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CLOSED LOOP MAGNETIC FIELD SENSOR WITH CURRENT CONTROL

Abstract

Method and apparatus for a closed loop CAPS magnetic field sensor having an emitter coil current that corresponds to a distance from a target. An emitter coil drive circuit outputs an emitter current to an emitter coil for generating an emitter field and a reference coil drive circuit outputs a reference current to a reference coil for generating a reference field. The combined fields generate an applied field and a magnetic field sensing element generates an electric signal. The sensor has a closed loop configuration with a feedback path that includes the emitter coil drive circuit and the emitter coil and is configured to modify an amplitude of the emitter current signal based on a distance from the target to the magnetic field sensing element.

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Background/Summary

BACKGROUND

[0001] Magnetic field sensors utilize magnetic field sensing elements to detect one or more magnetic fields. Magnetic field sensors are often used to detect a ferromagnetic or conductive target and may generally act to detect motion or position of the target. Such sensors are found in many technology areas including robotics, automotive, manufacturing and so forth. For example, a magnetic field sensor may be used to detect when a vehicle wheel locks up (stops rotating), which triggered the vehicle's control processor to engage an anti-lock braking system. Magnetic field sensors may also detect distance to an object. As examples, magnetic field sensors may be used to detect the position of a hydraulic piston or angular position of a steering column.

[0002] A 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 half-bridge or full-bridge (Wheatstone) configuration. Depending on the device type and/or other application requirements, a magnetic field sensing element may include, e.g., 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).

[0003] Hall effect elements are one type of magnetic field sensing elements that generate a variable voltage in response to changes in an applied or sensed magnetic field. Magnetoresistance elements are another type of magnetic field sensing element that has a variable resistance that changes in response to changes in an applied or sensed magnetic field. There are different types of magnetoresistance elements, for example, semiconductor magnetoresistance elements such as ones including Indium Antimonide (InSb), anisotropic magnetoresistance (AMR) elements, giant magnetoresistance (GMR) elements, and tunneling magnetoresistance (TMR) elements, which are also referred to as magnetic tunnel junction (MTJ) elements. Some magnetoresistance elements, e.g., GMR and TMR elements, may have a limited linear output range in which a change in sensed magnetic field intensity is linear with respect to a corresponding change in the resistance of the elements.

SUMMARY

[0004] Example embodiments of the disclosure provide methods and apparatus for a coil activated position sensor (CAPS) having current consumption control. In example embodiments, a sensor includes a reference coil and an emitter coil driver, which are in the feedback path of the closed loop sensor. With this arrangement, air gap distance, for example, can correspond to emitter coil current level used for sensing targets.

[0005] In one aspect, a magnetic field sensor comprises: an emitter coil drive circuit for outputting an emitter current to an emitter coil for generating an emitter field; a reference coil drive circuit for outputting a reference current to a reference coil for generating a reference field; a combiner to combine a reflected field generated by a target in response to the emitter field and the reference field and output an applied field; a magnetic field sensing element to receive the applied field and generate an electric signal; an amplifier to amplify the electric signal, wherein an output of the amplifier is coupled to the emitter coil drive circuit; a transconductance module to generate an output current from the electric signal; wherein the sensor comprises a closed loop configuration with a feedback path that includes the emitter coil drive circuit and the emitter coil and is configured to modify an amplitude of the emitter current signal based on a distance from the target to the magnetic field sensing element.

[0006] A sensor can further comprise one or more of the following features: the applied field comprises a signal at carrier frequency, the output signal from the magnetic field sensing element is demodulated to a baseband frequency and input to the amplifier, the distance d is determined as:

