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HIGH-RESOLUTION FORCE MEASUREMENT SYSTEMS: MEASURING HORIZONTAL DIRECTED FORCES FOR FLOW METERING OF LOW CONDUCTIVE MEDIA IN CHANNELS

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Abstract – Recent advance in flow metering of electrolytes through contactless method of Lorentz Force Velocimetry (LFV) demands application specific developments of high precision horizontal force measurement systems. In contrast to the measurand Lorentz force- directed horizontally and ranges as 10^{-8}-10^{-5} N -there is 10N vertically acting dead load accompanying measurements. In this work we present overview of two force measuring setups resolving these measurements particularly suitable for metering flow velocity of purely conducting liquids in channels. The first setup is based on principle of differential force measurements and uses two equivalent state-of-the-art *e*lectromagnetic *f*orce *c*ompensation (EMC) precision weighing balances in order to compensate mechanical vibrations and force drift. Measurement resolution of 20-30 nN in the range of up to 100uN is achived. The second, optimized, setup demonstrates applicability of measurement method for the same horizontal forces based on direct EMC principle. The term 'direct' in last indicating the fact that in the setup EMC is done using magnetic field of high power magnet system. Magnets are required component of LFV setup and are suspended from force measuring setup producing 10N unavoidable dead load.

Keywords: Lorentz Force Velocimetry, horizontal micro- and nano-forces, Electromagnetic force compensation, noncontact flowmeter.

1. OUTLINE

Recent advance in flow metering of electrolytes through contactless method of Lorentz Force Velocimetry[1,10] demands application specific developments of high precision Force Measurement Systems. A key ingredient of Lorentz Force Velocimetry is the measurements of the force onto magnet system while its magnetic field is transversely imposed to the velocity field of the flow.

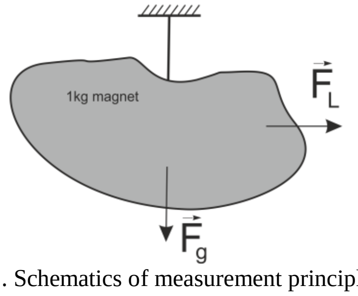

Fig.1. Schematics of measurement principle.

In contrast to the measurand force, which is in horizontal direction and typically ranges as 10^{-8}-10^{-5} N, there is dead load of magnets 10N vertically acting to the force measurement system (cf Figure 1).

In this work we present two systems [2, 3] and provide overview in terms of stand-alone measurement capabilities of - single axis - horizontal directed - ultraprecise forces. Experimental results are presented in metering electrolyte (conductivity 0.1-10S/m) flow in 50x50mm and 26x46mm rectangular channels for velocities 0.2-4m/s. Measurements are provided, for the first system by differential method, with achieved resolution of 20nN for forces from several tens of µN to 100nN and below. In second system, direct Lorentz force compensation method is introduced by means of EMC with particular focus on simplified system complexity and increased stability.

2. INTRODUCTION

In research and industrial to measure liquid flow velocity in channels sometimes become challenging, particularly in cases when walls of the channel are opaque or inaccessible due to high temperature of liquid or when it is non-transparent or chemically aggressive against sensors (like electrodes in magneto-inductive flow meters). In order to fulfil this gap a noncontact/non-intrusive method is desirable. In resent decade a method, namely Lorentz Force Velocimetry, was introduced and extensively discussed in research [1, 4-8]. Essence of this method is based on interaction (a relative motion) of magnetic and electrically conducting flow velocity fields (1), when configuring this two in certain orientation an electromagnetic force results. The force is commonly known Lorentz force that tends to brake flow motion. In turn, equal magnitude but opposite directed force acts to the magnetic field generating system.

$$\vec{F}_L \sim \vec{j} \times \vec{B} \tag{1}$$

Initially, grounding on theory introduced by Shercliff[9] it become an applicable flowmeter in resent year reexamined by Thess [1,5] in theory and practice. By metering reaction force that experiences magnet system one can define the flow velocity, while the conductivity of flow liquid is known (2). Proper dimensional analysis (detailed derivation given in [1]) based on (1) provides following scaling relation

