Inductive level sensor: experiment and calculation

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Abstract. A non-contact induction technique for registering the free surface position of liquid metal is studied numerically and experimentally. A localized inductive level sensor (ILS) generates an alternating magnetic field and measures the resulting magnetic field. If an electrically conductive medium appears in the sensitive area of the sensor, this field changes. In the experiment, signals from the ILS were measured for a rotating cylinder with a beveled upper boundary, for different frequencies of alternating current, supplying the sensor generating coil. A set of calibration curves was obtained, that can be used to determine the cylinder rotation angle from the signal. In the numerical simulations, the three-dimensional fields of magnetic induction were obtained. The influence of the alternating current frequency, as well as the cylinder rotation angle on the ILS measurement, was studied. Numerical simulations show that increasing current frequency results in higher ILS sensitivity. The numerical and experimental results are in agreement. The developed technique is applicable for measuring the oscillation frequency of the liquid metal free surface.

1. Introduction
An integral part of many technological industries is the constant monitoring of certain process parameters. It can be a variety of physical parameters that are typical to a specific task. However, of particular interest is the industry associated with electrically conductive media, namely, with liquid metals. In such problems, an additional parameter is the position of the free surface of the melt. It is important to determine the position and shape of its free surface, for example, during continuous casting of metal. In the development of liquid-metal batteries [1], it is also important to monitor the shape and position of the metal-electrolyte interface in order to evaluate the effect of various factors on the stability of the multilayer structure. Classical ultrasonic and optical methods in this case are not applicable, due to high temperatures, optical opacity and, as a rule, high aggressiveness of the medium.

The most obvious way to determine the level of liquid metal in a tank is a conductive method. However, in application to metallurgical problems it may have insufficient accuracy, owing to the formation of oxide caps on the melt surface. Another method is the inductive one, based on the excitation of eddy currents in a metal and the subsequent measurement of the resulting magnetic field. Already there are industrial devices based on this method for measuring, for example, the level of aluminum [2] and steel [3] melts. At the same time, the disadvantage of such systems is the need to place the sensor directly in a container with liquid metal, above its surface. As a result, the sensors are exposed to high temperatures and metals, which complicates their design and use. There are alternative configurations of such devices [4], however, they are rather narrow-profile and are developed for a specific installation. In addition, such systems also cannot guarantee adequate measurement accuracy.
It should be noted that there are measuring devices of yet another configuration [5], allowing non-contact measurement of the position of the free surface of liquid metal, while the same sensor can be used on different installations. A set of such inductive level sensors (ILSs) provides a picture of the two-dimensional structure of the melt free surface, which is similar to the idea of magnetic tomography. However, at the moment there is only information about the prototype of this sensor. Also, in [5], studies were performed on a gallium alloy in a liquid state at room temperature and a transparent non-conductive wall, while in real industrial applications, the material of containers is usually opaque and electrically conductive.

The possibility of detecting vibrations of the free surface of a liquid metal using an inductive level sensor (ILS) is studied numerically and experimentally in this paper. In numerical and laboratory experiments, the distorted free surface of a conducting medium is modeled using a beveled cylindrical body made of duralumin.

2. Methods

2.1. Experimental setup

A solid duralumin cylinder with a beveled upper surface acts as a model for the rotation of the free surface of a liquid metal (see Fig. 1). The bevel angle is 45 degrees. The cylinder is mounted on a platform that is connected to an electric motor. Opposite the cylinder, an inductive level sensor (ILS) is installed coaxially with the radial axis at the height of the middle of the bevel.

The sensor is a system of three coils connected in series and coaxially. With the central coil magnetic field is generated, and the two outer coils are measuring. The generating coil contains 50 wicks of enameled wire with a diameter of 1.12 mm. Each of the measuring coils consists of \(~1300\) wicks of enamel wire with a diameter of 0.3 mm. The external dimensions of the sensor are \(72 \times 46 \times 42 \ mm^3\). A more detailed description of the inductive level sensor is presented in [6].

The ILS is placed on three mutually perpendicular micrometric platforms, which allow moving the sensor up to 50 mm in each direction. Using a sinusoidal signal generator (GZ-109), alternating current is supplied to the sensor generating coil. Two measuring and one generating coils of ILS are connected to the National Instruments data acquisition boards (NI9225 and NI9227), through which experimental data is recorded using the LabView system.

