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Sensitivity of electromagnetic method for gas bubble detection in liquid metal flows

O. Andreev*, T. Gundrum, T. Wondrak, S. Eckert, G. Gerbeth
Helmholtz-Zentrum Dresden-Rossendorf, Institute of Fluid Dynamics,
Bautzner Landstraße 400, 01328 Dresden, Germany

*Corresponding author: o.andreev@hzdr.de

Abstract

Electromagnetic induction (EMI) is known as a technique which is very sensitive to variation of electrical conductivity of materials. In the present study we simulate numerically the work of electromagnetic sensor which consists of two differential coils. Such a detector rejects the basic signal and monitors the perturbations of electromagnetic field caused by the heterogeneity of electrical conductivity. We investigate the capability of this method for detecting non-metallic inclusions, such as gas bubbles in liquid metal (GaInSn) and sensitivity of differential detector to variation of its configuration.

Key words: electromagnetic induction technique, two-phase flow, bubble detection

Introduction

Liquid metals are widely used in industrial processes and scientific investigations. For example, the homogeneity of liquid sodium flows in the cooling systems of fast reactors is very important for the safety of nuclear power plants. The presence of any gaseous admixture is an indicator of very undesirable processes in the sodium flows: leakage, cavitation and so on. It can make the work of hydraulic system unstable or lead to ignition. Thus, it becomes mandatory to develop sensors capable of detecting any gaseous voids in the sodium liquid which can be used as emergency indicators of boiling or gas inflow into the loop. In the present work we develop a simple sensing technique for electronic detection of gas bubbles in liquid metal flow using the electromagnetic inductance (EMI). This method has been proved [1, 2] to be an inexpensive, non-intrusive system with low but sufficient resolution of the internal distribution of material parameters. The technique can deliver information on the distribution of electrically conductive and magnetically permeable material within the object space. EMI is the most appropriate method for monitoring metallic objects and media with inhomogeneous distribution of electrical conductivity. In particular, liquid metal flows with gas bubbles inside can be easily monitored by this method. Measurements can be acquired by passing through the liquid metal an alternating primary magnetic field. This magnetic field interacts with conductive objects in the medium to produce eddy currents, which, in turn, produce a secondary magnetic field, which is measured by sensing coils. In our numerical experiments we used a simplified system, which consists of one excitation coil and two detector coils. The excitation is a rectangular coil while the detector should be a gradiometer type of coil. In the case of no bubble, the receiver voltage should be zero. When the bubble enters the sensing area in the duct, the receiver will produce a voltage. The main task of present investigation is to define a proper configuration of receiving coils in order to ensure the maximal sensitivity of detector to the presence of gas bubbles (non-metallic enclosures) for the whole interior of a liquid metal target.

Numerical model

A formal description of the instrument system can be derived from Maxwell's equations in complex amplitude of vector potential \vec{A} notation as described in [2, 3] for a practical case:

$$\nabla^2 \vec{A}(\vec{x}) - \frac{2i}{\delta^2} \vec{A}(\vec{x}) = \frac{\sigma'(\vec{x})}{\bar{\sigma}} \cdot \left(\frac{2i}{\delta^2} \vec{A}(\vec{x}) - \vec{\nabla}(\vec{\nabla} \circ \vec{A}(\vec{x})) \right)$$

Here, $\bar{\sigma}$, σ' averaged and perturbed electrical conductivities, $\delta^2 = 2/\mu_0\omega\bar{\sigma}L^2$ the dimensionless "skin depth" defined by the magnetic permeability of vacuum μ_0 , frequency of applied magnetic field ω and length scale L of the problem. The frequency $\omega=100$ Hz has been selected as a trade-off to provide sufficient primary field penetration across the pipe (skin depth – 27.45 mm) and to have a good induction multiplication factor for the measured signal on the receiver coil. The cross-sectional scheme of calculation domain is shown in Figure 1(a). It consists of four principle zones. The interior zone 3 ($-1 \leq x \leq 1$) contains the rectangular duct, which is filled with the working fluid. The half-width of the duct is used as length scale $L=25$ mm. The electrical conductivity varies in this zone from zero (outside of the duct) to the maximal value, which corresponds to conductivity of GaInSn taken for the dimensionless statement of the problem as a scaling value. Other three zones 1, 2 and 4 (Fig.1(a)) are considered to be non-conducting. The excitation