$$F_L \sim \sigma \cdot v_0 \cdot B \tag{2}$$

σ - Electric conductivity of flow substance, v_0 - mean flow velocity, $\vec{j}$ - Eddy currents, $\vec{B}$ - magnetic field, $\vec{F}_L$ - Lorentz force. The induced force in accord to Newton's 3rd low is equal to reaction force exerting backwards onto a magnetic field generating system. Hence, measuring Lorentz forces for known electric conductivity of liquid and for some calibration factor of setup one is able to define liquid flow velocity based on linear relation given in (2). In spite of possibility to use electromagnets to generate necessary orders of magnitudes of magnetic fields, handling such systems yet remains problematic due to their high weights, consideration of energy consumption and more importantly stability and power dissipation produced by applied high currents. In our case, however, structure of magnet systems are defined by custom built systems of rear-earth permanents magnets (NdFeB, grade N48 and N52), coupled with each other in classical form or in a chain as Halbach array encompassing channel from both sides Fig. 2, 3.

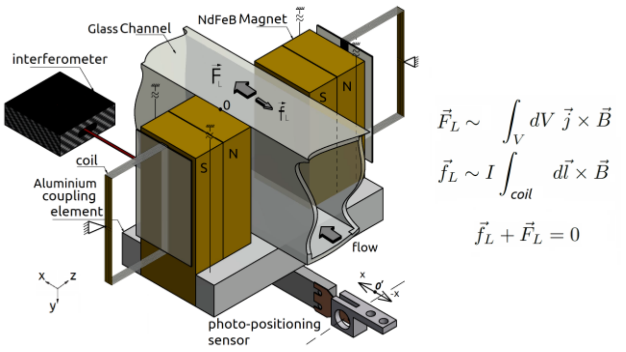

Fig.2. Adapted from [2]. a) A schematic diagram of noncontact flow meter with direct compensation method

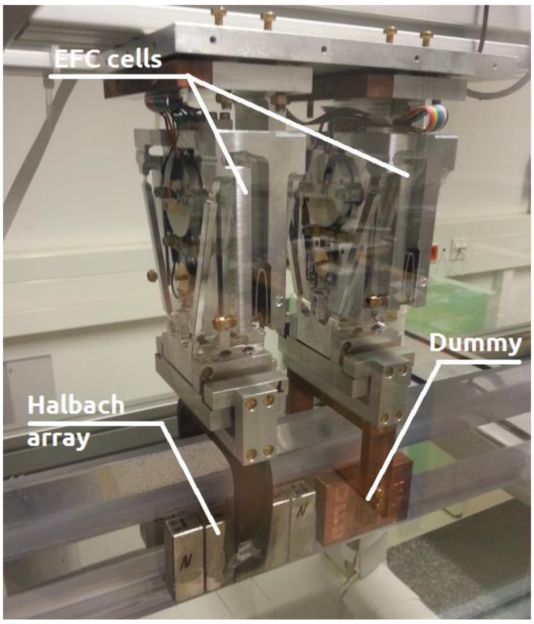

Fig.3. Image of differential force measurement setup, based on EMC weighing balances.

In the first case (cf Fig. 3) interaction of magnetic field of Halbach array (5 bar magnets from each side of channel) suspended from one EMC balance with the flow of electrolyte (salt water) flowing in 50x50 mm channel produces Lorentz forces which is measured by the balance as a raw signal. Simultaneously, second identic balance is measuring raw signal of all influences on the common measurement x-axis that have no magnetic origin and are mainly mechanical vibrations and existing force drift. Notice that magnet system suspended from one EMC balance as well as dummy weight suspended from second have equal weight of ≈1.3kg and producing equivalent dead loads of ≈13N on to each of them. Resulting difference of both signals is the measure of Lorentz force. The State-of-the-art EMC balances are used to conduct measurements, provided from Sartorius AG (Göttingen), the resolution of static force measurement is given as 1ug [12] over the range of ± 5.5g.

