

INVESTIGATION TO THE TILT SENSITIVITY OF THE LORENTZ FORCE VELOCIMETRY SYSTEM FOR THE FLOW RATE MEASUREMENT OF LOW CONDUCTING FLUIDS

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Abstract: In this paper a force measurement system is discussed, among others its main application is for the flow rate measurement of conducting fluids by the method of Lorentz force velocimetry. The system is designed to measure forces with high resolution in horizontal direction on the 1 kg dead load using high precision weighing balances. The influences of the tilt on the setup are investigated, in order to minimize this effect various sets of cross-checking test measurements are carried out and presented here using several counter-balancing techniques.

Keywords: force measurement, tilt sensitivity, Lorentz force, high dead load.

1. INTRODUCTION

This paper discusses the force measurement system, whose main application is the flow rate measurement of conducting fluids by Lorentz force velocimetry (LFV) technique [1]. There are known and are widely used several methods for velocity measurements of the flows such as particle image velocimetry (PIV) and ultrasound Doppler velocimetry (UDV). However, they have certain limitations when the flow is opaque, or has high temperature or when it is chemically aggressive. Therefore the LFV technique suggests a non-contact measurement method which is expected to measure velocity of conducting flows in critical industrial situations.

The physical implementation and the functionality of the LFV have been introduced in several papers previously (such as [1] and [2]). The channel with electrically conductive flow is located in the magnet field \vec{B} generated by a permanent magnet. In case when the conducting fluid with electrical conductivity σ flows in the channel with velocity v there will be a breaking force F_L acting on the flow according to Lenz's Law. The F_L depends linearly on the electrical conductivity σ , flow velocity v and the magnet field B in the second power:

$$F_L \sim \sigma v B^2 \quad (1)$$

With the knowledge of Newton's third law a force F'_L with the same magnitude but in the opposite direction will act on the magnet. With the force F'_L measured by a force measurement system the flow velocity v can be calculated.

In previous works the magnetic field was generated by a Halbach magnet whose weight is about 1 kg [3]. The Lorentz force generated by low conducting flows is

somehow in the range of Micro newton and below. Therefore the challenge for the force measurement setup is to measure small forces in horizontal direction in combination with high dead loads. We aim to measure small forces acting on the magnets (1 kg dead load) in horizontal direction with resolution of 10^{-9} N.

2. STATE OF THE ART

In the past few years the force measurement system (FMS) for LFV has been continuously developed and improved in TU Ilmenau. At first the force was measured by a pendulum carrying a magnet [2]. The displacement resulted by Lorentz force was detected by the interferometer. With this pendulum the force resolution of $2 \sim 3 \mu\text{N}$ was achieved. After that a single electromagnetic force compensation (EMFC) weighing cell as a robust system to measure the force was introduced and the resolution of about $1 \mu\text{N}$ [4] was achieved. To minimize the disturbances generated by surrounding environment, such as temperature, vibration and related other errors, the differential force measurement method was introduced. In that setup two EMFC weighing cells were used in vertically suspended position [6, 7]. One of the EMFC measures the Lorentz force with all associated errors while the second measures only the error signals. In this way the differential signal from the two weighing cells is the expected Lorentz force signal. With this method the resolution was improved to about 20 nN.

3. TILT SENSITIVITY OF EMFC WEIGHING CELL

Since the working principle of the balance is the compensation measurements of the proportional lever arm, therefore, in some cases the inclination of the measurement setup may result to measurement error due to imbalance of the lever arm. The influence of the inclination angle should be investigated in relation to different operational conditions and orientations of the entire mechanism of the balance and its coupling elements. To minimize or to eliminate this force measurement error several approaches can be considered, here we will focus on a) changing weight of the dead load, b) adding counterweights on the opposite arm of the lever, and c) controlling the inclination angle by high precision tilt stage on which the balance is adjusted.