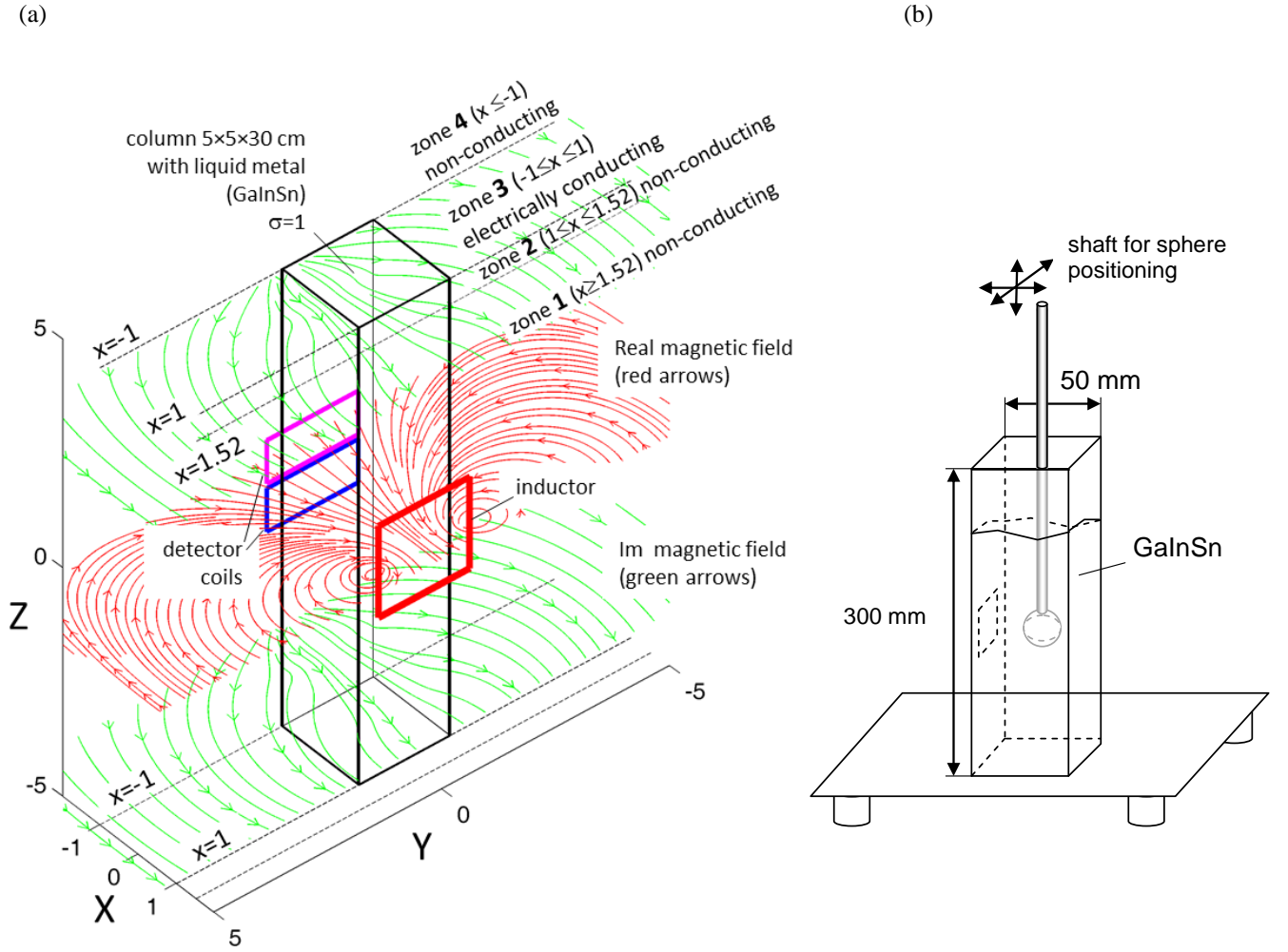


Fig. 1: (a) Sketch of numerical domain, (b) scheme of a spherical target (gas bubble) positioning.

coil (inductor in Fig. 1(a)) is installed on the half-length of the column filled with eutectic alloy GaInSn. In dimensionless notation it has size of 2×2 . The detector consists of two rectangular coils (Fig. 1(a)). It was posed on the opposite side of the column. The top (magenta) and bottom (blue) coils are wound in series opposition. Actually the resulting output signal from such a detector, often known as a planar gradiometer, is proportional to the difference of magnetic fluxes passing through the coils. In the numerical experiments we vary the vertical l_z , and horizontal l_y size of the coils in the range of $(l_z, l_y) = 0.6 \dots 3$ in order to define the maximal value of output signal for the current position of a single gas bubble inside the liquid metal. In this study, instead of the real gas bubbles we use a single non-conducting spherical target ($\varnothing 0.2$) placed inside the fluid as it is shown in Figure 1(b). Position the sphere was varied in three directions.