[00001]$d = K_{\mathrm{EC}}^{-1}\left(\frac{I_{RC} \text{ .Math. } K_{RC}}{I_O \text{ .Math. } K}\right),$
where Io is the output current from the transconductance module, I.sub.RC is the reference current, TABLE-US-00001 K.sub.EC(d) [G/A] Ratio between the emitting coil current IEC and the reflected magnetic field BR K.sub.FC, K.sub.RC [G/A] Feedback and reference coils sensitivity K [A/A] Transconductances ratio
the emitter current is determined as:
[00002]$I_{\mathrm{EC}} = I_{RC} \text{ .Math. } K_{RC} \cdot \frac{1}{K_{\mathrm{EC}}(d)},$
where I.sub.RC is the reference current, and
TABLE-US-00002 K.sub.EC(d) [G/A] Ratio between the emitting coil current I.sub.EC and the reflected magnetic field BR K.sub.FC, K.sub.RC [G/A] Feedback and reference coils sensitivity
[0007] the magnetic field sensing element comprises a magnetoresistance (MR) element, and/or the magnetic field sensing element comprises a Hall element.
[0008] In another aspect, a method comprises outputting an emitter current to an emitter coil for generating an emitter field; outputting a reference current to a reference coil for generating a reference field; combining a reflected field generated by a target in response to the emitter field and the reference field and output an applied field; receiving the applied field and generating an electric signal by a magnetic field sensing element in a magnetic field sensor; amplifying the electric signal with an amplifier, wherein an output of the amplifier is coupled to an emitter coil drive circuit for generating the emitter current; and generating an output current from the electric signal, wherein the sensor comprises a closed loop configuration with a feedback path that includes the emitter coil drive circuit and the emitter coil and is configured to modify an amplitude of the emitter current signal based on a distance from the target to the magnetic field sensing element.
[0009] A method can further include one or more of the following features: the applied field comprises a signal at carrier frequency, the output signal from the magnetic field sensing element is demodulated to a baseband frequency and input to the amplifier, the distance d is determined as:
[00003]$d = K_{\mathrm{EC}}^{-1}\left(\frac{I_{RC} \text{ .Math. } K_{RC}}{I_O \text{ .Math. } K}\right),$
where Io is the output current from the transconductance module, I.sub.RC is the reference current, TABLE-US-00003 K.sub.EC(d) [G/A] Ratio between the emitting coil current IEC and the reflected magnetic field BR K.sub.FC, K.sub.RC [G/A] Feedback and reference coils sensitivity K [A/A] Transconductances ratio
the emitter current is determined as:
[00004]$I_{\mathrm{EC}} = I_{RC} \text{ .Math. } K_{RC} \text{ .Math. } \frac{1}{K_{\mathrm{EC}}(d)},$
where I.sub.RC is the reference current, and
TABLE-US-00004 K.sub.EC(d) [G/A] Ratio between the emitting coil current I.sub.EC and the reflected magnetic field BR K.sub.FC, K.sub.RC [G/A] Feedback and reference coils sensitivity
the magnetic field sensing element comprises a magnetoresistance (MR) element, and/or the magnetic field sensing element comprises a Hall element.
[0010] In a further aspect, a magnetic field sensor comprises: an emitter coil drive circuit for outputting an emitter current to an emitter coil for generating an emitter field; a reference coil drive circuit for outputting a reference current to a reference coil for generating a reference field; a combiner to combine a reflected field generated by a target in response to the emitter field and the reference field and output an applied field; a magnetic field sensing element to receive the applied field and generate an electric signal; an amplifier to amplify the electric signal, wherein an output of the amplifier is coupled to the emitter coil drive circuit; a transconductance module to generate an output current from the electric signal; and a means for providing a closed loop feedback.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] The foregoing features of this disclosure, as well as the disclosure itself, may be more fully understood from the following description of the drawings in which:

[0012] FIG. **1** is a block diagram of an example magnetic field sensor having for detecting an applied magnetic field;

[0013] FIG. **2** shows an example implementation of the magnetic field sensor of FIG. **1**;

[0014] FIG. **3** is a schematic representation of an open loop magnetic field coil activated position sensor (CAPS);

[0015] FIG. **3**A shows an example distance d from a target to a sensing element on a die;

[0016] FIG. **4** is a schematic representation of a closed loop magnetic field coil activated position sensor (CAPS) in which the target and the reflected magnetic field BR are not part of the loop (BR is the input);

[0017] FIG. **5** is a schematic representation of a closed loop magnetic field coil activated position sensor (CAPS) having emitter coil current that corresponds to air gap distance in which the target and the reflected magnetic field are part of the feedback loop;

[0018] FIG. **6** is a block diagram of a closed loop sensor having feedback shown as a generalization of the sensor of FIG. **5**;

[0019] FIG. **7** is a flow diagram showing an example sequence of steps for controlling emitter coil current based on distance in a closed loop magnetic field coil activated position sensor (CAPS); and

[0020] FIG. **8** is a schematic representation of an example computer that can perform at least a portion of the processing described herein.

DETAILED DESCRIPTION

[0021] Some introductory information is provided prior to describing example embodiments of the disclosure. A sensed magnetic field, referred to herein alternatively as the applied magnetic field, can be from an external magnetic field source or a reflected field and can be amplified and fed back to the magnetic field sensing elements, e.g., MR elements, by a feedback coil such that the magnetic field sensing elements operate in a linear range. The feedback configuration can be a negative feedback configuration, in exemplary embodiments.

[0022] As used herein, the term “magnetic field sensor” is used to describe a circuit that uses one or more magnetic field sensing elements, generally in combination with other circuits. Magnetic field sensors are used in a variety of applications, including, but not limited to, angle sensors that sense an angle of a direction of a magnetic field, current sensors that sense a magnetic field generated by a current carried by a current-carrying conductor, magnetic switches that sense the proximity of a ferromagnetic object, rotation detectors that sense 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 magnetic field sensors that sense a magnetic field density of a magnetic field.

[0023] As used herein, the term “target” is used to describe an object or portion of an object to be sensed or detected by a magnetic field sensor or a magnetic field sensing element such as a magnetoresistance element. The target may include a conductive material that allows for eddy currents to flow within the target.

[0024] FIG. **1** is a block diagram of an example of a magnetic field coil activated position sensor (CAPS) **100**. Magnetic field sensor **100** includes magnetoresistance circuitry **110** that is part of a magnetic closed loop (a.k.a., feedback loop) **140** including feedback circuitry **130** and feedback coil circuitry **136** that generates a feedback magnetic field (B.sub.FB).

[0025] The magnetoresistance circuitry **110** is configured to sense or detect one or more magnetic fields, including a residual magnetic field (a.k.a., a resultant or error magnetic field) resulting from a combination of an external applied (B) or reflected (B.sub.RF) magnetic field, which may be modulated at a first frequency (f.sub.1), and the feedback magnetic field (B.sub.FB). Magnetoresistance elements **110** can have relatively poor signal to offset ratios and, in fact, can have offset levels that are much larger than the maximum signal to be sensed.

