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Diaconu

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(54) **MAGNETIC FIELD SENSOR WITH IMPROVED ACCURACY AND METHOD OF OBTAINING IMPROVED ACCURACY WITH A MAGNETIC FIELD SENSOR**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 205 days.

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G01D 5/14 (2006.01)
G01R 33/00 (2006.01)

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CPC ***G01R 33/077*** (2013.01); ***G01D 5/142*** (2013.01); *G01R 33/0023* (2013.01)

(58) **Field of Classification Search**
CPC G01R 33/0023
See application file for complete search history.

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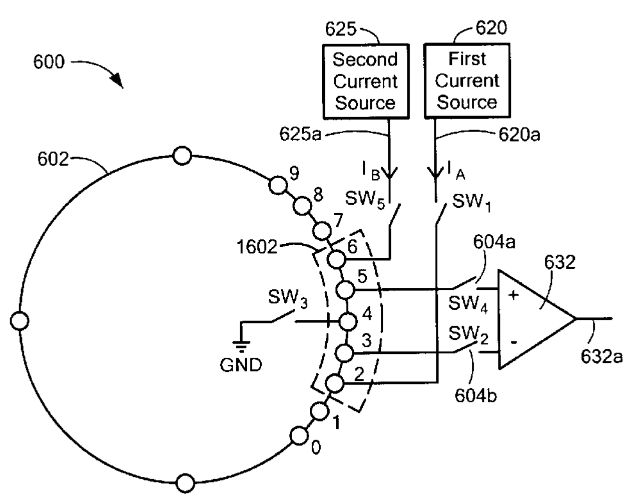
(57) **ABSTRACT**

A magnetic field sensor includes a circular vertical Hall (CVH) sensing element comprising a plurality of vertical Hall elements, each one of the plurality of vertical hall elements comprising respective first and second current receiving contacts. The magnetic field sensor additionally includes a sequence switches circuit coupled to the plurality of vertical Hall elements. The magnetic field sensor also includes a first current source sequentially coupled by the sequence switches circuit to the first current receiving contact of sequentially selected ones of the plurality of vertical Hall elements. The magnetic field sensor further includes a second current source sequentially coupled by the sequence switches circuit to the second current receiving contact of the sequentially selected ones of the plurality of vertical Hall elements. The first and second current sources can swap couplings in half-period intervals for each of a plurality of coupling arrangements. A corresponding method is also described.

20 Claims, 10 Drawing Sheets



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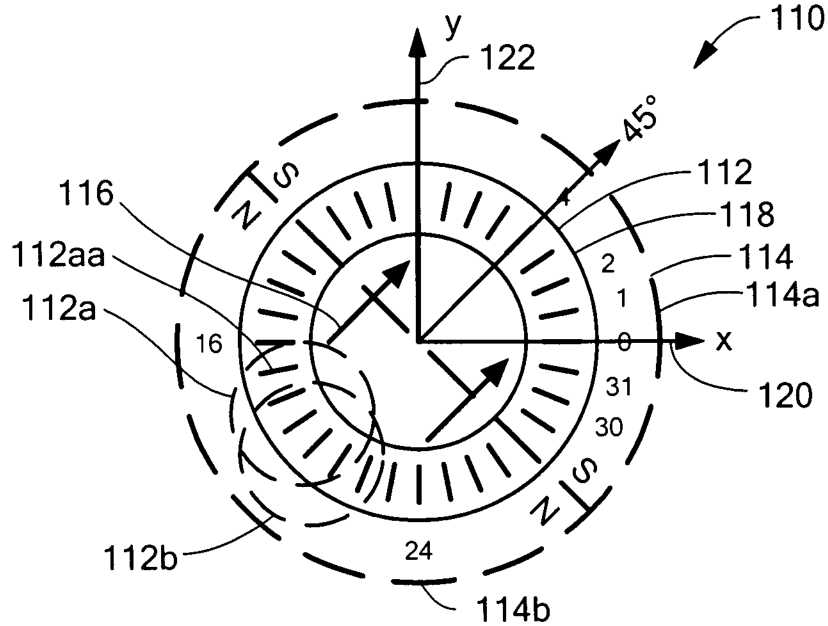
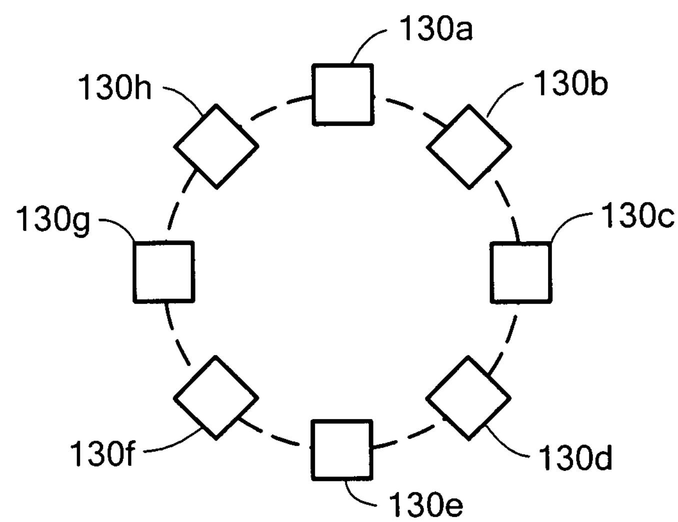

110
y
122
45°
112
118
114
114a
116
112aa
112a
S
N
4
2
1
0
x
16
31
30
120
S
N
24
112b
114b

FIG. 1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130h
130b
130g
130c
130f
130d
130e

FIG. 1A

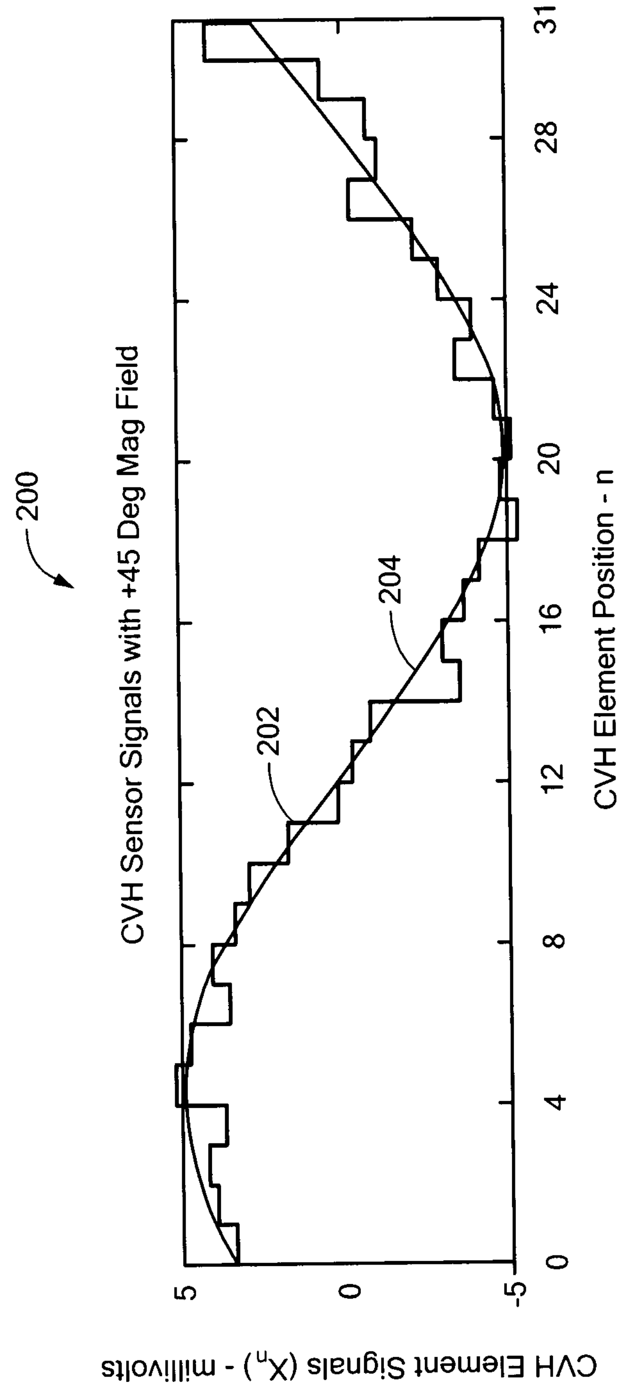

200
CVH Sensor Signals with +45 Deg Mag Field
202
204
5
0
-5
0
4
8
12
16
20
24
28
31
CVH Element Position - n
CVH Element Signals (X_n) - millivolts

FIG. 2

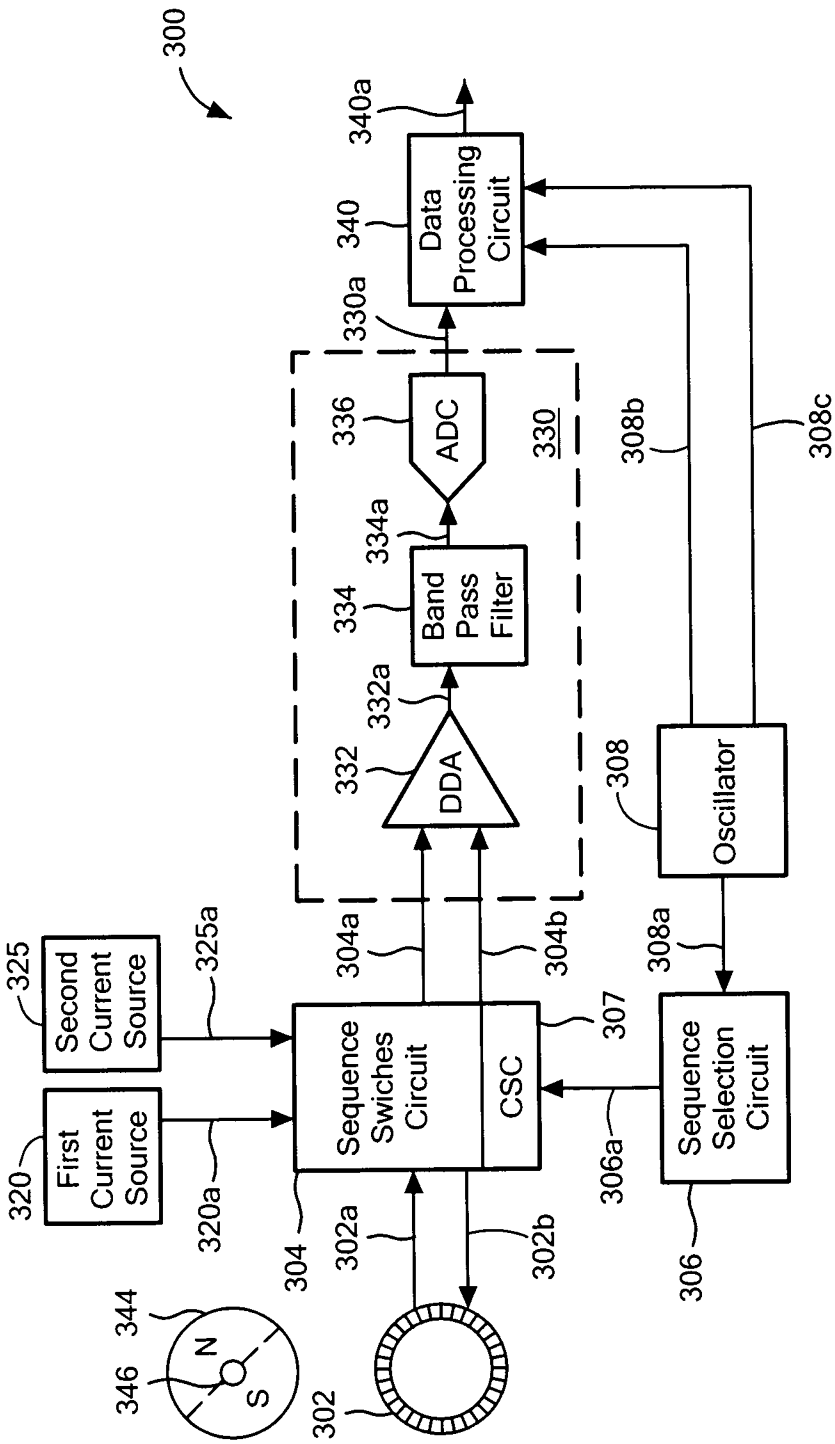
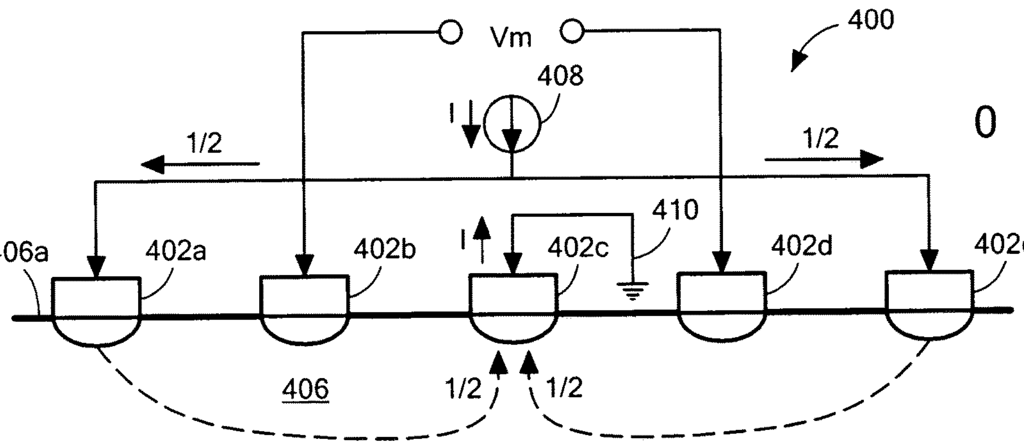
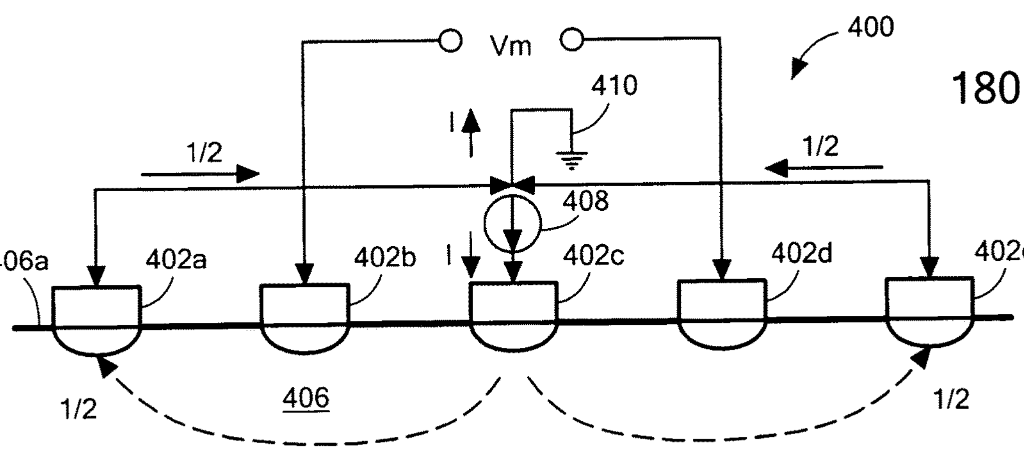