The investigations on the force measurement setup have been made in combination with a high precision dual axis

tilt stage, which is developed in TU Ilmenau. This stage provides a range of the tilting angle within ± 17.6 mrad with a repeatability of $0.35 \mu\text{rad}$ [8]. In this work the tilt stage was used such to provide controllable tilt angles for the force measurement setup, at the same time, the output signal of the balance was recorded. Based on these measurements several useful operational characteristics of the setup have been determined, such as full measurement range, linearity, and tilt sensitivity. These EMFC weighing cells made by Sartorius are originally designed as a setup to measure the mass. This means that the force generated by any test weight is measured in gravity direction. In the differential force measurement method the two EMFCs are adjusted in suspended position in order to measure the force in horizontal direction. Due to these reasons we arranged a single EMFC weighing cell into four different configurations as it is shown in the figure 1, in order to test and investigate their functional performance.

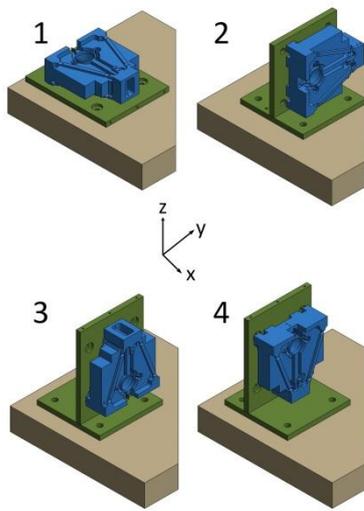


Figure 1: Measurement configurations, presenting four different orientation of the balance:
 1- common usage; 2- sidewise; 3- suspended and pointing upwards; 4- pointing downwards.
 (blue: balance, green: balance holder; brown: tilt stage).

The measurement processes of all four configurations are similar. In previous works [5, 6, 7], the EMFC weighing cell was used only in suspended mode as a pendulum (see figure 1, position 4). Here, in order to introduce the measurement procedure this configuration is taken as an example.

The tilt stage is controlled to generate inclination angles around one axis from -9 mrad to $+9$ mrad with 19 steps, at the same time the other axis is kept at static zero position. The force signal is measured during this process as shown in figure 2. This procedure was repeated five times.

It can be deduced from figure 2 that the inclination (blue line in the upper figure) results in a virtual force signal (black line in the lower figure). The output force signal changes according to the inclination even though no external force was acted on the weighing cell. This is due to imbalanced lever arm of weighing cell, whose simplified mechanical configuration is presented in figure 3.

The weight of the weighing pan is m_1 and on the other side there is a counter weight m_2 . In case of

$$m_1 \cdot g \cdot \sin \alpha \cdot L_1 \neq m_2 \cdot g \cdot \sin \alpha \cdot L_2 \quad (2)$$

(meanwhile $m_1 \cdot L_1 \neq m_2 \cdot L_2$), if the balance tilts by a small angle around y, the lever will be driven to rotation and the displacement will be detected by the position sensor, this will lead to the change in the output signal.

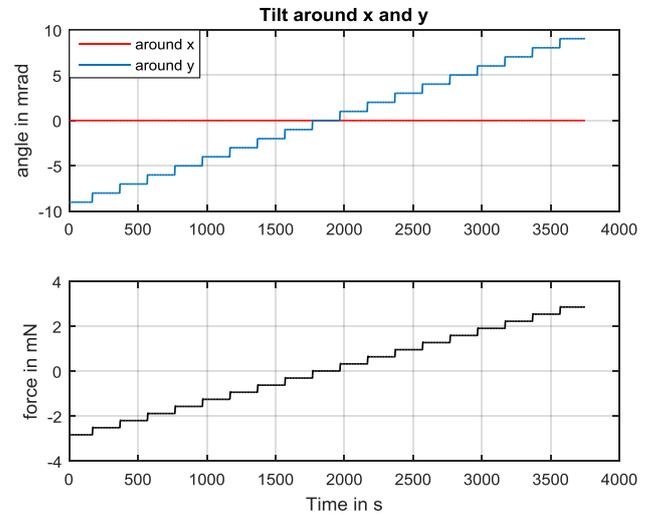


Figure 2: Tilt angle of both axis and the resulted force signal.

The amount of the change of the output force signal in relation to the tilt angle of the system is, thus, so called tilt sensitivity. From here one is able compute the tilt sensitivity of the system.