In the second case (cf Fig. 2) method is implemented on prototype setup with the conventional magnet system coupled by aluminum plate on suspended pendulum. The magnet system has ≈1.24kg weight and encompasses 30x50mm (26x46mm flow) channel from both sides. The pendulum is free to oscillate therefore it is sensitive to acting Lorentz forces. Resulting 1D deflection of pendulum, traced by an interferometer in um range by 1nm resolution, earlier [10] was measured as a shift from stabile zero position after reaching settling time of system (≈11s). Deflection is indication of acting Lorentz force when multiplying it with stiffness of system. Here we impose into the static field of the magnet system a current carrying conductor, in form of rectangular coil, meanwhile considering symmetricity of both distribution of magnetic field and configuration of the coil [2]. Applying electric current externally onto the solidly fixed coil in the close vicinity of magnets the produced f_L EMC force is compensating deflection proportionally as shift from zero position. In other words, developed servo system controls position of pendulum(magnet) deflection on stable zero position such to have indication of Lorentz forces (produced by electrolyte flow) as an applied current to the coil. The method is comparably robust; also measurements have shown better stability and reduced response time. The settling time of 2.4 is achieved by developed digital PID control, which is expected to be improved with analog PID control. Instead of laser interferometer an opto-electronic position sensor is used consist of aperture solidly fixed to the pendulum which obstructs an axis between LED diode and differential photodiode. The measured voltage of differential photodiode is proportional to deflection of aperture that is being input signal for PID control.

The method employed in the last setup is analogues to know method used in projects of redefining international artifact of 1kg by Watt Balances [13] using electromagnetic force measurements. Particularly, the open loop (measuring only deflection of pendulum) of our Lorentz force measurements corresponds to so called velocity mode in Watt balance measurements, whereas closed loop (PID control) corresponds to force mode of measurements. Main differences, among others, are a) the precision of measurements, since our interest is to develop portable and robust force measurement applications as flowmeters for continuous and stabile measurements of dynamical forces with minimum response time. b) Measurements in our case consider horizontal (gravity free) force measurements in plane perpendicular to gravity force.

In this paper we discuss special case of force measurement setups which are capable to measure electrolyte flow velocity when the conductivity is in order of 10^{-1} – 10^{1} S/m. For experimental convenience a tap water is used with characteristic conductivity of $4{\cdot}10^{-2}$ S/m and to set conductivities for higher ranges a saline water is added gradually for each measurement (cf Eq. 2). For metering flow velocities of 0.2-4m/s a force measurement systems resolving sub uN forces in horizontal direction are desired. In Table 1 presented main details of experimental facilities.

Table 1. Details of experimental facilities.

Parameter name	Dimensions	
	Fig. 2	Fig. 3
Single magnet size	30x30x70mm (2x)	18x15x46mm (10x)
Magnetic field	410 mT	210 mT
Conductivity	10^{0} - 10^{2} S/m	10^{-1} - 10^{1} S/m
Velocities	0.3 - 2.2 m/s	0.2 - 4 m/s
Volume of electrolyte	11 L	300 L
Typical range of forces	5 - 100 uN	0.1 - 10 uN
Resolution	1-2 uN	20 - 30 nN

3. DIFFRENTIAL FORCE MEASUREMENT SETUP

As an example for typical range of resulting force measurements with differential force measurement setup may described as follows: ≈4.5uN measured force in downstream direction corresponding to the flow of saline water with conductivity of 1S/m and velocity of 1m/s in a rectangular channel with 50x50mm cross-section.

The differential force measurement system is introduced based on previous work [11] of single EMC balance system. The working principle of EMC balance and the common tilt error evolving during measurement period presented in schematics diagram in Fig. 4. Here the tilt figurate as an error involved in the measurements mostly dependent from the mechanical stresses existing in the supporting system and thermal expansion of the material that leads to random drift mostly dependent from thermal stability of surrounding environment. However, as it was presented in [14] after proper calibration, complexity reduction of supporting construction and reduced dead weights one can consider it as a high precision tiltmeter. Since the EMC balance is sensitive only to single axis tilt the angle is calculated from measured forces as follows

$$F_{tilt} = m_0 \cdot g \cdot \sin \beta \tag{3}$$

Where m_0≈1.3kg is dead weight, g is local gravity, F_{tilt} is tilt force and β is tilt angle. Assuming the resolution of EMC balance is 1ug a tilt angles with 0.77nrad may expect to measure.

