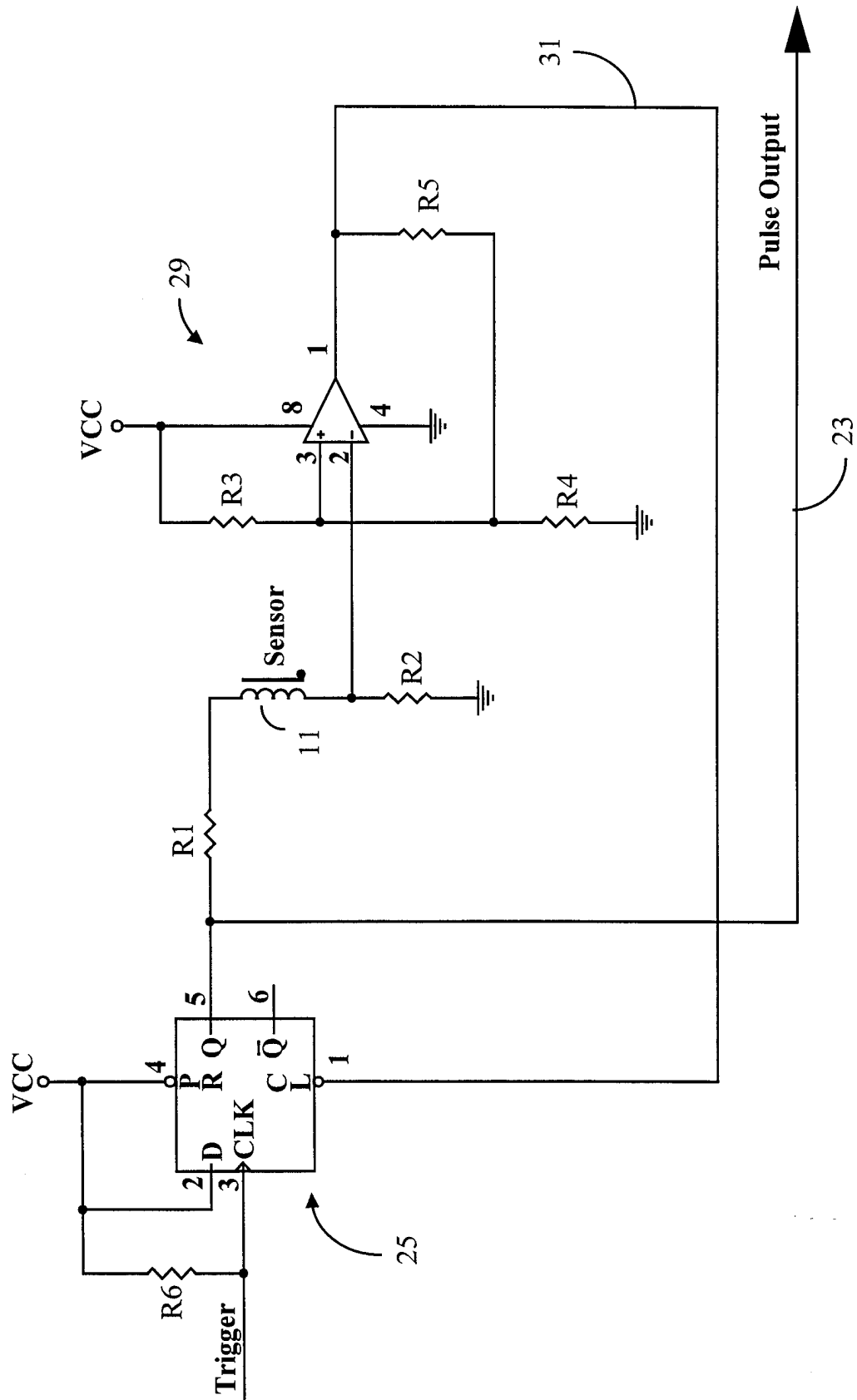
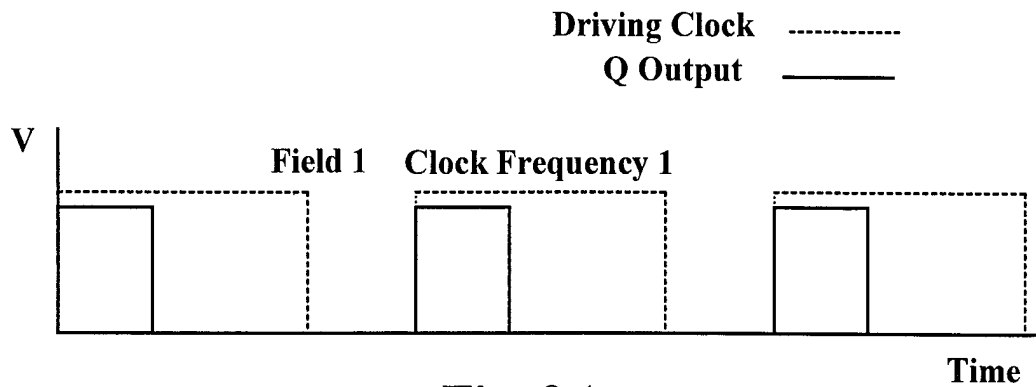
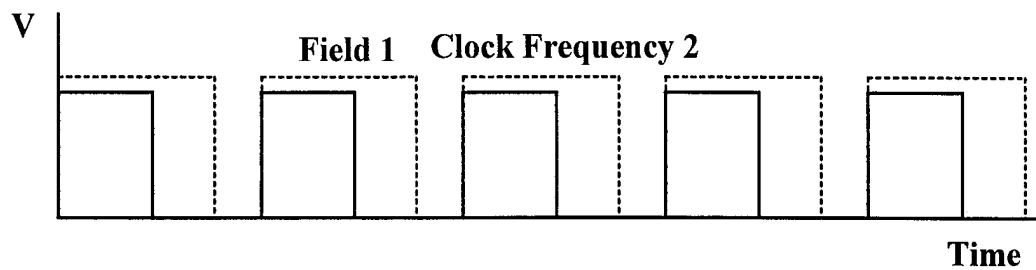
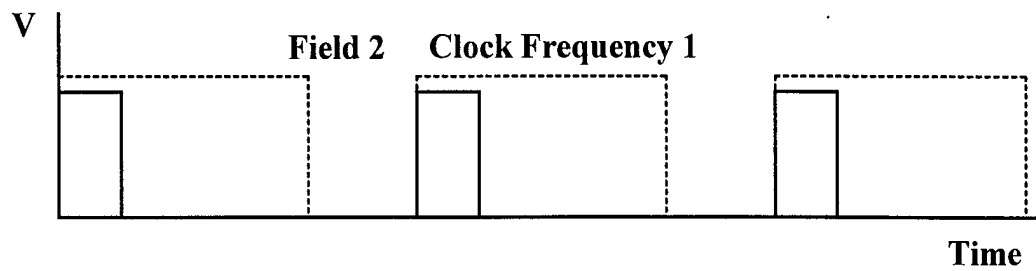
