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LORENTZ FORCE VELOCIMETRY USING ELECTROMAGNETIC FORCE COMPENSATED LOAD CELLS

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Abstract: This paper discusses the flow rate measurement of poorly conducting fluids (such as electrolytes) using Lorentz force velocimetry (short: LFV).

The Lorentz force caused by the moving electrolytes is in the range of micronewton. This tiny Lorentz force is determined using a high resolution force measurement systems based on electromagnetic force compensated (short: EMC) load cells.

In this paper the force measurement system, the principle of LFV and the environmental influences on this kind of force measurement system are described.

Keywords: electromagnetic force compensation, load cells, Lorentz force velocimetry, flow measurement

1. INTRODUCTION

The Lorentz force velocimetry is a novel flow rate measurement technique enabling a contactless measurement of hot and chemically aggressive fluids such as molten metals. The moving charge carriers such as electrons in molten metal or ions in electrolytes with an electrical conductivity σ and an external magnetic field with a magnetic field strength B causing eddy currents with a current density j in the fluid. The electrical field strength E is zero in this case.

$$\vec{j} = \sigma\left(\vec{E} + \vec{u} \cdot \vec{B}\right) \quad (1)$$

These eddy currents and the magnetic field strength causing the Lorentz force F_L in the measurement volume V_{Fl}.

$$\vec{F}_L = \iiint_{V_{Fl}} \left(\vec{j} \times \vec{B}\right) dV \quad (2)$$

An approximation for the solution of equation (2) results for the Lorentz force.

$$F_L = c_{Fl} \cdot u \cdot \sigma \cdot V_{Fl} \cdot B^2 \quad (3)$$

The Lorentz force is proportional to the velocity of the fluid its electrical conductivity, the measurement volume, the square of the magnetic field strength and a constant c_{Fl} [1]. This constant combines the shape of the magnetic field, the shape of the measurement volume and other influences.

The Lorentz force velocimetry of molten metal is well investigated and on a level of successful field experiments [2]. Here the Lorentz force is in the range of several milli Newton [3]. Hence the electrical conductivity of electrolytes is several orders of magnitude lower the measured Lorentz force is consequently much smaller than on molten metals. The Lorentz force is in the range of some micro Newton for electrolytes. Therefore a high resolution force measurement is needed such as EMC load cells.

2. FORCE MEASUREMENT

2.1. Measurement Setup

The generated Lorentz force is also proportional to the square of the magnetic flux density. This magnetic field is generated by a magnet system consisting of NdFeB (neodymium-iron-boron) permanent magnets. The mass of the magnet system is limited to m_0 = 1 kg. This results in a gravity of approximately F_G = 10 N. Hence the Lorentz force is up to seven orders of magnitude lower than the gravity the direction of the acting Lorentz force is decoupled from the gravity. The gravity always acts in vertical direction therefore the Lorentz force has to act in horizontal direction. Figure 1 shows the measurement setup.

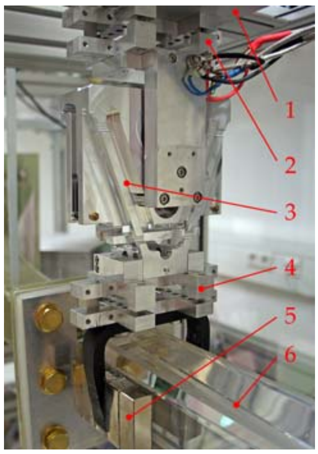

Figure 1: Setup of the Lorentz force flow meter
1 – frame, 2,4 – adjusting elements, 3 – EMC load cell, 5 – magnet system, 6 – channel

The electrolyte is salt water and flows in horizontal direction through the channel. The electrical conductivity of the fluid can be changed by the concentration of dissolved salt (NaCl) in a range of σ = 0…6 Sm^{-1}. The flow velocity is variable in the range of u = 0…3 ms^{-1}.

2.2. Magnet system

The investigations were done for two types of magnet systems. The first one is made of two permanent magnets connected via a holder made of carbon fibre composite. The second magnet system is a so called Halbach array which consists of two times five permanent magnets resembling two Halbach arrays. Those two Halbach arrays are also connected by a holder made of carbon fibre composite (see Figure 2).

Figure 2: Used magnet systems, left classical magnet system, right magnet system with Halbach arrays

The carbon fibre composite used as it has a very low mass. The normally used iron yoke is too heavy as a lot of material is needed to guide the high magnetic flux. Both magnet systems have a mass of approximately 1 kg.

The Halbach array magnet system has a much lower stray field than the classical magnet system and a better distribution of the magnetic field. Simulations have shown, that the Halbach array magnet system should increase the generated Lorentz force by the factor of 2.8 [4].

2.3. Measurement results

The acting Lorentz force with was measured with the classical magnet system is shown in figure 3. The measurement was performed for several different electrical conductivities ($\sigma_1 = 2.03$ Sm^{-1}, $\sigma_2 = 4.06$ Sm^{-1}, $\sigma_3 = 6.06$ Sm^{-1}).