300
340a
340
Data Processing Circuit
330a
336
ADC
330
334a
334
Band Pass Filter
332a
332
DDA
308b
308c
308
Oscillator
325
Second Current Source
325a
320
First Current Source
320a
304a
304b
Sequence Swiches Circuit
CSC
307
308a
Sequence Selection Circuit
306a
306
304
302a
302b
344
N
S
346
302

FIG. 3



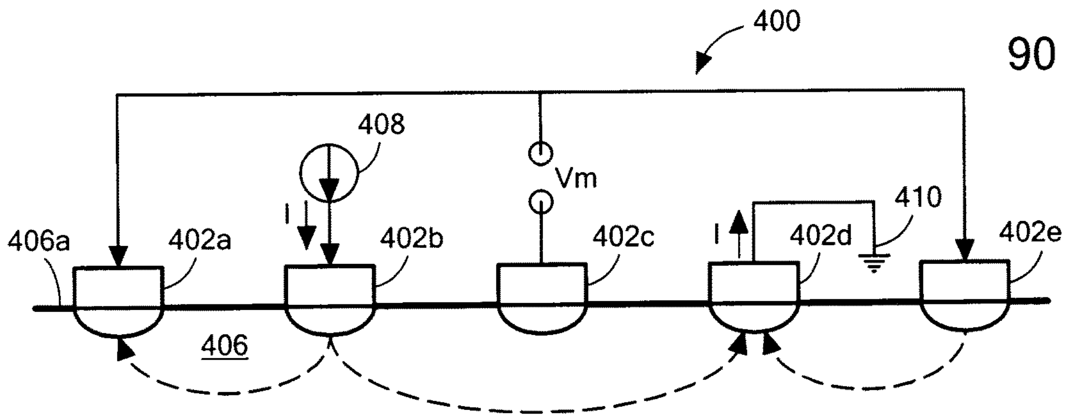
400
Vm
408
I
0
1/2
1/2
410
I
406a
402a
402b
402c
402d
402e
406
1/2
1/2

FIG. 4



400
Vm
410
180
I
1/2
1/2
408
406a
402a
402b
I
402c
402d
402e
1/2
406
1/2

FIG. 4A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408
Vm
410
I
406a
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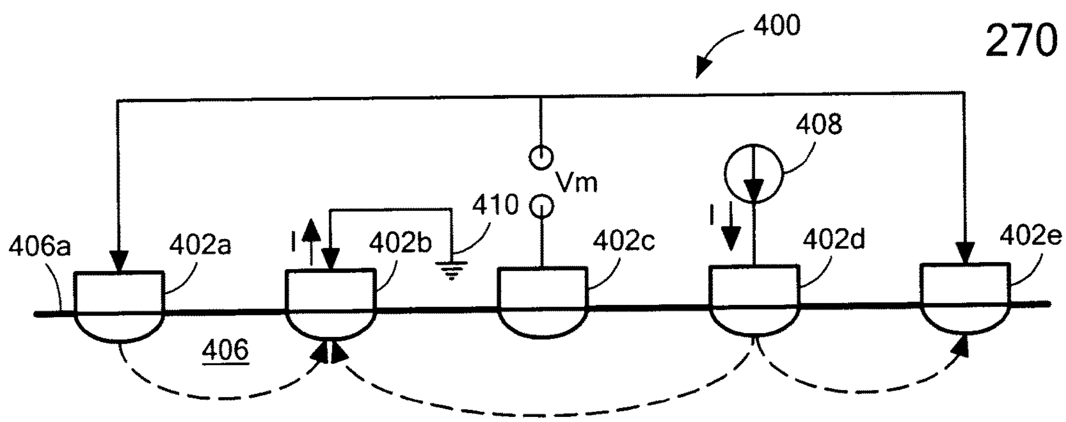
402b
402c
402d
402e
406

FIG. 4B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270
408
Vm
410
I
406a
402a
402b
402c
402d
402e
406

FIG. 4C

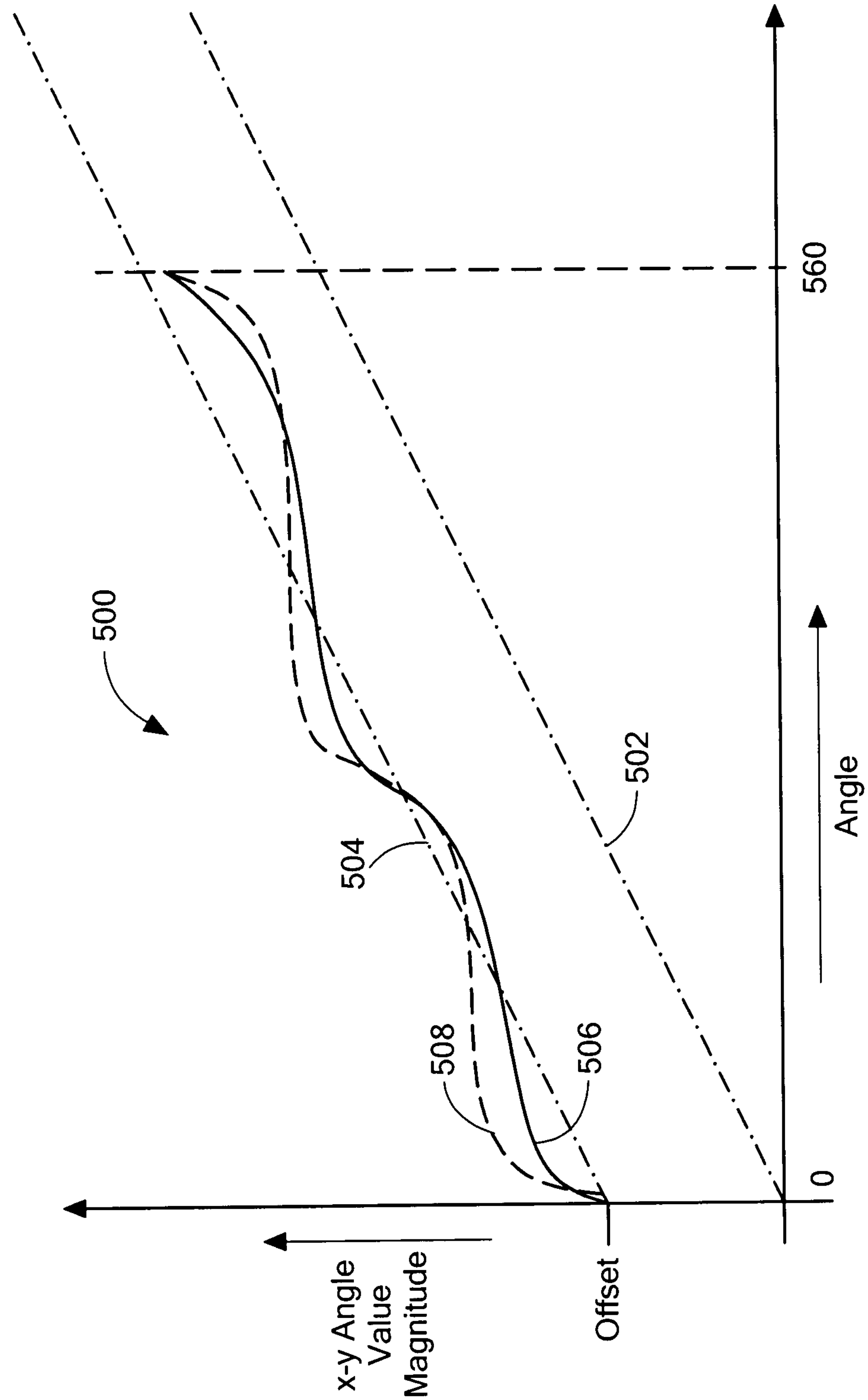
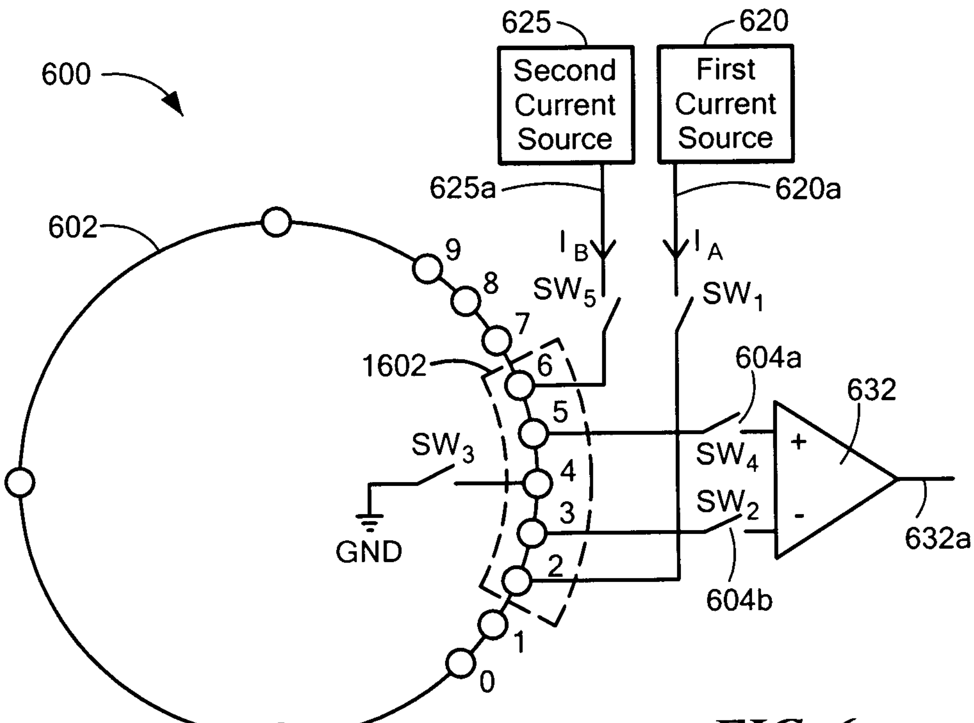
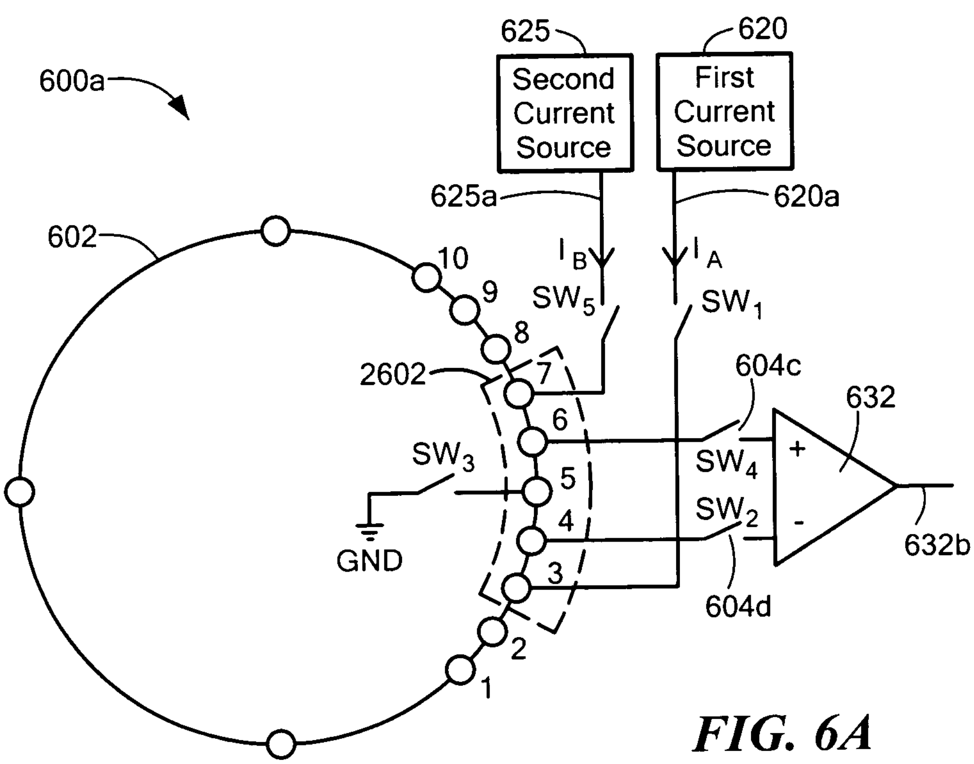