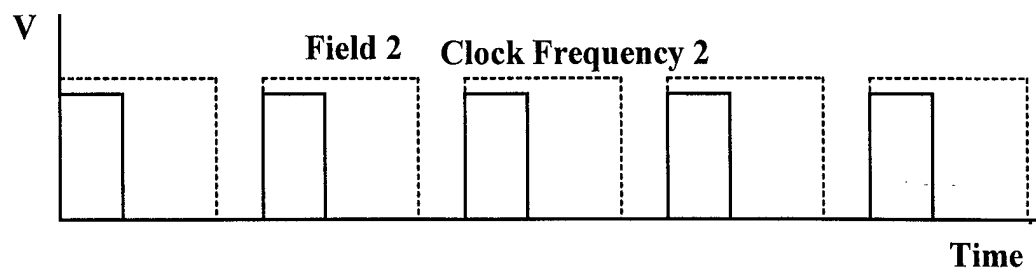
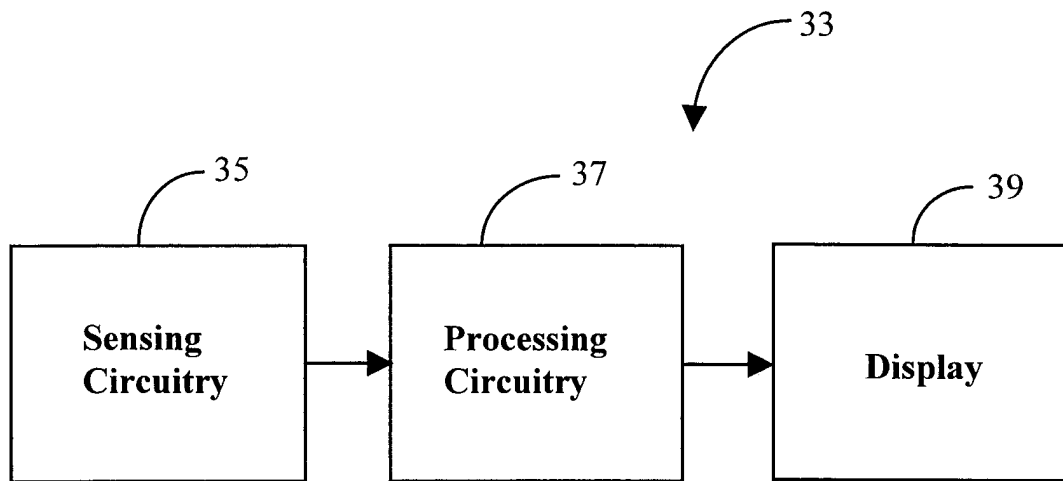
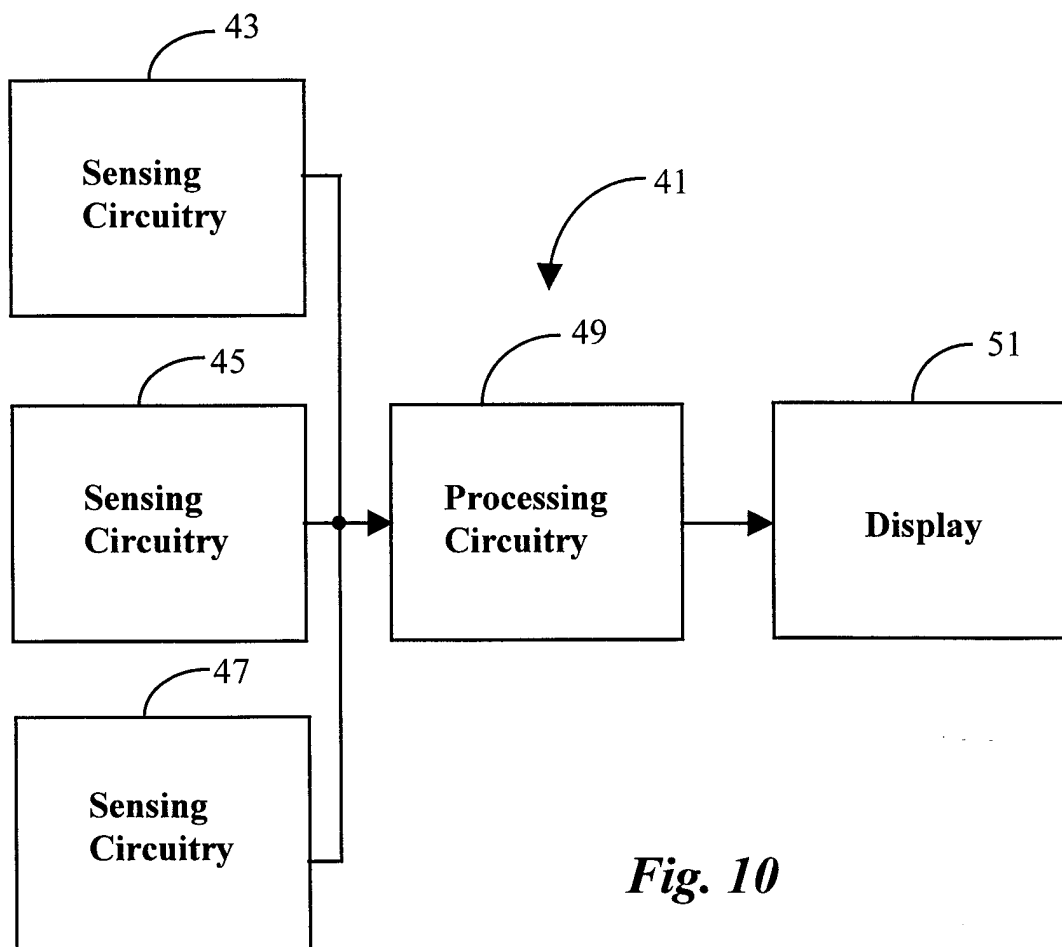


