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PRECISE TILTMETER AND INCLINOMETER BASED ON COMMERCIAL FORCE COMPENSATION WEIGH CELLS

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Abstract: High precision measurements and monitoring of tilt or inclination are essential in the field of ultraprecise force and mass measurements. We present a new concept for high resolving tilt/ inclination measurements. Therefore a commercial electromagnetic force compensation (EMC) weigh cell is mounted in a hanging position and loaded with a defined weight. Thus the system conforms to a pendulum. By measuring the tilt depended deflection of the pendulum with the position sensor of the weigh cell we achieved a standard deviation of 7.1 nrad (3.4 nrad filtered) within a sampling time of 15 min. In future investigations we will compensate the deflection and take the compensation force as a measure for the tilt.

Keywords: tiltmeter, inclinometer, electromagnetic force compensation

1. INTRODUCTION

High precision measurements of tilting/ inclination are required in diverse fields. Above all they are long-established in the scope of geophysics and geodesy where observations of local tilting are carried out. Local tilting bases on several natural phenomena such as wind-blown vegetation, body waves or surface waves (seismic waves), atmospheric pressure changes deforming the ground or thermoelastic deformations and pore pressure changes as well as joint deformation related to groundwater motion and human made machinery [1]. Besides these, earth tides are the best known effect. Depended on the location and direction of measurement, they cause tilting of the Earth´s crust in the 70 nrad amplitude range with a semidiurnal period (~12.5 h) [1, 2]. Deformations of the founding or the floor of buildings caused by a moving person can be in the range some µrad [3] and are an additional source of tilting of a laboratory or a measurement setup.

In the field of force and mass metrology even small changes of the inclination of measurement setups generate significant measurement deviations. If this tilting is monitored and its influence is corrected or compensated its contribution to the measurement uncertainty can be reduced. For example, due to the change of the weight force component that acts perpendicular on the balance the tilting φ generates a deviation Δm of a mass measurement [4]:

$$\frac{\Delta m}{m} = \frac{\varphi^2}{2} \quad (1)$$

In case of ultraprecise mass comparators, such as the Sartorius CCL 1007, a tilt as small as $\varphi \approx 14$ µrad causes a measurement deviation of one balance digit ($\Delta m = 0.1$ µg) if the mass to measure is $m = 1$ kg.

Depending on the mechanical design of the balance lateral components of the weight force resulting from the tilting can be additional sources for measurement deviations. For instance, the torsion balance described in [5] is almost as sensitive for tilting as for force measurements.

In current researches traceable force measurements in the piconewton range are described [6, 7, 8, 9]. Nesterov for instance measured the force of 47 pN that is induced by the light pressure of a 7 mW laser beam acting on a mirror [8]. A tilting of the used “Nanonewton Force Facility” of just 1 nrad would generate a measurement deviation of 40 pN. Thus, a measurement of tilting with a resolution of < 1 nrad is included in the “Nanonewton Force Facility” to compensate and correct the influence of tilting.

In conclusion, it is obvious that local tilt measurements in the micro- to nanoradian range are not only needed in the scope of geophysics but also in other fields of metrology such as force and mass measurements.

The aim of the presented investigations is to develop a tiltmeter/ inclinometer with a reasonable resolution of ~ 1 nrad at a, compared to the state of the art, expanded measurement range of up to ~ 17 mrad (1°). This would extend the field of application of such highly resolving tiltmeters. Only one device would be needed to cover both: measurements of very small and large changes of inclination with a resolution of ~ 1 nrad. Furthermore, calibrations of tiltmeters with different measurement ranges could be carried out with one setup.

2. STATE OF THE ART

Several principles for the measurement of tilt/ inclination are known. The most common ones apply pendulums, gas bubbles (level) or liquid surfaces as a reference [1].

The Askania borehole tiltmeter was developed in the late 1960s and was later manufactured by BODENSEEWERKE GEOSYTEM GmbH. It still represents the state of the art in the field of geophysics [10]. Basically it consists of a 0.6 m pendulum, a capacitive deflection measurement and a force feedback applied by Helmhotz coils [1]. It achieves a resolution of ~ 1 nrad in a range of 50 µrad [1, 10].

The Leica Nivel 210 inclinometer made by LEICA GEOSYSTEMS AG features a resolution of 1 µrad and a measurement range of ±3 mrad [11]. It uses a liquid horizon which is optoelectronically sensed.

