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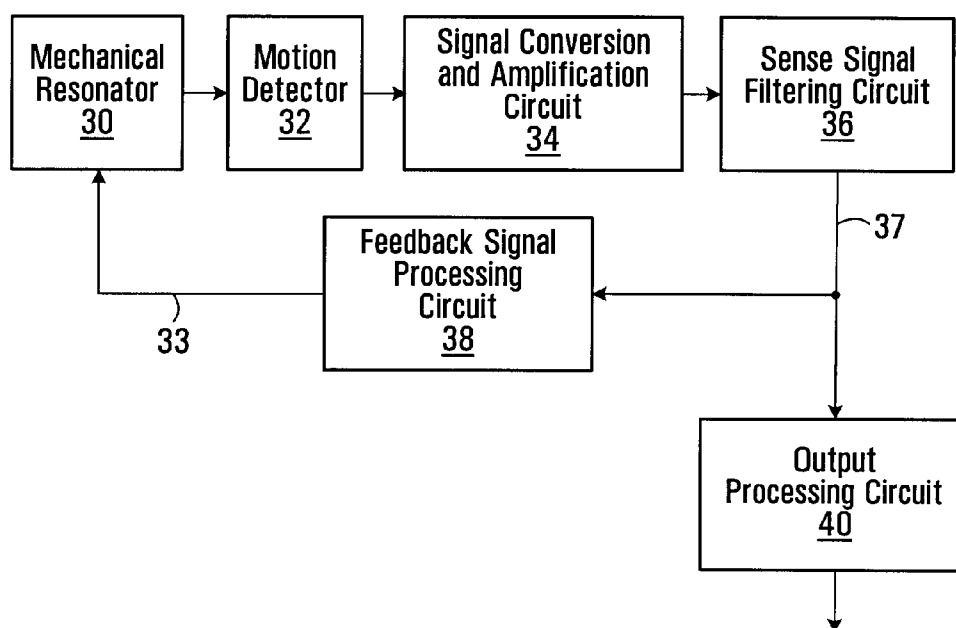
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(54) Title: SYSTEM AND METHOD FOR MEASURING MAGNETIC FIELD STRENGTH USING A MECHANICAL RESONATOR



(57) Abstract: Methods and apparatus for measuring magnetic field are provided. A resonator having a resonant frequency is that varies as a function of magnetic field is driven with a drive signal, and produces an output that is converted to electrical form. This output is then processed to isolate interference components due to the drive signal and to produce a sense signal. The sense signal is the processed to produce the drive signal. The sense signal is also processed to produce an output representative of the magnetic field.

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SYSTEM AND METHOD FOR MEASURING MAGNETIC FIELD STRENGTH
USING A MECHANICAL RESONATOR

RELATED APPLICATION

This application claims the benefit of prior U.S.
5 provisional application no. 60/799,005 filed May 10, 2006.

FIELD OF THE INVENTION

The invention relates to methods and systems for
measuring magnetic field strength.

BACKGROUND OF THE INVENTION

10 Micromachining is becoming a mature technology and
many of the micromachining projects are in the process of
commercialization. As is the case for microelectronic
technology, if fabrication, or at least prototyping, of a
sensor is possible using a standard process, considerable
15 savings can result in terms of overall cost and development
time for a device. See for example M.N. Horenstein and P.R.
Stone, Journal of Electrostatics, vol. 51-52, pp. 515-521,
May 2001.

An example of the analytic modeling and Finite
20 Element Simulations of a resonant micromachined magnetic
field sensor is described in Bahreyni, Behraad; Shafai,
Cyrus, "Analytic Modeling and FEM Simulation of a Resonant
Micromachined Magnetic Field Sensor", Canadian Conference of
Electrical & Computer Engineering, May, 2004 hereby
25 incorporated by reference in its entirety. The resonant
frequency of the sensor changes in response to the magnitude
and direction of the present magnetic field. The output of
the micromachined magnetic field sensor is input to a
frequency measurement device such as a spectrum analyzer.
30 An AC input voltage drives the arrangement, and the

frequency of the AC voltage is swept across a range of interest. The overall frequency response is examined to determine the peak, and that corresponds to the resonant frequency. The resonant frequency, once determined, is
5 used to determine the magnetic field using knowledge of the relationship between the resonant frequency and magnetic field.

SUMMARY OF THE INVENTION

According to one broad aspect, the invention
10 provides an apparatus for measuring magnetic field comprising: a mechanical resonator having a resonator output and having an input for receiving a drive signal; signal conversion and amplification circuitry for converting the resonator output of the mechanical resonator into a voltage
15 output; and a sense signal filtering circuit to isolate a sense signal from an interfering feedthrough signal.

In some embodiments, the sense signal filtering circuit comprises at least one of: a notch filter having a notch at the expected resonant frequency divided by two; one
20 or more bandpass filters to isolate the sense signal from the interference signal; and one or more additional high-Q bandpass filters to remove beating components.

In some embodiments, the apparatus connected to form an oscillator loop with a feedback signal processing
25 circuit that processes the sense signal to produce the drive signal; wherein the sense signal has a frequency shift representative of a magnetic field within which the apparatus is situated.

According to another broad aspect, the invention
30 provides an apparatus for measuring magnetic field comprising: a mechanical resonator that undergoes mechanical

motion and has an input for receiving a drive signal, the mechanical resonator having a resonant frequency that changes as a function of magnetic field; a motion detector that detects the mechanical motion of the mechanical resonator; and a sense signal filtering circuit for filtering a signal representative of the mechanical motion of the mechanical resonator to isolate a sense signal from interference due to the drive signal.

In some embodiments, the apparatus further comprises: signal conversion and amplification circuitry for converting an output of the motion detector into a voltage output as the signal representative of the mechanical motion of the mechanical resonator.

In some embodiments, the sense signal filtering circuit comprises at least one of: a notch filter having a notch at an expected resonant frequency divided by two; one or more bandpass filters to isolate the sense signal from the interference due to the drive signal; and one or more additional high-Q bandpass filters to remove beating components.

In some embodiments, the apparatus further comprises: a feedback signal processing circuit that processes the sense signal to produce the drive signal; wherein the sense signal has a frequency shift representative of a magnetic field within which the apparatus is situated.

In some embodiments, the feedback signal processing circuit comprises: a constant amplitude circuit to make the sense signal have substantially constant amplitude; a divide by 2 circuit; a phase adjustment circuit.

In some embodiments, the apparatus further comprises: an output processing circuit that processes the sense signal to produce an output representative of the magnetic field within which the apparatus is situated.

5 In some embodiments, the output processing circuit comprises: a frequency dependent phase shifting circuit that produces a phase shifted output; and a circuit that determines a phase shift introduced by the phase shifting circuit.

10 In some embodiments, the circuit that determines a phase shift introduced by the phase shifting circuit comprises: a phase detector.

 In some embodiments, the apparatus further comprises a phase difference to voltage converter, that
15 produces a voltage that represents a value for the magnetic field.

 In some embodiments, the apparatus further comprises a downconverter circuit that downconverts a frequency of the sense signal.

20 In some embodiments, the phase shifting circuit comprises an all pass filter.

 In some embodiments, the mechanical resonator comprises a resonant micromachined magnetic field sensor.

 In some embodiments, the mechanical resonator is
25 driven by means of electrostatic, optical, thermal, piezoelectric, piezoresistive.

 In some embodiments, the motion detector comprises one of an electrostatic motion detector, optical motion detector, thermal motion detector, piezoelectric motion
30 detector, and piezoresistive motion detector.

According to another broad aspect, the invention provides a method comprising: placing a mechanical resonator having a resonator output and having an input for receiving a drive signal in an area for which a magnetic field measurement is to be determined; converting and amplifying the resonator output into an electrical signal output; and filtering the electrical signal output to isolate a sense signal from an interfering feedthrough signal.

In some embodiments, the method further comprises: feeding a version of the sense signal back as the drive signal to form a closed loop.

In some embodiments, the method further comprises: performing feedback signal processing upon the sense signal to produce the drive signal.

In some embodiments, the method further comprises: processing the sense signal to produce an output representative of the magnetic field.

According to another broad aspect, the invention provides a resonator arrangement comprising: a mechanical resonator having a drive signal and a resonator output; a drive signal generation circuit that generates the drive signal for the mechanical resonator from the resonator output.

In some embodiments, the mechanical resonator is a MEMS resonator.

In some embodiments, the drive signal generation circuit comprises: signal conversion and amplification circuitry for converting the resonator output of the mechanical resonator into a voltage output; and a sense

signal filtering circuit to isolate a sense signal from an interfering feedthrough signal.

