Inductive methods of detection the boundary of electrically conductive media in experiment

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Abstract. Induction methods of localization the electrically conductive media were implemented experimentally. Local and integral techniques are considered. Relations were represented between of the local level probe (LLP) signal, its position and the frequency of alternating current. The dependences of the integral level probe (ILP) signal on the frequency of the alternating current are obtained. The methods were tested in laboratory experiments in which it was possible to determine the metal level with an error not exceeding 1 mm. The LLP is more designed for small changes in the liquid metal boundary, comparable to the size of the probe. The ILP has its advantages when used in installations in which the change in the level of the liquid metal is greater than the pitch with which the measuring coils are installed.

1. Introduction

Processes with a deformable boundary of the electrically conductive medium are often found in academic and engineering problems. There are also a number of problems in which it’s necessary to control the liquid metal surface level. Such situations arise, for example, in aluminum and titanium electrolyzers, in liquid metal batteries, as well as in applications related to the metallurgy [1–3]. In these cases, fluctuations and any change in the liquid metal boundary are highly undesirable processes.

The excellent electrical conductive property of liquid metal is used as the basis for point contact, resistance and inductive types of level measuring probes. In the first type of measurement, electrodes forming a part of an electric circuit are immersed into the liquid metal, and the electrical circuit resistance is varied by the direct contact with the liquid metal [4, 5]. However, wetting is a critical factor in the use of an electrical circuit which depends upon electrode contact with the liquid metal.

High process temperatures, large masses and dimensions as well as the complexity of the technological process require a contactless measurement method [6]. The electrical conductivity of metal is considerably greater than the conductivity of the media surrounding it, and hence electromagnetic control methods are the most effective for solving this problem. These methods are used in other problems, for example in induction velocity measuring methods based on eddy currents generation. They were actively studied and used for many years. For example, velocity measurements in conductive liquids were performed by Miralles [7]. And in the last century, measurement of velocity and electroconductivity of ionized gas fluxes were made by Poberejsky [8].
Induction methods are also used in flowmeters with external placement of the generating and measuring parts, which have received basic development [9–11]. The main advantage of such systems is the possibility of placing the measuring coils into the system of thermal stabilization and cooling of the entire system, which allows them to be used even at high temperatures. Additionally, such flowmeters provide the ability to implement the liquid metal electrical conductivity measurement [12], or the registration of a gas phase in the liquid metal [13].

The task to create a reliable method of detecting the liquid metal boundary position based on inductive methods, structurally similar to the electromagnetic flowmeters faces our research team. It is not always possible to carry out investigations on real installations for various reasons, which leads to the relevance of the model laboratory studies.

In the present work, local and integral techniques for the induction determination of the liquid metal level are described, which are experimentally investigated on a duralumin cylinder. The features of the techniques realization and their comparison are given.

2. Methods

2.1. Local level probe (LLP)

The local level probe (LLP) is used as a device for local determination of the boundary between two media. It is a system of three coils placed close each other and coaxially (fig. 1a). A magnetic field is generated by the central coil, and the two outer coils are used for measuring. Measurement of the magnetic field induced by the generating coil along the probe axis shows that the measuring coils are in linear sections (fig. 1b). The LLP parameters are presented in the table 1.

![Local level probe](image_url)

**Figure 1.** Local level probe: a) axonometric projection, b) cross section of the magnetic field along the central axis.

|                     | Generating coil | Measuring coil 1 | Measuring coil 2 |
|---------------------|-----------------|------------------|------------------|
| Frame width, mm     | 6               | 10               | 10               |
| Frame thickness, mm | 12              | 12               | 12               |
| Frame height, mm    | 42              | 42               | 42               |
| Wire section, mm    | 1.12            | 0.3              | 0.3              |
| Number of turns     | 50              | ~1300            | ~1300            |
| Resistance, Ohm     | 0.34452         | 44.526           | 43.935           |
| Inductance, mH      | 0.11951         | 48.970           | 48.783           |

*Table 1. Local level probe parameters.*
According to the law of electromagnetic induction, an alternating magnetic field created by the generating coil induces EMF in the measuring coils. If on one side of the LLP (near one of the measuring coils) there is an electrically conductive medium, then due to eddy currents arising in this medium, a counter alternating magnetic field will be created. This phenomenon underlies the skin effect. Based on the principle of superposition of magnetic fields, the potential difference in the measuring coil placed close to the electrically conductive medium is less than in the opposite one. In the absence of a conductive media, the potentials on both coils are equivalent. This phenomenon is used to determine the presence of an electrically conductive medium near the sensor.

The LLP testing is provided with the use of duralumin cylinder of the grade D16 (3) with a height of 202 mm and a diameter of 173 mm. Opposite the cylinder there is a measuring system including the LLP (2) placed on three mutually perpendicular micrometric platforms (5) (ThorLabs). With a fixed position of the measuring system, these platforms allow moving the sensor up to 50 mm in each direction in space.