500
502
504
506
508
560
0
Angle
x-y Angle
Value
Magnitude
Offset

FIG. 5



600
625
Second Current Source
620
First Current Source
625a
620a
602
I_B
I_A
9
8
SW_5
SW_1
7
1602
6
604a
632
5
SW_3
4
SW_4
+
GND
3
SW_2
-
632a
2
604b
1
0

FIG. 6



600a
625
Second Current Source
620
First Current Source
625a
620a
602
10
I_B
I_A
9
SW_5
SW_1
8
2602
7
604c
632
6
SW_3
SW_4
+
5
GND
4
SW_2
-
632b
3
604d
2
1

FIG. 6A

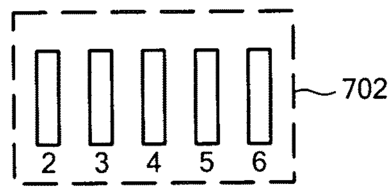

702
2
3
4
5
6

FIG. 7

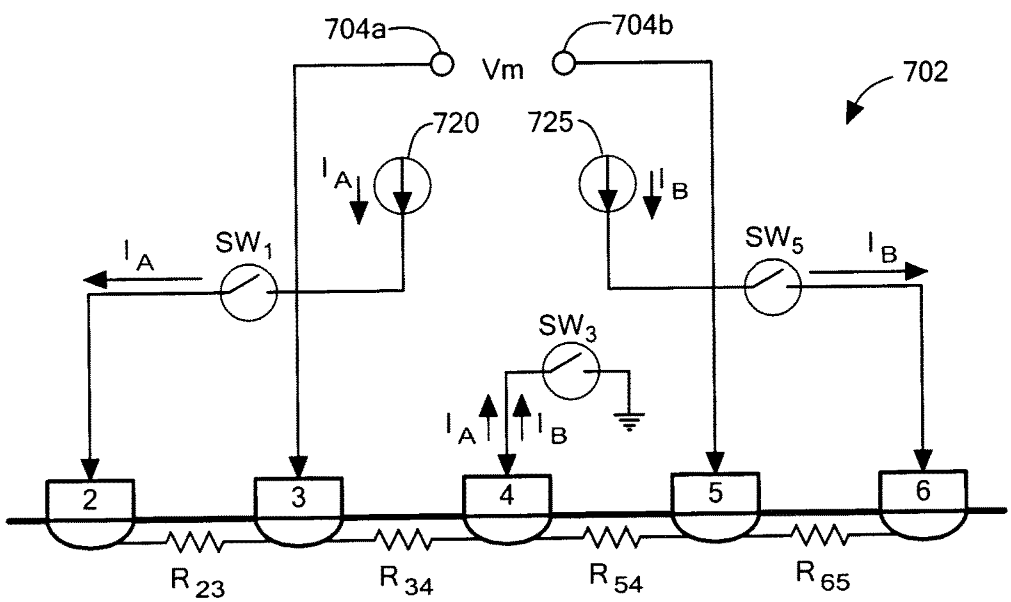
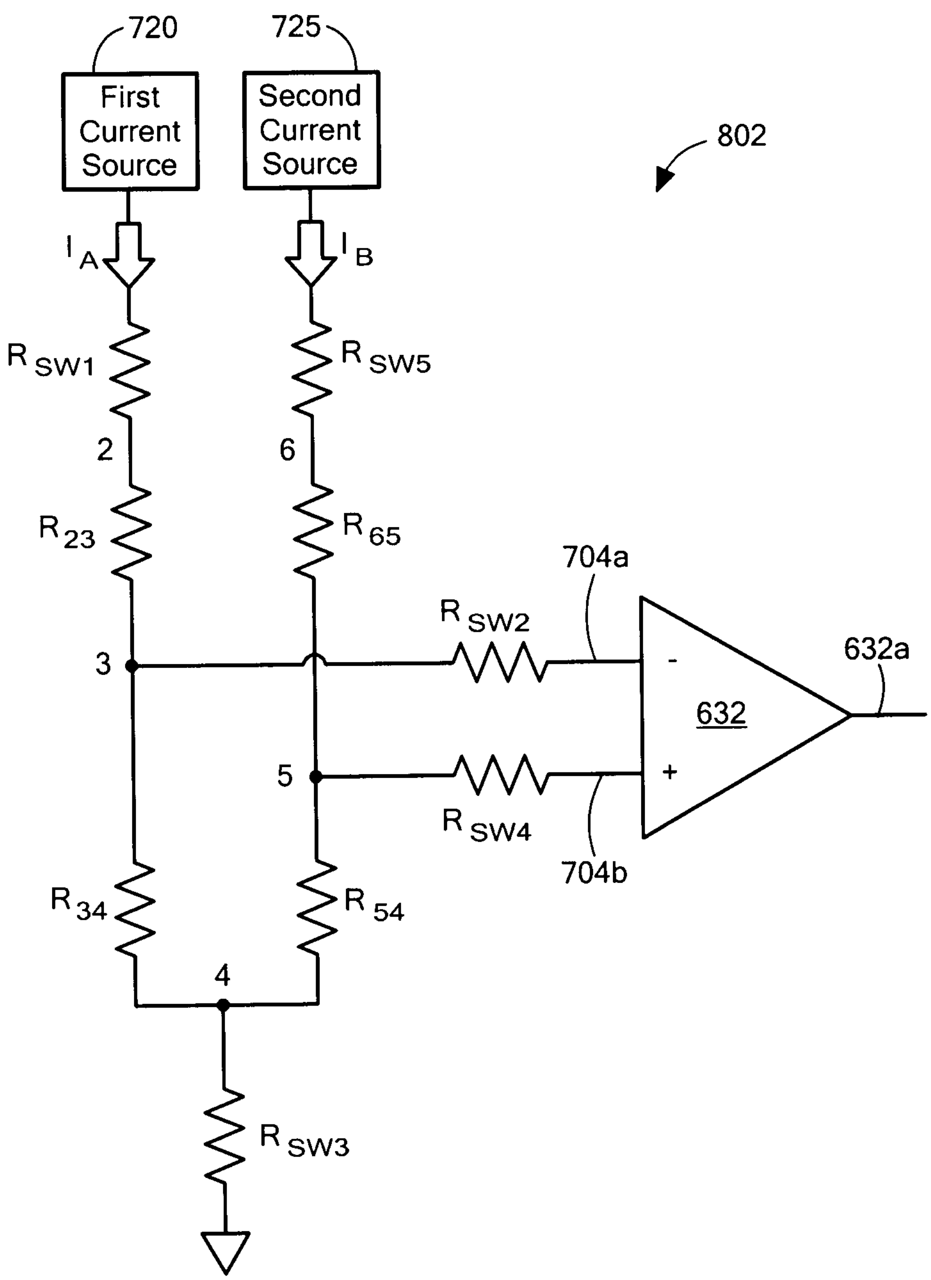

704a
Vm
704b
702
720
725
I A
I B
SW1
SW5
SW3
2
3
4
5
6
R 23
R 34
R 54
R 65

FIG. 7A

1700

Vertical Hall element	First output signal generating contact	Second output signal generating contact	Sequenced Signal steps produced at the corresponding output signal generating contacts
1	2	4	$I_B R_{4,3} - I_A R_{2,3}$
2	3	5	$I_B R_{5,4} - I_A R_{3,4}$
3	4	6	$I_B R_{6,5} - I_A R_{4,5}$
4	5	7	$I_B R_{7,6} - I_A R_{5,6}$
5	6	8	$I_B R_{8,7} - I_A R_{6,7}$
6	7	9	$I_B R_{9,8} - I_A R_{7,8}$
7	8	10	$I_B R_{10,9} - I_A R_{8,9}$
8	9	11	$I_B R_{11,10} - I_A R_{9,10}$
9	10	12	$I_B R_{12,11} - I_A R_{10,11}$
10	11	13	$I_B R_{13,12} - I_A R_{11,12}$

FIG. 7B



720
725
First Current Source
Second Current Source
802
I A
I B
R SW1
R SW5
2
6
R 23
R 65
704a
R SW2
3
632a
-
632
5
+
R SW4
704b
R 34
R 54
4
R SW3

FIG. 8

MAGNETIC FIELD SENSOR WITH IMPROVED ACCURACY AND METHOD OF OBTAINING IMPROVED ACCURACY WITH A MAGNETIC FIELD SENSOR

CROSS REFERENCE TO RELATED APPLICATIONS

Not Applicable.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

Not Applicable.

FIELD OF THE DISCLOSURE

This disclosure relates generally to magnetic field sensors and, more particularly, to a magnetic field sensor that can provide an output signal with improved accuracy that is representative of an angle of rotation and a speed of rotation of a target object.

BACKGROUND OF THE DISCLOSURE

Magnetic field sensing elements can be used in a variety of applications. In one application, a magnetic field sensing element can be used to detect a direction of a magnetic field, i.e., and angle of the direction of the magnetic field. In another application, a magnetic field sensing element can be used to sense an electrical current. One type of current sensor uses a Hall Effect magnetic field sensing element in proximity to a current-carrying conductor.

Planar Hall elements and vertical Hall elements are known types of magnetic field sensing elements. A planar Hall element tends to be responsive to magnetic field perpendicular to a surface of a substrate on which the planar Hall element is formed. A vertical Hall element tends to be responsive to magnetic field parallel to a surface of a substrate on which the vertical Hall element is formed.

Other types of magnetic field sensing elements are known. For example, a so-called "circular vertical Hall" (CVH) sensing element, which includes a plurality of vertical Hall elements, is known and described in PCT Patent Application No. PCT/EP2008056517, entitled "Magnetic Field Sensor for Measuring Direction of a Magnetic Field in a Plane," filed May 28, 2008, and published in the English language as PCT Publication No. WO 2008/145662, which application and publication thereof are incorporated by reference herein in their entirety. The CVH sensing element is a circular arrangement of vertical Hall elements arranged over a common circular implant region in a substrate. The CVH sensing element can be used to sense a direction (i.e., an angle) (and optionally a strength) of a magnetic field in a plane of the substrate.

Various parameters characterize the performance of magnetic field sensing elements and magnetic field sensors that use magnetic field sensing elements. These parameters include sensitivity, which is a change in an output signal of a magnetic field sensing element in response to a change of magnetic field experienced by the magnetic sensing element, and linearity, which is a degree to which the output signal of the magnetic field sensing element varies in direct proportion to the magnetic field. These parameters also include an offset, which is characterized by an output signal from the magnetic field sensing element not representative of a zero magnetic field when the magnetic field sensing element experiences a zero magnetic field.

The above-described CVH sensing element is operable, with associated circuits, to provide an output signal representative of an angle of a direction of a magnetic field. Therefore, as described below, if a magnet is disposed upon or otherwise coupled to a so-called "target object," for example, a camshaft in an engine, the CVH sensing element can be used to provide an output signal representative of an angle of rotation of the target object.

The CVH sensing element provides output signals from a plurality of vertical Hall elements from which it is constructed. Each vertical Hall element can have an undesirable and different DC offset.

The CVH sensing element is but one sensing element that can provide an output signal representative of an angle of a magnetic field, i.e., an angle sensor. For example, an angle sensor can be provided from a plurality of separate vertical Hall elements or a plurality of magnetoresistance elements.

It would be desirable to reduce the DC offsets of a plurality of magnetic field sensing elements (e.g., vertical Hall elements of a CVH sensing element). It would be further desirable to provide a magnetic field sensor with improved accuracy.

SUMMARY

The present disclosure relates generally to concepts, systems, circuits, and techniques for reducing DC offsets in a magnetic field sensor. The present disclosure also relates to a magnetic field sensor with improved accuracy.

