IMEKO 24th TC3, 14th TC5, 6th TC16 and 5th TC22 International Conference
11 – 13 October 2022, Cavtat-Dubrovnik, Croatia

A NOVEL EMFC TILTMETER WITH EXTENDED MEASUREMENT RANGE

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Abstract:
This work presents a new tiltmeter that utilises the principle of electromagnetic force compensation (EMFC) in order to increase its measurement range and measurement dynamics compared to an uncompensated pendulum tiltmeter. The development included investigations on the design of the pendulum mechanics, the position sensor and the actuators. With the chosen parameters a resolution of 1 µrad in a measurement range of 20 mrad can be achieved currently on a short-term timescale.

Keywords: EMFC; tilt measurement; instrument design; tilt calibration

1. INTRODUCTION

Tiltmeters, which measure the inclination relative to the direction of local gravity, have wide range of applications for example in geodesy and geophysics [1]. Furthermore, the tilt of instruments is a significant source of systematic errors in mass metrology as well as the tilt and shape deviation of weighing slabs.

Previous developments of tiltmeters at TU Ilmenau were either composed of a passive pendulum whose deflection is measured with an optical sensor [2] or were based on commercial EMFC load cells [3]. While the passive pendulum tiltmeter is relatively easy to manufacture and provides a high measurement resolution, its measurement range is limited by the deflection of the flexure hinge that poses as the pendulums bearing and the nonlinearity of the position sensor. The tiltmeter based on EMFC load cells provides a greater measurement range and better linearity, but its components are complex and comparatively expensive. In addition, the use of commercial load cells limits the possibilities of miniaturisation of the system.

2. INSTRUMENT DESIGN

In order to design a miniaturised cost efficient tiltmeter with an extended measurement range, the newly developed system is based on a pendulum with flexure hinge bearings, an optical position sensor and voice coil actuators (VCA). This design is similar to an EMFC balance that can also be utilised as a tiltmeter, but in contrast its complexity is reduced. An EMFC load cell possesses a transmission lever, a coupling band and a Roberval mechanism to increase its measurement range and to provide a low corner load error, which describes the deviation of the weighing result depending on the position of the load on the weighing pan. Since the tiltmeter only compensates the restoring force of the pendulums mass that has a fixed position, these elements are unnecessary for an EMFC tiltmeter and can be omitted to reduce complexity and manufacturing costs.

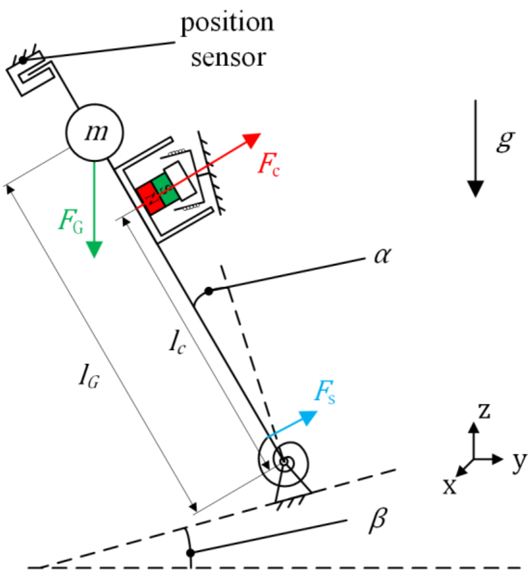

Figure 1: Schematic of the tiltmeter design

As depicted in Figure 1, the new EMFC tiltmeter is composed of an inverse pendulum whose bearing is provided with a rotational spring since it is realised as a flexure hinge. An inverse pendulum provides the advantage that the force F_G, which is generated by the mass m under the influence of the gravitational acceleration g, points in the opposite direction of the restoring force F_s of the spring. With the lever length l_G of the gravitational force and the lever length l_c of the actuator force F_c, the equilibrium of torques that act on the pendulum can be written as

$$F_{\mathrm{G}} \cdot l_{\mathrm{G}} \cdot \sin(\alpha + \beta) - c_{\mathrm{s}} \cdot \alpha - F_{\mathrm{c}} \cdot l_{\mathrm{c}} = 0 \qquad (1)$$

where c_{s} denotes the spring constant of the flexure hinge, while α and β represent the deflection of the pendulum and the tilt of the ground. Therefore, the inverse acts like a spring with a negative spring constant and the combination with the spring constant c_{s} of the flexure hinge can be used to reduce the overall spring constant of the system. A low overall spring constant ensures a higher sensitivity and thus a small error of force measurement that is generated by a given error of the position measurement and can also be provided by a hanging pendulum with a thinner flexure hinge, but with the cost of a reduced robustness regarding the use and transport of the instrument.