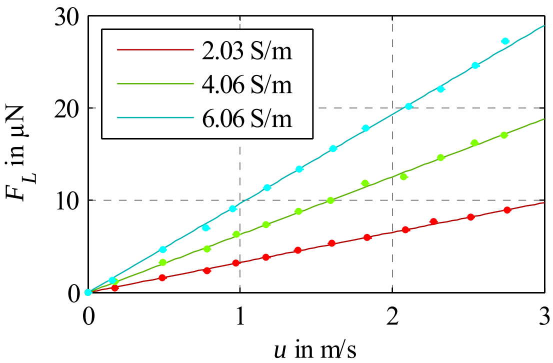

Figure 3: Measured Lorentz force F_L versus flow velocity u and electrical conductivity σ

The Lorentz force depends linear on the flow velocity u. The slope of the curves is sensitivity of measurement system:

$$E_L = \frac{F_L}{u} \tag{4}$$

The sensitivity of the measurement system versus the conductivity of the fluid is shown in figure 4.

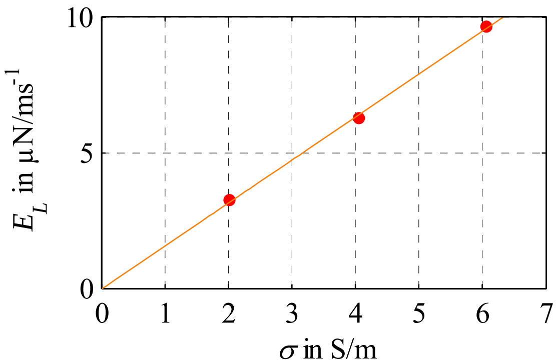

Figure 4: Sensitivity of measurement system E_L versus electrical conductivity of fluid σ

The Lorentz force also depends linear on the electrical conductivity of fluid.

The measurement proofs the theory described by equation 3.

Figure 5 depicts the measured Lorentz force by the given fluid velocity with an electrical conductivity of $\sigma = 6.06$ Sm^{-1}. The red curve is the measurement system with the classical magnet system and the green curve with the magnet system with Halbach arrays.

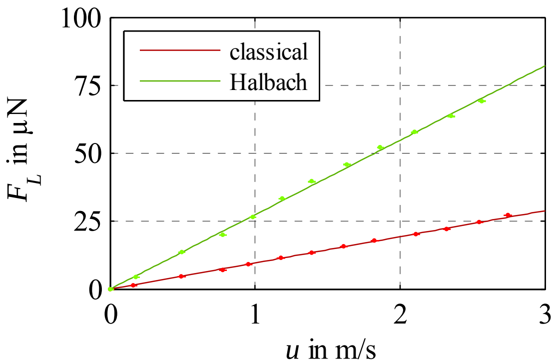

Figure 5: Measured Lorentz force FL versus velocity of fluid u and the magnet system (red: classical magnet system, green: Halbach array magnet system)

The measured Lorentz force with the Halbach array is increased by the factor of 2.8 compared to the measurement system using the classical magnet system. This corresponds to the simulation.

3. ENVIRONMENTAL INFLUENCES

3.1. Tilting of measurement setup

The Lorentz force acts in horizontal direction and the weight of the magnet system in the direction of gravity. If the measurement setup tilts by an angle φ, a component of the weight of the magnet system acts as a force due to tilting in the direction of the Lorentz force resulting a measurement error (see figure (6)).

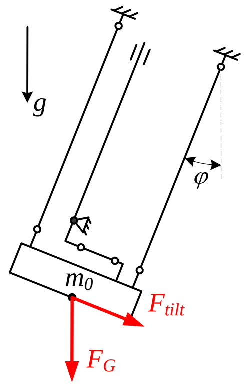

Figure 6: Tilted measurement system, F_G – weight of magnet system, F_{tilt} – force due to tilting, φ – tilt angle, m_0 – mass of magnet system, g – gravitational acceleration

The force due to tilting F_{tilt} can be expressed as:

$$F_{tilt} = m_0 \cdot g \cdot \sin\varphi \qquad (5)$$

As the mass of the magnet system is approximately $m_0 = 1$ kg a small tilting angle in the micro-radiant range causes force in the range of some micro Newton which corresponds to the measurement range of the Lorentz force (see measurements above).

The whole measurement system was tilted by an angle φ to investigate this influence on the measurement of the Lorentz force. The tilting was recorded by a commercial inclinometer (Leica Nivel 210) with a resolution of 1 µrad [5]. Figure 7 depicts this measurement and also shows the influence of the mass of the magnet system m_0.

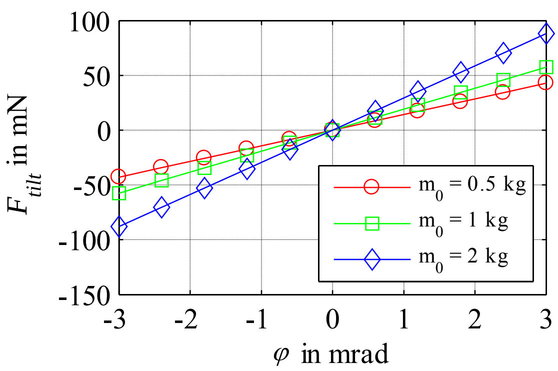

Figure 7: Force due to tilting F_{tilt} versus the tilting angle φ and different masses of the magnet system.