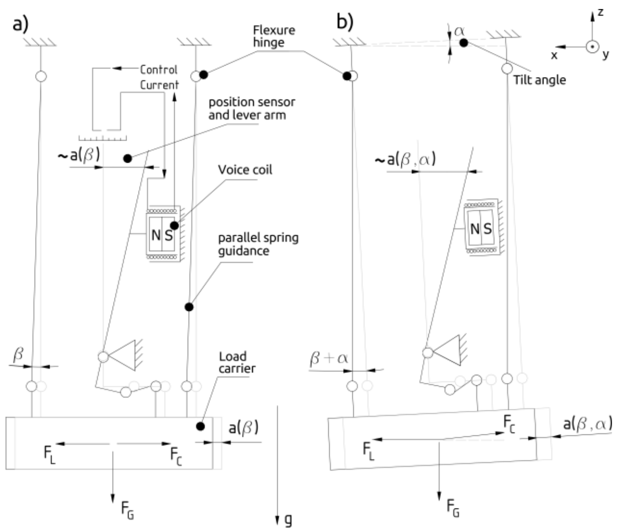

Fig.4. Schematics of EMC deflection measurement principle (grey un-deflected): a) ideal case of deflection, b) impaired with the tilt angle error. F_C-total measured force represented as EMC compensation force, F_G-gravity force.

In order to compensate errors caused by tilt angles we introduce second an identic EMC balance with dummy weight. Subtraction from recorded raw signal of EMC balance with magnets the signal from EMC balance with dummy weight, expected to be the measure of forces only produce by magnetic interaction.

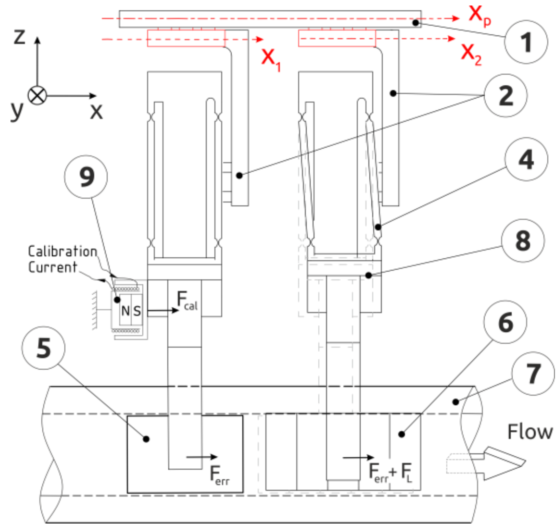

Fig.5. Functional diagram and geometrical configuration of EMC differential system; side view presented as two pendulum system, dashed line in the right indicates actual state, (1) hanging common plate, (2) separate suspension for tuning EMC on horizontal plane, (4) deflected EMC, (5) dummy weight, (6) Halbach array magnet, (7) channel, (8) – weight bearing joint, (9) Calibration element (linear motor consist of externally fixed voice coil and magnet, fixed to suspended dummy weight). $x_{p;\_1;\_2}$; - axes for fine tuning of each suspension block, items (2) and (1). Subindexes of axes represent $_{\_1,\ \_2}$ (red) for individual EMC and $_{\_P}$ for common plate.

Although electronics provides around 80 to 100 sampling rate we limit ourselves with sufficient measurement frequency of 24 to 26 Hz, since a) the settling time of EMC balance itself is somewhat about 1.4s and b) measurement of Lorentz forces yet is in order of several Hz frequency. Below presented (4a-c) calculation principle revealing basic principle underlying in our measurements.

$$F_{M1} = F_{L(C)} + F_T + F_{GV} = F_{L(C)} + F_{err} \quad (4a)$$

$$F_{M2} = F_T + F_{GV} = F_{err} \quad (4b)$$

$$F_{M1} - F_{M2} = F_{L(C)} \quad (4c)$$

here, F_{M2} - is indication of force signal detected by EMC balance that measures errors of F_T - tilt force and F_{GV} - mechanical vibrations, the second EMC balance measures, given as $F_{M1,}$ the same errors together with Lorentz force $F_{L(C)}$ or the calibration force.

Before measuring Lorentz forces produced by flow of electrolyte with such a method we have perform calibration procedure (cf schematics in Fig. 5) by replacing magnet system by another dummy weight, thereby having from both EMC balances suspended equivalent dummy weights made of copper, instead of item 6 another item 5 in Fig.5. This is done to measure mechanical vibrations and force drift simultaneously and independent of electromagnetic interaction of electrolyte flow and magnets, further by mounted linear voice coil actuator on to one of the EMC we apply current to the coil in order to mimic typical forces measured in flow metering mode.

The system in the preliminary development state has shown already capability to resolve distinguished force measurements of ≈90 nN and below with approximate standard deviation of 20 to 30 nN dependent from filtering and operating mode (see Fig. 6).