An alternating current is supplied to the generating coil by the sinusoidal signal generator (GZ-109) (4). Two measuring coils are connected to the National Instruments data acquisition boards (1) (NI 9225 NI 9227). These boards allow the LabView IDE (6) records the experimental data. The values of the output voltage and current from the generator are also recorded. The coordinate system origin is placed on the edge of the duralumin cylinder (see fig. 2): the $h$ axis is directed downward and the $r$ axis is directed to the left.

![Figure 2. Laboratory setup for local level probe: 1 – data acquisition boards, 2 – local level probe, 3 – duralumin cylinder, 4 – generator, 5 – micrometric platforms, 6 – Personal Computer.](image)

The sensitivity and characteristics of the LLP are investigated by varying the frequency of the alternating current in the generating coil, as well as by changing the vertical position of the LLP and the radial distance between it and the conducting cylinder. The parameter $D_{pd}$ is selected as a quantitative characteristic measured in volts, which is determined by the expression:

$$
D_{pd}(f, r, h) = \sqrt{\frac{\sum_{i=1}^{N} U_{2,i}^2}{N}} - \sqrt{\frac{\sum_{i=1}^{N} U_{1,i}^2}{N}} = RMS(U_2) - RMS(U_1),
$$

where $U_{1,i}$ is the voltage at the first measuring coil (closest to the conductive medium) at the $i$-th time instant, $U_{2,i}$ is the voltage at the second measuring coil in $i$-th time instant.
2.2. *Integral level probe (ILP)*

The position of the upper boundary of the cylindrical conductive volume is also determined by using the integral level probe (ILP). In this case, a series of coils is located around the cylinder with a certain step. Each coil generates an alternating magnetic field. Each coil also resolve the resulting magnetic field by the measurements of the voltage. The voltage at the coil depends on its inductance (impedance), which depends on the position of the cylinder for fixed current. So, it is possible to calculate the impedance of each coil by measuring the voltage and current. The relationship between the impedance and the level of the coils characterizes the position of the cylinder.

The laboratory model was developed to investigate the properties of the ILP. The laboratory setup includes stainless steel wall and 38 coils. The duraluminum cylinder D16 was used as a conductive medium (fig. 3).

![Figure 3. Laboratory setup for integral level probe: a) real photo, b) scheme.](image)

A special board (Commutator) was developed for switching the coils (fig. 4). The board is applied to reconnect the coils with the AC power source Pacific 360-ASX, which allows to change the frequency. The National Instruments boards (NI 9225 and NI 9227) are used for registration of the current and voltage on the coil. The NI 9401 board is used to communicate with the Commutator. Special software was developed in LabView IDE to automate the experiment.
The power source sets the alternating current in the coil \(I_{rms} = 1\text{ A}\). During one measurement series, the coils are switched in turn. The series of experiments included the following frequencies: 100 Hz, 200 Hz, 300 Hz.

The impedance of each coil \(R_i\) is calculated from the experimental data at the selected frequency:

\[
R_i = \sqrt{\frac{\sum_{j=1}^{N} U_{ij}^2}{N}} = \frac{RMS(U_i)}{RMS(I_i)},
\]

where \(i\) is the coil number, \(U_{ij}\) is the voltage at the \(i\)-th coil at the \(j\)-th time instant, \(I_{ij}\) is the current in \(i\)-th coil at the \(j\)-th time instant.

Then, the plot \(R(h)\) is developed, based on the obtained points \(R_i\) and \(h_i\) (height of the \(i\)-th coil). For this, a polynomial of \(n\)-th degree is calculated using the method of least squares. On the resulting plot it is possible to fix a previously known point where the boundary is located. Thus, the parameters of this relation and the real position of the boundary attached to the relation are determined. So, it is possible to analyze the measured signals and determine the unknown position of the boundary in advance using this plot. The plot of the function \(R(h)\) for the new unknown position of the boundary will be shifted along the \(h\) axis relative to the initial plot. To test the sensitivity of the method to random errors \(Error\), an error from 1 to 20 percent is entered into the experimental data. Then, the standard deviation \(\delta\) is plotted as a function of the \(Error\) in percent.

3. Results

The experimental investigation of the LLP was carried out for the different frequencies of an alternating current on the generating coil in the range \([50; 500]\) Hz \((I_{rms} = 1.5\text{ A})\). The figure 5 shows the plots of the parameter \(D_{pd}\) as a function of height at \(r = 0\) mm for various frequencies of the alternating current.

![Figure 5](image-url)
The normalized plots was also represented (in the conductive medium $F_D = 1$, otherwise $F_D = 0$). The black vertical dotted line shows the real boundary of the electrically conductive medium.