[0026] Offset reduction circuitry **120** is responsive to the magnetoresistance circuitry **110** and is configured to reduce undesired baseband components such as components attributable to the magnetoresistance circuitry **110**. Example offset reduction circuitry **120** can take the form of AC coupling circuitry as shown and described in connection with FIG. **2**. The offset reduction circuitry **110** prevents undesired DC signal components from creating high frequency ripple, which would undesirably generate excessive power consumption due to current through the feedback coil and would increase the dynamic residual offset and thus, reduce the dynamic range of the system. Thus, stated differently, the offset reduction circuitry **120** prevents such ripple generation, thus optimizing power consumption, minimizing residual offset and maximizing output dynamic range (i.e., ensuring that the dynamic range of the system is available for processing the useful signal).

[0027] Sensor **100** can also include analog circuitry **122**, e.g., one or more amplifiers, and digital circuitry **126**, e.g., one or more filters, which can be used to process and/or condition the output signals of the offset reduction circuitry **120** to generate a feedback signal **124**. The closed loop **140** is configured to use the feedback signal **124** to generate the feedback magnetic field (B.sub.FB) and supply the feedback magnetic field (B.sub.FB) to the magnetoresistance circuitry **110**. The feedback loop **140** can be an analog closed loop as illustrated by the solid line feedback signal **124** from analog circuitry **122** or a digital closed loop as illustrated by the dotted line feedback signal **124** from the digital circuitry **126**. It will be appreciated by those of ordinary skill in the art that, in the case of a digital feedback circuit, a DAC is provided (as may be part of the feedback circuitry **130**) in order to convert the digital signal back to the analog domain in order to drive the coil.

[0028] Main signal circuitry **160** can process a main signal from the magnetoresistance circuitry **110**, e.g., for measuring a position of a source **1** or target **2**, in order to generate a sensor output signal **170** that can be indicative of the position and/or motion of the source **1** or target **2**.

[0029] The applied magnetic field can be a magnetic field (B) generated by a magnetic field source **1** and/or a reflected magnetic field (B.sub.RF) reflected from a target **2**, e.g., a conductive target. In example embodiments, a target **2** may include, but is not limited to, a portion of a moving metal machine component such as a gear tooth, a camshaft lobe, a magnetic domain on a rotating shaft, or a magnetic domain on a rotating/moving element, etc. For embodiments sensing a reflected magnetic field (B.sub.RF) reflected from a target **2**, the sensed magnetic field can result from a main coil magnetic field (BMC) that is generated by a main coil as part of main coil circuitry **112** that is reflected from the target **2** as the reflected magnetic field (B.sub.RF), with the reflected magnetic field allowing measurement of a parameter associated with the target **2**.

[0030] FIG. **2** shows an example of a closed loop magnetic field sensor **200** for detecting an applied magnetic field (BHF) **222**. The magnetic field sensor **200** includes a magnetic closed loop **220** including magnetoresistance circuitry **226**, feedback circuitry **244**, and a feedback coil **246** configured to generate a feedback magnetic field **250**. The magnetoresistance circuitry **226** is configured to receive or detect a residual magnetic field **225** resulting from a combination of applied magnetic field **222** and feedback magnetic field **250** and produce a corresponding electrical output signal **226***a*, e.g., as a differential output voltage signal. Magnetoresistance circuitry **226** can be driven by a magnetoresistance driver **228**. In example embodiments, the magnetoresistance circuitry **226** can include multiple magnetoresistance elements, e.g., four elements, in a bridge configuration.

[0031] Magnetic field **222** can be generated by a magnetic source **210** including a target **212** and a main coil **214** and driver **216**. In this configuration, the applied field **222** can be a reflected magnetic field (B.sub.RF) reflected from a conductive target **212**. In example embodiments, target **212** may include, but is not limited to, a portion of a moving metal machine component such as a gear tooth, a camshaft lobe, a magnetic domain on a rotating shaft, or a magnetic domain on a rotating/moving element, etc. For embodiments sensing a reflected magnetic field (B.sub.RF) reflected from a target **212**, the sensed magnetic field can result from a main coil magnetic field (BMC) that is generated by the main coil **214** driven by driver **216** and that is then directed to and reflected from the target **212** as the reflected magnetic field (B.sub.RF), with the reflected magnetic field allowing measurement of a position of the target. In such embodiments, the applied magnetic field **222** can include a signal having a relatively high frequency f.sub.1 that is indicative of a useful signal of interest for processing by a main signal path **260** to generate an output signal **274** of the sensor **200**.

[0032] In example embodiments, the feedback magnetic field **250** can be combined with the applied magnetic field **222** in a negative feedback configuration (as indicated by negative sign at **224**) to form a residual magnetic field **225** that is near zero, e.g., in the linear operational range of the magnetoresistance circuitry **226**. For example, by having opposite polarities, the applied magnetic field **222** and the feedback magnetic field **250** may sum to near zero. In alternate embodiments, the feedback magnetic field **250** can be combined with the applied magnetic field **222** in a negative feedback configuration with a large open loop gain, e.g., such that the residual magnetic field **225** is near zero. It is understood that this feedback is always negative.

[0033] Applied magnetic field **222** and feedback magnetic field **250** are indicated as being combined by sum unit **224**, however an electronic sum unit **224** is not necessary for combination of the magnetic fields **222**, **250** as they may be combined (e.g., be superposed) in any medium or in free space. For example, placement and/or geometry of sensing elements of magnetoresistance circuitry **226** with respect to the magnetic source **210** and feedback coil **246** can result in generation of the residual magnetic field **225** as the difference between the applied magnetic field **222** and the feedback magnetic field **250**. As shown, when the fields are combined, feedback magnetic field **250** can be subtracted from applied magnetic field **222** to result in residual magnetic field **225**.