In some embodiments, the sense signal filtering circuit comprises at least one of: a notch filter having a
5 notch at the expected resonant frequency divided by two; one or more bandpass filters to isolate the sense signal from the interference signal; and one or more additional high-Q bandpass filters to remove beating components.

In some embodiments, the drive signal generation
10 circuit comprises: a motion detector that detects the mechanical motion of the mechanical resonator; and a sense signal filtering circuit for filtering a signal representative of the mechanical motion of the mechanical resonator to isolate a sense signal from interference due to
15 the drive signal.

In some embodiments, the resonator arrangement further comprises: signal conversion and amplification circuitry for converting an output of the motion detector into a voltage output as the signal representative of the
20 mechanical motion of the mechanical resonator.

In some embodiments, the apparatus drive signal generation circuit further comprises: a feedback signal processing circuit that processes the sense signal to produce the drive signal.

25 In some embodiments, the feedback signal processing circuit comprises: a constant amplitude circuit to make the sense signal have substantially constant amplitude; a divide by 2 circuit; a phase adjustment circuit.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will now be described with reference to the attached drawings in which:

Figure 1A is a block diagram of an apparatus that
5 can be used for measuring magnetic fields;

Figure 1B is a block diagram of an apparatus for measuring magnetic fields;

Figure 2 is a circuit diagram used to drive a resonator according to an embodiment of the invention;

10 Figure 3 is a block diagram of an example of an oscillator network according to an embodiment of the invention;

Figure 4 is a block diagram of an example of the oscillator network of Figure 3 along with output processing
15 components; and

Figure 5 is a schematic of an example micromachined magnetic field sensor employed as a electrostatic resonator according to an embodiment of the invention.

20 DETAILED DESCRIPTION

Various methods of employing a mechanical resonator using electrostatic, piezoelectric, piezoresistive, thermal, or other actuation mechanism as a magnetic field sensor will be described. Particular
25 implementations employ micromachined magnetic field sensors described with reference to Figure 5 in detail below. However, more generally any mechanical structure that has a resonant frequency that varies as a function of an axial

stress can be employed, for example due to an applied magnetic field.

Figure 1A is a block diagram of an apparatus that can be used for measuring magnetic fields. The system comprises a mechanical resonator 10 that has a resonant frequency that varies as a function of magnetic field in which the apparatus is located. The mechanical resonator 10 undergoes mechanical motion that is detected by a motion detector 12. The mechanical resonator 10 receives a drive signal 18. The motion detector produces a signal representative of the mechanical motion of the mechanical resonator. This is followed by an optional signal conversion and amplification circuit 14 that performs any necessary signal conversion from the form output by the motion detector 12 into a form suitable for electronic processing. This might for example simply consist of a current to voltage conversion and amplification. The output of the signal conversion and amplification circuit 14 is fed to a sense signal filtering circuit 16. This output is also representative of the mechanical motion of the mechanical resonator. The sense signal filtering circuit 16 performs filtering on the signal to isolate a sense signal 20 from interference due to the drive signal 18. The sense signal can be analyzed to determine the resonant frequency of the mechanical resonator assuming an appropriate drive signal, for example any AC drive signal that is swept across a range of frequencies.

Figure 1B is a block diagram of an apparatus for measuring magnetic fields. The system comprises a mechanical resonator 30 that has a resonant frequency that varies as a function of magnetic field in which the apparatus is located. The mechanical resonator 30 undergoes mechanical motion that is detected by a motion detector 32.

The mechanical resonator receives a drive signal 33. The motion detector 32 produces a signal representative of the mechanical motion of the mechanical resonator 30. This is followed by an optional signal conversion and amplification circuit 34 that performs any necessary signal conversion from the form output by the motion detector 32 into a form suitable for electronic processing. This might for example simply consist of a current to voltage conversion and amplification. The output of the signal conversion and amplification circuit 34 is fed to a sense signal filtering circuit 36. This output is also representative of the mechanical motion of the mechanical resonator 30. The sense signal filtering circuit 36 performs filtering on the signal to isolate a sense signal 37 from interference due to the drive signal 33. In the closed loop configuration of Figure 1B, the sense signal 37 is representative of the resonant frequency of the mechanical resonator as described later.

The sense signal 37 output by the sense signal filtering circuit 36 is then fed through a feedback signal processing circuit 38 and back into the mechanical resonator 30 as the drive signal 33 to form an oscillator loop. The output of the sense signal filtering circuit 36 is representative of the resonant frequency of mechanical resonator, and this in turn is representative of the magnetic field. In some embodiments, additional circuitry is provided to convert that sense signal into a more representative form. Figure 1 shows an output processing circuit 40 that can be used to this effect.

In the description below, various detailed examples of the functionality that might be included in the various circuits of Figures 1A and 1B will be described. However, it is to be understood that the embodiments of

Figures 1A and 1B are not to be limited to those specific examples.

The mechanical resonator is driven by means of an appropriate drive signal. Examples of the form this signal might take include electrostatic, optical, thermal, piezoelectric, piezoresistive, but others are possible.

The motion detector is any device capable of measuring the mechanical motion of the mechanical resonator. Examples include an electrostatic motion detector, optical motion detector, thermal motion detector, piezoelectric motion detector, and piezoresistive motion detector, but others are possible. The mechanical resonator may provide a suitable output on its own without a separate motion detector. The motion detector and mechanical resonator may be separate devices or an integrated device.

Driving the resonator with no bias

When driving an electrostatic or thermal resonator, a DC bias voltage can be used in order to bring down the level of the input AC voltages. An example of this is shown in Figure 2 where an electrostatic resonator 50 is shown with a bias voltage V_G 52, and an input AC voltage 54 having an input frequency ω_a . In practice, there is also a very large feedthrough/interference signal at the drive signal frequency which makes accurate electrical measurements (amplitude or phase) of the sense signal very difficult. This is shown in Figure 2, where an example of the spectrum of the output is shown. The spectrum includes a component 56 at ω_a . This is the drive frequency (ω_a) given by the driving circuit 54. There is a second component at frequency $2\omega_a$ (twice the frequency of ω_a), and this represents the motion of resonator 50, due to the drive frequency ω_a . In the case of an electrostatically driven

resonator embodiment of the sensor, the spike at frequency ω_a is the electrical drive signal 54 which acts as an interference signal to the measurement and can be removed by subsequent filtering circuitry, and the spike at frequency
5 $2\omega_a$ is the signal due to the speed of oscillatory motion of the resonator itself and is indeed a measure of the oscillatory motion of the resonator itself.

If V_G is set to 0V for the system shown in Figure 2, the output current should theoretically have a single
10 component representative of the motion of the resonator at the second harmonic of the drive signal for electrostatic and thermally actuated resonators because of the quadratic relationship between the drive voltage and electrostatic or thermal force. Interference and feedthrough signals may
15 still pose problems in taking accurate measurements. However, since the output signal of the device is at twice the frequency of the interfering signals, it is possible to recover the sense signal with proper filtering of the output signal. If the non-linearities of the electronics are kept
20 to a minimum, the signal at the second harmonic will be entirely from the resonator operation.

Using a notch filter

If bandpass or highpass filtering alone is to be employed to separate the sense signal from the interference
25 signal, the small separation of the interference signal and the sense signal in the frequency domain and the needed amount of attenuation may require high order filters to extract the sensing signal. For example, if it is intended to attenuate the interference signal by a factor of about
30 5×10^3 or 74dB, a highpass filter with a minimum of 12 poles may be needed. Designing and implementing such a filter is not a straightforward process, and requires careful attention to the practical limits of the devices, their

tolerances, and matching of components between the cascaded stages.

Instead of relying on achievable attenuation from poles, in some embodiments the interference signal is dealt with by placing the zeros of the transfer function of a filter at the frequency of the interference. Such a filter is often referred to as a notch filter. The filter's quality factor may be set to maximize the attenuation of the interfering signals. One or more bandpass filters at the frequency of the second harmonic may be used in addition to the notch filter to attenuate the interfering signals further and amplify the main signal. In some implementations, both of the filters are realized with switched capacitor filters.

15 **Removing beating**

The desired sense signal can be recovered by using a filter block consisting of a notch filter and bandpass filter as described above. However, beating between the output signal from the sensor and interfering signals from various sources (e.g., computer monitors and digital measurement equipment) may cause considerable variation in amplitude of the filter block output. Beating occurs when adding two sinusoidal signals whose frequencies are close to each other. In practice, neither the amplitude nor the frequency of the interfering signals is stable, which makes accurate measurements of the desired signal more difficult.