The measurement shows clearly that the force due to tilting depends linear on the tilting angle and the mass of the magnet system.

3.2. Temperature Influences

The change of the ambient temperature causes a thermal expansion of all parts. Measurements have shown that the temperature distribution in the room varies by 2 °C by the use of the fluid channel. This heating is causing a thermal expansion of the supporting frame of the measurement system consequently the supporting frame expands. An expansion of the frame is causing a tilt of measurement system. If this tilting is in the direction of the Lorentz force it causes the force due to tilting described above. Figure 8 shows the supporting frame and its thermal expansion in principle.

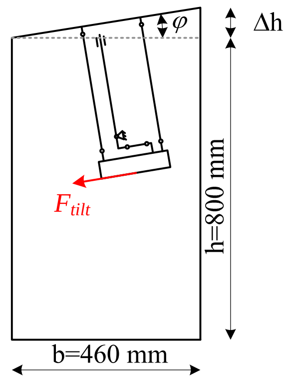

Figure 8: Principle of thermal expansion Δh of supporting frame causing a tilting angle φ

The tilting angle φ due to the thermal expansion Δh by the temperature change of T is described by equation 6.

$$\varphi = \tan \frac{h \cdot \alpha_{Al} \cdot T}{b} \qquad (6)$$

The coefficient of thermal expansion of aluminium is $\alpha_{Al} = 23$ ppm K^{-1}.

As the thermal expansion is very small the small-angle approximation can be used. By the given length h and width b of the supporting frame the tilting angle can be estimated to:

$$\varphi = 40 \ \mu rad \ K^{-1} \cdot T$$

By using equation 5 for the force due to tilting this force is approximately:

$$F_{tilt} = 392 \ \mu N \ K^{-1} \cdot T$$

This is a rough estimation of the thermal influence if one side is heated up more than the other. In practice there is a temperature distribution in the supporting frame as well as other temperature influences which can't be calculated.

Figure 9 shows the temperature in the supporting frame and the measured force.

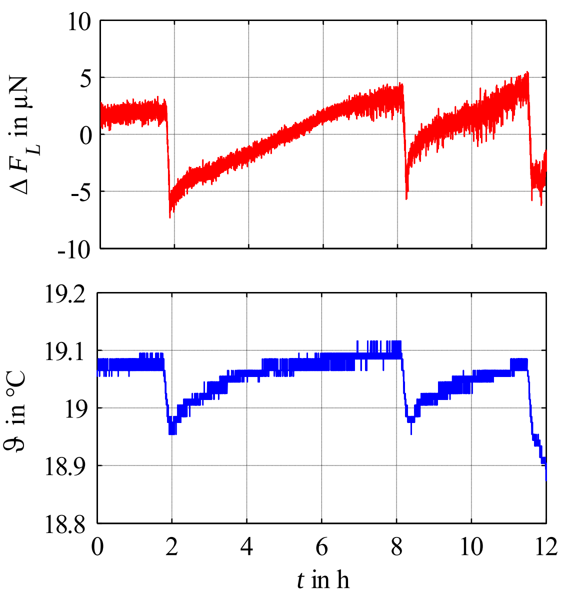

Figure 9: Change of Lorentz force F_L over time (top) and temperature (bottom)

The correlation between the temperature and the Lorentz force is approximately 75 %. The temperature coefficient for the measurement shown above is:

$$F_L = 38.1\ \mu\text{N K}^{-1} \cdot T$$

Additional environmental influences are the temperature coefficient of the magnetic material of the magnet system used for Lorentz force velocimetry as well as the magnet of the EMC load cell. The EMC load cell is also sensitive to changes of temperature and humidity. These influences can be compensated by the known temperature and humidity coefficients of the system.

3.3. Compensation of environmental influences

In a next step the force measurement system is equipped with a compensation system. Therefore a second, identical EMC load cell is attached near to the first one and equipped with a dead load with the same mass of the magnet system. This second EMC load cell will measure the tilting and other environmental influences the same as the measurement system does. It will not measure the Lorentz force as the dead load is non magnetic. This method could improve the measured Lorentz force signal by subtracting both signals.

4. CONCULSION

A measurement system based on an EMC load cell was used to measure the Lorentz force caused by a low conducting fluid using Lorentz force velocimetry.

The measurements have shown that the Lorentz force is in the range of some micro Newton for fluids with an electrical conductivity of $\sigma \leq 6.06$ Sm^{-1} and a velocity of $u \leq 3$ ms^{-1}. The Lorentz force is proportional to the velocity and the electrical conductivity of the fluid.

A main environmental influence on the measurement is the tilting of the measurement system which is caused e.g. by thermal influences. It was shown that small differences in the temperature distribution cause a significant influence on the measured force. Therefore a compensation system was presented enabling a compensation of the tilting effects.

5. ACKNOWLEDGEMENTS

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