[0034] The feedback magnetic field **250** generated by the feedback coil **246** can accordingly be used, in example embodiments, to reduce or attenuate the residual magnetic field such that the magnetoresistance circuitry **226** is operational in a linear region of the transfer function curve of the magnetoresistance elements. In example embodiments, the feedback magnetic field **250** can include a scaled replica of the applied magnetic field **222**. Use of the feedback magnetic field **250** can accordingly allow the magnetoresistance circuitry **226** to be used in a linear range of operation and mitigate negative effects arising from undesirable signal components, for example, stray magnetic fields or by temperature or mechanical stresses that may be included in the applied magnetic field **222**. The closed magnetic loop **220** can include one or more amplifiers **236** to provide a desired loop gain, without relying on the sensitivity or gain of the magnetoresistance circuitry **226**.

[0035] Output signal **226***a* of the MR elements **226** can contain high frequency components of interest (i.e., components corresponding to the useful signal to be sensed) at the first frequency f.sub.1 and undesirable offset components at baseband as may be attributable to offset of the MR elements **226**.

[0036] Offset reduction circuitry **230** configured to reduce the undesired baseband components includes series coupled capacitors, as shown. Capacitors **230** block the undesired baseband components due to offset to thereby generate a signal **230***a* having little or no undesired baseband components.

[0037] A modulator **232** is coupled to the capacitors **230** and is configured to shift the frequency of the received signal so that an output signal **232***a* of the modulator **232** includes a baseband portion indicative of a useful signal of interest (referred to herein as a main signal portion) and any undesirable offset component at frequency f.sub.1.

[0038] Amplifier **236** is coupled to receive the modulator output signal **232***a* and to amplify the signal in order to generate a superimposed signal **236***a* containing a main signal portion of interest at DC and an offset reduced signal portion (i.e., any remaining undesirable offset components) at frequency f.sub.1. The superimposed signal **236***a* can be provided to feedback circuitry to drive feedback coil **246** and generate the feedback magnetic field **250**. For example, the superimposed signal **236***a* can be filtered by a filter **242** and converted from a voltage to a current by a transconductance amplifier **244**. Ideally, any undesirable offset components are significantly attenuated by the capacitors **230** and so that the superimposed signal **236***a* at the output of amplifier **236** contains only the main signal of interest at baseband and little to no high frequency components representing offset components; however, in the event that such high frequency undesirable offset components remain in signal **236***a*, they can be removed by low pass filter **242** for example.

[0039] A second modulator **245** can be coupled to receive the output current signal from the transconductance amplifier **244** and generate a feedback signal Ifb for coupling to the coil driver **248**. Feedback coil driver **248** can generate the drive signal for the feedback coil **246** to generate the feedback magnetic field **250** based on the feedback signal.

[0040] It will be appreciated by those of ordinary skill in the art that although the magnetic feedback loop **220** shown in the embodiment of FIG. **2** is analog (i.e., the superimposed signal is analog and conversion to the digital domain is performed by ADC **238** for digital processing by the main signal path **260**), in other embodiments the closed loop **220** can include digital signals and components (e.g., as illustrated by the dotted line in FIG. **1**).

[0041] The superimposed signal **236***a* can also be provided to main signal path **260** for extracting the main signal component and producing an output signal **274** of the magnetic field sensor **200**. The signal **236***a* may be provided to an analog-to-digital converter **238** to convert the signal **236***a* from an analog signal to a digital signal. One or more filters, e.g., cascaded integrator-comb (CIC) filter **240** and/or digital filter **262**, may be included for filtering, as low pass filters to remove high frequency components.

[0042] Main signal path **260** can include a temperature correction circuit **264**, a temperature sensor **266**, a programming and memory circuit **268**, a bandwidth selection block **265**, and a segmented linearization block **270**, providing main signal output **274**. Temperature correction block **264** may scale the output voltage signal according to temperature, e.g., a temperature measured by the temperature sensor **266**. Main signal path **260** can provide main signal output **274**, which in example embodiments may be indicative of an angle or position or other parameter such as speed associated with the target **212**.

[0043] FIG. **3** shows a high level schematic representation of an open loop CAPS sensor **300** for sensing a target **302** distance d using a field B.sub.EC emitted by an emitting coil **304** controlled by a coil driver **306** that outputs a coil current I.sub.EC. A field BR reflected by the target **302** is sensed by magnetic field sensing element(s) (MFSE) **308** having a given sensitivity S.sub.T. An output voltage V.sub.TMR is combined with a clock signal ModCk and input to an amplifier **310** which generates an output voltage Vo that corresponds to the strength of field B.sub.R. In embodiments, as shown in FIG. **3**A, distance d can be defined as the distance from a surface of the target **302** closest to the MFSE **308** on a die **320** that can provide circuitry in addition to MFSE. In the illustrated embodiment, circuitry, such as amplifier **310** and MFSE **308**, are shown in one section and magnetics, such as emitting coil **304** and target **302**, are shown in a different section for ease of understanding. In example embodiments, a sensor IC package will be positioned in relation to the target.

[0044] The signal of interest (at base band) is modulated at the carrier frequency f.sub.c to generate eddy currents in the target **302**. The relationship of the different system parameters can be represented in Equation (1) as follows:

[00005] $V_O = I_{\mathrm{EC}}$ .Math. $K_{\mathrm{EC}}(d)$ .Math. S_T .Math. A (1) where $K_{\mathrm{EC}} = B_R / I_{\mathrm{EC}}$

[0045] Example parameters used in one or more of the equations used herein are set forth in the below table.