Below is typical measurement of system against calibration forces introduced by linear voice coil motor [15]. The magnitude, direction and frequency of the force are chosen as identic as the presumable character of the Lorentz force predicted to be measured.

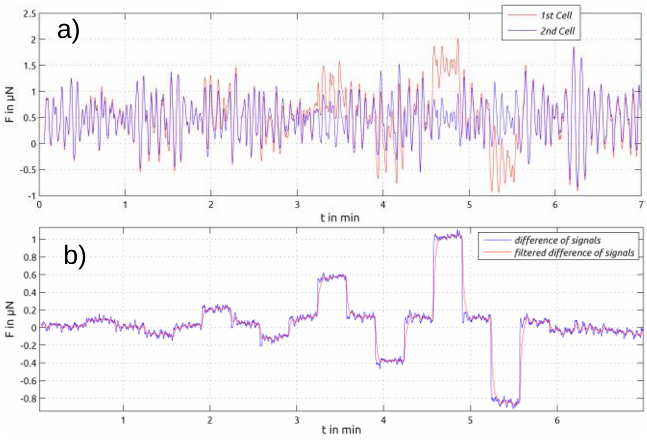

Fig. 6. a) Raw response signal of both F_{M1} and F_{M2} EMC balances against minimal calibration forces up to 1uN, b) difference of signals $F_{L(C)}$.

Hence, we have achieved relatively stable measurement signal for different 3 orders of magnitude forces sub-10^{-7} to 10^{-4} with the best achieved standard deviation of ≈$2x10^{-8}$N (notice that ours are dynamic force measurements while factory standard is given as ≈$1x10^{-8}$N readability for static force measurements). This advance in force measurements, compared with previous work in [3,11] where signal was not stable and resolution of measurements were limited to $1x10^{-6}$N, let as to make further investigations in the actual application of interest, the LFV measurements.

Summary of differential force measurement setup is presented in table 2.

Table 2. Details of best achieved results of force measurement setup

Force measurement	Units	EMC	Difference
Resolution			
Raw	nN	600	150
Filtered		250, (350)‡	19, (25)‡
Range	μN	±100, available to ±5.5 mN	
Sampling frequency	Hz	25, available up to 80	
Response time			
Raw	s	1.4	
Filtered		6, (1.2)‡	
Loading frequency	Hz	up to 0.18, (0.7)‡	

‡numbers in brackets obtained with built in filters

4. DIRECT COMPENCATION MEASUREMENTS

In the State-of-the-art EMC balances is used measurement principle of zero point balance with electromagnetic voice coil actuator which is built-in the balance in an optimal configuration for precision weighing proposes. The sensitivity of system is greatly limited to the *Bl* factor of voice coil actuator (the flux integral). Also, implementation method of EMC balance measurements are mostly tuned based on geometrical configuration and size of the balance. Moreover, usage of EMC balances for Lorentz force measurements is limited to the dead load suspended from the balance and measurements are indirect assuming the fact that deflection of magnet system as a response to the flow of electrolyte is compensated by a second magnet-coil system. To simplified aforementioned reasons and to optimize setup further a model of measurements has been proposed. Particularly focusing on implementation scheme of force measurement, we discuss performance of the system which is designed considering superposition of two different Lorentz forces F_L and f_L on magnets (counter-balancing on equilibrium point). The F_L is induced due to interaction of magnet field and electrolyte flow has direction of flow while the f_L is induced due to external applied current in current carrying conductor in the same magnet field. This conductor is static fixed in close vicinity of magnets in a way to develop opposing LF (see Fig.2) and keep pendulum in zero balance position.

In other words implementation scheme of Lorentz force measurements now consist of a 1D linear guide, position sensor, custom made coil (dependent from magnets size and field distribution) and the magnetic field of magnet system for producing both, F_L and compensation f_L forces.