In some embodiments, additional high-Q bandpass filters are employed to shrink the bandwidth around the desired signal frequency and reject the signals outside of this band. However, tuning of these filters can be troublesome due to their narrow frequency response. In some embodiments, switched capacitor filters are used to greatly

simplify the design flow, especially since the clock signal of the first filter block can be used for these high-Q filters, assuming it is also implemented with switched capacitor technology.

5 Dividing the frequency by two

The sense signal can be recovered using the setup described above. In some embodiments, to alleviate the need for a signal source, the resonator is used in an oscillator loop. The implementation of Figure 1B takes this approach.

10 The problem of the feedthrough signal in the oscillator design case can still be circumvented with the same circuitry described above. However, in some designs the electrostatic resonator has to be driven at half the resonant frequency of the device in this setup. Therefore,
15 in such instances the frequency of the processed signal has to be divided by two.

Driving the resonator with a constant amplitude

In some embodiments, since the magnetic field data is extracted from the frequency shifts of the signal from
20 the sensor, the amplitude information is discarded. This can be done by processing the sinusoidal signal with an analog comparator to convert the sinusoidal wave into a square wave. Counting over a window produces a moving average representative of the sense frequency. Dividing the
25 signal frequency by two can then be simply done with a T-flipflop. To minimize the spurious signals at the output of the oscillator, the output of the frequency divider is then converted back to sinusoidal, for example with a 4th order lowpass filter which attenuates the 3rd harmonic of the
30 output of the frequency divider by about 40dB. Using this configuration, the amplitude of the excitation signal is completely defined and set by the user and does not rely on

the properties of the linear and nonlinear elements in the loop. A phase adjustment circuit between the lowpass filter and the resonator can also be used to assure excitation of the resonator at the correct frequency and phase.

5 Figure 3 is a block diagram of an example of the oscillator network, this being a very specific example of the implementation of the mechanical resonator, motion detector, signal conversion and amplification circuit, sense signal filtering circuit and signal processing circuit of
10 Figure 1B. This configuration improves the quality of the oscillator as a whole and greatly reduces phase-noise and jitter. This configuration includes all of the components discussed above, but not every implementation need include all of the components.

15 Shown is a mechanical resonator connected to a motion detector comprising a first amplifier element 102, and a second amplifier element 104. The output of the second amplifier element 104 is connected to the input of a notch filter 106 having frequency response F_1 which includes
20 a notch at frequency $f_r/2$, where $f_r/2$ is a nominal resonant frequency of the mechanical resonator 100. The notch frequency is set to match the frequency of the drive signal, thereby allowing an efficient elimination of most of the interference due to the drive signal. The output of the
25 notch filter 106 is input to filters 108, 110, 112 connected together in sequence which are bandpass filters having frequency responses F_2 , F_3 , F_4 respectively that have passbands centred at the frequency f_r of the second harmonic. These are provided in addition to the notch filter 106 to
30 attenuate the interfering signals further and amplify the main signal. In some implementations, both of the filters are realized with switched capacitor filters. In the example of Figure 3, three bandpass filters (108, 110, and

112) are provided to remove beating. Less or more such filters can be used as needed in a practical implementation.

The output of filter 112 is connected to the input of a lowpass filter 114 has frequency response F_5 which is a lowpass filter having a cutoff frequency of 60 kHz in the particular example illustrated. This filter 114 is used to provide extra filtering to remove high frequency noise from the signal and the filters 108, 110, and 112 are used to remove the beating.

The output of the lowpass filter 114 is connected to an amplifier 116. The output of amplifier 116 is connected to the input of a comparator 118. The comparator output effectively produces a moving average of the twice the resonant frequency. Elements 116,118 function to remove the amplitude information from the sense signal, and give a digital indication of the resonator frequency. The output of the comparator 118 is divided by two with frequency divider circuit 120 to produce a drive signal near the resonant frequency of the mechanical resonator 100.

To reduce the spurious signals at the output of the oscillator, the output of the frequency divider is then converted back to sinusoidal, for example with a lowpass filter 122 having frequency response F_2 which attenuates the 3rd harmonic of the output of the frequency divider by about 40dB. Using this configuration, the amplitude of the excitation signal is completely defined and set by the user and does not rely on the properties of the linear and nonlinear elements in the loop. A phase adjustment circuit 124 is provided between the lowpass filter 122 and the resonator 100 to assure excitation of the resonator at the correct frequency and phase. Element P1 124 may for example be implemented using an "all-pass filter", which is used to adjust the phase of the signal coming from filter 122, so

that it is in phase with the motion of the resonator 100.
Element A4 126 represents the gain for the all pass filter
P1. This is shown as a separate block as this amplification
can be inherent to the filter P1, and/or be from an
5 additional amplifier.

Frequency shift measurement

Additional signal processing of the sense signal
can be performed outside the loop to extract the magnetic
field measurement. In some embodiments, this can be done by
10 applying a frequency dependent phase-shift to the sense
signal to convert the information embedded in the frequency
of the signal to a phase difference between the sense signal
and its delayed version. This can potentially improve the
accuracy of measurements by converting small frequency
15 shifts to relatively large phase differences. If the
amplitude of the signal is controlled, the shifts in the
resonant frequency of the structure are instantaneously
converted to phase differences and can be measured.
Therefore, sensitivity and bandwidth of measurements are
20 both enhanced by using this technique.

The next step is to measure the phase difference
in order to extract information about the amount of
frequency shift. This can be done by using a phase detector
which compares the relative phase of the signals at its
25 inputs. As an example, the original signal and its phase-
shifted (i.e., delayed) version can be converted to square
waves by use of comparators. The phase difference between
these square waves can then be measured with different
digital phase detectors, such as an XOR gate. The output of
30 the phase detector is then lowpass filtered to yield a DC
voltage which is proportional to the phase difference
between the input signals, and therefore, the amount of
frequency shift in the original signal.

Use of allpass filters

To avoid the resulting complexities of using passive phase shift networks, in some embodiments an allpass (or delay) filter is used to implement the phase shift.

- 5 Allpass filters do not modify the amplitude of the signal through them but will cause a predetermined phase shift at the designed frequency. This is done by properly choosing the location of poles and zeros of a given transfer functions. More specifically, the zeros and poles have the same frequency (to produce a flat amplitude response) but
10 the zeros are placed in the right-half portion of the s-plane (to increase the phase difference between high and low frequencies). If allpass networks of orders larger than one are used, it is possible to independently control the
15 frequency and phase performance (i.e., Q) of the circuit.

The phases of the delayed signal and the signal that was not delayed are compared with the phase detector block which produces an output proportional to the phase difference. This output is representative of the magnetic
20 field measurement.

Down conversion of frequency

- If the phase difference detection is to be done at the signal frequency, very high-Q allpass filters may be required. For example, if it is desired to have a 45° phase
25 shift for a 1Hz shift at the signal frequency of 40kHz, a 2nd order allpass filter with a Q of about 6000 is needed, which is obviously difficult to realize. On the other hand, high-Q filters are generally prone to instability. Furthermore, tuning of high-Q filters is not easy because of
30 their narrow bandwidth. To overcome these issues, in some embodiments a downconverter is used to bring down the frequency of the sense signal before feeding it to the delay

circuitry. This reduction in signal frequency, which is essentially the same as removing the frequency offset that does not convey information, allows for performing sensitive phase difference measurements with relatively low-Q allpass filters. Additionally, if the difference between the downconverting signal and the sensor signal is kept constant, a stable and tuned circuit can be designed to produce the delay at the difference frequency, which greatly improves the versatility of the sensing electronics.

An example of a circuit including all of the output processing components described above is shown in Figure 4, this circuit including the same components as described above with reference to Figure 3 plus additional components for realizing a specific implementation of the output processing circuit of Figure 1. More generally, a particular implementation may include no output processing, or an arbitrary subset of the output processing components discussed above.

The output processing components include a lowpass filter 130 having frequency response F_7 that may be implemented having a cutoff frequency f_r that is the same as that of filters 108, 110, 112 for convenience, but other cutoff frequencies can be employed. The output of filter 130 is passed to downconverter 132 that is controlled by a reference voltage V_{ref} which serves to produce a sense signal at a lower frequency. The output of downconverter 132 is subject to further filtering in filters 134, 136 having frequency responses F_8 , F_9 respectively to isolate the relevant component of the output of the downconverter 132. Filter 134 is a lowpass filter having cutoff frequency f_0 . Filter 136 is a bandpass filter having passband centre frequency. The specific frequency f_0 value is not important, but the role of these filters is to eliminate

high frequency noise after mixer 132. A different filter(s) may alternatively be employed in place of filters 134,136. The output of filter 136 is processed by two paths. The first path has a phase shifter 138 and a comparator 140. 5 The second path has a comparator 142. The comparators convert the respective input signals to square waves. The outputs of the two comparators 140,142 are input to phase detector 144 which produces an output that is lowpass filtered with filter 146 having frequency response F_{10} . In 10 the illustrated example, this has a cutoff frequency of 10 Hz.

