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Calibration of the Lorentz Force Flowmeter

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Abstract

Lorentz force velocimetry is an innovative technique for non-contact measurement of the flow rate in electrically conducting fluids like high-temperature liquid metal alloys. In this work the metrological characteristics of a Lorentz force flowmeter and calibration equipment are presented. Estimating the input and output quantities of the mathematical model of calibration the accuracy of the flowmeter can be obtained.

Introduction

When a liquid of electrical conductivity σ flows at mean velocity $\mathbf{u}$ into an externally applied stationary magnetic field $\mathbf{B}$, eddy currents $\mathbf{j}$ are induced within the liquid. As the result of the interaction of these currents and the applied field, Lorentz forces $\mathbf{F}_\mathrm{L}$ are generated. These Lorentz forces tend to break the flow. This well known electromagnetic braking effect is described by the equations of magnetohydrodynamics

$$\mathbf{j} = \sigma (\mathbf{E} + \mathbf{u} \times \mathbf{B}), \mathbf{F}_\mathrm{L} = \mathbf{j} \times \mathbf{B}. \tag{1}$$

Here, $\mathbf{E}$ is the electrical field. In turn, by the Newton's 3rd law, the moving liquid exerts a counter force of equal strength on the system that generates the magnetic field [1]. Lorentz force velocimetry is based on the measurement of this counterforce as, by equations (1), it is proportional to the flow-rate of the liquid [2, 3]. To apply Lorentz force velocimetry to metallurgical processes like production of the secondary aluminum and steel casting, calibration of such flow-meters is necessary.

1. Scheme of Calibration of LFV

The scheme of calibration of Lorentz force velocimeter is drawn in Fig. 1. Here, a solid aluminium bar 1 is pushed by a motor 2 at a constant speed v through the magnetic system 3. The force F_L is measured using a digital strain gage 4. The signal from the force sensor is amplified and, after analog/digital conversion, is registered by the acquisition system on PC basis. The data processing module is based on LabView® software.

2. Mathematical model of calibration

The force F_L measured by the sensor can be represented by the linear equation

$$F_i = K_1 \cdot E_i, \tag{2}$$

where E_i is the instant level of the sensor signal and K_1 is the calibration factor.

Also, using equations (1), the measured velocity u_i can be represented by

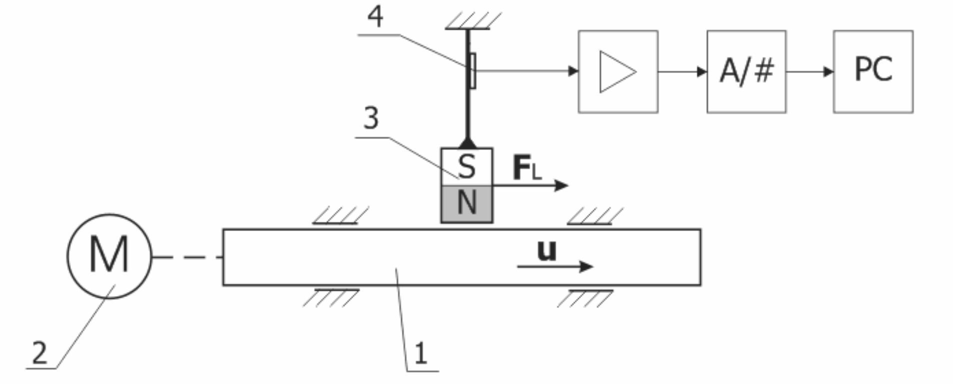

Fig. 1. Scheme of calibration of Lorentz force velocimeter:
1 – aluminium bar, 2 – drive, 3 – magnetic system, 4 – Lorentz force sensor

$$u_i = \frac{K_2 \cdot F_i}{\sigma \cdot B^2}, \tag{3}$$

where K_2 – is another calibration factor taken to be constant. Magnetic field in our case is significantly inhomogeneous with variation up to 40% from the center to the periphery of the magnetic system. Hence it is impossible to consider parameter B as a constant as it will depend on the height of the block. Moreover, it is impossible to separate the variables K_2 and B. We introduce a new calibration constant K_3 in a form

$$K_3 = K_2 / B^2. \tag{4}$$

The aim of the calibration measurement is to evaluate the values and uncertainties of the factors K_1 and K_3 as well as the sensitivity of the measurement with respect to uncertainties of determination of σ.