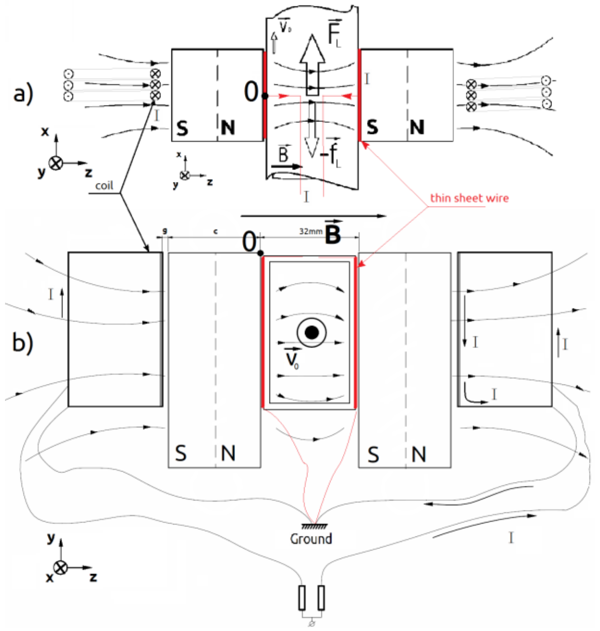

Fig.7. Sketch of setup: a) top view x-y plane, b) lateral cross-section view of symmetry centre y-z plane. See Fig.2.

Another advantage follows from straightforward theory that with proper computation of f_L developed by coil one can obtain theoretical estimate of calibration factor analytically (or define *Bl* factor), given magnetization properties of magnets and dimensions of system. We used charge model to derive an analytic expression for magnetic field distribution outside of single rectangular bar magnet. In ideal case, assuming geometry of system (cf Fig. 7) only B_z component (6) contributes to total f_L while B_x is zero at symmetry axis or canceling each other out in every next symmetrical turn of coil.

$$f_L = I \cdot \int_{coil} d\vec{l} \times \vec{B} \quad (5)$$

$$B_z(x,y,z) = \frac{\mu_0 M_s}{4\pi} \cdot \sum_{k,p,q=1}^{2} (-1)^{k+p+q} \cdot$$

$$\cdot \tan^{-1}\left[\frac{(x-x_k)(y-y_p)(z-z_q)}{(x-x_k)^2+(y-y_p)^2+(z-z_q)^2}\right] \quad (6)$$

here, *I* is applied current to the coil, *l* is length of the coil, $\mu_0 M_s$ is permeability of air and saturation magnetization which is pointed along *z* axis, integers *k*, *p*, *q* are determining computation signature for negative and positive poles within the bar magnet.

We perform open loop measurements to calibrate the system against laser interferometer. Procedure is defined as follows: for applied *I* current in accord to (5) we produce deflection on pendulum whose position is measured by laser interferometer and opto-electrical position sensor (cf Fig.2). Thus measured voltage of position sensor is traceable to actual deflection which is multiplied by stiffness is the compensation force experiencing pendulum. Typical measurement signature of the setup presented in Fig. 8.

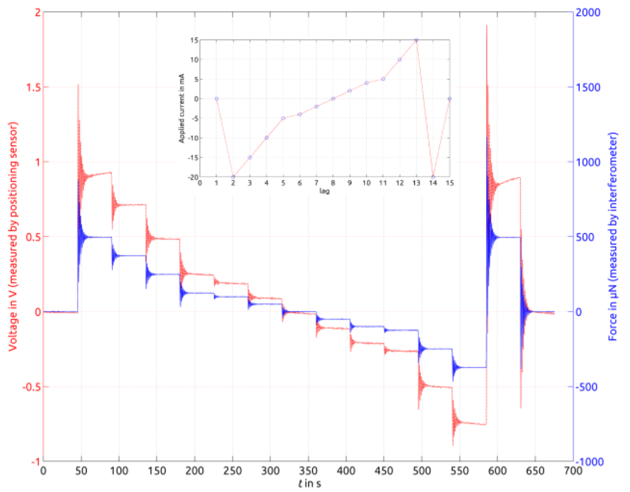

Fig.8. System initialization procedure (long term). Recorded positioning sensor signal in volts and force measurements by reference interferometer against stepwise applied current to the rectangular coil (30x50) with 15 turns.

As a result of geometrical configuration the sensitivity of the setup may define in terms of *Bl* factor against number of turns in the coil. Also, (5-6) provide ground to compute the same factor theoretically based on analytical expression and actual parameters of setup. Comparison of experimental values with computation presented in Fig. 9 for various numbers of turns in the coil, yet in certain degree of discrepancy ≈13% (cf [2]). Origin of this difference is mainly dependent from; unrefined positioning of coil in magnetic field, homogenization of magnetic field of magnets given as value of saturation magnetization Ms of rectangular bar magnet and its dependence from temperature as well the measurement/calibration error of interferometer which is 2-4%.