A schematic of an example micromachined magnetic field sensor that can be employed as the electrostatic resonator with the above-described system and method is 15 illustrated in Figure 5. This includes a resonator and motion detector. More generally, any mechanical resonator can be used as long as it can be put in a configuration where the magnetic force from the magnetic field can be transferred and applied to the resonator body. The sensor is 20 composed of an electrostatic resonator, beam springs, and two crossbars. The shuttle of the sensor is kept under mechanical resonance during the sensor operation. When inside a magnetic field B , the current ISB , which flows through the crossbars (from pin 1 to pin 2 and then pin 3 to 25 pin 4), causes exertion of an axial force on the beam springs according to Lorentz force equation. The axial force modifies the stiffness of the flexural beams, and consequently, the resonant frequency of the structure changes. Although a comb-drive actuator is shown in the 30 Figure, lateral or vertical parallel plate electrostatic resonators can also be employed as the main resonating body of the sensor. The operation of the sensor involves simultaneous interaction of multiple physical domains with

each other, including electrostatics, magnetostatics, elasticity, dynamics, and electro-thermo-mechanics.

Magnetic fields are measured by this sensor not by means of any magnetic material, but by using Lorentz force.

5 Therefore, this sensor does not suffer from non-linearity or hysteresis effects, especially for high magnetic field measurements.

Lorentz force is the force upon a moving electric current (electrons) in the presence of a magnetic field.

10 This force is proportional to the multiplication of the magnitude of the electric current and the magnitude of the magnetic field. Thus, when electrons move in a magnetic field, Lorentz force tends to push or pull upon the electrons, and so upon the wire carrying the electrons.

15 Hall effect magnetic field sensors also use Lorentz force to displace moving electrons within a semi-conducting material, and so create a differential voltage. The sensor of Figure 5, however, does not require semi-conducting materials, and simply requires the use of an
20 electrically conducting material, which for example can be either a metal or semiconductor.

Since no magnetic or semi-conducting materials are needed for the construction of the sensor, it can be fabricated in standard commercial micromachining processes,
25 without needing any special post processing fabrication steps. This sensor can be readily designed and/or fabricated by many companies in the MEMS industry, such as Micralyne, MEMSCAP, or Analog Devices. Consequently, the fabrication cost of this sensor will be low.

30 In the illustrated example, a mechanical vibrator is first fabricated on a substrate. This can be a

micromachined vibrator, commonly referred to as a MEMS (micro-electro-mechanical system), in order to make a small sub-millimetre sized device that can be easily packed on a silicon chip. In the illustrated example, the vibrator is comprised of a "comb actuator". However, any mechanical structure capable of being driven into oscillation at a controlled frequency can be used (bridge, cantilever, membrane, etc.). The supporting micromachined crossbars are anchored to the substrate such that an electric current can be passed through them. In the presence of a magnetic field the Lorentz force on the crossbars will push/pull on the beam springs themselves, thereby causing a mechanical load on the microsprings, which changes the spring constant of the micro-springs. This will result in a change in the resonant frequency of oscillations of the mechanical vibrator. This change in frequency is used as the magnetic field sense mechanism.

The sensor is operated at its mechanical resonant frequency. At this frequency, the amplitude of oscillation is significantly higher than normal. This increases the measurement sensitivity.

The magnetic field is measured by monitoring the change in the mechanical resonant frequency of the mechanical vibrator, due to the change in the spring constant of the micro-springs caused by the Lorentz force. The amount of frequency shift is proportional to the magnetic field. The direction of frequency shift (increase or decrease in resonant frequency) is dependant on the direction of the magnetic field and the current in the crossbars. This is different from most of the conventional sensors, which produce a voltage or a current signal at their output. Consequently, the output signal of the

designed sensor is more robust against noise and interference.

The embodiments have been described in their application to sensing magnetic field strength. More generally, the closed loop embodiments can be used as resonators that do not require externally generated drive signals. For example, the described MEMS resonator in conjunction with the circuit described makes a arrangement that features a MEMS resonator that does not need an external frequency generation system. For example, the embodiments of Figures 1B and 3 provide can be used as such arrangements and may find applications other than sensing magnetic field strength. A specific example is a tuner circuit for a radio/cell phone. Instead of an external frequency generation system, spurious/environmental noise picked up by the circuit is filtered, and fed back to the mechanical resonator at the desired drive frequency. For such applications, there is no need for the output processing circuits of Figures 1B and 4 since no magnetic field is being measured. In some embodiments, the mechanical resonator is a MEMS resonator. Specific examples of MEMS resonators have been described above, but more generally, any MEMS resonator can be employed for such embodiments.

A specific example of a resonator arrangement that does not require an external drive signal has been described. In another embodiment, a MEMS resonator is provided together with a drive signal generation circuit that generates a drive signal for the MEMS resonator from an output of the MEMS resonator. The elements 32,34,36,38 of Figure 1B provide one example of a drive signal generation circuit. Elements 102,104,106,108,110,112,114,

116,118,120,122,124,126 of Figure 3 provide another example of a drive signal generation circuit.

Numerous modifications and variations of the present invention are possible in light of the above
5 teachings. It is therefore to be understood that within the scope of the appended claims, the invention may be practiced otherwise than as specifically described herein.

CLAIMS:

1. An apparatus for measuring magnetic field comprising:

a mechanical resonator having a resonator output
5 and having an input for receiving a drive signal;

signal conversion and amplification circuitry for converting the resonator output of the mechanical resonator into a voltage output; and

a sense signal filtering circuit to isolate a
10 sense signal from an interfering feedthrough signal.

2. The apparatus of claim 1 wherein the sense signal filtering circuit comprises at least one of:

a notch filter having a notch at the expected resonant frequency divided by two;

15 one or more bandpass filters to isolate the sense signal from the interference signal; and

one or more additional high-Q bandpass filters to remove beating components.

3. The apparatus of claim 1 connected to form an
20 oscillator loop with a feedback signal processing circuit that processes the sense signal to produce the drive signal;

wherein the sense signal has a frequency shift representative of a magnetic field within which the apparatus is situated.

25 4. An apparatus for measuring magnetic field comprising:

a mechanical resonator that undergoes mechanical motion and has an input for receiving a drive signal, the mechanical resonator having a resonant frequency that changes as a function of magnetic field;

5 a motion detector that detects the mechanical motion of the mechanical resonator; and

 a sense signal filtering circuit for filtering a signal representative of the mechanical motion of the mechanical resonator to isolate a sense signal from
10 interference due to the drive signal.

5. The apparatus of claim 4 further comprising:

 signal conversion and amplification circuitry for converting an output of the motion detector into a voltage output as the signal representative of the mechanical motion
15 of the mechanical resonator.

6. The apparatus of claim 4 wherein the sense signal filtering circuit comprises at least one of:

 a notch filter having a notch at an expected resonant frequency divided by two;

20 one or more bandpass filters to isolate the sense signal from the interference due to the drive signal; and

 one or more additional high-Q bandpass filters to remove beating components.

7. The apparatus of claim 4 further comprising:

25 a feedback signal processing circuit that processes the sense signal to produce the drive signal;

wherein the sense signal has a frequency shift representative of a magnetic field within which the apparatus is situated.

8. The apparatus of claim 7 wherein the feedback
5 signal processing circuit comprises:

a constant amplitude circuit to make the sense signal have substantially constant amplitude;

a divide by 2 circuit;

a phase adjustment circuit.

10 9. The apparatus of claim 4 further comprising:

an output processing circuit that processes the sense signal to produce an output representative of the magnetic field within which the apparatus is situated.

10. The apparatus of claim 9 wherein the output
15 processing circuit comprises:

a frequency dependent phase shifting circuit that produces a phase shifted output; and

a circuit that determines a phase shift introduced by the phase shifting circuit.

20 11. The apparatus of claim 10 wherein the circuit that determines a phase shift introduced by the phase shifting circuit comprises:

a phase detector.

12. The apparatus of claim 11 further comprising a
25 phase difference to voltage converter, that produces a voltage that represents a value for the magnetic field.

13. The apparatus of claim 1 further comprising a downconverter circuit that downconverts a frequency of the sense signal.

14. The apparatus of claim 10 wherein the phase
5 shifting circuit comprises an all pass filter.

15. The apparatus of any one of claims 4 to 14 wherein the mechanical resonator comprises a resonant micromachined magnetic field sensor.