TABLE-US-00005 Parameter Magnitude Description B.sub.R [1] [G] Reflected magnetic field B.sub.EC[2] [G] Emitted by the emitting coil magnetic field B.sub.FC[1] [G] Feedback magnetic field B.sub.e[1] [G] Error magnetic field for the closed loop architectures. B.sub.REF[.sup.1] [G] Reference magnetic field for the proposed architecture B.sub.N[1] [G] Input equivalent noise I.sub.EC [A] Emitting coil current K.sub.EC(d) [G/A] Ratio between the emitting coil current IEC and the reflected magnetic field BR S.sub.T [V/G] MFSE sensitivity A [V/V] Amplifier gain I.sub.ΣΔ, [A] Input to sigma delta modulator current V.sub.O [V] Amplifier output voltage K.sub.FC, K.sub.RC [G/A] Feedback and reference coils sensitivity K [A/A] Transconductances ratio ModCk — Clock used to modulate/demodulate the signal of interest (1) - These magnetic fields are located at the MFSE. (2) - This magnetic field is located at the emitting coil.
[0046] It should be noted that the sensitivity of the magnetic field sensing element S.sub.T can have variations due different effects.
[0047] In other embodiments, a second MSFE, or more, is used to normalize the output and make Equation 1 independent on the sensitivity S.sub.T. However, variations due to different effects in this parameter can still have a significant impact in the measure. For example, TMR elements have relatively large amounts of variation in resistance values.
[0048] FIG. **4** shows an example sensor **400** that addresses such effects in the variations of MFSE **308** sensitivity and implements a closed loop architecture with the MFSE are in the forward path, where like reference numbers indicated like elements in FIG. **3**. With a large enough open loop gain, the sensor sensitivity becomes independent on S.sub.T. To close the loop, an auxiliary coil (feedback coil) **404** generates an equal in amplitude field B.sub.FC but opposite in direction field to reflected magnetic field B.sub.R. Thus, the loop is closed at the magnetic field level. A feedback coil driver **402** drives the feedback coil **404** with a drive signal combined with clock signal ModCk. The feedback coil field B.sub.FC is summed with the reflected magnetic field B.sub.R the output Be of which is sensed by the sensing element **308**. As can be seen, the feedback coil driver **402** and the feedback coil **404** are in the feedback path.
[0049] Equation 2 below shows that the system sensitivity has no dependence on S.sub.T. The output current Io corresponds to target distance, and more particularly, the emitting coil current I.sub.EC and the ratio between the emitting coil current I.sub.EC and the reflected magnetic field B.sub.R. It should be noted that feedback coil sensitivity K.sub.FC has no variation issues because it only depends on the geometry.
[00006]

$$I_O = I_{\mathrm{EC}} \text{ .Math. } K_{\mathrm{EC}}(d) \text{ .Math. } \frac{1}{K_{\mathrm{FC}} \text{ .Math. } K} \overset{\text{If}}{=} > (S_T \text{ .Math. } A \text{ .Math. } G_m \text{ .Math. } K_{\mathrm{FC}} >> 1) \quad (2)$$

[0050] It is understood that (S.sub.T. A. G.sub.m. K.sub.FC) refers to the open loop gain. The above expression is accurate if the open loop gain is much greater than 1.
[0051] Another parameter for sensor performance is the signal to noise ratio (SNR). Equation 3 shows parameters for the system shown in FIG. **4**. In this equation B.sub.N is the whole system input equivalent noise. As K.sub.EC (d) depends on target distance, the SNR depends on it too. SNR decreases as distance increases.
[00007] $SNR = \frac{B_{\mathrm{REF}}}{B_N} = \frac{K_{\mathrm{EC}}(d) \text{ .Math. } I_{\mathrm{EC}}}{B_N} \quad (3)$
[0052] As defined above B.sub.N is the input equivalent noise.
[0053] One of the issues that conventional sensors configurations present is that the amplitude of the emitting coil current I.sub.EC delivered to the emitting coil is constant. When the distance d between the sensor die and the target is large, a large current amplitude is necessary. However, when the distance is short, the current amplitude can be smaller. For example, an emitter coil current may be a 1 MHz square wave at 8 mA, which may generate a relatively large reflected field B.sub.R when the target is closed to the sensor IC package.
[0054] In example embodiments of the disclosure, the dynamic adaptability of a closed loop sensor

configuration is used to set an emitting coil current amplitude that corresponds to the distance between the die and the target.

[0055] FIG. **5** shows an example closed loop sensor **500** having an emitting coil **502** and a target **504** that are part of the feedback loop. To be able to set the operating point of the loop, a reference magnetic field B.sub.REF is generated by a reference coil **510** driven by a reference coil driver circuit **512** which generates a reference coil current I.sub.RC. This reference can be injected in the loop using a coil like the one used to implement the feedback loop in FIG. **4** but now used as the input to the system. The reference field B.sub.REF and the reflected field B.sub.R are summed **507** to generate an output Be that can be applied to the sensing element **508**. The voltage output V.sub.TMR from the sensing element(s) **508** and be combined with clock signal ModCk and input to amplifier **511** to generate the output voltage Vo. A transconductance circuit **513** receives the output voltage Vo and generates an output current Io based on transconductance G.sub.m and transconductances ratio K. The output voltage Vo is feed back to the emitter coil driver **515**, which has transconductance G.sub.m. The emitter coil driver **515** drives the emitter coil **502** with emitter coil current I.sub.EC to generate a reflected field B.sub.R from the target **504**.