In one aspect of the concepts described herein, a magnetic field sensor includes a circular vertical Hall (CVH) sensing element including a plurality of vertical Hall elements. The plurality of vertical hall elements of the CVH sensing element include respective first and second current receiving contacts, respective first and second output signal generating contacts, and a respective at least one reference contact. Additionally, the at least one reference contact is positioned between the first and second current receiving contacts, the first output signal generating contact is positioned between the at least one reference contact and the first current receiving contact, and the second output signal generating contact is positioned between the at least one reference contact and the second current receiving contact. The plurality of vertical Hall elements is configured to generate a plurality of magnetic field signals, each magnetic field signal responsive to a magnetic field.

The magnetic field sensor additionally includes a sequence switches circuit coupled to the plurality of vertical Hall elements. In one aspect, the sequences switches circuit is operable to sequentially select from among the plurality of vertical Hall elements to generate sequenced signal steps (or steps of a sequenced signal).

The magnetic field sensor also includes a first current source sequentially coupled by the sequence switches circuit to the first current receiving contact of sequentially selected ones of the plurality of vertical Hall elements. In one aspect, the first current source is operable to provide, at first sequential times, a first current signal to the first current receiving contact of the sequentially selected ones of the plurality of vertical Hall elements.

The magnetic field sensor further includes a second current source sequentially coupled by the sequence switches circuit to the second current receiving contact of the sequentially selected ones of the plurality of vertical Hall elements. In one aspect, the second current source is operable to provide, at the same first sequential times, a second current signal to the second current receiving contact of the sequentially selected ones of the plurality of vertical Hall elements.

The magnetic field sensor additionally includes an amplifier circuit coupled to receive the sequenced signal steps produced at the first and second output signal generating contacts of the sequentially selected ones of the plurality of vertical Hall elements. In one aspect, in response to the sequenced signal steps, the amplifier circuit is configured to generate an amplified signal representative of sequentially selected ones of the plurality of magnetic field signals.

Features of the magnetic field sensor may include one or more of the following in any combination. The magnetic field sensor may not be configured in a current spinning arrangement. The first current signal and the second current signal may be substantially equal in magnitude. The first current signal and the second current signal may be unequal in magnitude. The amplifier circuit may be coupled to the select first and second output generating contacts in a Kelvin connection arrangement. An input impedance of the amplifier circuit may be substantially more than an output impedance of the first and second output generating contacts of the sequentially selected ones of the plurality of vertical Hall elements. Each selected one of the plurality of vertical Hall elements may include five vertical Hall element contacts. Each selected one of the plurality of vertical Hall elements may comprise more than five vertical Hall element contacts. The at least one reference contact may be coupled to a reference potential. The reference potential may be ground, which may be a system ground, earth ground, or otherwise.

In another aspect of the concepts described herein, a method includes generating a plurality of magnetic field signals with a circular vertical Hall (CVH) sensing element, the CVH sensing element including a plurality of vertical Hall elements. Each one of the plurality of vertical hall elements includes respective first and second current receiving contacts, respective first and second output signal generating contacts, and a respective at least one reference contact. The at least one reference contact is positioned between the first and second current receiving contacts, the first output signal generating contact is positioned between the at least one reference contact and the first current receiving contact, and the second output signal generating contact is positioned between the at least one reference contact and the second current receiving contact. Each magnetic field signal is responsive to a magnetic field.

The method additionally includes sequentially selecting from among the plurality of vertical Hall elements. The method also includes generating a first current signal and providing, at first sequential times, the first current signal to the first current receiving contact of sequentially selected ones of the plurality of vertical Hall elements. The method further includes generating a second current signal and providing, at the same first sequential times, the second current signal to the second current receiving contact of the sequentially selected ones of the plurality of vertical Hall elements.

The method additionally includes generating a first sequenced signal step (or first step of a sequenced signal), responsive to an external magnetic field, at the first and second output generating contacts of the sequentially selected ones of the plurality of vertical Hall elements. The method further includes generating an amplified signal representative of sequentially selected ones of the plurality of magnetic field signals in response to at least the first sequenced signal step.

Features of the method may include one or more of the following in any combination. The first current signal and the second current signal may be substantially equal in magnitude. The first current signal and the second current signal may be unequal in magnitude. Each selected one of the plurality of vertical Hall elements may include five vertical Hall element contacts. Each selected one of the plurality of vertical Hall elements may comprise more than five vertical Hall element contacts. The at least one reference contact may be coupled to a reference potential. The reference potential may be ground, which may be a system ground, earth ground, or otherwise.

In another aspect of the concepts described herein, a magnetic field sensor includes a circular vertical Hall (CVH) sensing element including a plurality of vertical Hall elements. The plurality of vertical hall elements of the CVH sensing element include respective first and second current receiving contacts, respective first and second output signal generating contacts, and a respective at least one reference contact. Additionally, the at least one reference contact is positioned between the first and second current receiving contacts, the first output signal generating contact is positioned between the at least one reference contact and the first current receiving contact, and the second output signal generating contact is positioned between the at least one reference contact and the second current receiving contact. The plurality of vertical Hall elements is configured to generate a plurality of magnetic field signals, each magnetic field signal responsive to a magnetic field.

The magnetic field sensor additionally includes means for sequentially selecting from among the plurality of vertical Hall elements to generate sequenced signal steps. The magnetic field sensor also includes means for providing, at first sequential times, a first current signal to the first current receiving contact of the sequentially selected ones of the plurality of vertical Hall elements. The magnetic field sensor further includes means for providing, at the same first sequential times, a second current signal to the second current receiving contact of the sequentially selected ones of the plurality of vertical Hall elements. The magnetic field sensor additionally includes means for generating an amplified signal representative of sequentially selected ones of the plurality of magnetic field signals in response to receiving the sequenced signal steps produced at the first and second output signal generating contacts of the sequentially selected ones of the plurality of vertical Hall elements.

Features of the magnetic field sensor may include one or more of the following in any combination. The first current signal and the second current signal may be substantially equal in magnitude. The means for generating an amplified signal is coupled to the select first and second output generating contacts in a Kelvin connection arrangement.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing features of the disclosure, as well as the disclosure itself may be more carefully understood from the following detailed description of the drawings, which:

FIG. **1** is a pictorial showing a circular vertical Hall (CVH) sensing element having a plurality of vertical Hall elements arranged in a circle over a common implant region upon a substrate, and a two pole magnet disposed close to the CVH sensing element;

FIG. **1**A is a pictorial showing a plurality of magnetic field sensing elements;

FIG. 2 is a graph showing an output signal as may be generated by the CVH sensing element of FIG. 1 or by the plurality of magnetic field sensing elements of FIG. 1A;

FIG. 3 is a block diagram of an example magnetic field sensor having a CVH sensing element, a plurality of current sources, and a sequence switching circuit operable to sequentially select from among a plurality of vertical Hall elements of the CVH sensing element;

FIGS. 4-4C are side views of example vertical Hall elements of the CVH sensing element of FIG. 3 when coupled into four current spinning phases, the four phases phase associated with operation of each one of the vertical Hall elements of a typical CVH sensing element;

FIG. 5 is a graph showing ideal and non-ideal operation of the magnetic field sensor of FIG. 3;

FIG. 6 is a block diagram of a portion of an example magnetic field sensor similar to the magnetic field sensor of FIG. 3 with first and second current sources coupled to a sequentially selected one of the vertical Hall elements of the CVH sensing element of the magnetic field sensor;

FIG. 6A is a block diagram of the portion of the example magnetic field sensor of FIG. 6 with the first and second current sources coupled to another sequentially selected one of the vertical Hall elements;

FIG. 7 is a block diagram showing vertical Hall element contacts of an example sequentially selected vertical Hall element;

FIG. 7A is a side view of the sequentially selected vertical Hall element of FIG. 7 showing bulk resistance that exists between the respective first and second current receiving contacts, the respective reference contact, and the respective first and second output signal generating contacts;

FIG. 7B is a table illustrating example offset voltage cancellations of selected vertical Hall elements of an example CVH sensing element; and

FIG. 8 is a schematic showing an equivalent circuit of the vertical Hall element of FIG. 7A coupled to an amplifier circuit.

DETAILED DESCRIPTION

The features and other details of the concepts, systems, and techniques sought to be protected herein will now be more particularly described. It will be understood that any specific embodiments described herein are shown by way of illustration and not as limitations of the disclosure. The principal features of this disclosure can be employed in various embodiments without departing from the scope of the concepts sought to be protected. Embodiments of the present disclosure and associated advantages may be best understood by referring to the drawings, where like numerals are used for like and corresponding parts throughout the various views.

As used herein, the term "magnetic field sensing element" is used to describe a variety of electronic elements that can sense a magnetic field. The magnetic field sensing element can be, but is not limited to, a Hall Effect element, a magnetoresistance element, or a magnetotransistor. As is known, there are different types of Hall Effect elements, for example, a planar Hall element, a vertical Hall element, and a Circular Vertical Hall (CVH) element. As is also known, there are different types of magnetoresistance elements, for example, a semiconductor magnetoresistance element such as Indium Antimonide (InSb), a giant magnetoresistance (GMR) element, for example, a spin valve, an isotropic magnetoresistance element (AMR), a tunneling magnetoresistance (TMR) element, and a magnetic tunnel junction (MTJ). The magnetic field sensing element may be a single element or, alternatively, may include two or more magnetic field sensing elements arranged in various configurations, e.g., a halfbridge or full (Wheatstone) bridge. Depending on the device type and other application requirements, the magnetic field sensing element may be a device made of a type IV semiconductor material such as Silicon (Si) or Germanium (Ge), or a type III-V semiconductor material like Gallium-Arsenide (GaAs) or an Indium compound, e.g., Indium-Antimonide (InSb).

As is known, some of the above-described magnetic field sensing elements tend to have an axis of maximum sensitivity parallel to a substrate that supports the magnetic field sensing element, and others of the above-described magnetic field sensing elements tend to have an axis of maximum sensitivity perpendicular to a substrate that supports the magnetic field sensing element. In particular, planar Hall elements tend to have axes of sensitivity perpendicular to a substrate, while metal based or metallic magnetoresistance elements (e.g., GMR, TMR, AMR) and vertical Hall elements tend to have axes of sensitivity parallel to a substrate.

As used herein, the term "magnetic field sensor" is used to describe a circuit that uses a magnetic field sensing element, generally in combination with other circuits. Magnetic field sensors are used in a variety of applications, including, but not limited to, an angle sensor that senses an angle of a direction of a magnetic field, a current sensor that senses a magnetic field generated by a current carried by a current-carrying conductor, a magnetic switch that senses the proximity of a ferromagnetic object, a rotation detector that senses passing ferromagnetic articles, for example, magnetic domains of a ring magnet or a ferromagnetic target (e.g., gear teeth) where the magnetic field sensor is used in combination with a back-biased or other magnet, and a magnetic field sensor that senses a magnetic field density of a magnetic field.

As used herein, the term "processor" is used to describe an electronic circuit that performs a function, an operation, or a sequence of operations. The function, operation, or sequence of operations can be hard coded into the electronic circuit or soft coded by way of instructions held in a memory device. A "processor" can perform the function, operation, or sequence of operations using digital values or using analog signals.

In some embodiments, the "processor" can be embodied in an application specific integrated circuit (ASIC), which can be an analog ASIC or a digital ASIC. In some embodiments, the "processor" can be embodied in a microprocessor with associated program memory. In some embodiments, the "processor" can be embodied in a discrete electronic circuit, which can be an analog or digital.

As used herein, the term "module" is used to describe a "processor."

A processor can contain internal processors or internal modules that perform portions of the function, operation, or sequence of operations of the processor. Similarly, a module can contain internal processors or internal modules that perform portions of the function, operation, or sequence of operations of the module.

While a circular vertical Hall (CVH) element, which has a plurality of vertical Hall elements, is described in examples below, it should be appreciated that the same or similar techniques and circuits apply to any type of magnetic field sensing element(s) arranged in a manner to detect an angle of a pointing direction of a magnetic field, i.e., a rotation angle of a target object to which a magnet is attached.

Referring to FIG. **1**, a circular vertical Hall (CVH) element **112** includes a circular implant and diffusion region **118** in a substrate (not shown). The CVH sensing element **112** has a plurality of vertical Hall elements, of which a vertical Hall element **112***a* is but one example. In some embodiments, the common implant and diffusion region **118** can be characterized as a common epitaxial region upon a substrate, bounded by semiconductor isolation structures.

Each vertical Hall element has a plurality of Hall element contacts (e.g., four or five contacts), e.g., **112***aa*. Each vertical Hall element contact can be comprised of a metal contact over a contact diffusion region (a pickup) diffused into the common implant and diffusion region **118**.

A particular vertical Hall element (e.g., **112***a*) within the CVH sensing element **112**, which, for example, can have five adjacent contacts, can share some, for example, four, of the five contacts with a next vertical Hall element (e.g., **112***b*). Thus, a next vertical Hall element can be shifted by one contact from a prior vertical Hall element. For such shifts by one contact, it will be understood that the number of vertical Hall elements is equal to the number of vertical Hall element contacts, e.g., 32 or 64. However, it will also be understood that a next vertical Hall element can be shifted by more than one contact from the prior vertical Hall element, in which case, there are fewer vertical Hall elements than there are vertical Hall element contacts in the CVH sensing element.

As shown, a center of a vertical Hall element **0** can positioned along an x-axis **120** and a center of vertical Hall element **118** can be positioned along a y-axis **122**. In the exemplary CVH sensing element **112**, there are thirty-two vertical Hall elements and thirty-two vertical Hall element contacts. However, a CVH can have more than or fewer than thirty-two vertical Hall elements and more than or fewer than thirty-two vertical Hall element contacts.