The tilt measurement included in "Nanonewton Force Facility" works on a similar principle as the Askania borehole tiltmeter [6, 7, 8]. The inclination dependent deflection of a pendulum is measured with an interferometer and is compensated by an applied feedback force that is generated electrostatically. The applied capacitor voltage is then a measure for the force and thus for the inclination. The resolution is given with < 1 nrad.

In Summary it can be stated, that a resolution of ~ 1 nrad represents the state of the art in the field of tilt or inclination measurements. However, the measurement range of those high resolution devices is limited to < 2 mrad.

3. MEASUREMENT SETUP

As well as the state of the art devices, the chosen principle of measurement bases on a pendulum. The pendulum is realized by the mechanics of a commercial electromagnetic force compensation (EMC) weigh cell made by SARTORIUS WEIGHING TECHNOLOGY GmbH. In contrast to its designated use, the weigh cell is not mounted horizontally but in a vertical (hanging) position as shown in Fig.1. and Fig 2. The hanging weigh cell consists of a pendulum which is designed as a monolithic parallel spring guidance made of aluminum, a weight *m* attached to this pendulum as well as a transmission lever system, an optical position sensor and a voice coil. The position sensor is realized by a fixed LED and a fixed differential photo diode. An aperture mounted to the transmission lever is placed between the two diodes. Thus, the illumination of the two sensitive sectors of the photo diode changes when the lever moves [12].

3.1 Setup pendulum deflection

A tilting of the setup by the angle φ generates the lateral force component *F*, see Fig. 1. Depending on the length *l* of the pendulum and the stiffness of the weigh cell *c* the force component *F* deflects the weight *m* by the distance *x* whereas *g* is the gravitational acceleration ($F_G = m \cdot g$):

$$\varphi = x\left(\frac{c}{m \cdot g} + \frac{1}{l}\right) \quad (2)$$

The maximum deflection arises if the stiffness *c* of the weigh cell approaches zero or the mass *m* is chosen to be infinite. In this case the angle deflection of the pendulum φ^* is equal to the tilting of the system φ. The voice coil is only used to damp the movement of the pendulum. The stiffness of the system is in the range of $c \approx 200$ N/m [13]. Assuming a reasonable resolution of the deflection *x* of < 0.2 nm, a length of the pendulum $l = 75$ mm and a mass $m = 0.5$ kg, a useful resolution of the tilt φ of < 11 nrad should be achievable. With the maximum deflection of $x \approx \pm 40$ µm a measurement range of $\varphi \approx \pm 2.2$ mrad can be attained.

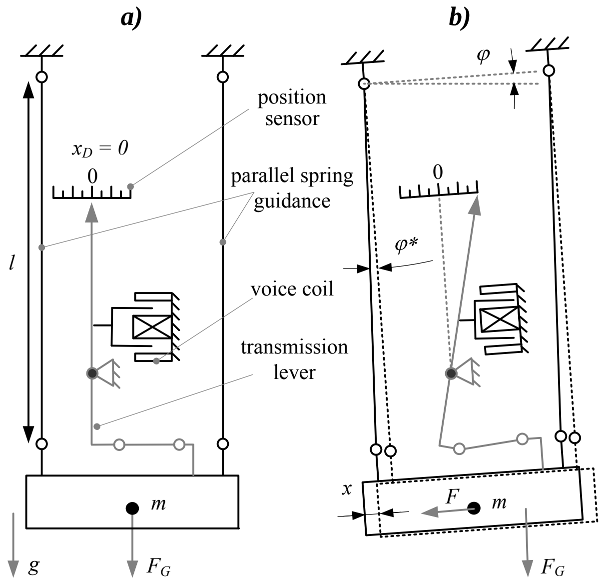

Figure 1: *a)* hanging weigh cell *b)* weigh cell tilted by φ; in this case the coil is not generating a compensation force

