GRADIENTMETRIC METHOD FOR THE FERROMAGNETIC INCLUSIONS DETECTION*

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The paper presents a magnetic field gradientmeter meant to detect the very small size ferromagnetic inclusions. The detection of the magnetic field gradient is useful in certain applications permitting to eliminate some disturbing factors and to localize the local inhomogeneities of the magnetic field or certain close field sources. The gradientmeter makes use of two identical magnetic transducers of fluxgate type, connected in opposition, such that the output signal is proportional with the difference of the field from every transducer. The error sources are presented as well as the solutions to reduce them. The main error source in gradient measurement is the difference of sensitivities and the transducers misalignement. The two components of the local magnetic field – the longitudinal and transversal ones – determine the appearance of some error signals. The longitudinal component of the magnetic field applied to the transducer produces a measuring error proportional with its size. The measuring error proportional to the field component normal to the measuring direction can be eliminated by an accurate sensors alignment. The block diagram and the operation principle of the gradientmeter are described.

The experimental results reveal the possibility to use this method for the detection of small size ferromagnetic inclusions.

Key words: gradientmeter, magnetic detection, ferromagnetic inclusion, fluxgate sensor.

1. INTRODUCTION

The magnetic detection of the ferromagnetic inclusions can be applied in various fields: food industry, pharmaceutical and medical domain, textile industry.

In the medical domain the detection of ferromagnetic objects is especially used in clinics and hospitals in the magnetic resonance imaging (MRI) installations to prevent personnel and patient's injuries or equipment damage. The accidental penetration of some ferromagnetic objects into the scanning space

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represents a real danger if they reach near the large magnet that encompasses the patient during scanning, being able to seriously injure or even kill patient or the personnel in the vicinity. Specialized detectors have been accomplished that can operate in close proximity to magnets without interfering with the image quality of the MRI system. Their configuration also minimizes external interferences from cars, street railways, etc. The detector sensitivity depends on the ferrous content, object size and its distance from the detector. The performances enable the detection of spherical objects with diameters smaller than 1 mm and fragments of office staple which have been detected at different distances ranging between 1mm and 25 mm. The sensitivity up to a distance of 25 mm demonstrates the possibility to detect ferromagnetic objects under the skin and to scan dressed patients, as well as persons accompanying them in the scan room. The operating principle of these detectors does not permit to sense aluminium or other non-ferromagnetic objects, thus preventing false alarms.

The detection of very small size ferromagnetic particles in food or medicine control, meant to classify and eliminate these contaminants, as well as to prevent the installation damages, can be accomplished using high sensitivity SQUID magnetometers [1]. The main problem is that such a magnetometer should operate in an industrial environment where the level of electromagnetic disturbances exceeds the apparatus sensitivity. In order to avoid this shortcoming gradientmeter systems were realized able to work in an unshielded environment.

In certain technical situations, the presence of ferromagnetic inclusions in a non-ferromagnetic medium can create problems [2]. For instance, presence of small ferromagnetic particles in turbine disks are dangerous and have to be detected before its utilization; the housing of the superconducting particle accelerators which is made from niobium must not contain ferromagnetic particles, in order to avoid its destruction; during the manufacturing of tools or parts, these can split or break and very small ferromagnetic particles may remain on the surface and they occur as defects close to the surface. In all these situations the utilization of a fluxgate gradientmeter permits the detection of previously magnetized ferromagnetic inclusions with the mass of some milligrams from a distance of up to 100 mm.

2. METHOD DESCRIPTION

The presence of a small size inclusion in a magnetic field produces the field variation in this zone, which can be estimated by a gradient field detection method. The magnetic field gradient is a vector that characterizes the spatial inhomogeneity of the magnetic field. The gradient detection permits to eliminate some disturbing factors (daily variation of the magnetic field, electromagnetic interferences) and to locate the local field inhomogeneities.

A gradientmeter consists of two identical magnetic field transducers connected in opposition, such that the output signal is proportional to the difference of the fields of each transducer, and from a signal processing electronic block.

The main problem which appears when building a gradientmeter consists in making two perfectly aligned field transducers with identical characteristics. The transducers misalignment and their difference in sensitivity result in the appearance of measuring errors, such that the detected signal can be comparable with the measured gradient. At the same time, the two components of the surrounding magnetic field can also result in the appearance of error signals [3].

In order to determine the influence of the longitudinal field component on the measuring error, two magnetic field transducers are considered, with the sensitivities S and $S + \Delta S$, placed at a distance d apart from each other in a magnetic field of intensity H and $H + \Delta H$ respectively (Fig. 1).

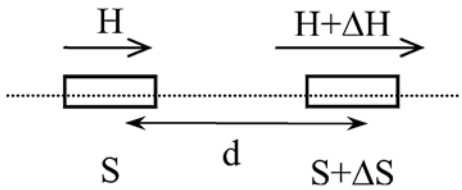

Fig. 1 – The measuring error due to the longitudinal field.

The signals from the two transducers are given by the relations:

$$U_1 = SH \tag{1}$$

$$U_2 = (S + \Delta \mathrm{S})(\mathrm{H} + \Delta \mathrm{H}) \tag{2}$$

Since the signal windings are connected in opposition, the signal at the gradientmeter input will be:

$$\Delta U = U_2 - U_1 = S\Delta H + \Delta SH + \Delta S\Delta H \cong S\Delta H + \Delta SH \tag{3}$$

From the above relation, one can notice that the first term is proportional to the product between the magnetic field intensity and the difference between the sensitivities of the two transducers. The second term represents an error term, for its diminution being necessary to change H. If $H = 0$, the gradient error vanishes.