Fig. 7

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*Fig. 8A**Fig. 8B**Fig. 8C**Fig. 8D*

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*Fig. 9**Fig. 10*

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/06451**A. CLASSIFICATION OF SUBJECT MATTER**

IPC(6) : G01R33/02; G01C17/00; G01C17/28

US CL : 324/247,253,258,260,207.16; 33/361

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 324/207.16, 244, 247, 249, 253-255, 260, 345; 33/361, 363R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS (U.S. PAT.)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y,P	US 5,642,046 A (HAWKS) 24 June 1997 (24.06.97), Figs. 1A and 8; Col 4, line 47-col.6, line 56; and Col.11, line 49-col.12, line 51.	1-19
Y	US 5,334,935 A (COOK) 02 August 1994 (02.08.94), Col. 5, lines 45-64.	1-19
Y	US 5,351,004 A (DANIELS et al) 27 September 1994 (27.09.94) Col.15, lines 15-18.	1-19
Y	US 4,403,515 A (IWASAKI) 13 September 1983 (13.9.83), Col. 5, lines 8-57.	1-8
A	US 5,239,264 A (HAWKS) 24 August 1993 (24.08.93), see the entire document.	1-19

☒ Further documents are listed in the continuation of Box C.
 ☐ See patent family annex.

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"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)	"&"	document member of the same patent family
"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		

Date of the actual completion of the international search

08 JULY 1998

Date of mailing of the international search report

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/06451

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A,P	US 5,694,952 A (LIDMAN et al) 09 December 1997 (09.12.97), see the entire document.	1-19
A,E	US 5,757,184 A (KURIHARA et al) 26 May 1998 (26.5.98), see the entire document.	1-19