2.1. Calibration factor K_1

In a first step, initial level of output signal from the force sensor E_0 is registered without application of an external force. As an averaged value $\overline{E}_0$ and the uncertainty U_{E0} we obtain [4]:

$$\overline{E}_0 = \frac{1}{n}\sum_n E_{0i}\,,\; U_{E0} = \sqrt{\frac{1}{n-1}\sum_n (E_{0i} - \overline{E}_0)^2}\,. \tag{5}$$

The next step is application of the maximal force. The uncertainty of measurement U_{EMAX} for the sensor signal E_{MAX} is evaluated using the same procedure as above. Finally, the averaged value of the calibration factor K_1 is given by

$$\overline{K}_1 = \frac{\overline{F}_{MAX}}{\overline{E}_{MAX} - \overline{E}_0}. \tag{6}$$

For the sensitivity coefficients we obtain

$$c_{FMAX} = \frac{1}{\overline{E}_{MAX} - \overline{E}_0}\,;\; c_{EMAX} = -\frac{\overline{F}_{MAX}}{(\overline{E}_{MAX} - \overline{E}_0)^2}\,;\; c_{E0} = \frac{\overline{F}_{MAX}}{(\overline{E}_{MAX} - \overline{E}_0)^2}\,. \tag{7}$$

And finally for the uncertainty of measurement of K_1 we have

$$U_{K1} = \sqrt{(\overline{K}_1 \cdot U_{NLS})^2 + \left(c_{FMAX} \cdot U_{FMAX}\right)^2 + \left(c_{E0} \cdot U_{E0}\right)^2 + \left(c_{EMAX} \cdot U_{EMAX}\right)^2}\,. \tag{8}$$

2.2. Velocity u of the reference bar

The velocity of the reference bar is given by:

$$u_{RB} = \frac{L}{t}\,.$$

Here *L* is the displacement of the bar and *t* is the duration of this displacement. The displacement *L* is defined by the step-drive positioning system. Its uncertainty U_L is given in technical specifications. For time and its uncertainty we obtain:

$$t = \bar{t} = \frac{1}{n}\sum_n t_i\,,\; U_t = \sqrt{\frac{1}{n-1}\sum_n (t_i - \bar{t})^2}\,.$$

The sensitivity coefficients are defined by:

$$c_L = 1/t\,,\; c_t = \ln L\,.$$

Finally, the resulting uncertainty of measurement of u_{RB} is given by:

$$U_{URB} = \sqrt{\left(\frac{1}{t}U_L\right)^2 + (U_t \ln L)^2}\,.$$

2.3. Electrical conductivity σ

In case of aluminium bar the electrical conductivity is provided by the supplier. However, in application the determination of σ is a difficult as σ depends strongly on temperature and on the alloy composition [5]. We consider different approaches to overcome this problem: in-situ electromagnetic measurement of σ, thermophysical property database and others. Results of these approaches will be given elsewhere.

2.4. Calibration factor K₃

Introducing (4) into (3) we obtain

$$u_{RB} = \frac{K_3 \cdot K_1 (E_{URB} - E_0)}{\sigma}\,.$$

Here, E_0 and E_{URB} – sensor signal amplitude for zero velocity and definite velocity respectively; K_3 – linear function scale coefficient. Velocity of the reference block and its uncertainty is known. Estimates $\overline{E}_{URB}$ and $\overline{E}_0$ the respective uncertainties of measurement are evaluated using equations (5), (6). Estimate $\overline{K}_3$ is calculated using the following equation:

$$\overline{K}_3 = \frac{\overline{u}_{RB} \cdot \sigma}{\overline{K}_1 (\overline{E}_{URB} - \overline{E}_0)}.$$

To obtain the equations for the sensitivity coefficients and the uncertainties the same approach can be used as for equations (7), (8).

Linearity of the sensor signal vs. velocity for a given constant cross-section of the bar is proven in our experiments.

Conclusions

In this article the procedure of calibration of Lorentz force velocimeter using solid aluminium bars is presented. We present a mathematical calibration model that allows to evaluate the relevant calibration factors and to give estimates of the uncertainties of the measurement. For precise measurement in metallurgical applications, extended calibration measurement are necessary to account for inhomogeneous distribution of the velocity field and for temperature variations.

References

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