[0056] In the illustrated embodiment, the target is external to the IC package. It is understood that in other embodiments some components, such as a coil, can be external to the IC package.

[0057] In this way, the applied magnetic field (BE) to the MFSE **508** can be considered as very small, because of the large open loop gain. Thus, the MFSE **508** works without applied magnetic field.

[0058] Equation 4 shows the relationship between the output current Io and the distance d to be measured.

[00008]

$$I_o = I_{RC} \text{ .Math. } K_{RC} \text{ .Math. } \frac{1}{K_{EC}(d) \text{ .Math. } K} \overset{\text{If}}{=} > (S_T \text{ .Math. } A \text{ .Math. } G_m \text{ .Math. } K_{EC}(d) >> 1) \quad (4)$$

[0059] To calculate the distance, an inverse function can be used, such as that shown in Equation 5.

[00009] $d = K_{EC}^{-1}\left(\frac{I_{RC} \text{ .Math. } K_{RC}}{I_O \text{ .Math. } K}\right) \quad (5)$

[0060] Equation 6 shows the relationship between the distance d and the emitting coil current. As the function K.sub.EC decreases when d increases, the larger the distance d, the lower the value of K.sub.EC and the larger I.sub.EC.

[00010] $I_{EC} = I_{RC} \text{ .Math. } K_{RC} \text{ .Math. } \frac{1}{K_{EC}(d)} \quad (6)$

[0061] In addition, the SNR is independent of the distance d as the input magnetic field amplitude is defined by the reference coil **512**. Equation 7 shows an example expression for this parameter. As noted, it does not depend on the distance.

[00011] $SNR = \frac{B_{REF}}{B_N} = \frac{K_{RC} \text{ .Math. } I_{RC}}{B_N} \quad (7)$

[0062] While example embodiments of the disclosure are shown and described in conjunction with a CAPS sensor, it is understood that embodiments of the disclosure are applicable to any sensor functionality that can be generalized to a function f that depends on a variable (x in this case) that is to be measured.

[0063] It is understood that any suitable magnetic field sensing element, such as Hall and MR elements can be used. While a voltage output from a sensing element may be designated as V.sub.TMR indicated a TMR sensing element for an example embodiment, a wide range of sensing element types can be used.

[0064] FIG. **6** shows a function f(x) for the ratio between the current IFB to be managed and a variable X.sub.FB used to feedback a closed loop architecture in accordance with Equation 8. It is understood that the variable X; can comprise a voltage, current, magnetic field, and the like

[00012] $\frac{X_{FB}}{I_{FB}} = f(x) \quad (8)$

[0065] Equation 9 shows the ratio between the reference X.sub.REF and the output of the closed loop amplifier X.sub.0.

[00013] $\frac{X_0}{X_{REF}} \overset{A\ \text{.Math.}\ f(x)\ \text{.Math.}\ \gg 1}{=} \frac{1}{f(x)\ \text{.Math.}}$ (9)

[0066] Equation 10 shows that the value of IFB can be defined by the reference X.sub.REF and the function f(x) that depends on the variable to measured x. Then, given a value of X.sub.REF, the larger f(x) the shorter the feedback current IFB and vice versa.

[00014] $I_{FB} = \frac{X_{REF}}{f(x)}$ (10)

[0067] The Equation 11 shows how the variable to be calculated x can be obtained.

[00015] $x = f^{-1}\left(\frac{X_{FEF}}{X_0\ \text{.Math.}}\right)$ (11)

[0068] The SNR is presented below in the Equation 12.

[00016] $SNR = \frac{X_{REF}}{X_N} = \frac{f(x)\ \text{.Math.}\ I_{FC}}{X_N}$ (12)

[0069] FIG. **7** shows an example sequence of steps for closed loop CAPS having emitter coil current that corresponds to a distance (d) between a die/sensing element and a conductive target. In step **700**, an emitting coil driver generates an emitter current signal to an emitter coil. In step **702**, a target generates a reflected field B.sub.R in response to the field from the emitter coil. In step **704**, a reference coil driver generates a reference current signal to a reference coil which generate a reference field B.sub.REF, which in step **706**, can be summed with the reflected field to generate field Be applied to a magnetic field sensing element in step **708**. In step **710**, The output of the MFSE is amplified to generate an output voltage for a transconductance module that generates an output current in step **712**. In step **714**, the output voltage is fed back to the emitter coil driver to form a closed loop feedback path with the emitter coil.

[0070] Example embodiments of the disclosure provide closed loop sensors that allow measurement of the distance (d) between a die and a conductive target instead. A magnetic field generates eddy currents in the target that reflects a magnetic field back to the die. A reflected magnetic field (B.sub.R) is detected by magnetic field sensing elements with a certain sensitivity S.sub.T, and then amplified. An emitting coil and the target are in the feedback loop to control a current to the emitting coil based on a distance to the target. With this arrangement, lower current levels can be used for closer targets.

[0071] Example CAPS implementations are shown and described in U.S. Pat. Nos. 10,996,289; 10,917,092; 11,624,791, each of which is incorporated herein by reference.