Result and discussion

In Figure 2 (a) we show three-dimensional distribution of sensitivity of the differential detector to the presence of a gas bubble. The numerical experiment was performed in the following way. On the first step, the single spherical target was settled in a certain place and the corresponding distribution of magnetic field was calculated in the plane of detector. On the second step the voltage U generated in the coils was evaluated according to the following equation:

$$U = \iint_s (-\partial B_n / \partial t) ds \approx \iint_s -\omega \bar{B}_n ds$$

Here B_n is the amplitude value of the normal to the coil component of magnetic field, $s = l_z \times l_y$, is area of the rectangular coil. The size of coil was varied in the range of $(l_z, l_y) = 0.6 \dots 3$ as it is shown by the green lines in Figure 2 (a).

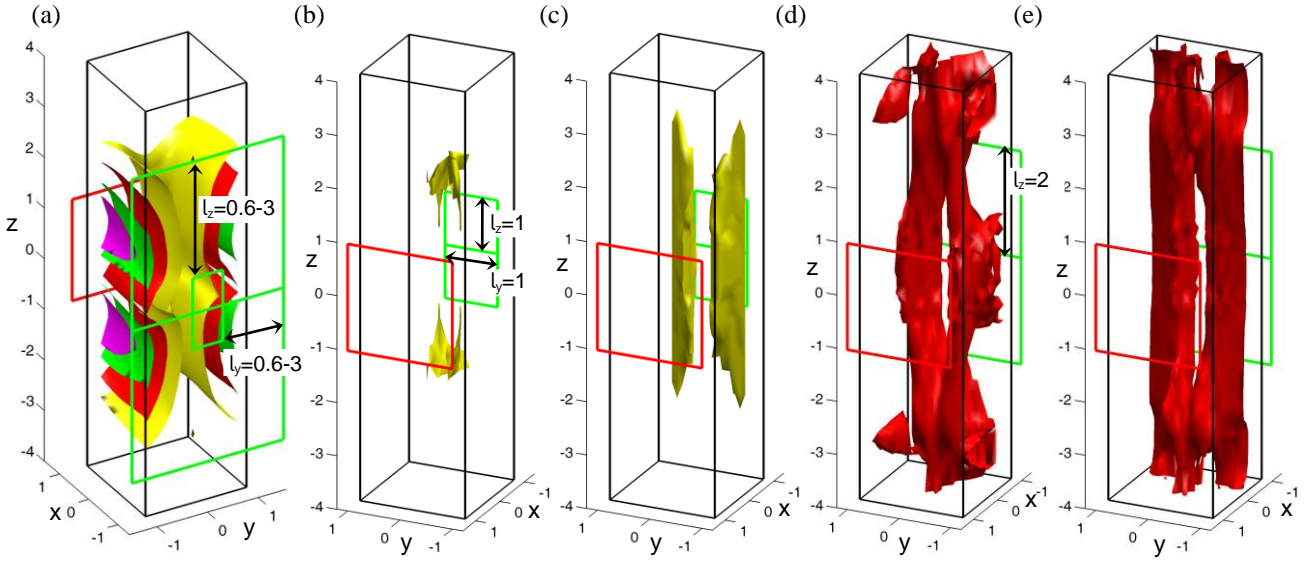


Fig. 2: (a) 3D distribution of sensitivity U of differential detector obtained for ‘adaptive’ configuration of the coils. $U=0.3\times 10^{-5}$ - yellow, 1×10^{-5} - red, 2×10^{-5} - green, 3×10^{-5} – magenta. Isosurfaces define the regions where the bubbles can be detected with the maximal sensitivity by the coils with (b) $\ell_z=1$, (c) $\ell_y=1$, (d) $\ell_z=2$, (e) $\ell_y=2$.