To minimize the tilt effect, a set of weights are added to the load pan or to the counterweight on the other side of the lever arm in order to change the value of m_1 or m_2 . Aim is to achieve the stationary zero balanced state, which means $m_1 \cdot L_1 = m_2 \cdot L_2$. The results are shown in figure 4. Different loads in the range from 0 g to 52 g are added consecutively on the system. Here the positive weight means that the weight is added on the weighing pan, as showed middle in figure 4. Negative weight means the weight is added on the counter weight on the other side of the level arm.

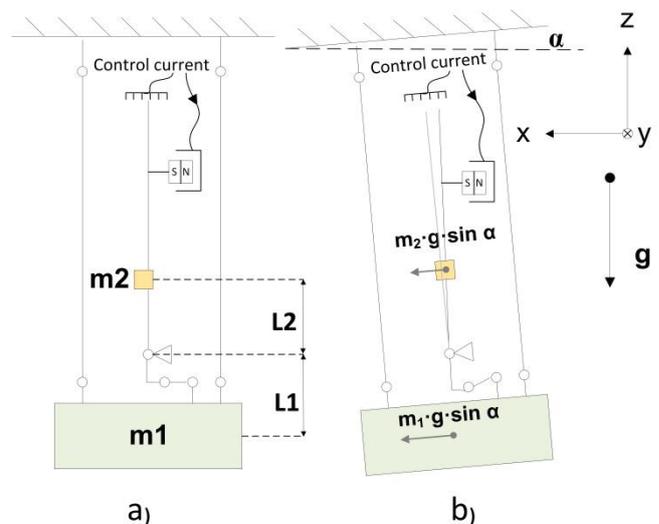


Figure 3: Mechanical diagram of the balance.

According to the experiment the tilt sensitivity has a linear relationship with the dead load. This is presented in figure 5, which shows a linearity slope of

$$T_{S_y} = -10.0717 \times m_0 + 314.5098 \text{ [mN / rad]}$$

T_{S_y} – Tilt sensitivity around y axis

m_0 – Dead load assembled on the weighing cell

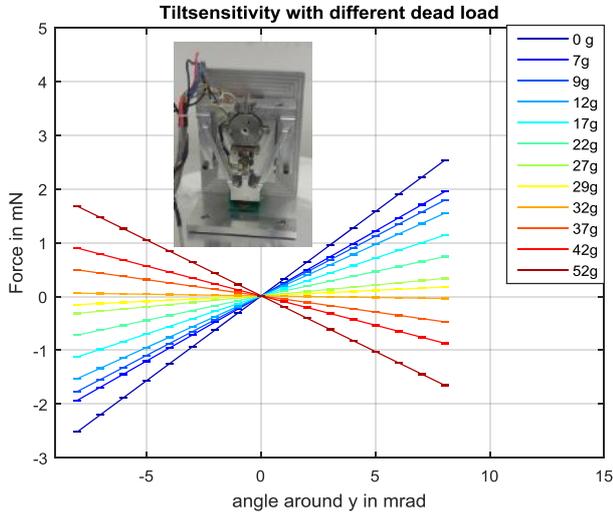


Figure 4: Measurement for the tilt sensitivity.

Then the weight of the dead load can be found when the tilt sensitivity is theoretically zero, that is $m_0 = 31.2271$ g. Using this result, a 31.2271 g weight can be added on the load pan to reduce the effect of inclination, and in this way the resolution of the force measurement system can be improved.

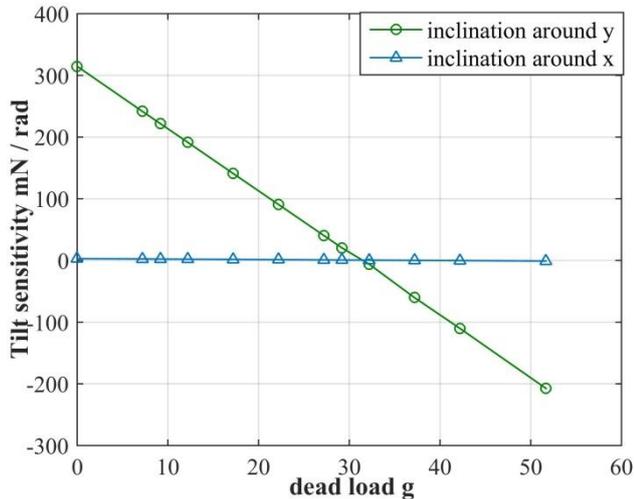


Figure 5: Tilt sensitivity with different dead load.