[0072] FIG. **8** shows an exemplary computer **800** that can perform at least part of the processing described herein. For example, the computer **800** can perform processing to control the emitter current. The computer **800** includes a processor **802**, a volatile memory **804**, a non-volatile memory **806** (e.g., hard disk), an output device **807** and a graphical user interface (GUI) **808** (e.g., a mouse, a keyboard, a display, for example). The non-volatile memory **806** stores computer instructions **812**, an operating system **816** and data **818**. In one example, the computer instructions **812** are executed by the processor **802** out of volatile memory **804**. In one embodiment, an article **820** comprises non-transitory computer-readable instructions.

[0073] Processing may be implemented in hardware, software, or a combination of the two. Processing may be implemented in computer programs executed on programmable computers/machines that each includes a processor, a storage medium or other article of manufacture that is readable by the processor (including volatile and non-volatile memory and/or storage elements), at least one input device, and one or more output devices. Program code may be applied to data entered using an input device to perform processing and to generate output information.

[0074] The system can perform processing, at least in part, via a computer program product, (e.g., in a machine-readable storage device), for execution by, or to control the operation of, data processing apparatus (e.g., a programmable processor, a computer, or multiple computers). Each such program may be implemented in a high-level procedural or object-oriented programming language to communicate with a computer system. However, the programs may be implemented in assembly or machine language. The language may be a compiled or an interpreted language and it may be deployed in any form, including as a stand-alone program or as a module, component, subroutine, or other unit suitable for use in a computing environment. A computer program may be deployed to be executed on one computer or on multiple computers at one site or distributed across multiple sites and interconnected by a communication network. A computer program may be stored on a storage medium or device (e.g., RAM/ROM, CD-ROM, hard disk, or magnetic diskette) that is readable by a general or special purpose programmable computer for configuring and operating the computer when the storage medium or device is read by the computer.

[0075] Processing may also be implemented as a machine-readable storage medium, configured with a computer program, where upon execution, instructions in the computer program cause the computer to operate.

[0076] Processing may be performed by one or more programmable processors executing one or more computer programs to perform the functions of the system. All or part of the system may be implemented as special purpose logic circuitry (e.g., an FPGA (field programmable gate array), a general purpose graphical processing units (GPGPU), and/or an ASIC (application-specific integrated circuit)).

[0077] Various embodiments of the concepts, systems, devices, structures, and techniques sought to be protected are described above with reference to the related drawings. Alternative embodiments can be devised without departing from the scope of the concepts, systems, devices, structures, and techniques described. For example, while reference is made above to use of magnetoresistance elements, other types of magnetic field sensing elements may be used within the scope of the present disclosure. Furthermore, implementations of the described techniques may include hardware, a method or process, or computer software on a computer-accessible medium. A system of one or more computers can be configured to perform particular operations or actions by virtue of having software, firmware, hardware, or a combination of them installed on the system that in operation causes or cause the system to perform the actions. One or more computer programs can be configured to perform particular operations or actions by virtue of including instructions that, when executed by data processing apparatus, cause the apparatus to perform the actions.

[0078] It is noted that various connections and positional relationships (e.g., over, below, adjacent, etc.) may be used to describe elements in the description and drawing. These connections and/or positional relationships, unless specified otherwise, can be direct or indirect, and the described concepts, systems, devices, structures, and techniques are not intended to be limiting in this respect. Accordingly, a coupling of entities can refer to either a direct or an indirect coupling, and a positional relationship between entities can be a direct or indirect positional relationship.

[0079] Also, the following definitions and abbreviations are to be used for the interpretation of the claims and the specification. The terms “comprise,” “comprises,” “comprising, “include,” “includes,” “including,” “has,” “having,” “contains” or “containing,” or any other variation are intended to cover a non-exclusive inclusion. For example, an apparatus, a method, a composition, a mixture, or an article, that includes a list of elements is not necessarily limited to only those elements but can include other elements not expressly listed or inherent to such apparatus, method, composition, mixture, or article.

[0080] Additionally, the term “exemplary” means “serving as an example, instance, or illustration. Any embodiment or design described as “exemplary” is not necessarily to be construed as preferred or advantageous over other embodiments or designs. The terms “one or more” and “at least one” indicate any integer number greater than or equal to one, i.e., one, two, three, four, etc. The term “plurality” indicates any integer number greater than one. The term “connection” can include an indirect “connection” and a direct “connection”.

[0081] References in the specification to "embodiments," "one embodiment, "an embodiment," "an example embodiment," "an example," "an instance," "an aspect," etc., indicate that the embodiment described can include a particular feature, structure, or characteristic, but every embodiment may or may not include the particular feature, structure, or characteristic. Moreover, such phrases are not necessarily referring to the same embodiment. Further, when a particular feature, structure, or characteristic is described in connection with an embodiment, it may affect such feature, structure, or characteristic in other embodiments whether explicitly described or not.
[0082] Use of ordinal terms such as "first," "second," "third," etc., in the claims to modify a claim element does not by itself connote any priority, precedence, or order of one claim element over another, or a temporal order in which acts of a method are performed, but are used merely as labels to distinguish one claim element having a certain name from another element having a same name (but for use of the ordinal term) to distinguish the claim elements.
[0083] The disclosed subject matter is not limited in its application to the details of construction and to the arrangements of the components set forth in the following description or illustrated in the drawings. The disclosed subject matter is capable of other embodiments and of being practiced and carried out in various ways.
[0084] Also, the phraseology and terminology used in this patent are for the purpose of description and should not be regarded as limiting. As such, the conception upon which this disclosure is based may readily be utilized as a basis for the designing of other structures, methods, and systems for carrying out the several purposes of the disclosed subject matter. Therefore, the claims should be regarded as including such equivalent constructions as far as they do not depart from the spirit and scope of the disclosed subject matter.
[0085] Although the disclosed subject matter has been described and illustrated in the foregoing exemplary embodiments, the present disclosure has been made only by way of example. Thus, numerous changes in the details of implementation of the disclosed subject matter may be made without departing from the spirit and scope of the disclosed subject matter.
[0086] Accordingly, the scope of this patent should not be limited to the described implementations but rather should be limited only by the spirit and scope of the following claims. All publications and references cited in this patent are expressly incorporated by reference in their entirety.