The maximal value of the signal in the range of variation was accepted as an ‘optimal’ one for the certain position of the spherical target. In Figures 2(b, c) the yellow isosurfaces confine the regions of liquid metal, where this ‘optimal’ detection of bubbles requires a coil with the sizes which do not exceed the values of $\ell_z=1$ and $\ell_y=1$. It is a rather narrow region situating very closely to the rear wall of the channel near the detector. The red shells in Figure 2(d, e) indicate the regions, where the gas bubbles can be effectively detected by the coils with $\ell_z=2$ and $\ell_y=2$. In Figure 3 this experiment is

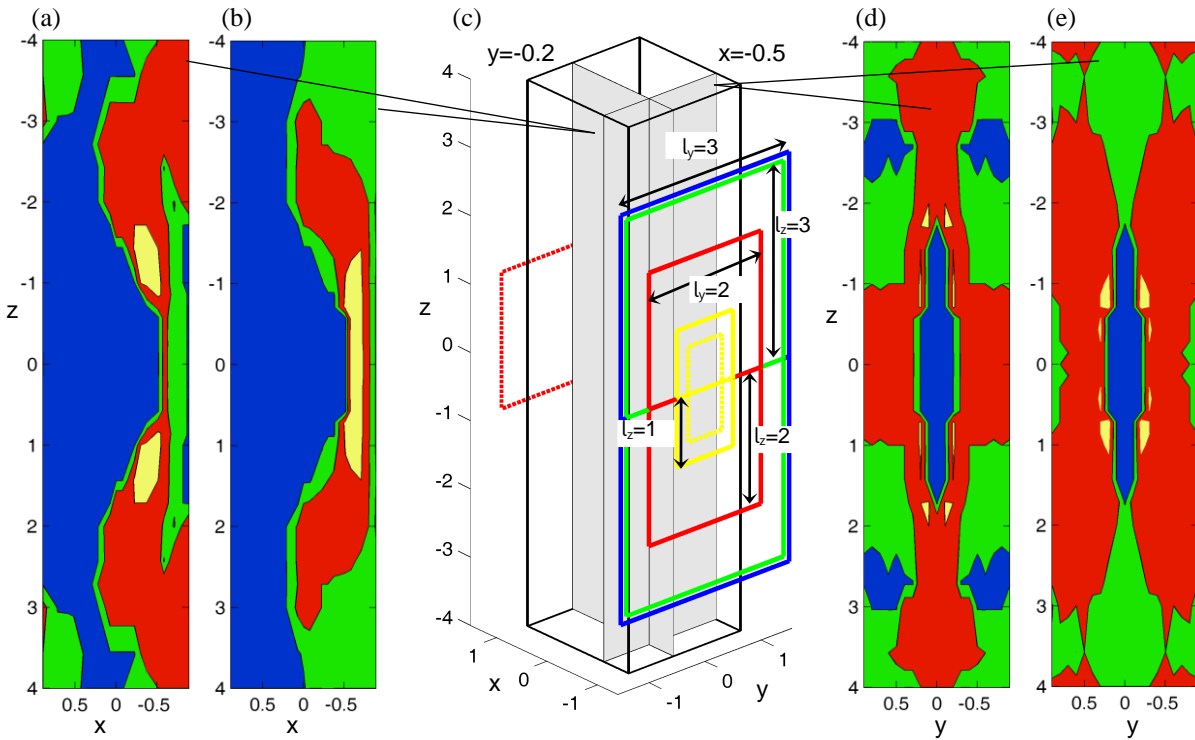


Fig. 3: Cross-sectional distribution of the ‘optimal’ sizes of detector coils. (a) ℓ_z , (b) ℓ_y for the vertical plane $y=-0.2$, (d) ℓ_z , (e) ℓ_y for the vertical plane $x=-0.5$. Yellow – $(\ell_z, \ell_y)=0.6 - 1$, red – $(\ell_z, \ell_y)=1 - 2$, green - $(\ell_z, \ell_y)=2 - 3$, blue > 3