![Figure 1. Experimental setup: 1 – National Instruments data acquisition boards; 2 – inductive level sensor (ILS); 3 – duralumin cylinder with a beveled upper surface; 4 – generator of a sinusoidal signal; 5 – micrometric platforms; 6 – computer with a LabView system; 7 – rotating platform](image-url)
The distance between the side surface of the cylinder and the ILS does not exceed 1 mm. The “peak” of the beveled cylinder corresponds to a polar angle equal to 180°. In the experiment, the ILS output signal from the angle of rotation of the beveled cylinder is studied at various values of the frequency of the alternating current on the generating coil. The effective value of the current is 1.5 A. During the experiment, a specific angle of rotation of the beveled cylinder is set. The value of the alternating current (AC) frequency on the generating coil is set and the output signal of the ILS is recorded. Then the AC frequency value changes and the measurement is repeated (ν ∈ [20, 600] Hz). Next, the beveled cylinder is rotated at a certain fixed angle and the series is repeated. The angle of rotation of the beveled cylinder occurs in the range from 0 to 350 degrees in increments of 10.

2.2. Numerical simulations

Numerical simulations are carried out using the Ansys Emag software. The computational domain consists of the cylinder 1, beveled at an angle of 45° (see Fig. 2) and a generating coil 2, surrounded by a non-ferromagnetic non-conductive space. The ILS consists of a generating coil, sandwiched between two measuring coils, is 1 mm away from the cylinder and is positioned so that its axis of symmetry passes through the center of the beveled surface of the cylinder. An unstructured mesh, consisting of triangular elements with maximum linear size of 5 mm is used. The rotation of the cylinder is determined by angle α, as pictured in Fig. 2b.

The dimensions and material parameters of the model are selected in accordance with the experimental study. Namely, D16 duralumin with conductivity of σ = 26 · 10^6 S m^-1 is used as the material of the cylinder. The cylinder diameter is D = 0.172 m, the height is H = 0.222 m. The generating coil has 50 wicks of wire, and the effective current value is 1.5 A. The coil size is determined by three parameters: the inner and outer radii R₁ = 0.006 m and R₂ = 0.015 m, respectively, as show Fig. 2c. The thickness of the generating coil is 0.006 m.

![Figure 2. Computational domain scheme](image)

The Cartesian coordinate system (see Fig. 2a), the origin of which is located in the center of the cylinder bottom end face, is used in calculations and results interpretation. The Oz axis of this system coincides with vertical symmetry axis of the cylinder, and the Oξ axis is pointed to the sensor.

3. Results

3.1. Experiments

Based on the experiments, the dependencies of the ILS output signal on the angle of rotation of the beveled duralumin cylinder are constructed (see Fig.3).
The value of $D_{pd}$ is defined as the difference of the root mean square voltage values on the measuring coils of the sensor. As can be seen from the figure 3, with increasing frequency of the alternating current on the generating coil, the sensitivity of the inductive level sensor increases. Qualitatively, the dependencies are identical and have a sigmoidal appearance. The maximum of the function $D_{pd}(\alpha)$ corresponds to the state when the peak of the beveled cylinder is at the smallest distance from the sensor, otherwise, the function takes the minimum value.

Thus, it is possible to introduce the normalized function $F(\alpha)$, which takes on a zero value when there is no metal opposite the working side of the sensor (the beveled surface of the cylinder is far) and a unit value when the peak of the beveled cylinder is opposite the sensor (see Fig.4).

From the obtained dependence $F(\alpha)$, it is possible to restore the position of the beveled surface of the cylinder at any time during its continuous rotation. In this case, the sensitivity of ILS depends both on the frequency of the alternating current on the generating coil of the sensor and on the speed of rotation of the beveled cylinder.

The measurements for the remaining angles of rotation of the beveled cylinder ($\alpha \in [180, 350]^\circ$) are mirror symmetric and coincide within the measurement error, which does not exceed 7% (for an alternating current frequency of 20 Hz). With increasing frequency of the alternating current on the generating coil, the relative measurement error decreases. The measurements were carried out for various AC frequencies up to 600 Hz. Qualitatively, the dependencies are similar to those presented above.