In some applications, a circular magnet **114** having a north side **114***b* and a south side **114***a* can be disposed over the CVH **112**. The circular magnet **114** tends to generate a magnetic field **116** having a direction from the north side **114***b* to the south side **114***a*, here shown to be pointed to a direction of about forty-five degrees relative to x-axis **120**.

In some applications, the circular magnet **114** is mechanically coupled to a rotating target object, for example, an automobile steering shaft of an automobile camshaft, and is subject to rotation relative to the CVH sensing element **112**. With this arrangement, the CVH sensing element **112**, in combination with an electronic circuit described below, can generate a signal related to the angle of rotation of the magnet **114**, i.e., an angle of rotation of the target object to which the magnet is coupled.

Referring now to FIG. **1**A, a plurality of magnetic field sensing elements **130***a*-**130***h*, in a general case, can be any type of magnetic field sensing elements. The magnetic field sensing elements **130***a*-**130***h* can be, for example, separate vertical Hall elements or separate magnetoresistance elements, each having an axis of maximum response parallel to a surface of a substrate **34**, each pointing in a different direction in the plane of the surface. These magnetic field sensing elements can be coupled to an electronic circuit the same as or similar to electronic circuits described below in conjunction with FIGS. **3** and **6**. There can also be a magnet the same as or similar to the magnet **114** of FIG. **1** disposed proximate to the magnetic field sensing elements **130***a*-**130***h*.

Referring now to FIG. **2**, a graph **200** has a horizontal axis with a scale in units of CVH vertical Hall element position, n, around a CVH sensing element, for example, the CVH sensing element **112** of FIG. **1**. The graph **200** also has a vertical axis with a scale in amplitude in units of millivolts. The vertical axis is representative of output signal levels from the plurality of vertical Hall elements of the CVH sensing element taken sequentially, one at a time, about the ring of contacts of the CVH sensing element.

The graph **200** includes a signal **202** representative of output signal levels from the plurality of vertical Hall elements of the CVH taken with the magnetic field of FIG. **1** pointing in a direction of forty-five degrees.

Referring briefly to FIG. **1**, as described above, vertical Hall element **0** is centered along the x-axis **120** and vertical Hall element **8** is centered along the y-axis **122**. In the exemplary CVH sensing element **112**, there are thirty-two vertical Hall element contacts and a corresponding thirty-two vertical Hall elements, each vertical Hall element having a plurality of vertical Hall element contacts, for example, five contacts. In other embodiments, there are sixty-four vertical Hall element contacts and a corresponding sixty-four vertical Hall elements.

In FIG. **2**, for the magnetic field **116** pointing at positive forty-five degrees, a maximum positive signal is achieved from a vertical Hall element centered at position **4**, which is aligned with the magnetic field **116** of FIG. **1**, such that a line drawn between the vertical Hall element contacts (e.g., five contacts) of the vertical Hall element at position **4** is perpendicular to the magnetic field. A maximum negative signal is achieved from a vertical Hall element centered at position **20**, which is also aligned with the magnetic field **116** of FIG. **1**, such that a line drawn between the vertical Hall element contacts (e.g., five contacts) of the vertical Hall element at position **20** is also perpendicular to the magnetic field.

A sine wave **204** is provided to more clearly show ideal behavior of the signal **202**. The signal **202** has variations due to vertical Hall element offsets, which tend to cause corresponding variations of output signals causing them to be too high or too low relative to the sine wave **204**, in accordance with offset errors for each element. The offset signal errors are undesirable.

Full operation of the CVH sensing element **112** of FIG. **1** and generation of the signal **202** of FIG. **2** are described in more detail in the above-described PCT Patent Application No. PCT/EP2008/056517, entitled "Magnetic Field Sensor for Measuring Direction of a Magnetic Field in a Plane," filed May 28, 2008, which is published in the English language as PCT Publication No. WO 2008/145662.

Groups of contacts of each vertical Hall element can be used in a chopped arrangement (also referred to herein as current spinning) to generate chopped output signals from each vertical Hall element. Thereafter, a new group of adjacent vertical Hall element contacts can be selected (i.e., a new vertical Hall element), which can be offset by one element from the prior group. The new group can be used in the chopped arrangement to generate another chopped output signal from the next group, and so on.

Each step of the signal **202** is representative of an unchopped output signal, i.e., from one respective group of vertical Hall element contacts, i.e., from one respective vertical Hall element. Thus, for a CVH sensing element having 32 vertical Hall elements taken sequentially, there are thirty-two steps in the signal **202** when current spinning is not used. However, for embodiments in which current spinning is used or in which a current swapping operation is performed, each step of the signal **202** can be comprised of several sub-steps (not shown, e.g., two sub-steps or four sub-steps). Each sub-step may, for example, be indicative of a current spinning "phase" in embodiments where current spinning is used.

Current spinning and current spinning phases are described more fully below in conjunction with FIGS. **4**-**4**C.

It will be understood that a phase of the signal **202** is related to an angle of the magnetic field **116** of FIG. **1** relative to position zero of the CVH sensing element **112**. It will also be understood that a peak amplitude of the signal **202** is generally representative of a strength of the magnetic field **16**. Using electronic circuit techniques described above in PCT Patent Application No. PCT/EP2008/056517, or using other techniques described below, a phase of the signal **202** (e.g., a phase of the signal **204**) can be found and can be used to identify the pointing direction of the magnetic field **116** of FIG. **1** relative to the CVH sensing element **112**.

The signal **202** is also referred to herein as a "sequenced signal" **202**, which will be understood to be comprised of sequential ones of a plurality of magnetic field signals or "steps," each magnetic field signal generated by a respective one of a plurality of magnetic field sensing elements, e.g., the plurality of vertical Hall elements within a CVH sensing element.

Referring now to FIG. **3**, an example magnetic field sensor **300** includes a CVH sensing element **302** having a plurality of vertical Hall elements, with each vertical Hall element comprising a group of vertical Hall element contacts (e.g., five vertical Hall element contacts). More specifically, each vertical Hall element comprises respective first and second current receiving contacts, respective first and second output signal generating contacts, and a respective at least one reference contact, as will be further discussed below.

In some embodiments, the CVH sensing element **302** can be the same as or similar to the CVH sensing element **112** described above in conjunction with FIG. **1**, and in one aspect the CVH sensing element **302** can be disposed proximate to a two pole magnet **314** coupled to a target object **316**, which magnet **314** can be the same as or similar to the magnet **114** of FIG. **1**. However, in other embodiments, the CVH sensing element **302** can be replaced by a group of magnetic sensing elements that are the same as or similar to those described above in conjunction with FIG. **1**A. The CVH sensing element **302** is configured to generate a plurality of magnetic field signals **302*a***, one at a time. Thus, couplings that carry the magnetic field signals **302*a*** can include a plurality of couplings to the plurality of vertical Hall elements within the CVH sensing element **302**.

The CVH sensing element **302** can be coupled to a sequence switches circuit **304** that sequences through and sequentially selects from among the vertical Hall elements of the CVH sensing element **302**. The sequence switches circuit **304** can also select respective first and second current receiving contacts, respective first and second output signal generating contacts, and a respective at least one reference contact of the sequentially selected vertical Hall elements to generate a differential sequenced signal **304*a***, **304*b***. The differential sequenced signal **304*a***, **304*b*** can be the same as or similar to the sequenced signal **202** of FIG. **2**.

The sequence switches circuit **304** can be coupled to a sequences selection circuit **306**, which can be configured to generate a sequence control signal **306*a***. The sequence control signal **306*a*** may, for example, control and/or indicate switching (or indexing) of the vertical Hall elements and selection of the respective first and second current receiving contacts, the respective first and second output signal generating contacts, and the respective at least one reference contact.

The sequence selection circuit **306** can also be coupled to an oscillator **308**. The oscillator **308** can be configured to provide a clock signal **308*a*** to the sequence selection circuit **306** for sequential selection of sequential ones of the vertical Hall elements of the CVH sensing element **302**.

The sequence switches circuit **304** can also be coupled to or can comprise a current switches circuit (CSC) **307** for coupling current sources (here, first and second current sources **320**, **325**, as will be discussed below) to selected vertical hall element contacts of selected ones of the vertical Hall elements within the CVH sensing element **302**. Current spinning or chopping described below in conjunction with FIGS. **4**-**4**C is not used. Instead, a particular phase (i.e., coupling of current sources and coupling of output contacts to each vertical hall element) is selected, which remains the same phase for each selected vertical Hall element within the CVH sensing element **302**. It will become apparent from discussion below that the selected phase is a phase shown below in FIG. **4**.

The sequence switches circuit **304** can additionally be coupled to a plurality of current sources (here, first and second current sources **320**, **325**), which can be configured to generate a respective plurality of current signals **320*a***, **325*a***. The sequence switches circuit **304** can be configured to couple the first and second current sources **320**, **325** to the respective current receiving contacts of sequentially selected ones of the plurality of vertical Hall elements and to provide the current signals **320*a***, **325*a*** generated by the current sources **320**, **325** to the respective current receiving contacts. In response thereto, the differential sequenced signal **304*a***, **304*b*** can be produced at the first and second output signal generating contacts of the sequentially selected ones of the vertical Hall elements.

The differential sequenced signal **304*a***, **304*b*** can be coupled to a signal processing system **330**, which can be configured to receive and process the differential sequenced signal **304*a***, **304*b***. In the example embodiment shown, the signal processing system **330** comprises a differential amplifier (DA) **332**, a band-pass filter **334**, and an analog-to-digital converter (ADC) **336**. The DA **332**, the band-pass filter **334**, and the analog-to-digital converter (ADC) **336** may be provided separately or in any suitable sub combination.

The DA **332** can be coupled to receive the differential sequenced signal **304*a***, **304*b*** and configured to generate an amplified signal **332*a***. In one embodiment, the DA **332** is coupled to receive the differential sequenced signal **304*a***, **304*b*** from the first and second output signal generating contacts in a Kelvin connection arrangement described more fully below in conjunction with FIG. **8**.

A bandpass filter **334** can be coupled to receive the amplified signal **332*a*** and configured to generate a filtered signal **334*a***. An analog-to-digital converter (ADC) **336** can be coupled to receive the filtered signal **334*a*** and configured to generate a converted digital signal **330*a***.

The signal processing system **330**, particularly the ADC **336** of the signal processing system **330**, can be coupled to a data processing circuit **340**. The data processing circuit **340** can be coupled to receive the converted digital signal **330*a*** from the ADC **336** and clock signals **308*b***, **308*c*** from the oscillator **308** and can be configured to generate an x-y angle signal **340*a*** having x-y angle values indicative of an angle of a magnetic field generated by the magnet **314**. In one embodiment, the data processing circuit **340** compares a relative phase of the converted digital signal **330***a* and one or more of the clock signals **308***b*, **308***c* in generating the x-y angle signal **340***a*. A phase of the x-y angle signal **340***a* can change, and therefore, can be representative of a rotating magnetic field when the magnet **314** rotates.

In operation, the x-y angle signal **340***a* would have a larger angle error component were it not for sequential selection from among the plurality of vertical Hall elements of the CVH sensing element **302** and selection of the respective first and second current receiving contacts, the respective first and second output signal generating contacts, and the respective at least one reference contact by the sequence switches circuit **304**. The angle error component is described more fully below in conjunction with FIG. **5**. Let it suffice here to say that the angle error component is an angle error component that would otherwise cause the x-y angle signal **340***a* to not be perfectly representative of the true angle of the magnetic field generated by the magnet **314**.

Additional aspects of the example magnetic field sensor **300**, with particular focus on the coupling and sequential selection from among the plurality of vertical Hall elements and their respective current receiving contacts, respective output signal generating contacts, and respective reference contacts are described in greater detail below in conjunction with FIGS. **6-8**.

Referring now to FIGS. **4-4**C, the block diagrams shown are representative of a four phase current spinning or chopping that can be used for any vertical Hall element having five contacts. The four phases are described herein for clarity. However, it will become apparent that current spinning is not used with the magnetic field sensor of FIG. **3**, and instead, each selected vertical Hall element uses the arrangement of FIG. **4**.

It should be appreciated that such current spinning can be used for each selected vertical Hall element within the conventional CVH sensing element **112** of FIG. **1**. It should also be appreciated that such current spinning can also be used for separate magnetic field sensing elements, for example, the magnetic field sensing elements **130***a*-**130***h* of FIG. **1**A, where the magnetic field sensing elements **130***a*-**130***h* are selected and chopped one of the time.

Orientation of current driven nodes and signal notes of FIGS. **4-4**A are shown from the perspective of looking from outside of a ring of vertical Hall elements, e.g., from outside of a CVH sensing element. It will be understood that, naming conventions described below in terms of 0, 90, 180, and 270 degree phases are somewhat arbitrary. These naming conventions come from use of similar naming conventions used for planar Hall effect elements, where, during the sequence of current spinning, current is sequentially injected into nodes that are physically ninety degrees apart. There are no such physical angles that are ninety degrees apart for vertical Hall elements. Nevertheless, FIGS. **4**, **4**A, **4**B, and **4**C are referred to herein as zero, ninety, one hundred eighty, and two hundred seventy degrees phases, respectively.

