A Novel Method for Integrated Magnetometer and Gradiometer Fluxgate Sensor Fabrication and Application of Fluxgate Gradiometer in Fine Magnetic Particles Detection

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https://doi.org/10.15017/1785428

出版情報：九州大学, 2016, 博士（学術）, 課程博士
バージョン：

（様式３）Form 3

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(マグネトメータを組み込んだフラックスゲートグラディオメータおよびフラックスゲートグラディオメータによる高感度微小異物検出)

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論　文　内　容　の　要　旨

Thesis Summary

Many advances have been witnessed in the applications related to the field of fine magnetic particle detection using different types of sensitive magnetic sensors in the last decades. Examples such fine magnetic particle detection applications are magnetic nano-particle (MNP) detection and metallic contaminant detection in food production and lithium ion battery manufacturing industry. The principle idea is based on using highly sensitive sensors, such as SQUID, magnetoresistive sensor and fluxgates, for measuring small spatial magnetic field gradient (in order of hundreds of pico-Tesla per meter) emitted from the tiny point-like sources. Detection of such fine magnetic particles is still challenging as these tiny magnetic fields gradients are contaminated with environmental magnetic field interferences. Several magnetic sensors have been used in gradiometer configuration that is capable of detection of spatial magnetic field gradient while suppressing uniform magnetic field interferences. However, magnetic shielding is indispensable to provide a magnetically quiet environment for sensors to work within to improve signal-to-noise ratio by additional suppression of magnetic field interferences which are present in factory production lines. Moreover, several times averaging of measurements is required to improve signal-to-noise ratio. Consequently, cost, weight and size are very high for such detection setups.

Recently, a new method for building a Fundamental mode Orthogonal Fluxgate (FM-OFG) gradiometer has been proposed by our lab for building a gradiometer, which is composed of two identical sensor heads having the pickup coils of the two heads connected in counter series; thus allowing the differentiation of the signal on the sensor head level. The proposed configuration allows the gradiometer to have the advantage of a flexible baseline while minimizing the used electronics set and also allowing more amplification of the measured signal. The measured sensitivity of the gradiometer is 5.98 mV/(μT/m) with noise floor of 100 pT/m/√Hz at 10 Hz.

In this thesis, FM-OFG gradiometer is utilized in a magnetic particle detection system to demonstrate its detection capability with real-time measurements in unshielded environment. First, numerical simulation is conducted to analyze system design parameters and improve detection performance. Then, experimental detection setup construction is discussed. Detection of steel ball of diameter 50 μm producing 4 nT/m gradient at the gradiometer's location achieved 5 signal-to-noise ratio. Detection of dry Fe_3O_4 nanoparticles sample of 0.5 μg weight producing 3.2 nT/m gradient at gradiometer's location achieved 6.5 signal-to-noise ratio. Additionally, improved fine magnetic particle detection setup was proposed for suppression of uniform field interferences through placement of the gradiometer sensor heads on a Permalloy shielding disk. Numerical analysis was conducted to investigate the effective shielding area of the shielding disk. Experiments were conducted using Permalloy disk of 10 cm diameter where the gradiometer uniform magnetic field susceptibility is reduced by a factor of 0.25 at 10 mm sensor baseline. A 10 Hz magnetic field interference of 150 nT/m in peak-to-peak was reduced to 46.8 nT/m while using the disk. The signal-to-noise ratio of the 120 μm steel ball detection under the said interference was increased by a factor of 4.6 times.

Finally, based on the same construction method for the FM-OFG gradiometer, an extension is made for the construction of a novel integrated gradiometer and magnetometer fluxgate sensor. The measured sensitivity of the gradiometer is 3.77 mV/(μT/m) with noise floor of 140 pT/m/√Hz at 10 Hz. The measured magnetometer sensitivity is 965 mV/μT with noise floor of 2.7 pT/√Hz at 10 Hz. Gradiometer susceptibility to uniform magnetic field was measured to be 0.36 (nT/m)/nT and through balancing the sensitivity of the two sensor heads by fine tuning of dc bias current, the gradiometer susceptibility can be reduced by a factor of 0.7 to reach 0.26 (nT/m)/nT