The same measurement process was made when the stage is tilted around x axis and the y is kept at static zero position. The experiment shows that the tilt sensitivity of the EMFC weighing cell for different dead load is:

$$T_{S_x} = -0.0758 \times m_0 + 2.9389 \text{ [mN / rad]}$$

The tilt sensitivity is much smaller compared to the y axis which is also indicated in figure 5. The reason is that the lever arm of the weighing cell has only rotational degree of

freedom around y axis. So it is insensitive against the angle around the x and theoretically the tilt sensitivity against the angle around x should be zero. In the measurement the tilt effect around x can be a result of the misalignment between the weighing cell and the tilt stage, therefore a cross sensitivity should be measured.

The measurements for the other three configurations have been carried out with the same procedure. All the results are shown in table 1.

configuration	T_{S_y} without deadload [mN/rad]	Weight to compensate [g]
1-common	-14.4 ± 0.15	-1.2562
2-sidewise	314.6 ± 0.19	31.2369
3-upwards	314.7 ± 0.47	31.1770
4-downwards	314.5 ± 0.06	31.2271

Table 1: Measurement results of the four configurations.

In table 1 is to be seen that for the configuration sidewise, upwards and downwards the tilt sensitivities T_{S_y} agree with each other and with an additional weight of about 31.1937 ± 0.0432 g the tilt effect can be minimized. For the common configuration there is an obvious deviation from the others.

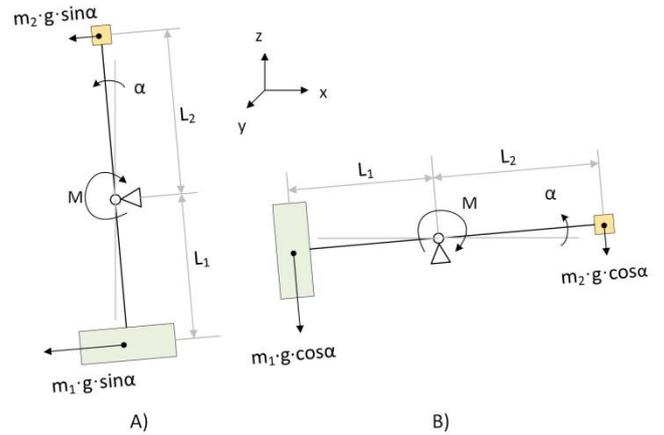


Figure 6: Compare tilt situation of four configurations.

The cause of the deviation in common configuration is shown in figure 6. Situation A) shows the downwards position while B) indicates the common position as a balance. The sidewise and upwards position can be considered as the construction in A) turns itself around x by 90° (sidewise) or 180° (upwards) and the calculation of the tilt force for these three configurations are same. In case of an inclination with an angle α , the motion of the lever is driven by a force/torque which depends on $\sin \alpha$ by configurations 2, 3 and 4, while it depends on $\cos \alpha$ in case 1. In the angle range of -9 mrad to 9 mrad the small angle approximation can be applied:

$$\sin \alpha \approx \alpha \quad (3)$$

$$\cos \alpha \approx 1 - \frac{\alpha^2}{2} \quad (4)$$

So in the tilt sensitivity in case 1 where it depends on α^2 is smaller than that in the other cases where the tilt sensitivity depends on α . Therefore, compared to configuration 2, 3 and 4 the common configuration has lower tilt sensitivity.

4. DEVELOPMENT OF A NEW SETUP

For the four configurations the tilt sensitivity of the balance with different dead loads has been determined. It was found that it is possible to minimize undesirable tilt sensitivity with changing the dead load.

Since for the Lorentz force velocimetry application the balance has to carry up to 1 kg dead load (magnet), to countervail this weight on the high precision balances is not generally desirable.

Therefore a new setup whose working principle is based on so called torsion balances will be developed. The structure of the new setup is shown in figure 7.