Referring now to FIG. **4**, a vertical Hall element **400** is comprised of five vertical Hall element contacts, namely, first, second, third, fourth, and fifth vertical Hall element contacts, **402***a*, **402***b*, **402***c*, **402***d*, **402***e*, respectively. In a first chopping or current spinning phase (zero degree phase), a drive circuit **408**, can be coupled to the first and fifth vertical Hall element contacts **402***a*, **402***e*, respectively, which are coupled together, and can provide a total current of I, half of the current, I/2, flowing to the first vertical a Hall element contact **402***a* and half of the current, I/2, flowing to the fifth vertical Hall element contact **402***e*. The third vertical Hall element contact **402***c* is coupled to a voltage reference **410**, for example, ground. Currents from the current source **408** flow from the first and fifth vertical Hall element contacts **402***a*, **402***e*, respectively, through a substrate **406** (e.g., through an epitaxial layer upon a substrate) of the vertical Hall element **400** to the third vertical Hall element contact **402***c*, as represented by dashed lines.

A signal, Vm, responsive to an external magnetic field, results between the second and fourth vertical Hall element contacts **402***b*, **402***d*, respectively. Thus, in the first current spinning phase, current spinning switches can select the second and fourth vertical Hall element contacts **402***b*, **402***d* to provide an output signal, and can select the first, fifth, and third vertical Hall element contacts **402***a*, **402***e*, **402***c*, respectively. Couplings during other current spinning phases described below will be apparent.

Referring now to FIG. **4**A, in which like elements of FIG. **4** are shown having like reference designations, in a second current spinning phase (one hundred eighty degree phase) of the same vertical Hall element **400** (same five vertical Hall element contacts), couplings are changed by current spinning switches. In the second phase, the current source **408** is coupled to the third vertical Hall element contact **402***c*, and the first and fifth vertical Hal element contacts **402***a*, **402***e*, respectively, are coupled together and to the reference voltage **410**. Thus, the currents flow through the substrate **406** in opposite directions from those shown in FIG. **4**.

As in FIG. **4**, a signal, Vm, responsive to an external magnetic field, results between the second and fourth vertical Hall element contacts, **402***b*, **402***d*, respectively. The signal, Vm, of FIG. **4**A is like the signal, Vm, of FIG. **4**. However, the offset voltage within the signals can be different, e.g., different in signal.

Referring now to FIG. **4**B, in which like elements of FIGS. **4** and **4**A are shown having like reference designations, in a third current spinning phase (ninety degree phase) upon the same vertical Hall element **400** (same five vertical Hall element contacts), couplings are again changed by current spinning switches. In the third phase, the current source **408** is coupled to the second vertical Hall element contact **402***b*, and the fourth vertical Hall element contact **402***d* is coupled to the reference voltage **410**. Thus, a current flows from the second vertical Hall element contact **402***b* through the substrate **406** to the fourth vertical Hall element contact **402***d.*

The first and fifth vertical Hall element contacts **402***a*, **402***e*, respectively, are coupled together. Some current also flows from the second vertical Hall element contact **402***b* through the substrate **406** to the first vertical Hall element contact **402***a* and through the mutual coupling to the fifth vertical Hall element contact **402***c*. Some current also flows from the fifth vertical Hall element contact **402***e* through the substrate **406** to the fourth vertical Hall element contact **402***d.*

A signal, Vm, responsive to an external magnetic field, results between the first vertical Hall element contact **402***a* first (and the fifth vertical Hall element contact **402***e*) and the third vertical Hall element contact **402***c*. The signal, Vm, of FIG. **4**B is like the signal, Vm, of FIGS. **4** and **4**A. However, the offset voltage within the signal can be different.

Referring now to FIG. **4**C, in which like elements of FIGS. **4-4**B are shown having like reference designations, in a fourth chopping phase (two hundred seventy degree phase) upon the same vertical Hall element **400** (same five vertical Hall element contacts), couplings are again changed by current spinning switches. In the fourth phase, the current is reversed from that shown in FIG. **4**B. The current source **408** is coupled to the fourth vertical Hall element contact **402***d*, and the second vertical Hall element contact **402***b* is coupled to the reference voltage **410**. Thus, a current flows from the fourth vertical Hall element contact **402***d* through the substrate **406** to the second vertical Hall element contact **402***b*.

The first and fifth vertical Hall element contacts **402***a*, **402***e*, respectively, are coupled together. Some current also flows from the fourth vertical Hall element contact **402***d* through the substrate **406** to the fifth vertical Hall element contact **402***e*, through the mutual coupling to the first vertical Hall element contact **402***a*. Some current also flows from the first vertical Hall element contact **402***a* through the substrate **406** to the second vertical Hall element contact **402***b*.

A signal, Vm, responsive to an external magnetic field, results between the first vertical Hall element contact **402***a* (and the fifth vertical Hall element contact **402***e*) and the third vertical Hall element contact **402***c*. The signal, Vm, of FIG. **4**C is like the signal, Vm, of FIGS. **4**-**4**B. However, the offset voltage within the signal can be different.

The signals, Vm, provided by the four phases of chopping of FIGS. **4**-**4**C are responsive to an external magnetic field.

As described above, after generating the four current spinning phases on any one vertical Hall element within the CVH sensing element **402**, the current spinning arrangements of FIGS. **4**-**4**C can move to a next vertical Hall element, e.g., five vertical Hall element contacts offset by one vertical Hall element contact from those shown in FIGS. **4**-**4**C, and the four current spinning phases can be performed on the new vertical Hall element by operation of current spinning switches.

As discussed above, while four current spinning phases are described in FIGS. **4**-**4**C, it will become apparent from the discussions below in conjunction with FIGS. **6**-**8** that in accordance with the concepts, systems and techniques sought to be protected herein, only one phase, e.g., the coupling of FIG. **4**, is used in the magnetic field sensor **300** of FIG. **3**. Thus, in one aspect, current spinning is not used with the example embodiments disclosed herein.

Referring now to FIG. **5**, a graph **500** has a horizontal axis with a scale in units of angular degrees and a vertical axis with a scale in units of value of an x-y angle value magnitude, for example, a magnitude of x-y angle values within the x-y angle signal **340***a* of FIG. **3**.

A line **502** is representative of an x-y angle signal (i.e., a plurality of x-y angle values) that has no angle error. When the x-y angle signal has no angle error, the x-y angle signal is perfectly linear with respect to actual angle, i.e., the x-y angle signal is a perfect and true representation of the angle of the magnetic field generated by the magnet **314** of FIG. **3**, and the line **502** passes through zero.

A line **504** is representative of an x-y angle signal that has only an average or DC angle error, such that all angles represented by the x-y angle signal are offset by a fixed number of degrees. The line **504** does not pass through zero.

A curve **506** is representative of an x-y angle signal that has errors in representation of the true angle of the magnetic field generated by the magnet **314**, average or DC errors and also an error that has a sinusoidal appearance.

A curve **508** is representative of an x-y angle signal that has other errors in representation of the true angle of the magnetic field generated by the magnet **314**.

A variety of circuit characteristics of the magnetic field sensor **300** contribute to the errors, i.e., to both the DC (or average) angle error represented by the curves **506**, **508**, and to the sinusoidal shapes of the curves **506**, **508**. One factor that contributes to the errors is switching noise generated by the sequence switches circuit **304** and/or by the current switches circuit **307** of FIG. **3**. Another factor is different offset voltages among the vertical Hall elements within the CVH sensing element **302**, for example, different offset voltages described above in conjunction with the signal **202** of FIG. **2**. Another factor is different sensitivities of the various vertical Hall elements.

First, regarding the sequence switches circuit **304**, it will be understood that charge injection or switching spikes (together referred to as noise) generated by the sequence switches **304** are not necessarily exactly the same as each sequential vertical Hall element is selected in the CVH sensing element **302**. When the noise generated by the sequence switches **304** is not the same as each vertical Hall element is selected, a DC (or average) angle error is generated and also a sinusoidal type error such as that represented by the curves **506**, **508**. The sinusoidal error characteristic can be, in part, a result of the noise generated by the sequence switches being repetitive for each cycle around the CVH sensing element **302**, and thus, the noise will have an angle error frequency component at a frequency of the signal **202** of FIG. **2**, and will add to the signal **202** (**304***a*, **304***b* of FIG. **3**). The angle error frequency component is essentially fixed in phase relative the differential sequenced signal **304***a*, **304***b*, and therefore, the addition of the angle error causes different phase shift errors depending on the phase of the differential sequenced signal **304***a*, **304***b*. Higher harmonics can also result from the noise.

Next, regarding the current switches circuit **307**, it will be understood that charge injection or switching spikes (together referred to as noise) generated by the current switches circuit **307** are not necessarily exactly the same as each sequential vertical Hall element is selected in the CVH sensing element **302**. When the noise generated by the current switches circuit **307** is not the same as each vertical Hall element is selected, a DC (or average) angle error is generated and also a sinusoidal type error such as that represented by the curves **506**, **508**. The sinusoidal error characteristic can, in part, result from the noise generated by the current switches circuit **307** being repetitive for each cycle around the CVH sensing element **302**.

Other circuit characteristics can also contribute to the angle errors, i.e., to both the DC (or average) angle error represented by the error curves **506**, **508**, and to the sinusoidal shapes of the error curves **506**, **508**. Namely, a speed with which the dual differential amplifier **322** of FIG. **3**, and also other circuit elements of FIG. **3**, are unable to settle to final values as the sequence switches circuit **304** switches among the vertical Hall elements of the CVH sensing element **302**, and also as the current switches circuit **307** switch to each sequential vertical Hall element, contribute to the errors.

The above-described circuit characteristics, including, but not limited to, different offset voltages of the various vertical Hall elements within the CVH sensing element **302** of FIG. **3**, differences of sensitivities of the various vertical Hall elements, and switching noise and lack of circuit elements settling to final values, tend to be influenced by (i.e., changed by) a variety factors including, but not limited to, temperature of the magnetic field sensor **300** of FIG. **3**, a rate of sequencing around the CVH sensing element **302**, peak magnitude of the magnetic field experience by the CVH sensing element **302** as the magnet **314** rotates, and selected current spinning sequence(s)(or lack thereof) among the various vertical Hall elements.

Differences between the curves **506**, **508** can be attributed to changes in the same factors, namely, changes in the temperature, changes in or differences in peak amplitude of the magnetic field experience by the CVH sensing element **302** as the magnet **314** rotates, changes in offset voltages of the vertical Hall elements within the CVH sensing element **302**, changes of sensitivities of the various vertical Hall elements, changes in or differences in rates of sequencing around the CVH sensing element **302**, and changes in or differences in selected current spinning sequence(s) (or lack thereof) among the various vertical Hall elements within the CVH sensing element **302**. Among these factors, it will be understood that the changes in the temperature can occur at any time. The changes in the peak amplitude of the magnetic field can be influenced by positional changes, i.e., air gap changes, between the magnet **314** and the CVH sensing element **302** of FIG. **3**. The changes in the peak amplitude of the magnetic field can also be influenced by mechanical considerations, for example, wear of a bearing or the shaft **316** upon which the magnet **314** rotates. However, the changes in sequencing rates and the changes in current spinning sequences (or lack thereof) can be fixed, and changed only for different applications of the magnetic field sensor **300**. The changes in offset voltages and changes in sensitivity of the vertical Hall elements tend to be influenced by changes in temperature.

In general, it has been determined that the dominant angle error frequency components occur at first and second harmonics of the frequency of the signal **202** (i.e., differential sequenced signal **304***a*, **304***b*). The curves **506**, **508** are representative of angle error functions dominated by first and second harmonics of the frequency of the signal **202** (i.e., **304***a*, **304***b*).

As temperature varies, each harmonic component of the angle error represented by curves **506**, **508** can change independently in amplitude and phase.

Referring now to FIG. **6**, a portion of an example magnetic field sensor **600**, which may be the same as or similar to the magnetic field sensor **300** of FIG. **3**, includes a circular vertical Hall (CVH) sensing element **602**, first and second current sources **620**, **625**, a respective plurality of switches (SW_1, SW_2, SW_3, SW_4, SW_5), and an amplifier circuit **632** coupled as shown. The respective plurality of switches is representative of switches in a sequence switches circuit, which can be the same as or similar to the sequence switches circuit **304** of FIG. **3**. The magnetic field sensor **600** is shown configured in a first example coupling arrangement of a plurality of potential coupling arrangements. In a CVH sensing element comprising sixty-four vertical Hall elements, for example, there can be sixty-four potential coupling arrangements.

The CVH sensing element **602**, similar to the CVH sensing element **302** of FIG. **3**, comprises a plurality of vertical Hall elements (e.g., thirty-two or sixty-four vertical Hall elements), of which vertical Hall element **1602** is but one example. Vertical Hall element **1602** is representative of a sequentially selected one of the plurality of vertical Hall elements (e.g., a first selected one of the vertical Hall elements) that is selected and coupled to the first and second current sources **620**, **625**, first and second input terminals of the amplifier circuit **632**, and a reference terminal (GND) by the respective plurality of switches (SW_1, SW_2, SW_3, SW_4, SW_5).