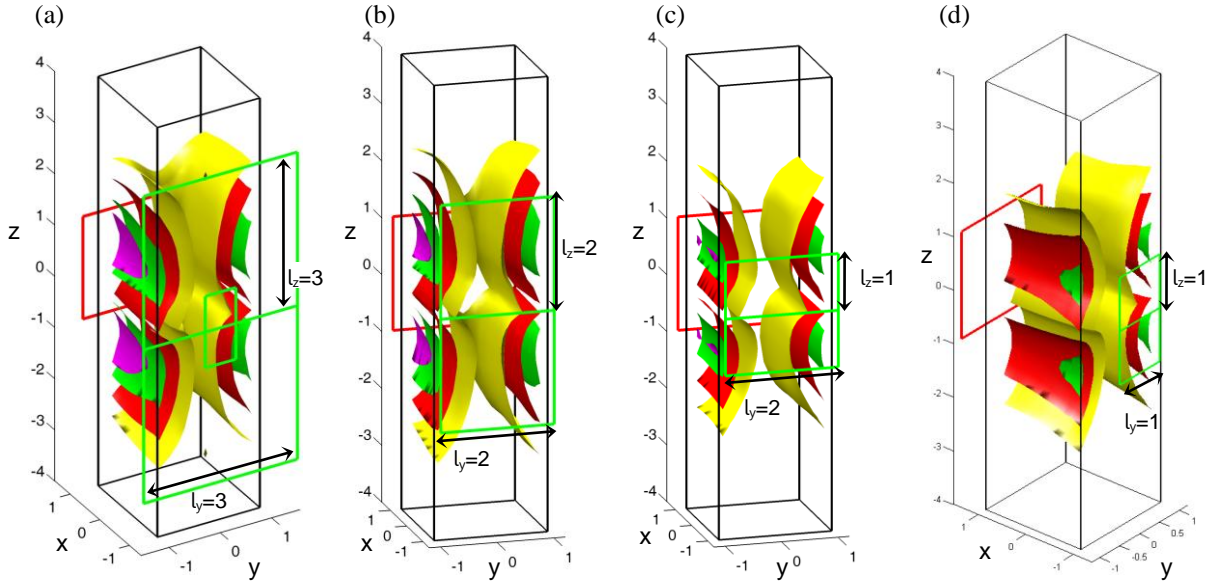


Fig. 4: 3D sensitivity maps obtained by experiments with (a) ‘adaptive’ and fixed configurations of detector coils: (b) $l_z=l_y=2$, (c) $l_z=1, l_y=2$, (d) $l_z=l_y=1$.

illustrated by 2D distributions of ‘optimal’ coils sizes l_z and l_y in two vertical cross-sections at $y=-0.2$ and $x=-0.5$. According to Figures 3 (a, b) the region, which is situated closely to the driving inductor, requires for the effective monitoring of gas bubbles installation of a measuring coil with the vertical and horizontal sizes equal at least to $(l_z, l_y)=3$ (or even more). This region (colored in blue in Figures 3 (a, b)) occupies almost 55% of the plot areas.

For any real gas bubble measurements one should choose an appropriate constant shape of the detector coils. In Figure 4 we show distributions of sensitivity for three fixed configurations of detector with $l_z=l_y=2$ (Fig. 4(b)), $l_z=1, l_y=2$ (Fig. 4(c)), $l_z=l_y=1$ (Fig. 4(d)) in comparison to the experiment with the ‘adaptive’ detector coils (Fig. 4(a)). The small detectors under evaluate the central region of the liquid metal column, especially on the vertical mid-plane $y=0$, where the eddy currents decay. The maximum of sensitivity displace toward the detectors, otherwise in the case of relatively large measuring coils, the most sensitive region is situated in the region of strong eddy currents, namely, near the inductor driving the magnetic field.

Conclusions

The differential electromagnetic detector considered in this work is not sensitive to the basic symmetrical magnetic field driven by the external excitation coil. The electrical signal delivered by this probe is generated by possible perturbations of magnetic field caused by a local impurity of electrical conductivity (gas bubble). Magnitude of such perturbations depends on the value of electrical current in its origin (position of gas bubble). Thus, the detector is very sensitive to the bubbles which are situated near the excitation coil and in the vicinity of the lateral walls, where the electrical current concentrates due to the “skin” effect. In particular case, when a bubble occurs exactly on the horizontal central plane ($z=0$), the detector does not “recognize” the bubble, because the distribution of perturbed magnetic field becomes symmetrical with respect of the central plane and both positive and negative coils generate the same signal. In order to obtain a recognizable signal caused by the gas bubbles occurred in the whole volume of the liquid metal domain, it is reasonable to use the relatively large detector coils. Their size should be commensurable with the cross-sectional area of the domain, namely, 2-3 its length scales.

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