16. The apparatus of any one of claims 4 to 15 wherein
10 the mechanical resonator is driven by means of electrostatic, optical, thermal, piezoelectric, piezoresistive.

17. The apparatus of any one of claims 4 to 16 wherein the motion detector comprises one of an electrostatic motion
15 detector, optical motion detector, thermal motion detector, piezoelectric motion detector, and piezoresistive motion detector.

18. A method comprising:

placing a mechanical resonator having a resonator
20 output and having an input for receiving a drive signal in an area for which a magnetic field measurement is to be determined;

converting and amplifying the resonator output into an electrical signal output; and

25 filtering the electrical signal output to isolate a sense signal from an interfering feedthrough signal.

19. The method of claim 18 further comprising:

feeding a version of the sense signal back as the drive signal to form a closed loop.

20. The method of claim 19 further comprising:

performing feedback signal processing upon the
5 sense signal to produce the drive signal.

21. The method of claim 18 further comprising:

processing the sense signal to produce an output representative of the magnetic field.

22. A resonator arrangement comprising:

10 a mechanical resonator having a drive signal and a resonator output;

a drive signal generation circuit that generates the drive signal for the mechanical resonator from the resonator output.

15 23. The resonator arrangement of claim 22 wherein the mechanical resonator is a MEMs resonator.

24. The resonator arrangement of claim 23 wherein the drive signal generation circuit comprises:

20 signal conversion and amplification circuitry for converting the resonator output of the mechanical resonator into a voltage output; and

a sense signal filtering circuit to isolate a sense signal from an interfering feedthrough signal.

25 25. The resonator arrangement of claim 24 wherein the sense signal filtering circuit comprises at least one of:

a notch filter having a notch at the expected resonant frequency divided by two;

one or more bandpass filters to isolate the sense signal from the interference signal; and

5 one or more additional high-Q bandpass filters to remove beating components.

26. The resonator arrangement of claim 23 wherein the drive signal generation circuit comprises:

10 a motion detector that detects the mechanical motion of the mechanical resonator; and

a sense signal filtering circuit for filtering a signal representative of the mechanical motion of the mechanical resonator to isolate a sense signal from interference due to the drive signal.

15 27. The resonator arrangement of claim 26 further comprising:

20 signal conversion and amplification circuitry for converting an output of the motion detector into a voltage output as the signal representative of the mechanical motion of the mechanical resonator.

28. The resonator arrangement of claim 26 wherein the apparatus drive signal generation circuit further comprises:

a feedback signal processing circuit that processes the sense signal to produce the drive signal.

25 29. The resonator arrangement of claim 28 wherein the feedback signal processing circuit comprises:

a constant amplitude circuit to make the sense signal have substantially constant amplitude;

a divide by 2 circuit;

a phase adjustment circuit.

AMENDED CLAIMS**received by the International Bureau on 12 April 2007 (12.04.2007)****+ STATEMENT UNDER ARTICLE 19 (1)**

1. An apparatus for measuring magnetic field comprising:

a mechanical resonator having a resonator output
5 and having an input for receiving a drive signal;

signal conversion and amplification circuitry for converting the resonator output of the mechanical resonator into a voltage output representing a frequency of the resonator output; and

10 a sense signal filtering circuit to isolate a sense signal from an interfering feedthrough signal.

2. The apparatus of claim 1 wherein the sense signal filtering circuit comprises at least one of:

a notch filter having a notch at the expected
15 resonant frequency divided by two;

one or more bandpass filters to isolate the sense signal from the interference signal; and

one or more additional high-Q bandpass filters to remove beating components.

20 3. The apparatus of claim 1 connected to form an oscillator loop with a feedback signal processing circuit that processes the sense signal to produce the drive signal;

wherein the sense signal has a frequency shift representative of a magnetic field within which the
25 apparatus is situated.

4. An apparatus for measuring magnetic field comprising:

a mechanical resonator that undergoes mechanical motion and has an input for receiving a drive signal, the mechanical resonator having a resonant frequency that changes as a function of magnetic field;

5 a motion detector that detects the mechanical motion of the mechanical resonator; and

 a sense signal filtering circuit for filtering a signal representative of the mechanical motion of the mechanical resonator to isolate a sense signal from
10 interference due to the drive signal.

5. The apparatus of claim 4 further comprising:

 signal conversion and amplification circuitry for converting an output of the motion detector into a voltage output as the signal representative of the mechanical motion
15 of the mechanical resonator.

6. The apparatus of claim 4 wherein the sense signal filtering circuit comprises at least one of:

 a notch filter having a notch at an expected resonant frequency divided by two;

20 one or more bandpass filters to isolate the sense signal from the interference due to the drive signal; and

 one or more additional high-Q bandpass filters to remove beating components.

7. The apparatus of claim 4 further comprising:

25 a feedback signal processing circuit that processes the sense signal to produce the drive signal;

wherein the sense signal has a frequency shift representative of a magnetic field within which the apparatus is situated.

8. The apparatus of claim 7 wherein the feedback
5 signal processing circuit comprises:

a constant amplitude circuit to make the sense signal have substantially constant amplitude;

a divide by 2 circuit;

a phase adjustment circuit.

10 9. The apparatus of claim 4 further comprising:

an output processing circuit that processes the sense signal to produce an output representative of the magnetic field within which the apparatus is situated.

10. The apparatus of claim 9 wherein the output
15 processing circuit comprises:

a frequency dependent phase shifting circuit that produces a phase shifted output; and

a circuit that determines a phase shift introduced by the phase shifting circuit.

20 11. The apparatus of claim 10 wherein the circuit that determines a phase shift introduced by the phase shifting circuit comprises:

a phase detector.

12. The apparatus of claim 11 further comprising a
25 phase difference to voltage converter, that produces a voltage that represents a value for the magnetic field.

13. The apparatus of claim 1 further comprising a downconverter circuit that downconverts a frequency of the sense signal.

14. The apparatus of claim 10 wherein the phase
5 shifting circuit comprises an all pass filter.

15. The apparatus of any one of claims 4 to 14 wherein the mechanical resonator comprises a resonant micromachined magnetic field sensor.

16. The apparatus of any one of claims 4 to 15 wherein
10 the mechanical resonator is driven by means of electrostatic, optical, thermal, piezoelectric, piezoresistive.

17. The apparatus of any one of claims 4 to 16 wherein the motion detector comprises one of an electrostatic motion
15 detector, optical motion detector, thermal motion detector, piezoelectric motion detector, and piezoresistive motion detector.

18. A method comprising:

placing a mechanical resonator having a resonator
20 output and having an input for receiving a drive signal in an area for which a magnetic field measurement is to be determined;

converting and amplifying the resonator output into an electrical signal output representing a frequency of
25 the resonator output; and

filtering the electrical signal output to isolate a sense signal from an interfering feedthrough signal.

19. The method of claim 18 further comprising:

feeding a version of the sense signal back as the drive signal to form a closed loop.

20. The method of claim 19 further comprising:

performing feedback signal processing upon the
5 sense signal to produce the drive signal.

21. The method of claim 18 further comprising:

processing the sense signal to produce an output representative of the magnetic field.

22. A resonator arrangement comprising:

10 a mechanical resonator having a drive signal and a resonator output at the resonator output having a frequency that is twice a frequency of the drive signal;

a drive signal generation circuit that generates the drive signal for the mechanical resonator from the
15 resonator output.

23. The resonator arrangement of claim 22 wherein the mechanical resonator is a MEMs resonator.

24. The resonator arrangement of claim 23 wherein the
20 drive signal generation circuit comprises:

signal conversion and amplification circuitry for converting the resonator output of the mechanical resonator into a voltage output; and

a sense signal filtering circuit to isolate a
25 sense signal from an interfering feedthrough signal.

25. The resonator arrangement of claim 24 wherein the sense signal filtering circuit comprises at least one of:

a notch filter having a notch at the expected resonant frequency divided by two;

one or more bandpass filters to isolate the sense signal from the interference signal; and

5 one or more additional high-Q bandpass filters to remove beating components.

26. The resonator arrangement of claim 23 wherein the drive signal generation circuit comprises:

a motion detector that detects the mechanical
10 motion of the mechanical resonator; and

a sense signal filtering circuit for filtering a signal representative of the mechanical motion of the mechanical resonator to isolate a sense signal from interference due to the drive signal.

15 27. The resonator arrangement of claim 26 further comprising:

signal conversion and amplification circuitry for converting an output of the motion detector into a voltage output as the signal representative of the mechanical motion
20 of the mechanical resonator.