The vertical Hall element **1602**, like other vertical Hall elements in the CVH sensing element **602**, includes a plurality of vertical Hall element contacts, of which vertical Hall element contacts **2**, **3**, **4**, **5**, **6** are examples. While the vertical Hall element **1602** is shown having five vertical Hall element contacts **2**, **3**, **4**, **5**, **6**, in other embodiments, a CVH sensing element can have vertical Hall elements with more than five or fewer than five vertical Hall element contacts, for example, four vertical Hall element contacts or six vertical Hall element contacts.

The vertical Hall element **1602**, also like other vertical Hall elements in the CVH sensing element **602**, includes respective first and second current receiving contacts **2**, **6**, respective first and second output signal generating contacts **3**, **5**, and a respective at least one reference contact **4**. In the example embodiment shown, the at least one reference contact **4** is positioned between the first and second current receiving contacts **2**, **6** and the first output signal generating contact **3** is positioned between the at least one reference contact **4** and the first current receiving contact **2**. Additionally, in the example embodiment shown, the second output signal generating contact **5** is positioned between the at least one reference contact **4** and the second current receiving contact **6**.

The coupling arrangement shown can be compared with the coupling arrangement of FIG. **4**. Here, however, the one current source **408** shown in FIG. **4**, which generates a split current to two different vertical Hall element contacts **402***a*, **402***e*, is replaced by the first and second current sources **620**, **625**, respectively, with no current splitting.

The reference potential (here, labeled GND) is sequentially coupled to the at least one reference contact **4** by a third switch SW_3 of the respective plurality of switches. In one embodiment, the reference potential can be provided as a system ground. In another embodiment, the reference potential can be provided as an earth ground. However, other reference potentials can also be used.

Additionally, the first current source **620**, which can be the same as or similar to the first current source **320** of FIG. **3**, is sequentially coupled to the first current receiving contact **2** by a first switch SW_1 of the respective plurality of switches. The first current source **620** is operable to provide, at a first sequential time, a first current signal **620***a* to the first current receiving contact **2**.

Moreover, the second current source **625**, which can be the same as or similar to the second current source **325** of FIG. **3**, is sequentially coupled to the second current receiving contact **6** by a fifth switch SW_5 of the respective plurality of switches. The second current source **625** is operable to provide, at substantially the same first sequential time, a second current signal **625***a* to the second current receiving contact **6**. In one embodiment, the first current signal **620***a* and the 15 second current signal **625***a* are substantially equal in magnitude. In another embodiment, the first current signal **620***a* and the second current signal **625***a* are unequal in magnitude. In some embodiments, particularly where the first current signal **620***a* and the second current signal **625***a* are unequal in magnitude, a current swapping operation described more fully below can be performed.

The vertical Hall element **1602**, in response to receiving first and second current signals **620***a*, **625***a* at the first and second current receiving contacts **2**, **6**, is configured to generate a first step of a first sequenced signal (or, more simply, a first sequenced signal step), responsive to an external magnetic field, at the first and second output signal generating contacts **3**, **5**. As discussed above, sequenced signals are comprised of sequential ones of a plurality of magnetic field signals or "steps."

The amplifier circuit **632**, which can be the same as or similar to the DA **332** of FIG. **3**, is coupled to receive the first sequenced signal step, which can be the same as or similar to a first portion in time of the differential sequenced signal **304***a*, **304***b* of FIG. **3**, from the first and second output signal generating contacts **3**, **5** at the first and second input terminals of the amplifier circuit **632**. In one embodiment, similar to DA **332**, the amplifier circuit **632** can be coupled to receive the first sequenced signal step from the first and second output signal generating contacts **3**, **5** in a Kelvin connection arrangement.

A Kelvin connection will be understood to be a four-wire sensing arrangement that uses two current-carrying and two voltage-sensing connections. Here, the Kelvin connection can, for example, substantially reduce or eliminate parasitic resistance contributions of switches SW_2 and SW_4 when coupling the first and second output signal generating contacts **3**, **5** to the amplifier circuit **632**.

The amplifier circuit **632**, in response to receiving the first sequenced signal step, is configured to generate a first amplified signal **632***a* representative of a sequentially selected one of a plurality of magnetic field signals at an output thereof. The first amplified signal **632***a* can, for example, be received by a bandpass filter and an ADC, the same as or similar to bandpass filter **324** and ADC **326** of FIG. **3**. A signal representative of the first amplified signal **632***a* can also be received by a data processing circuit, the same as or similar to data processing circuit **340**, for generating an x-y angle signal indicative of the angle of the magnetic field generated by a magnet.

Referring now to FIG. **6**A, in which like elements of FIG. **6** are shown having like reference designations, a magnetic field sensor **600***a* is the same as or similar to the magnetic field sensor **600** of FIG. **6**. Here, however, the magnetic field sensor **600***a* is shown with couplings to another vertical Hall element **2602**, which is representative of another sequentially selected one of the plurality of vertical Hall elements (e.g., a second sequentially selected one of the plurality of vertical Hall elements) of the CVH sensing element **602**. Additionally, here the contacts of the vertical Hall element **2602** are coupled (e.g., to first and second current sources **620**, **625**) via a set of switches (SW_1-SW_5), which are labeled the same (SW_1-SW_5) as the switches of vertical Hall element **1602** of FIG. **6** for convenience but are not actually the same. In particular, each contact comprises about five switches for switching between different positions (e.g., a switch for coupling to ground, a switch for coupling to the first current source **620**, a switch for coupling to the second current source **625**, and a plurality of switches for coupling to the amplifier circuit amplifier circuit **632**) and, thus, the switches for each sequentially selected one of the plurality of vertical Hall elements are not the same.

Returning now to FIG. **6**A, the vertical Hall element **2602**, like vertical Hall element **1602**, includes a plurality of vertical Hall element contacts, of which vertical Hall element contacts **3**, **4**, **5**, **6**, **7** are examples. The vertical Hall element **2602**, also like the vertical Hall element vertical Hall element **1602**, includes respective first and second current receiving contacts **3**, **7**, respective first and second output signal generating contacts **4**, **6**, and a respective at least one reference contact **5** in accordance with the concepts, systems, circuits and techniques sought to be protected herein. The magnetic field sensor **600***a* is shown configured in a second example coupling arrangement of the plurality of potential coupling arrangements described above. As apparent, the vertical Hall element **2602** is shifted by one vertical Hall element contact with respect to the vertical Hall element **1602** in the CVH sensing element **602**. While the vertical Hall element **2602** is shown being shifted by one vertical Hall element contact with respect to the vertical Hall element **1602** in the CVH sensing element **602**, in other embodiments, sequential vertical Hall elements may be shifted by more than one contact, for example, two or three contacts.

As illustrated, the reference potential (GND) is sequentially coupled to the at least one reference contact **5** by the respective third switch SW_3, the first current source **620** is sequentially coupled to the first current receiving contact **3** by the respective first switch SW_1, and the second current source **625** is sequentially coupled to the second current receiving contact **6** by the respective fifth switch SW_5.

The vertical Hall element **2602**, in response to receiving first and second current signals **620***a*, **625***a* at the first and second current receiving contacts **3**, **7**, is configured to generate a second step of the first sequenced signal (or, more simply, a second sequenced signal step or a first sequenced signal step of the second example coupling arrangement), responsive to an external magnetic field, at the first and second output signal generating contacts **4**, **6**.

The amplifier circuit **632** is coupled to receive the second sequenced signal step which can be the same as or similar to a second portion in time of the differential sequenced signal **304***a*, **304***b* of FIG. **3**, from the first and second output signal generating contacts **4**, **6** at the first and 35 second amplifier circuit inputs and is configured to generate a second amplified signal **632***b* (or, more simply, a first amplified signal of the second example coupling arrangement) representative of a second sequentially selected one of the above-mentioned plurality of magnetic field signals.

In embodiments where it is difficult, yet desirable to provide first and second current signals **620***a*, **625***a* of substantially equal magnitude, for example, a current swapping operation can be used. In particular, the first and second current sources **620**, **625** can swap couplings in half-period intervals (e.g., first and second half-period intervals, e.g., half sub-steps of the steps of FIG. **2**) for each of the plurality of coupling arrangements, e.g., the first example coupling arrangement of FIG. **6** and the second example coupling arrangement of FIG. **6**A, and for all of the plurality of coupling arrangements as samples are taken around the CVH sensing element **602**.

For example, in a first half-period interval of the second example coupling arrangement of FIG. **6**A, the first current source **620** can be coupled to the first current receiving contact **3** of the vertical Hall element **2602** by switch SW_1 and the second current source **625** can be coupled to the second current receiving contact **7** by switch SW_5 as shown. Additionally, in a second half-period interval of the second example coupling arrangement of FIG. **6**A, the second current source **625** can be sequentially coupled to the first current receiving contact **3** of the vertical Hall element **2602** by another switch (not shown) and the first current source **620** can be coupled to the second current receiving contact **7** of the vertical Hall element **2602** by another switch (not shown). During the first half-period interval, the vertical Hall element **2602**, in response to receiving first and second current signals **620***a*, **620***b* at the first and second current receiving contacts **3**, **7**, is configured to generate a first sub-step of a second sequenced signal step at the first and second output signal generating contacts **3**, **7**. Similarly, during the second half-period interval, the vertical Hall element **2602** is configured to generate a second sub-step of the second sequenced signal step at the first and second output signal generating contacts **3**, **7**.

Continuing with the example of the second coupling arrangement of FIG. **6**A, during both the first half-period interval and during the second half-period interval, the amplifier **632** remains coupled to the first and second output signal generating contacts **4**, **6**. Thus, both the first sub-step of the second sequenced signal step generated during the first half-period interval and the second sub-step of the second sequenced signal step generated during the second half-period interval are received by the amplifier **632**. With this current swapping technique, the resulting amplified signal **632** (e.g., **632***a*, **632***b*) has twice the number of samples (i.e., steps) as the number of sampled vertical Hall elements in the CVH sensing element **602**.

It should be understood that the above-described current swapping technique can result in a lower offset voltage in the amplified signal **632**, particularly when the first and second current sources **620**, **625** are not equal. The coupling and process illustrated above in conjunction with FIGS. **6** and **6**A can be completed for each sequentially selected one of the plurality of vertical Hall elements of the CVH sensing element **602**. In the case of the CVH sensing element **602** comprising sixty-four vertical Hall elements, the coupling and process can, for example, be completed for each of the sixty-four vertical Hall elements.

It can be shown that by cycling through each of the vertical Hall element contacts of a CVH sensing element (e.g., CVH sensing element **602**) and performing the above-mentioned coupling and process, the offset error associated with the CVH sensing element can be reduced or even eliminated, as will become apparent from the discussion below.

Referring now to FIG. **7**, a vertical Hall element **702** can be representative of the sequentially selected vertical Hall element **1602** of FIG. **6**. As described above, each sequentially selected one of the vertical Hall elements of the CVH sensing element **602** of FIGS. **6** and **6**A comprises a plurality of vertical Hall element contacts (e.g., five vertical Hall element contacts), here labeled **2-6** with the labels comparable in other figures above and below.

Referring now to FIG. **7**A, in which like elements of FIG. **7** are shown having like reference designations, the vertical Hall element **702** is shown to be fixed in a phase similar to that of FIG. **4**. Here, however, current receiving contacts **2**, **6** are shown coupled to first and second current sources **720**, **725** rather than the single current source **408** of FIG. **4**. In one embodiment, use of the first and second current sources **720**, **725** in contrast with the single current source **408** ensures that the current signals **720***a*, **725***a* received by the first and second current receiving contacts **2**, **6** are substantially the same. In another embodiment, the use of the first and second current sources **720**, **725** provides the capability of generating first and second current signals **720***a*, **725***a* of unequal magnitude.

As illustrated, resistors R_{23}, R_{34}, R_{54}, and R_{65} are shown between each adjacent pair of vertical Hall element contacts **2-3**, **3-4**, **4-5**, **5-6**, respectively. The resistors R_{23}, R_{34}, R_{54}, and R_{65} are representative of bulk resistance in a substrate upon which the vertical Hall element **702** is formed. The bulk resistance may, for example, arise due to properties of the substrate over which the vertical Hall element contacts **2**, **3**, **4**, **5**, and **6** are formed and can vary based upon a wide variety of factors including the composition of the substrate material and the temperature thereof.

In cycling through each of the vertical Hall element contacts of a CVH sensing element (e.g., CVH sensing element **602** of FIG. **6**) and performing the coupling and process described in conjunction with the above figures, the offset errors associated with each of the vertical Hall elements of the CVH sensing element can be significantly reduced, as illustrated in Table **1700** shown in FIG. **7**B. Referring now to FIG. **7**B, Table **1700** illustrates offset voltage cancellations of the first ten vertical Hall elements of an example CVH sensing element comprising sixty-four vertical Hall elements, with each vertical Hall element comprising five vertical Hall element contacts. A high frequency offset, rather than a first or subsequent harmonic, is added to an output signal as may be generated by a CVH sensing element (e.g., CVH sensing element **602** of FIG. **6**). As illustrated in Table **1700**, when current signals IA and IB are substantially the same as a result of first and second current sources (e.g., first and second current sources **620**, **625** of FIG. **6**) being capable of producing first and second current signals (e.g., first and second current signals **620***a*, **625***a* of FIG. **6**) of a substantially equal magnitude or as a result of the current swapping operation discussed above in conjunction with FIG. **6**A, for example, corresponding current terms substantially cancel in each sequential coupling arrangement. In particular, an average current of (IA+IB)/2 is produced at each half-period of each sequential coupling arrangement, which results in one or more offset cancellations upon completion of each full-period of the sequential coupling arrangements.