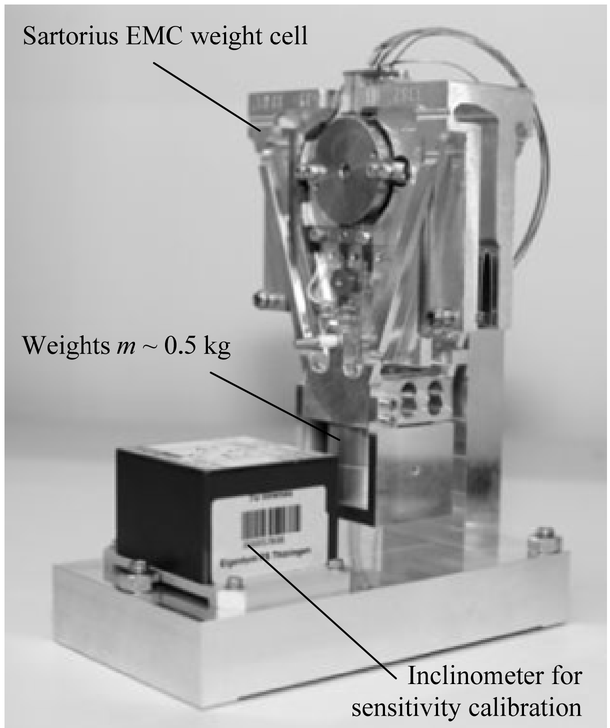

Figure 2: single axis measurement setup

3.2 Setup force compensated pendulum

A second option is to use the voice coil to compensate the lateral force component *F* so that φ^* or *x* remains zero when the system is tilted by φ. This refers to the use of the system as a compensation balance. The force *F* to compensate can be expressed as:

$$F = F_G \cdot \sin\varphi = m \cdot g \cdot \sin\varphi \quad (3)$$

With the resolution $\Delta m_{balance}$ of the applied compensation balance the resolution of the tilt measurement can be expressed as:

$$\varphi = \frac{\Delta m_{balance}}{m} \tag{4}$$

Thus, if the mass is chosen to be m = 0.5 kg a balance with a resolution of 1 µg is needed to resolve a tilt angle of φ = 2 nrad. Assuming a measurement range ± 10 g, the range of the tilt measurement can be increased by the factor of 10 to 20 mrad. With a loss of measurement range the resolution can be increased by applying a bigger mass.

4. RESULTS

4.1 Setup pendulum deflection

For all the following experiments a mass of $m \approx$ 0.5 kg was applied to the pendulum. The amplified signal of the differential photo diode was recorded with an Agilent 34411 Multimeter. The Temperature of the setup was stabilized within ~ ± 0.2 K.

In the first step the sensitivity of the output signal was calibrated to ≈ 0.34 mrad/V. A LEICA Nivel 210 was used as the reference inclinometer. Furthermore a measurement range of φ ± 2 mrad was verified. This corresponds to the expected value that was determined above.

For the determination of the standard deviation we placed the system on a 3 ton granite stone that is supported on the basement of the laboratory building.

At a measurement frequency of 5 Hz (NPLC 10) we achieved a standard deviation of the tilt signal within 15 minutes of $s(\varphi)$ = 7.1 nrad, see Fig 3 (blue curve).

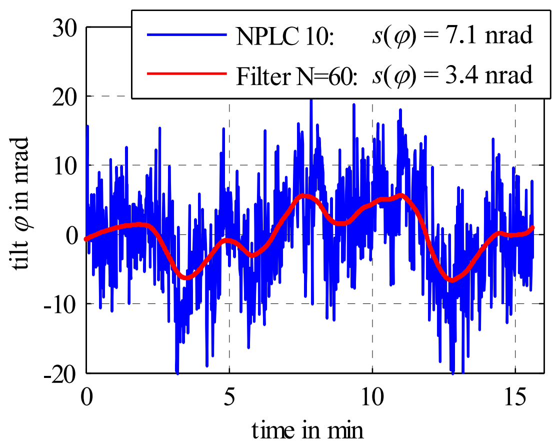

Figure 3: short term measurement of tilting including standard deviation $s(\varphi)$ within 15 min

In this case only every tenth measurement value was stored and is displayed. Applying a floating mean value filter with the length of N = 60 to this data (corresponds to a filter time of 1 minute) improves the standard deviation of the data sampled within 15 minutes to $s(\varphi)$ = 3.4 nrad, see Fig 3 (red curve). This corresponds to a standard deviation of the deflection measurement of $s(\varphi)$ < 70 pm. Hence, we achieved slightly better values than the expected 11 nrad and the 0.2 nm respectively.

The computed standard deviation comprises several contributions: Noise of the electrical deflection measurement, oscillations of the pendulum but also a real short term tilting of the granite stone or the fundament. For instance, a 70 kg person walking by the granite stone on the floor of the laboratory generates a tilting of the stone of ~ 500 nrad.

In the next step long term measurements of the tilting have been carried out. The setup was aligned with respect to the horizontal axis of the granite stone which are oriented in WNW- and in SSW-direction. The measured tilt around the WNW- and the SSW- axis of earth is shown in Fig. 4 and Fig. 5 respectively.