28. The resonator arrangement of claim 26 wherein the apparatus drive signal generation circuit further comprises:

a feedback signal processing circuit that processes the sense signal to produce the drive signal.

25 29. The resonator arrangement of claim 28 wherein the feedback signal processing circuit comprises:

a constant amplitude circuit to make the sense signal have substantially constant amplitude;

a divide by 2 circuit;

a phase adjustment circuit.

5 30. The apparatus of claim 1 wherein the resonator output has a frequency that is twice a frequency of the drive signal.

31. The apparatus of claim 4 wherein the resonator output has a frequency that is twice a frequency of the
10 drive signal.

32. The method of claim 18 wherein the resonator output has a frequency that is twice a frequency of the drive signal.

Statement Under Article 19(1)

Claims 1 and 18 have been amended to indicate that the voltage output produced by the signal conversion and amplification circuitry represents a frequency of the resonator output. Thus, it is the frequency of the resonator output that is used to determine the sense signal. For embodiments specific to measuring magnetic field, the resonant frequency of the arrangement will change as a function of the magnetic field.

This is a different approach to that of D1. The device of D1 measures magnetic field strength as follows. The lateral displacement of the comb teeth in the presence of a magnetic field causes a different capacitance between each pair of comb teeth. One tooth pair goes up in capacitance (let's call this capacitance C1), and the other goes down (let's call this capacitance C2). They vibrate their comb drive at resonance so that it moves farther, in order to maximize the values of C1 and C2, to give a better measurement. They then measure the magnetic field by measuring the difference between C1 and C2. If no field is present $C1 = C2$.

The claimed sensor operates quite differently. The vibration frequency of the sensor at resonance is determined, and in a magnetic field, the vibration frequency of the sensor changes. In other words, while the sensor by Emmerich and Schofthaler measures magnetic field by measuring the change in the vibration amplitude of the resonator, the claimed sensor measures magnetic field by measuring the change in vibration frequency of the resonator. As such there is a completely different principle of operation from D1 to that being claimed in the subject application.

Claim 22 has been amended to indicate a particular relationship between the resonator output frequency and the frequency of the drive signal. Note that in D1, the output frequency is the same as the drive frequency. New claims 30, 31 and 32 which depend on independent claims 1, 4, 18 respectively recite a similar limitation.

Claims 1, 18 and 22 have been amended; all the other claims are unchanged.

The amendments made to the claims are as follows:

Claim 1. An apparatus for measuring magnetic field comprising:

a mechanical resonator having a resonator output and having an input for receiving a drive signal;

signal conversion and amplification circuitry for converting the resonator output of the mechanical resonator into a voltage output representing a frequency of the resonator output; and

a sense signal filtering circuit to isolate a sense signal from an interfering feedthrough signal.

Claim 18. A method comprising:

placing a mechanical resonator having a resonator output and having an input for receiving a drive signal in an area for which a magnetic field measurement is to be determined;

converting and amplifying the resonator output into an electrical signal output representing a frequency of the resonator output; and

filtering the electrical signal output to isolate a sense signal from an interfering feedthrough signal.

Claim 22. A resonator arrangement comprising:

a mechanical resonator having a drive signal and a resonator output at the resonator output having a frequency that is twice a frequency of the drive signal;

a drive signal generation circuit that generates the drive signal for the mechanical resonator from the resonator output.

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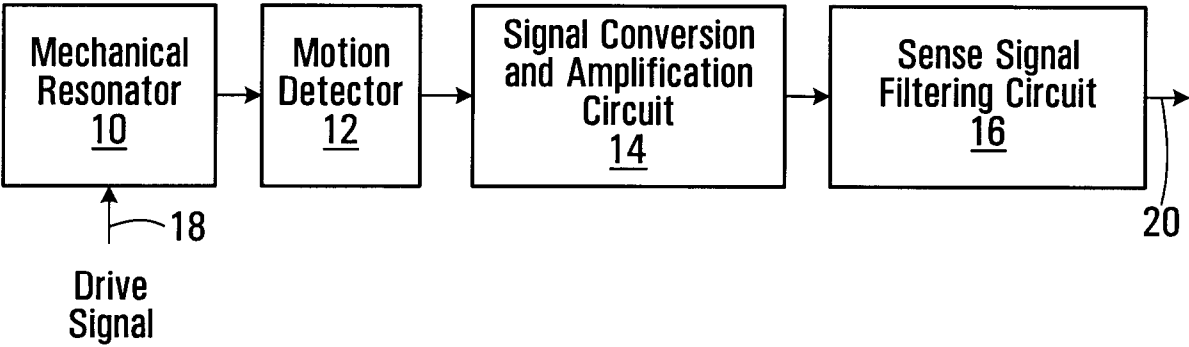