By denoting with ΔG the gradient error due to the magnetic field H, one can write:

$$\Delta G = (\Delta SH)/Sd = (\Delta S/S)G \tag{4}$$

where $G = \Delta H/d$ represents the magnetic field gradient.

One can calculate the admissible deviation of the inequity between the sensitivities of the two elements of the transducers, $\Delta S/S$ in order to have a relative gradient measuring error lower than the proposed value ε. The above relations give:

$$\frac{\Delta G}{G}=\frac{\Delta SH}{Sd}\frac{d}{\Delta H}=\frac{\Delta S}{S}\frac{H}{\Delta H}\leq \varepsilon \tag{5}$$

which can be written as:

$$\frac{\Delta S}{S}\leq \varepsilon\frac{\Delta H}{H} \tag{6}$$

It follows that a longitudinal field component applied to the transducer makes the gradient measuring error change in proportion to the magnitude of the longitudinal field H.

In order to evaluate the effect of the transversal field component, two transducers are considered which make an angle β with the direction along which the gradient is measured (Fig. 2).

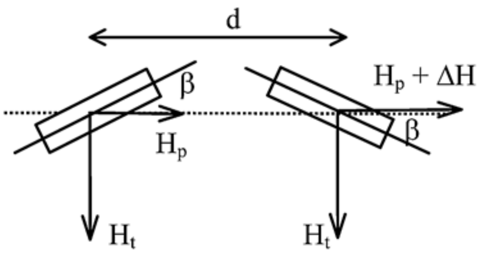

Fig. 2 – The measuring error due to the transversal field.

To simplify, we shall consider that the two transducers have the same sensitivity and then the second harmonic voltages generated by the transducers are given by the relations:

$$U_1 = S(H_p\cos\beta - H_t\sin\beta) \tag{7}$$

$$U_2 = S[(H_p + \Delta H)\cos\beta + H_t\sin\beta)] \tag{8}$$

The gradient signal is given by the relation:

$$U_2 - U_1 = SH\cos\beta + 2S\sin\beta$$

Since the real gradient is $G = \Delta H/d$, the relative error is given by:

$$\varepsilon=\frac{\Delta G}{G}=1-\cos\beta-2\frac{H_p}{\Delta H}\sin\beta \tag{9}$$

From the above relation it follows that, in order to reduce the error, one has to compensate the component perpendicular to the gradient measuring direction.

3. DESCRIPTION OF THE INSTALLATION AND EXPERIMENTAL RESULTS

For the study of the possibilities to use this method in the detection and localization of small size magnetic inclusions, an installation was executed with the block diagram given in Fig. 3.

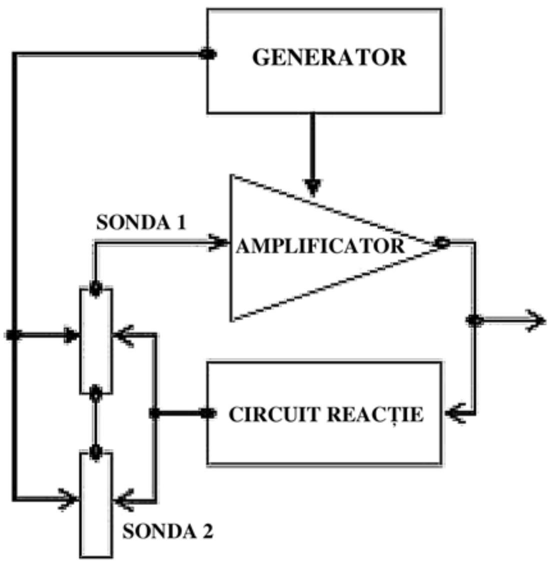

Fig. 3 – Block diagram of gradientmeter.

The circuit includes two magnetic field transducers of fluxgate type, connected in opposition and excited with a signal of frequency f coming from a generator which also delivers a reference signal $2f$ necessary for the synchronous detector - amplifier which extracts from the complex signal only the signal of frequency $2f$ whose amplitude is proportional to the gradient magnitude ΔH, its phase changing together with gradient polarity change. The synchronously detected voltage is applied through the circuit of gradient negative feedback

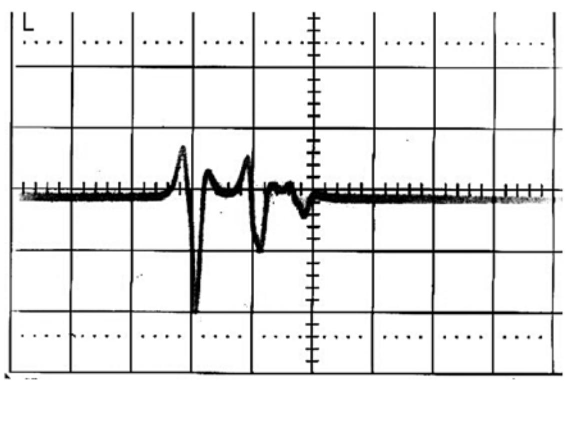

Fig. 4 – The gradient signal produced by the passage of three bodies of different sizes.

windings of the transducer. By an adequate choice of the transfer function of the network, the gradientmeter will accomplish the derivation of the measured gradient, the obtained output signal changing in proportion with the gradient derivative.

The gradient signal produced by the ferromagnetic inclusions of different masses situated at different distances from the gradientmeter is presented in the oscillogram from Fig. 4.

4. CONCLUSIONS

The gradient method permits to detect small size ferromagnetic inclusions in the presence of disturbing continuous or variable fields, as well as to improve the signal/noise ratio of the detection system.

The method can be applied in the activities that demand high purity products and a final quality control according to the UE norm, such as food products, medicines, textile materials used for cloths and furniture.

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