The tilt around the WNW-axis (Fig. 4) mainly comprises of a long term drift and a periodical part. The period length is in the range of 12.5 h and its amplitude can be estimated with 70-100 nrad. This conforms to the expected tidal tilting of the earth crust (see above). Up to that point it was not possible to distinguish whether the drift of the signal is caused by a time or temperature depended drift of the measurement setup or the stone and the basement of the laboratory.

For closer investigations on that and on the contributions to the standard deviation a more stable environment such as an underground laboratory of a geophysical observatory could be promising.

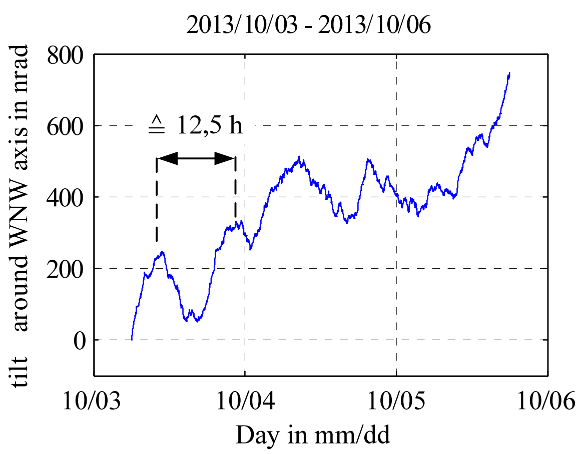

Figure 4: measured tilt around the WNW axis of earth

Afterwards the setup was aligned to measure the SSW component of tilting (Fig. 5). This signal is dominated by a periodical part with the period length of ~1.3 h. Furthermore a semidiurnal period seems to be present but can be distinguished clearly. The 1.3 h period was observed in each of our measurements if the setup is orientated in this direction. Up to now it was not possible to find the reason for this but we expect it to be a property of the building or its closer surrounding. Measurements in other buildings did no show this characteristic.

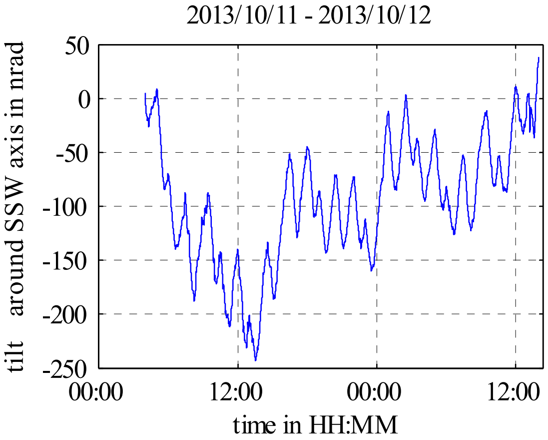

Figure 5: measured tilt around the SSW axis of earth

4.2 Setup force compensated pendulum

This configuration will be tested in future using a balance with a resolution of 1 μg and a measurement range of ± 10 g. Thus, a resolution of 2 nrad and a measurement range of ± 20 mrad can be expected, if a mass of 0.5 kg is applied, cf. section 3.2.

5. CONCLUSION AND OUTLOOK

The presented inclinometer setup works on the principle of the measurement of a pendulum deflection. As pendulum we applied a commercial electromagnetic force compensated weigh cell including its optical position sensor. Depending on the used filtering we achieved a standard deviation of the tilt signal in the range of 3.4 nrad – 7.1 nrad. Thus, the useful resolution of the system is in the 1 nrad range. Furthermore, the measurement range can be given with 2 mrad. Thus, concerning the resolution and measurement range we reached the state of the art for high precision inclinometers.

For further improvement the system parameters like noise, the time- and temperature- depended drift of the setup must be investigated. Therefore disturbances such as noise and drift must be distinguished from real tilting of the laboratory and the granite stone. The deflection measurement will be investigated independently. Other principles such a capacitive deflection measurement will be tested with the aim to reduce useful system resolution to ≤ 1 nrad. Increasing the applied mass *m* and lowering the stiffness *c* of the system would be another option to improve the resolution.

A promising approach to distinguish measurement deviations from a real tilting would be to carry out measurements in a well-known environment such as in underground laboratories of geophysical observatories.

By not just measuring the pendulum deflection but compensating the tilt depended lateral force component of the applied mass we believe to extend the measurement range by the factor of 10 at a similar resolution.

To measure both tilt components at the same time, a second weigh cell will be applied to build a two-axial setup.

6. ACKNOWLEDGEMENTS

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