FIG. 1A

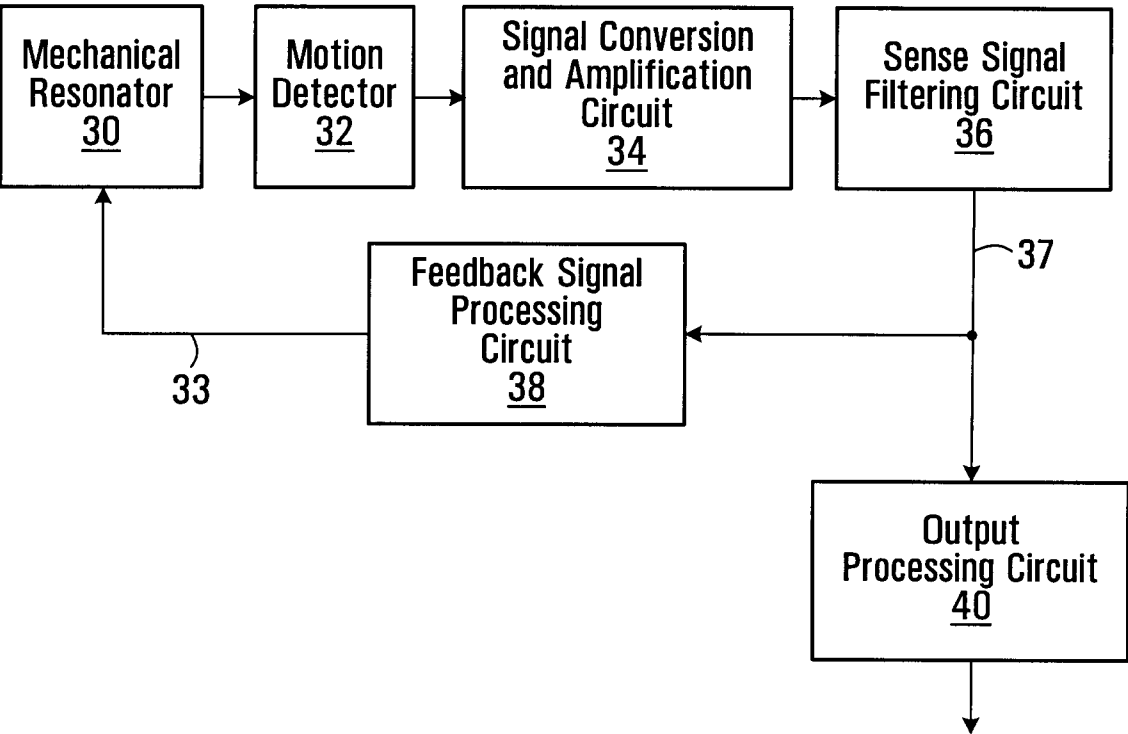


FIG. 1B

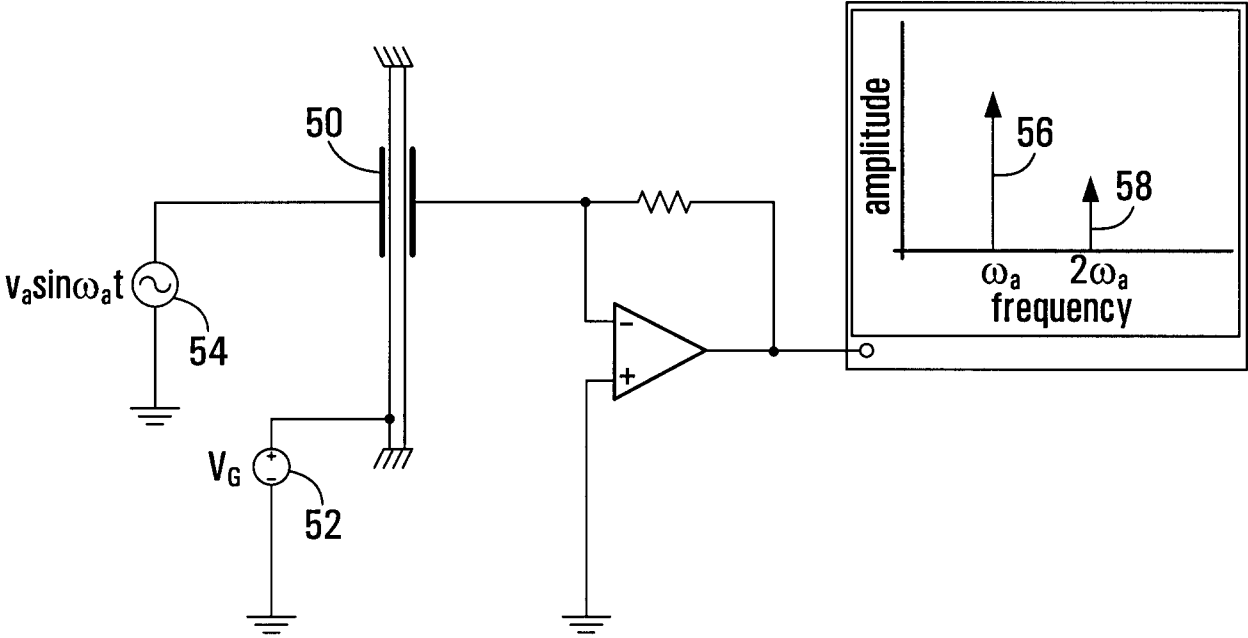


FIG. 2

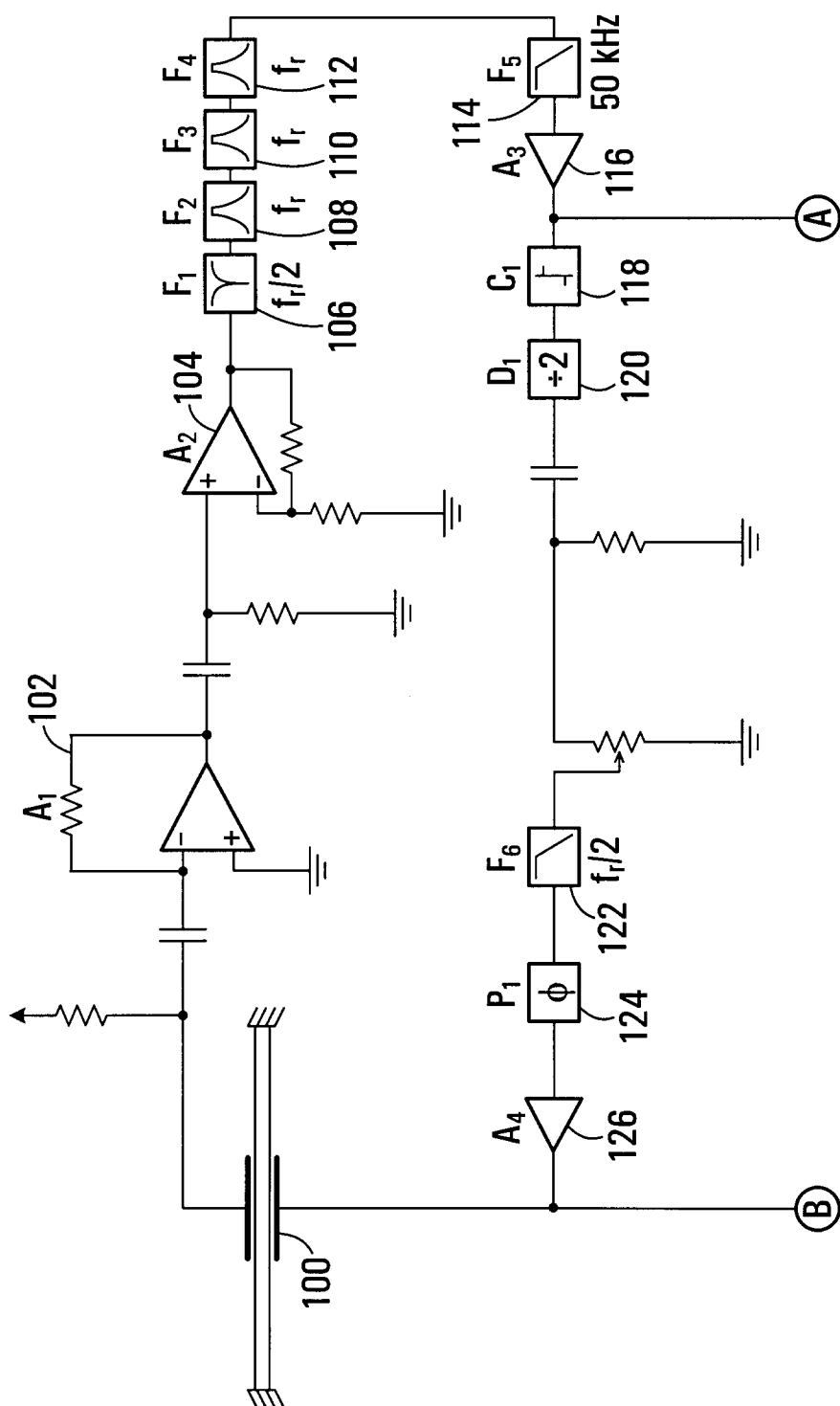
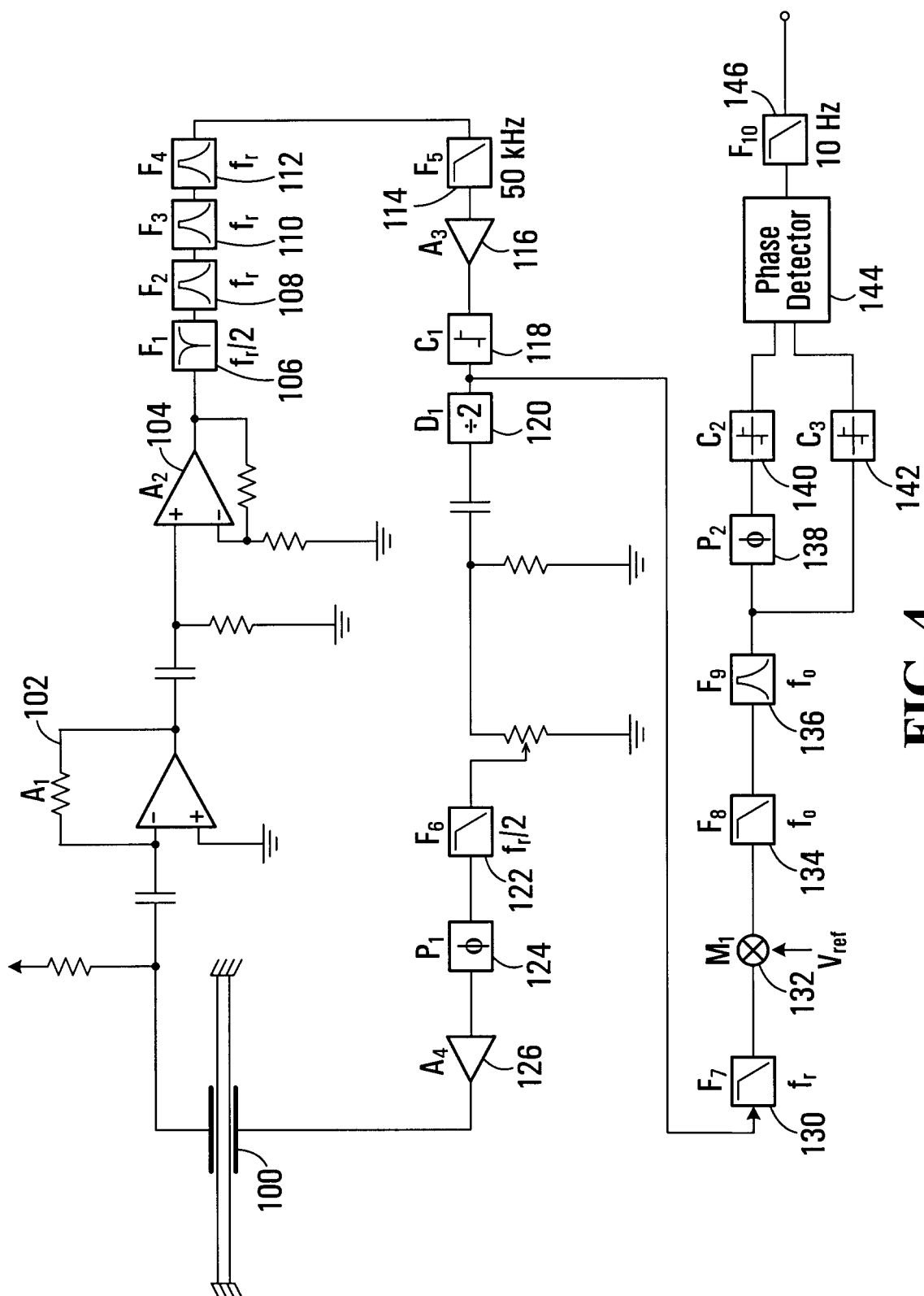
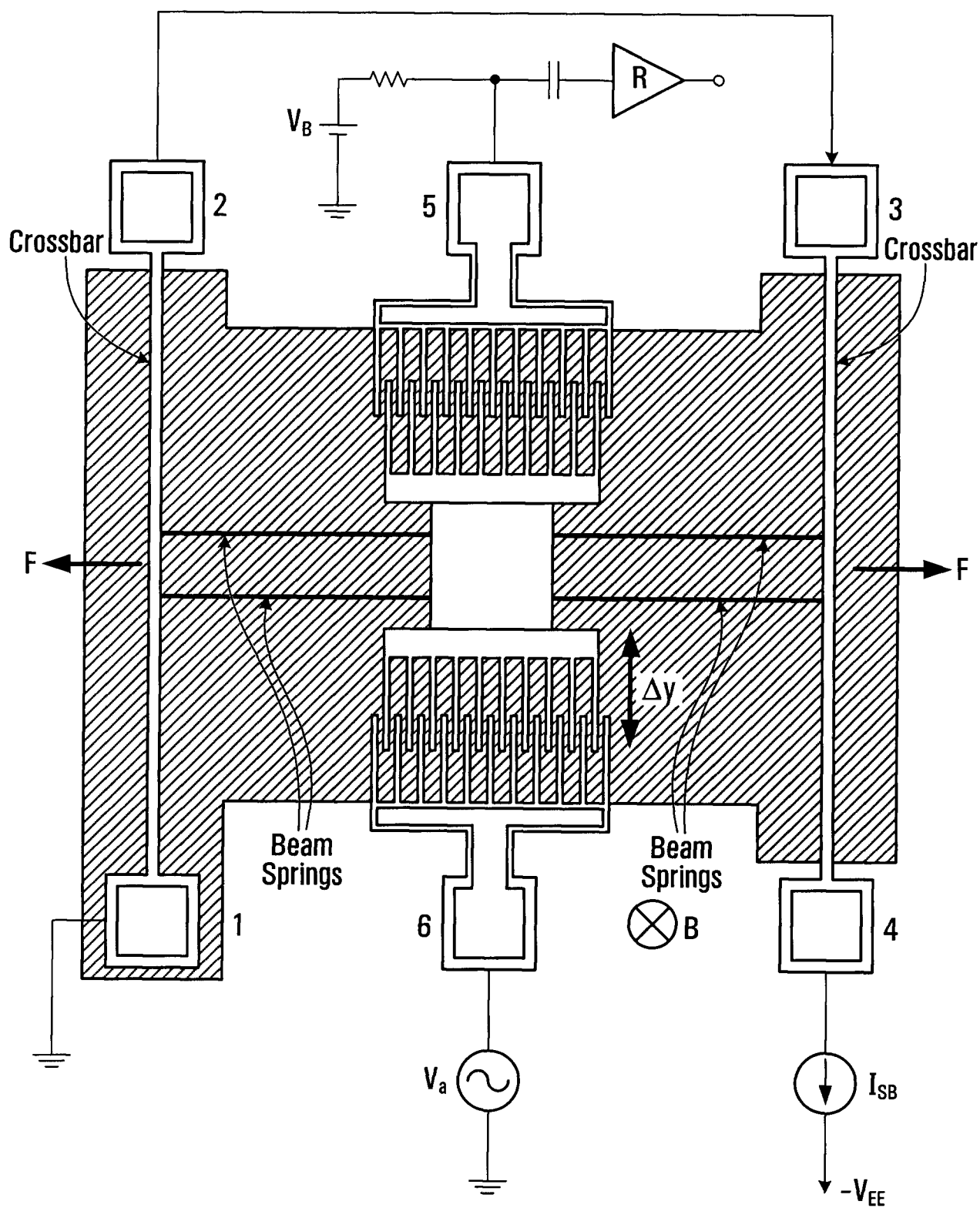