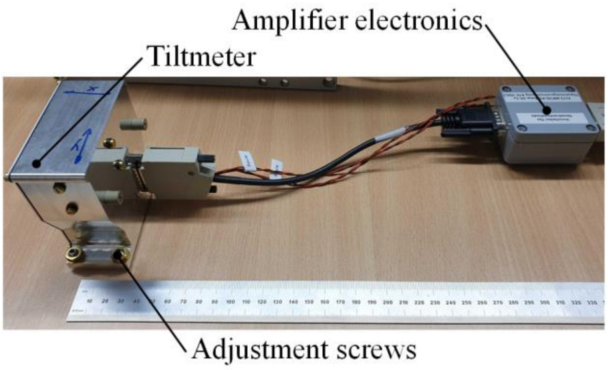

Figure 2: The tiltmeter and measurement circuitry

The deflection of the pendulum is measured with an optical sensor that consists of a light emitting diode, a four segment photo diode and a circular aperture attached to the pendulum. Similar to the position sensors used in EMFC load cells [4] and passive tiltmeters [2] the aperture position is measured by the difference of photo current generated by two halves of the photo diode system. In the new EMFC tiltmeter the four segments are aligned in a way that allows the position measurement through two orthogonal axes. The four photo currents are converted to voltage signals with a separate transimpedance amplifier (TIA) for each segment of the photo diode, in which the signal is amplified to adapt to the measurement ranges of common digital multimeters (DMM) and analogue-to-digital converter (ADC).

Theoretically, the so far described set up can be used as a passive tiltmeter, where the tilt β can be derived from the deflection α with

$$\beta = \alpha \cdot \left(\frac{c_{\mathrm{s}}}{m \cdot g \cdot l_{\mathrm{G}}} - 1 \right) \qquad (2)$$

under the conditions that both angles are small and no force is generated by the VCA. The deflection is measured by the position sensor but, due to the limited size of available photodiodes and the nonlinear behaviour of greater deflections, the measurement range is limited.

Thus, two VCA are attached to the pendulum and by the means of a controller system the deflection is compensated. The necessary compensation force is proportional to the tilt that caused the initial deflection and also – due to the good linearity of the VCA – the measured compensation current. Since the deflection α is controlled to a value of zero, the tilt can now be obtained by

$$\beta = \frac{F_{\mathrm{c}} \cdot l_{\mathrm{c}}}{m \cdot g \cdot l_{\mathrm{G}}} \qquad (3)$$

In the current instrument design, the magnet system of the VCA is fixed to the pendulum and therefore it also acts as seismic mass. The coil is fixed to the reference frame, which simplifies the connection of the wires since they cannot generate a parasitic force onto the pendulum.

The compensation current through the coil of the VCA is provided by an UI converter circuitry (UIC) that controls its output current proportional to its input voltage. By using a controlled current source, influences of the coil inductivity are reduced and the controller hardware can be replaced more easily, which allows the comparison and fast development of different controllers. The UIC also includes a shunt resistor R with a nominal value of 100 Ω that is used the measure the compensation current I_{c}, which is proportional to the voltage drop U_{c} over the shunt resistor.

In addition to the improved linearity and measurement range, the compensation method provides the possibility to adjust the dynamic behaviour by changing the gain of the controller. This allows an easy and fast adaption to a new application and an optimisation regarding measurement time and resolution. Furthermore, the robustness towards damages due to external accelerations is improved.

The tiltmeter, which is shown in Figure 2, is integrated into a sealed housing that features adjustable feet and a plug socket that needs to be connected to the measurement circuitry consisting of the TIA and the UIC. The feet possess an integrated spring that is pre-stressed by its mechanical limits. Under normal operation, this allows a stiff connection to the ground while it provides a shock protection during the placement of the instrument.

3. MEASUREMENT SET-UP

Test measurements with the system were performed under stable laboratory conditions. For each measurement axis, a control loop was implemented on a digital signal processor system (DSP) that was also used for tests on EMFC weighing systems in previous works [5]. It was supplemented by the TIA circuitry for the position sensor and the UCI for the VCA and allows a fast implementation of the controllers and the generation of excitation signals. As shown in Figure 3, an additional ADC of the DSP system is used to measure the voltage drop U_c as compensation signal.