Figure 3. The output signal of the sensor for different angles of rotation of the beveled cylinder at different frequencies of alternating current on the generating coil.
3.2. Numerical simulations

The cases of different electric current frequencies on the generating coil are considered for each angle $\alpha$ in the range from 0 to 140 degrees. A three-dimensional fields of magnetic induction $\vec{B}$ are obtained. The imaginary part of the magnetic field $x$-component Im $B_x(x)$ is used in results analysis. If there is no metal in the ILS proximity, then there is no induced field, thus $\text{Im} \, B_x(x) = \text{const}(x) = 0$.

Fig. 5 shows the example of the Im $B_x(x)$ profiles, plotted for different cylinder rotation angles $\alpha$. As follows from Fig. 2b, the case $\alpha = 90^\circ$ corresponds to the metal-air interface. At this value of $\alpha$ there is a moderate deformation of the resulting magnetic filed profile, which intensifies with a further increase in the rotation angle. That is, the profile deformation is higher when there is more metal in the ILS sensitivity area.
To quantitatively describe this result, the function \( f(\alpha) \) is introduced as follows:

\[
 f = |U(B_x(X - \delta)) - U(B_x(X + \delta))|,
\]

where \( U(g(X - \delta)) \) is the average value of some arbitrary function \( g(x) \) on the interval \([X - \delta; X]\) (see Fig. 6). In this study \( X \) is assumed to be the coordinate of the sensor center (generating coil), that is, \( X = 0.110 \) m. The parameter \( \delta = 0.013 \) m is selected as the distance between the centers of the generating coil and measuring coils. In the following, the value of the normalized function \( f \) will be denoted as \( F \). That is, \( F = 1 \) means that the maximum amount of metal is located near the sensor. The metal-air interface corresponds to some intermediate value (between 0 and 1), which is found in the sensor calibration process.

**Figure 6.** To the definition of the function \( F \)

In the initial position of the sensor, that is, when \( \alpha = 0^\circ \), the least amount of conductive medium is located in the sensor sensitivity area. This case corresponds to \( F = 0 \), as shown in Fig. 7. In this Figure, the dependencies \( F(\alpha) \) for several considered frequencies \( \nu = 10, 60, 100 \) and \( 300 \) Hz are pictured. Here the lines correspond to numerical results, and the symbols \( \ldots \) to experimental ones. With an increase in the angle \( \alpha \), a gradual increase in the value of \( F \) occurs, which sharply increases when approaching \( \alpha = 90^\circ \). In this position, the axis of the ILS is parallel to the beveled plane of the cylinder. This position corresponds to the metal-air interface case. With further rotation of the cylinder, the value of \( F \) tends to 1, because in this range of \( \alpha \) the change in metal amount near the sensor is small. It can also be seen from the Figure that for small angles (below 80 degrees) the data practically do not differ. At the same time, when approaching the value \( \alpha = 90^\circ \), the function \( F \) value is larger, the higher is the electric current frequency. This means that increasing the frequency \( \nu \) can result in higher ILS sensitivity. It should be noted, that in real industrial applications, where liquid metal is placed in a container with conductive walls, one has to make sure that the skin layer is greater than the thickness of the container wall.
4. Conclusions

The possibility of determining oscillations of the metal-air interface by an inductive level sensor (ILS) is studied numerically and experimentally. The interface was modeled by a duralumin cylinder, beveled at angle of 45°, rotating around its vertical axis. The position of the ILS was chosen so that the direction of its sensitivity passes though the center of the cylinder beveled surface. The calculation parameters are chosen in accordance with the experimental study. Various alternating current frequencies on the generating coil were considered, ranging from 10 to 600 Hz. In the experiments, the signals from the ILS are obtained, as well as the set of sensor calibration curves. The three-dimensional fields of magnetic induction are obtained in numerical simulations.

It is shown that the ILS of considered configuration allows to determine the presence of metal near the sensor. The sensitivity of the ILS depends on the electric current frequency on the generating coil. Namely, the best sensitivity was observed for the highest frequencies considered. The numerical and experimental results are in agreement.

Using an array of such sensors, after calibrating them for a given application, can determine not only the level of liquid metal in the container, but also the position of the free surface of the melt at each time point. Thus, this technique can be applied to measure the oscillation frequency of the free boundary of a liquid metal.

References

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