FIG. 3

**FIG. 4**

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**FIG. 5**

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA2006/001780

A. CLASSIFICATION OF SUBJECT MATTER IPC: G01R 33/02 (2006.01) , B81B 3/00 (2006.01) , B81B 7/02 (2006.01) According to International Patent Classification (IPC) or to both national classification and IPC																	
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) G01R 33/02 (2006.01) , B81B 3/00 (2006.01) , B81B 7/02 (2006.01) Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used) Delphion, QWeb, USPTO WEST, IEEE, Canadian Patents Database (Keywords: magnetometer, sensor, filter, resonator, mechanical, processing, feedback, loop, signal, frequency)																	
C. DOCUMENTS CONSIDERED TO BE RELEVANT <table border="1"> <thead> <tr> <th>Category*</th> <th>Citation of document, with indication, where appropriate, of the relevant passages</th> <th>Relevant to claim No.</th> </tr> </thead> <tbody> <tr> <td>X</td> <td>EMMERICH et al.: "Magnetic Field Measurements with a Novel Surface Micromachined Magnetic-Field Sensor", IEEE Transactions on Electron Devices, May 2000; Vol. 47, No. 5, Pages 972-977. * Pages 974-975, Section V*</td> <td>1-29</td> </tr> <tr> <td>A</td> <td>QIAN et al.: "Integrated Driving and Readout Circuits for Orthogonal Fluxgate Sensor", IEEE Transactions on Magnetics, October 2005; Vol. 41, No. 10, Pages 3715-3717. * Whole document *</td> <td>1-29</td> </tr> <tr> <td>A</td> <td>JOSEPHS et al. "Application of Digital Signal Processing to Vibrating Sample Magnetometry", IEEE Transactions on Magnetics, January 1987; Vol. Mag-23, No. 1, Pages 241-244 * Whole document *</td> <td>1-29</td> </tr> <tr> <td>A</td> <td>US 5,959,452 (GIVENS et al.) September 28, 1999 * Whole document *</td> <td>1-29</td> </tr> </tbody> </table>			Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.	X	EMMERICH et al.: "Magnetic Field Measurements with a Novel Surface Micromachined Magnetic-Field Sensor", IEEE Transactions on Electron Devices, May 2000; Vol. 47, No. 5, Pages 972-977. * Pages 974-975, Section V*	1-29	A	QIAN et al.: "Integrated Driving and Readout Circuits for Orthogonal Fluxgate Sensor", IEEE Transactions on Magnetics, October 2005; Vol. 41, No. 10, Pages 3715-3717. * Whole document *	1-29	A	JOSEPHS et al. "Application of Digital Signal Processing to Vibrating Sample Magnetometry", IEEE Transactions on Magnetics, January 1987; Vol. Mag-23, No. 1, Pages 241-244 * Whole document *	1-29	A	US 5,959,452 (GIVENS et al.) September 28, 1999 * Whole document *	1-29
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A	US 5,959,452 (GIVENS et al.) September 28, 1999 * Whole document *	1-29															
☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.																	
<table border="0"> <tr> <td style="vertical-align: top;"> * Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed </td> <td style="vertical-align: top;"> "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family </td> </tr> </table>			* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family													
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family																
Date of the actual completion of the international search 23 January 2007 (23-01-2007)		Date of mailing of the international search report 12 February 2007 (12-02-2007)															
Name and mailing address of the ISA/CA Canadian Intellectual Property Office Place du Portage I, C114 - 1st Floor, Box PCT 50 Victoria Street Gatineau, Quebec K1A 0C9 Facsimile No.: 001-819-953-2476		Authorized officer Hugh Chung 819-934-7568															

INTERNATIONAL SEARCH REPORTInternational application No.
PCT/CA2006/001780**Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of the first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons :

1. ☐ Claim Nos. :
because they relate to subject matter not required to be searched by this Authority, namely :
2. ☐ Claim Nos. :
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically :
3. ☐ Claim Nos. :
because they are dependant claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows :

The examiner considers that the application contains two inventions in the following groups of claims: group A (claims 1-21) and group B (claims 22-29)

The claims in group A are directed to an apparatus and method for magnetic field measurement.

The claims in group B are directed to a resonator arrangement.

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☒ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claim Nos. :
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim Nos. :

Remark on Protest ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CA2006/001780

Patent Document Cited in Search Report	Publication Date	Patent Family Member(s)	Publication Date
US5959452	28-09-1999	NONE	