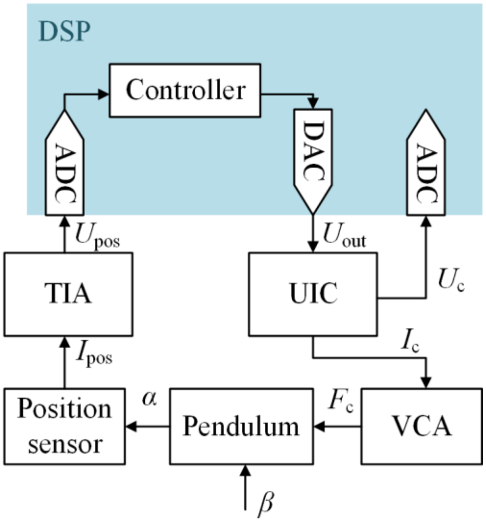

Figure 3: Signal flow of the closed loop set up

During later development, an analogue controller circuit was derived from the control algorithm, which was implemented on the DSP. The analogue controller is less flexible than the DSP system, but more cost effective and it requires less electrical components, which can possibly add up to the noise in the control loop. However, one ADC is still necessary for the acquisition of the compensation signal, which is done by a DMM of type Agilent 34411A.

For comparison, a passive pendulum tiltmeter (PPTM), which was developed in an earlier project and is well characterised [2], is integrated into the measurement set up and placed next to the new force compensated tiltmeter (FCTM). The output signal of the PPTM is measured with a DMM of the same type as it is used to measure the output signal of the FCTM. The comparison of both types of tiltmeter allows to conduct the experiment on the ground of a common basement laboratory without the need for a mechanically isolated weighing slab. The signal of the PPTM can be used to differentiate between existing ground tilt or acceleration and the effects that are produced by drift phenomena and noise inside the FCTM instrument.

The calibration coefficients of the PPTM are well known, while the FCTM is calibrated with a small tilt stage. The tilt stage consists of a plate that is adjusted with micrometer screws with a well-known pitch and distance to the pivot point of the stage. This method is used to determine the calibration coefficients of the FCTM in its intended closed-loop mode and also in an open-loop mode (FCTM-OL). In the open-loop mode, the FCTM is used as passive tiltmeter by evaluating the pendulum deflection signals without generating a force with the VCA. This is possible, since the restoring force of the spring is bigger than the pendulum force in the current FCTM design, which also allows an open-loop identification of dynamic behaviour of the pendulum for the controller design.

4. RESULTS

Several tests on the instrument were performed for the controller design and to identify the short-term and long-term behaviour. While the presented data focuses on the behaviour of the *x*-axis of the instrument, the characteristics of the *y*-axis are similar. The calibration factors were determined as described in section 3, where the measurement range of the FCTM of 20 mrad was confirmed. For the open-loop operation the range was reduced to 1 mrad.

4.1. Controller Design

The control algorithm, which is implemented on the DSP system, consists of a proportional, integral and derivative part (PID). It was designed such that it compensates the poles of the transfer function of the FCTM and the overall gain was chosen manually to ensure the step response behaviour shown in Figure 4. The gain needs to be chosen as trade-off between the noise of the compensation signal, which is lower for a small gain, and the necessity to prevent the pendulum from hitting its mechanical limits during operation.

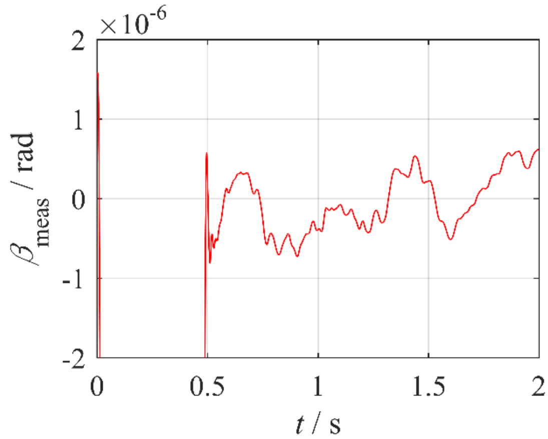

Figure 4: Filtered step response of the FCTM to a measurement disturbance

The identification of the dynamic properties of the pendulum was done adjusting the position close to zero in open-loop operation and applying a chirp signal with constant amplitude to the VCA that corresponds to x-measurement-axis. The chirp starts with a frequency of 0.1 Hz and excitation frequency is logarithmically increased to 30 Hz. The response of both position signals, which is shown in Figure 5, exhibit an exponential decrease of the amplitude, which is expected and usual for EMFC systems. Regarding the response of the y-axis, a relative crosstalk of approximately 1.8 % can be observed. This crosstalk is tolerable for the controller design but needs to be taken into account during the calibration of the instrument in the further development process.

The data of the chirp experiment was used to identify the parameters of a model that consists of a single gain and two time constants (PT_2). This type of model can usually be applied to the low frequency behaviour of EMFC systems and also shows good compliance with the behaviour of the FCTM pendulum as it is shown in Figure 6.