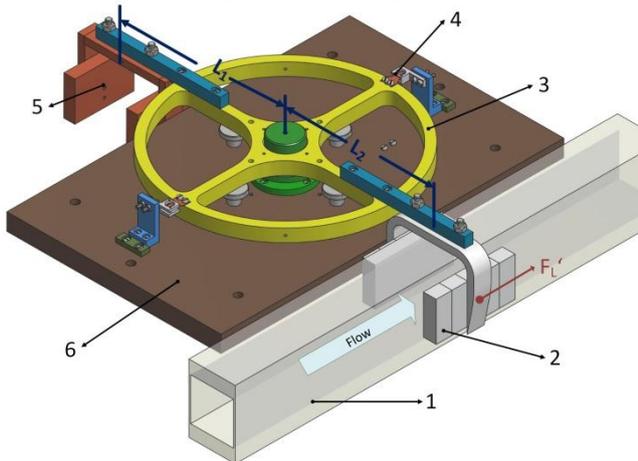


Figure 7: new force measurement system

(1-channel; 2-Halbach Magnet; 3-wheel;
4-position sensor; 5-copper dummy; 6-Base plate)

In case when the conducting fluid flows in the channel, the wheel will be driven to rotate and the motion will be detected by the position sensor. This displacement can be calculated into force signal when the stiffness of the system is known. A dummy weight made of copper (5) has the same mass as the Halbach magnet in order to balance the gravity force of the magnet. In comparison with the EMFC weighing cell this system shows a lower stiffness, which means that this system is more sensitive to the small force. Beside this, the wheel form provides the same arm length of L_1 and L_2 . Then in case that the magnet and dummy have the same mass, no additional weights are necessary to achieve the equation of $m_1 \cdot L_1 = m_2 \cdot L_2$. That means the system is theoretically insensitive to imbalanced and unequal lever arm inclination disturbances.

5. CONCLUSION AND OUTLOOK

In this work the tilt sensitivity of the EMFC weighing cell has been investigated with a set of experiments. The cause of the tilt sensitivity was found and a method to minimize this tilt effect by adding dead loads has been identified. By adding a certain weight on the weighing cell the zero tilt sensitivity is achievable.

Based on results achieved from tilt sensitivity of the force measurement setup, a new system has been developed which uses a principle commonly known as torsion balance. This new setup will have two main aims; to decrease the tilt

sensitivity of the measurements, and meanwhile it is expected to increase the resolution of the force measurement. Theoretically the new system is insensitive against the inclination. However, there can be some deviation due to intolerance in manufacturing capacitance. To ensure the functionality of the new system its tilt sensitivity together among other parameters will be investigated in the future.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

- [1] A. Thess, E. Votyakov and Y. Kolesnikov, "Lorentz force Velocimetry", *Phys. Rev. Lett.* 96 164501 (2006).
- [2] A. Wegfrass, C. Diethold, M. Werner, "Flow rate measurement of weakly conducting fluids using Lorentz force velocimetry", *Meas.Sci.Technol.*23 (2012).
- [3] M. Werner, B. Halbedel. Optimization of ndfeb magnet arrays for improvement of lorentz force velocimetry. *Magnetics, IEEE Transactions on*, 48(11):2925–2928, Nov 2012.
- [4] C. Diethold, F. Hilbrunner, "Force measurement of low forces in combination with high dead loads by the use of electromagnetic force compensation", *Meas.Sci.Technol.* 23 (2012).
- [5] S. Vasilyan, T. Ebert, M. Weidner, "Towards metering tap water by Lorentz force velocimetry", *Meas.Sci.Technol.* 26 (2015).
- [6] A. Wegfrass, C. Diethold, M. Werner, T. Fröhlich, B. Halbedel, F. Hilbrunner, C.Resagk, A. Thess. A universal noncontact flowmeter for liquids. *Applied Physics Letters*, 100(19):194103, 2012.
- [7] S. Vasilyan, M. Rivero, J. Schleichert, T. Fröhlich, "High-precision horizontally directed force measurements for high dead loads based on a differential electromagnetic force compensation system", *Meas. Sci. Technol.* 27 045107 (2016).
- [8] M.Rivero, M. Kühner, "High precision dual axis tilt stage", *IWK* 2014