Claims

1. A magnetic field sensor, comprising: an emitter coil drive circuit for outputting an emitter current to an emitter coil for generating an emitter field; a reference coil drive circuit for outputting a reference current to a reference coil for generating a reference field; a combiner to combine a reflected field generated by a target in response to the emitter field and the reference field and output an applied field; a magnetic field sensing element to receive the applied field and generate an electric signal; an amplifier to amplify the electric signal, wherein an output of the amplifier is coupled to the emitter coil drive circuit; a transconductance module to generate an output current from the electric signal; wherein the sensor comprises a closed loop configuration with a feedback path that includes the emitter coil drive circuit and the emitter coil and is configured to modify an amplitude of the emitter current signal based on a distance from the target to the magnetic field sensing element.
2. The sensor according to claim 1, wherein the applied field comprises a signal at carrier frequency.
3. The sensor according to claim 1, wherein the output signal from the magnetic field sensing element is demodulated to a baseband frequency and input to the amplifier.
4. The sensor according to claim 1, wherein the distance d is determined as $d = K_{\mathrm{EC}}^{-1}\left(\frac{I_{\mathrm{RC}}\ .\mathrm{Math.}\ K_{\mathrm{RC}}}{I_{O}\ .\mathrm{Math.}\ K}\right)$ where Io is the output current from the transconductance module, I.sub.RC is the reference current

TABLE-US-00006 K.sub.EC(d) [G/A] Ratio between the emitting coil current IEC and the reflected magnetic field BR K.sub.FC, K.sub.RC [G/A] Feedback and reference coils sensitivity K [A/A] Transconductances ratio.

5. The sensor according to claim 1, wherein the emitter current is determined as: $I_{EC} = I_{RC}$ .Math. K_{RC} .Math. $\frac{1}{K_{EC}(d)}$ where I.sub.RC is the reference current, and TABLE-US-00007 K.sub.EC(d) [G/A] Ratio between the emitting coil current I.sub.EC and the reflected magnetic field BR K.sub.FC, K.sub.RC [G/A] Feedback and reference coils sensitivity.

6. The sensor according to claim 1, wherein the magnetic field sensing element comprises a magnetoresistance (MR) element.

7. The sensor according to claim 1, wherein the magnetic field sensing element comprises a Hall element.

8. A method, comprising: outputting an emitter current to an emitter coil for generating an emitter field; outputting a reference current to a reference coil for generating a reference field; combining a reflected field generated by a target in response to the emitter field and the reference field and output an applied field; receiving the applied field and generating an electric signal by a magnetic field sensing element in a magnetic field sensor; amplifying the electric signal with an amplifier, wherein an output of the amplifier is coupled to an emitter coil drive circuit for generating the emitter current; and generating an output current from the electric signal; wherein the sensor comprises a closed loop configuration with a feedback path that includes the emitter coil drive circuit and the emitter coil and is configured to modify an amplitude of the emitter current signal based on a distance from the target to the magnetic field sensing element.

9. The method according to claim 8, wherein the applied field comprises a signal at carrier frequency.

10. The method according to claim 8, wherein the output signal from the magnetic field sensing element is demodulated to a baseband frequency and input to the amplifier.

11. The method according to claim 1, wherein the distance d is determined as $d = K_{EC}^{-1}\left(\frac{I_{RC} \text{ .Math. } K_{RC}}{I_O \text{ .Math. } K}\right)$ where Io is the output current from the transconductance module, I.sub.RC is the reference current, TABLE-US-00008 K.sub.EC(d) [G/A] Ratio between the emitting coil current IEC and the reflected magnetic field BR K.sub.FC, K.sub.RC [G/A] Feedback and reference coils sensitivity K [A/A] Transconductances ratio.

12. The method according to claim 1, wherein the emitter current is determined as: $I_{EC} = I_{RC}$ .Math. K_{RC} .Math. $\frac{1}{K_{EC}(d)}$ where I.sub.RC is the reference current, and TABLE-US-00009 K.sub.EC(d) [G/A] Ratio between the emitting coil current I.sub.EC and the reflected magnetic field BR K.sub.FC, K.sub.RC [G/A] Feedback and reference coils sensitivity.

13. The method according to claim 8, wherein the magnetic field sensing element comprises a magnetoresistance (MR) element.

14. The method according to claim 1, wherein the magnetic field sensing element comprises a Hall element.

15. A magnetic field sensor, comprising: an emitter coil drive circuit for outputting an emitter current to an emitter coil for generating an emitter field; a reference coil drive circuit for outputting a reference current to a reference coil for generating a reference field; a combiner to combine a reflected field generated by a target in response to the emitter field and the reference field and output an applied field; a magnetic field sensing element to receive the applied field and generate an electric signal; an amplifier to amplify the electric signal, wherein an output of the amplifier is coupled to the emitter coil drive circuit; a transconductance module to generate an output current from the electric signal; and a means for providing a closed loop feedback.