In Table **1700**, it should be recognized that resistance from vertical Hall element contact x to vertical Hall element contact y ($R_{x,y}$) is the same as resistance from vertical Hall element contact y to vertical Hall element contact x ($R_{y,x}$). In particular, at least a portion of the offset errors associated with the sequenced signals (or steps of the sequenced signals) produced at corresponding output signal generating contacts of each vertical Hall element are canceled upon cycling through each of the vertical Hall elements of the CVH sensing element. Remaining offset errors (if any) can, for example, be corrected in signal processing circuitry and data processing circuitry coupled to receive the sequenced signal (or steps of the sequenced signals), similar to signal processing circuitry **330** and data processing circuit **340** of FIG. **3**.

Referring now to FIG. **8**, in which like elements of FIG. **7**A are shown having like reference designations, an equivalent circuit **802** is shown which is representative of the vertical Hall element **702** of FIG. **7**. As illustrated in FIG. **8** and as described above with respect to FIG. **7**, a bulk resistance, as represented by resistors R_{23}, R_{34}, R_{54}, and R_{65}, exists between each adjacent pair of vertical Hall element contacts **2-3**, **3-4**, **4-5**, **5-6**, respectively. In addition to the aforesaid, a contact resistance R_{sw1} (i.e., a switch resistance) exists between the first current source **720** and the first current receiving contact **2**, a contact resistance R_{sw2} exists between the first input terminal of the amplifier circuit **632** and the first output signal generating contact **3**, a contact resistance R_{sw3} exists between the at least one reference contact **4** and the reference potential (GND), a contact resistance R_{sw4} exists between the second input terminal of the amplifier circuit **632** and the second output signal generating contact **5**, and a contact resistance R_{sw5} exists between the second current source **725** and the second current receiving contact **6**. The contact resistances are a result of the resistance associated with the first, second, third, fourth, and fifth switches, as denoted by R_{SW1}, R_{SW2}, R_{SW3}, R_{SW4}, and R_{SW5}, respectively.

In operation, the vertical Hall element represented by the equivalent circuit **802** generates a differential voltage between vertical Hall element contacts **3** and **5** in response to a magnetic field. The differential voltage is related to resistance changes of the bulk resistances, in particular R_{34}, R_{54}, that change with the magnetic field. Is should be understood that the bulk resistances R_{23}, R_{65} or changes thereof have little effect upon the differential voltage. The resistances R_{23}, R_{65} merely add in series to the high output impedances of the first and second current sources **720**, **725**, respectively, and thus, do not affect currents I_A and I_B.

With regard to the contact resistances, it will be understood that, if an input impedance of the amplifier **632** is high, then the contact resistances R_{sw2}, R_{sw4} do not affect the differential voltage. The contact resistance R_{sw3} also has little effect upon the differential voltage. Still further, the contact resistances R_{SW1} and R_{SW5} also merely add in series to the high output impedances of the first and second current sources **720**, **725**, respectively, and thus, do not affect currents I_A and I_B, and therefore, also have little or no impact upon the differential voltage. Thus by use of a Kelvin connection, influence of various contact resistances upon the differential voltage between the vertical Hall element contacts **3** and **5** can be reduced or eliminated.

The concepts discussed above in conjunction with FIGS. **6**-**7**A can also similarly be applied to equivalent circuit **802** for reducing the offset error associated with the vertical Hall element **702**. In particular, a magnetic field sensor with reduced offset error is achieved through cancellation of the offset errors associated with each of the vertical Hall elements.

A particular coupling according to FIG. **4** has been described above in FIGS. **6**-**8**. It will be apparent, however, that couplings according to FIGS. **4**A-**4**C can also be used, but with an undesirable increase in the influence of contact resistances upon the detected differential voltage.

Additionally, it will be apparent that the concepts discussed above provide several advantages over conventional magnetic field sensing elements and associated methods, including the substantial reduction or elimination of chopping at each CVH index, parasitic resistance contributions of switches for coupling output signal generating contacts (e.g., output signal generating contacts **3**, **5** of FIG. **6**) to amplifier circuits (e.g., amplifier circuit **632** of FIG. **6**), for example, and thus can eliminate the need for larger switches to reduce or eliminate unbalanced currents resulting from the parasitic resistance contributions of the switches. Further, the concepts discussed above provide methods for providing first and second current signals of substantially equal magnitude to first and second current receiving contacts (e.g., first and second current receiving contacts **2**, **6** of FIG. **6**) of sequentially selected ones of the plurality of vertical Hall elements.

As described above and will be appreciated by one of skill in the art, embodiments of the disclosure herein may be configured as a system, method, or combination thereof. Accordingly, embodiments of the present disclosure may be comprised of various means including entirely of hardware, entirely of software, or any combination of hardware and software. Furthermore, embodiments of the present disclosure may take the form of a computer program product on a computer-readable storage medium having computer readable program instructions (e.g., computer software) embodied in the storage medium. Any suitable non-transitory computer-readable storage medium may be utilized.

All references cited herein are hereby incorporated herein by reference in their entirety.

Having described preferred embodiments, which serve to illustrate various concepts, structures and techniques, which are the subject of this patent, it will now become apparent to those of ordinary skill in the art that other embodiments incorporating these concepts, structures and techniques may be used. Additionally, elements of different embodiments described herein may be combined to form other embodiments not specifically set forth above. Accordingly, it is submitted that that scope of the patent should not be limited to the described embodiments but rather should be limited only by the spirit and scope of the following claims.

What is claimed is:

1. A magnetic field sensor, comprising:

a circular vertical Hall (CVH) sensing element comprising:

a plurality of vertical Hall elements, each one of the plurality of vertical hall elements comprising respective first and second current receiving contacts, respective first and second output signal generating contacts, and a respective at least one reference contact, wherein the at least one reference contact is positioned between the first and second current receiving contacts, the first output signal generating contact is positioned between the at least one reference contact and the first current receiving contact, and the second output signal generating contact is positioned between the at least one reference contact and the second current receiving contact; wherein the plurality of vertical Hall elements is configured to generate a plurality of magnetic field signals, each magnetic field signal responsive to a magnetic field;

the magnetic field sensor further comprising:

a sequence switches circuit coupled to the plurality of vertical Hall elements, wherein the sequences switches circuit is operable to sequentially select from among the plurality of vertical Hall elements to generate sequenced signal steps;

a first current source sequentially coupled by the sequence switches circuit to the first current receiving contact of sequentially selected ones of the plurality of vertical Hall elements, and operable to provide, at first sequential times, a first current signal to the first current receiving contact of the sequentially selected ones of the plurality of vertical Hall elements;

a second current source sequentially coupled by the sequence switches circuit to the second current receiving contact of the sequentially selected ones of the plurality of vertical Hall elements and operable to provide, at the same first sequential times, a second current signal to the second current receiving contact of the sequentially selected ones of the plurality of vertical Hall elements; and

an amplifier circuit coupled to receive the sequenced signal steps produced at the first and second output signal generating contacts of the sequentially selected ones of the plurality of vertical Hall elements, and, in response to the sequenced signal steps, the amplifier circuit is configured to generate an amplified signal representative of sequentially selected ones of the plurality of magnetic field signals,

wherein the first current source is sequentially coupled by the sequence switches circuit to the second current receiving contact of the sequentially selected ones of the plurality of vertical Hall elements, and operable to provide, at second sequential times, the first current signal to the second current receiving contact of the sequentially selected ones of the plurality of vertical Hall elements; and

wherein the second current source is sequentially coupled by the sequence switches circuit to the first current receiving contact of the sequentially selected ones of the plurality of vertical Hall elements, and operable to provide, at the same second sequential times, the second current signal to the first current receiving contact of the sequentially selected ones of the plurality of vertical Hall elements.

2. The magnetic field sensor of claim 1, wherein the vertical Hall elements are not configured in a current spinning arrangement.

3. The magnetic field sensor of claim 1, wherein the first current signal and the second current signal are substantially equal in magnitude.

4. The magnetic field sensor of claim 1, wherein the amplifier circuit is coupled to the select first and second output generating contacts in a Kelvin connection arrangement.

5. The magnetic field sensor of claim 1, wherein an input impedance of the amplifier circuit is substantially more than an output impedance of the first and second output generating contacts of the sequentially selected ones of the plurality of vertical Hall elements.

6. The magnetic field sensor of claim 1, wherein each selected one of the plurality of vertical Hall elements comprises five vertical Hall element contacts.

7. The magnetic field sensor of claim 1, wherein the at least one reference contact is coupled to a reference potential.

8. The magnetic field sensor of claim 7, wherein the reference potential is ground.

9. The magnetic field sensor of claim 1, wherein the first current signal and the second current signal are substantially unequal in magnitude.

10. A method, comprising:

generating a plurality of magnetic field signals with a circular vertical Hall (CVH) sensing element, the CVH sensing element comprising a plurality of vertical Hall elements, each one of the plurality of vertical hall elements comprising respective first and second current receiving contacts, respective first and second output signal generating contacts, and a respective at least one reference contact, wherein the at least one reference contact is positioned between the first and second current receiving contacts, the first output signal generating contact is positioned between the at least one reference contact and the first current receiving contact, and the second output signal generating contact is positioned between the at least one reference contact and the second current receiving contact, each magnetic field signal being responsive to a magnetic field;

sequentially selecting from among the plurality of vertical Hall elements;

generating a first current signal and providing, at first sequential times, the first current signal to the first current receiving contact of sequentially selected ones of the plurality of vertical Hall elements;

generating a second current signal and providing, at the same first sequential times, the second current signal to the second current receiving contact of the sequentially selected ones of the plurality of vertical Hall elements;

generating a first sequenced signal step, responsive to an external magnetic field, at the first and second output generating contacts of the sequentially selected ones of the plurality of vertical Hall elements;

generating the first current signal and providing, at second sequential times, the first current signal to the second current receiving contact of sequentially selected ones of the plurality of vertical Hall elements;

generating the second current signal and providing, at the same second sequential times, the second current signal to the first current receiving contact of the sequentially selected ones of the plurality of vertical Hall elements;

generating a second sequenced signal step, responsive to the external magnetic field, at the first and second output generating contacts of the sequentially selected ones of the plurality of vertical Hall elements; and

generating an amplified signal representative of sequentially selected ones of the plurality of magnetic field signals in response to at least the first and second sequenced signal steps.

11. The method of claim 10, wherein the first current signal and the second current signal are substantially equal in magnitude.

12. The method of claim 10, wherein each selected one of the plurality of vertical Hall elements comprises five vertical Hall element contacts.

13. The method of claim 10, wherein the at least one reference contact is coupled to a reference potential.

14. The method of claim 13, wherein the reference potential is ground.

15. The method of claim 10, wherein the first current signal and the second current signal are substantially unequal in magnitude.

16. A magnetic field sensor, comprising:

a circular vertical Hall (CVH) sensing element comprising:

a plurality of vertical Hall elements, each one of the plurality of vertical hall elements comprising respective first and second current receiving contacts, respective first and second output signal generating contacts, and a respective at least one reference contact, wherein the at least one reference contact is positioned between the first and second current receiving contacts, the first output signal generating contact is positioned between the at least one reference contact and the first current receiving contact, and the second output signal generating contact is positioned between the at least one reference contact and the second current receiving contact; wherein the plurality of vertical Hall elements is configured to generate a plurality of magnetic field signals, each magnetic field signal responsive to a magnetic field;

the magnetic field sensor further comprising:

means for sequentially selecting from among the plurality of vertical Hall elements to generate sequenced signal steps;

means for providing, at first sequential times, a first current signal to the first current receiving contact of the sequentially selected ones of the plurality of vertical Hall elements;

means for providing, at the same first sequential times, a second current signal to the second current receiving contact of the sequentially selected ones of the plurality of vertical Hall elements;

means for providing, at second sequential times, the first current signal to the second current receiving contact of sequentially selected ones of the plurality of vertical Hall elements;

means for providing, at the same second sequential times, the second current signal to the first current receiving contact of the sequentially selected ones of the plurality of vertical Hall elements; and

means for generating an amplified signal representative of sequentially selected ones of the plurality of magnetic field signals in response to receiving the sequenced signal steps produced at the first and second output signal generating contacts of the sequentially selected ones of the plurality of vertical Hall elements.

17. The magnetic field sensor of claim 16, wherein the first current signal and the second current signal are substantially equal in magnitude.

18. The magnetic field sensor of claim **16**, wherein the means for generating an amplified signal is coupled to the select first and second output generating contacts in a Kelvin connection arrangement.

19. The magnetic field sensor of claim **16**, wherein the first current signal and the second current signal are substantially unequal in magnitude.

20. The magnetic field sensor of claim **16**, wherein each selected one of the plurality of vertical Hall elements comprises five vertical Hall element contacts.

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