It should be noted that at the boundary of the electrically conductive medium, the dependence $F_D(f)$ reaches a certain constant value close to 0.5 (fig. 6).

![Figure 6. The calibration function $F_D$ as a function of the frequency of the alternating current on the generating coil at $h = 0$ mm and $r = 0$ mm.](image)

In addition, there is an exponential decay of the amplitude of the output signal of the LLP with increasing distance between the probe and the conducting cylinder. The figure 7 shows this plot for $h = 0$ mm, that is, at the boundary of the electrically conducting medium.

![Figure 7. The parameter $D_{pd}$ as a function of the distance at $h = 0$ mm for the different frequencies of the alternating current.](image)

It is necessary to add that the relative error of the measured parameters does not exceed 1%.

The experimental investigation of the ILP was carried out for the following frequencies: 100 Hz, 200 Hz, 300 Hz ($I_{rms} = 1.5$ A). The figure 8 (a) shows the plots $R(h)$. The black vertical
line shows the real boundary position \( h = 688 \text{mm} \). The figure 8 (b) represents the plot of the standard deviation as a function of the entered error in percent \( \delta(\text{Error}) \) for 300 Hz.

\[ \text{Figure 8. The impedance } R(h) \text{ as a function of } h \text{ and the standard deviation } \delta(\text{Error}) \text{ as a function of Error.} \]

In the plots \( R(h) \), crossing the boundary of the conductive medium is more clearly visible only at 300 Hz. If an additional error is entered in the experimental data, the error of the method at 100 and 200 Hz will be much higher. Therefore, for the method it is advisable to use frequencies from 300 Hz.

The accuracy of each particular case can be estimated by plotting \( \delta(\text{Error}) \).

4. Conclusions

The experimental investigation of the LLP shows the possibility of detection the boundary of an electrically conductive medium. In practice, for given values of the frequency of the alternating current and its standard deviation, the values of \( D_{pd} \) “inside” and outside the conductive medium are determined. Thus, due to the calibration function \( F_D(h) \), it is possible to determine the position of the boundary of the electrically conducting medium relative to the center of the LLP. The probe position relative to the electrically conductive medium should be minimal, since the intensity of the output signal decreases exponentially with distance.

The experimental investigation of the ILP also shows the possibility of determination the level of the boundary. In practice, there are random errors in the experiment, for example, connected with the non-identity of the coils. Nevertheless, it is always possible to plot the standard deviation as a function of the entered error, estimate the accuracy of the method under various conditions and select the optimal parameters (frequency, number of coils, etc.) at which the error will be minimal.

Both methods were tested in laboratory experiments, which enabled us to estimate the measurements accuracy and the systems sensitivity to systematic and random interference. The algorithm stability analysis to random errors (Gaussian noise) and systematic errors was carried out.

In the end, it is worth adding that the LLP is more accurate in the laboratory task under consideration, which is determined by the rather precise possibility of its movement. The ILP has its advantages when used in installations in which the change in the level of the liquid metal is greater than the pitch with which the measuring coils are installed. In laboratory experiments, it was possible to determine the level of a metal with an error not exceeding 1 mm.

Acknowledgments

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References

[1] Weber N, Galindo V, Priede J, Stefani F and Weier T 2015 Physics of Fluids 27 014103
[2] Kelley D and Weier T 2017 arXiv:1710.03150
[3] Krauter N, Eckert S, Gundrum T, Stefani F, Wondrak T, Frick P, Khalilov R and Teimurazov A 2018 Metalurgical and materials transactions B
[4] Slocomb H 1967 Liquid metal level measurement (sodium) Tech. rep. Liquid Metal Engineering Center
[5] Singh Y, Raghuwanshi S and Kumar S 2018 IETE Technical Review
[6] Khalilov R, Khrichchenko S, Frik P and Stepanov R 2007 Measurement Techniques 50 861–866
[7] Miralles S, Verhille G, Plihon N and Pinton J F 2011 Rev. Sci. Instrum. 82 095112
[8] Poberejsky L 1963 Tech. Phys. (in Russian) 1464–1469
[9] Forbriger J and Stefani F 2015 Measurement science and technology 26
[10] Schulenberg T and Stieglitz R 2010 Nucl. Eng. Des. 240 2077–2087
[11] Priede J, Buchenau D and Gerbeth G 2009 Magnetohydrodynamics 45 451–458
[12] Sharma P, Kumar S S, Nashine B, Veerasamy R, Krishnakumar B, Kalyanasundaram P and Vaidyanathan G 2010 Ann. Nucl. Energy 37 332–338
[13] von Weissenfluh T 1985 Int. J. Heat Mass Transf. 28 1563–1574