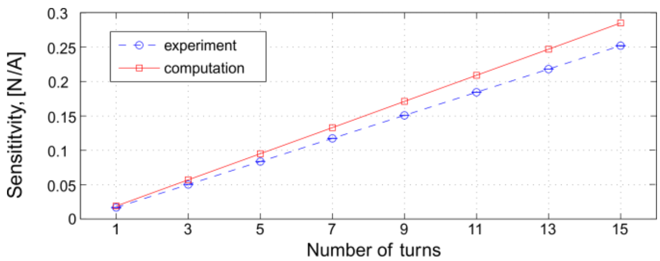

Fig.9. Sensitivity N/A against number of wires in the coil.

Settling time of pendulum in open loop regime is ≈11s, whereas closed loop shows 2.4s. Servo-controling implemented by standard digital PID controller, where delays are mostly conditioned by A/D to D/A conversation, data acquisition rate with PC. The response time might be further improved by analog PID controller after refining main systematic errors for each particular application; in practice, for each individual system complete automatized measurements can be done after identifying stability of zero point.

When flow of electrolyte is given as in Fig.10 stepwise or in square wave form a Lorentz force is prodused that is being compensated back to yero position by applied current to the coil and the force is measured, soforth as compensation *I* current (cf Fig10a)).

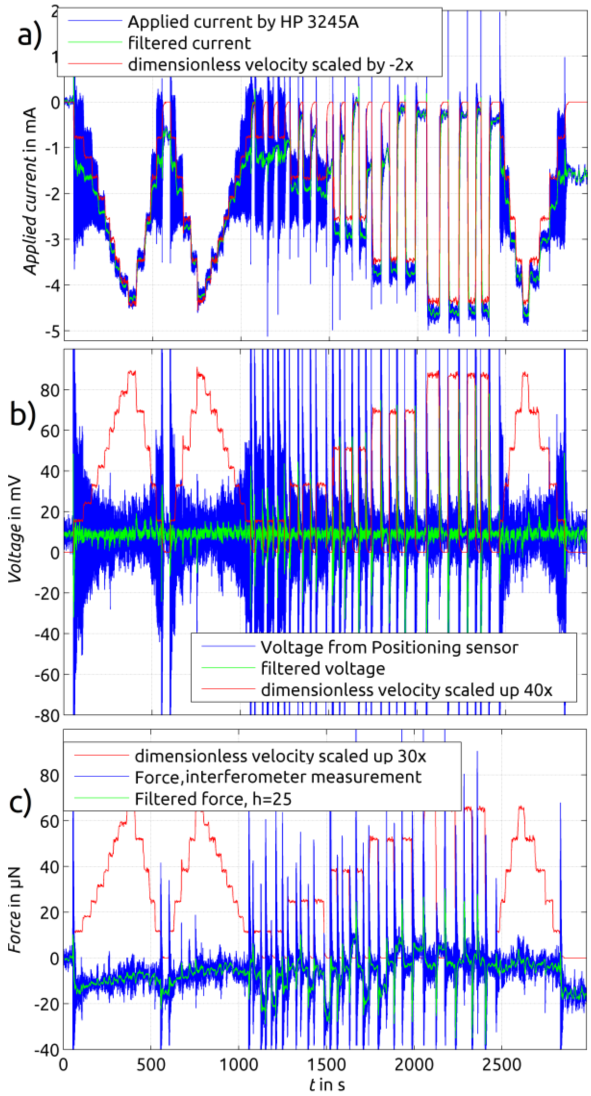

Fig.10. Typical set of measurement for a single value of conductivity (cf (2)) and 15 turns of coil while varying velocity of electrolyte in the channel a) Response of applied compensation current, b) signal of optical positioning sensor indicating of stable position control by PID controller at initial offset value, c) measurement by interferometer

5. CONCLUSION

Main objectives achieved in this research are as follows: a) the useful force resolution in LF measurements from ≈100ppb to ≈1.5ppb is increased, that is measurement resolution over dead load. This allows measurements of flow velocity in lower range of conductivities typically in order of 10^{-1}S/m. b) Optimized method is introduced based on direct Lorentz force compensation by means of electromagnetic repulsion principle. Method would provide understanding on how we can broaden the range of its applicability for higher ranges of conductivities and for lower range of forces to measure Lorentz forces below 10^{-7} N.

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