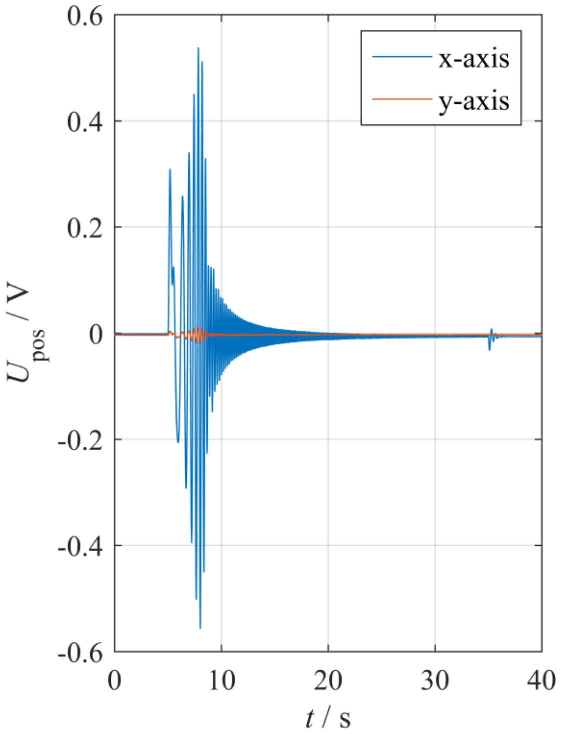

Figure 5: Response of the position sensor to a chirp excitation signal

The amplitude and phase response of the FCTM, which is obtained from the Fourier transform of the chirp experiment data, shows an almost ideal behaviour in the range of the resonance frequency of the system, which implies a good linearity of the behaviour. However, there are small deviations at very low frequency which result from drift effects, and greater deviations above 30 Hz due to the poor signal-to-noise ratio in this frequency range.

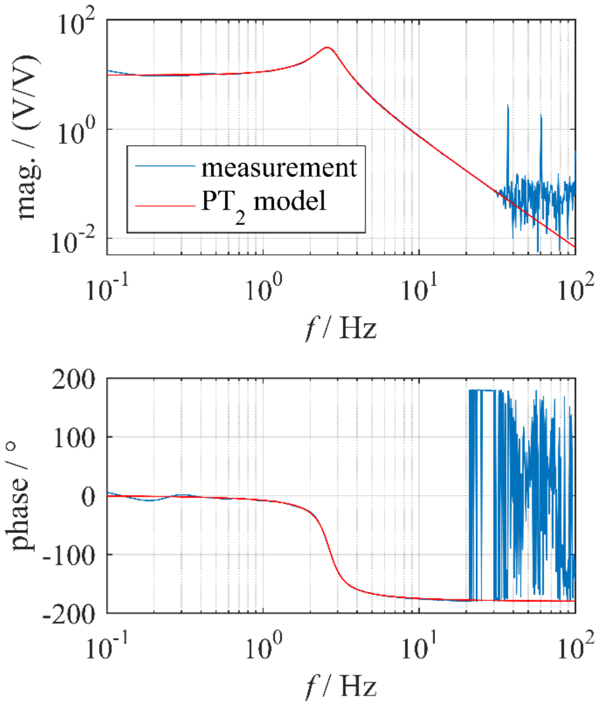

Figure 6: Bode plot of the pendulum's dynamic behaviour and the identified model

The time constants and gain of the PT_2 model were then used to calculate coefficients of a PID control algorithm. Since the characteristics of both measurement axes were quite similar, it was also sufficient to use the same coefficients for both axes.

4.2. Short-Term Behaviour

Initial tests of the system, which is shown in Figure 2, were done by adding a step signal to the output of the controller algorithm, which is implemented on the DSP system. This step generates a deflection of the pendulum that is compensated by the controller, which is similar to the response to an external change of the tilt. In comparison to an external stepwise change of the tilt, this disturbance can be performed as an almost ideal step and therefore without additional disturbances due to the mechanical properties of the tilt stage.

The response of the measurement signal to this type of disturbance is shown Figure 4. The measurement signal is calculated from the compensation current and filtered with a cascaded moving average filter with a total length of 0.5 s. Under the present stable laboratory conditions, a noise level of below 1 µrad (including real external disturbances) can be achieved while the measurement dynamic is dominated by the filter.

4.3. Long-Term Behaviour

The same controller was also used for long-term tests as it is shown in Figure 7. In order to identify slow tilt effects of the ground, the PPTM was placed next to the FCTM and their measurement axes were aligned to each other. In these long term measurement experiments, the FCTM signal as well as the PPTM signal were each acquired with a DMM instead of the ADC of the DSP system and an integration time of 20 ms was chosen for both instruments. Additionally, an averaging mean filter with a total length of 0.5 s was applied to the data. The measurement data shown in Figure 7 was acquired during a weekend to reduce the mechanical noise in the data.

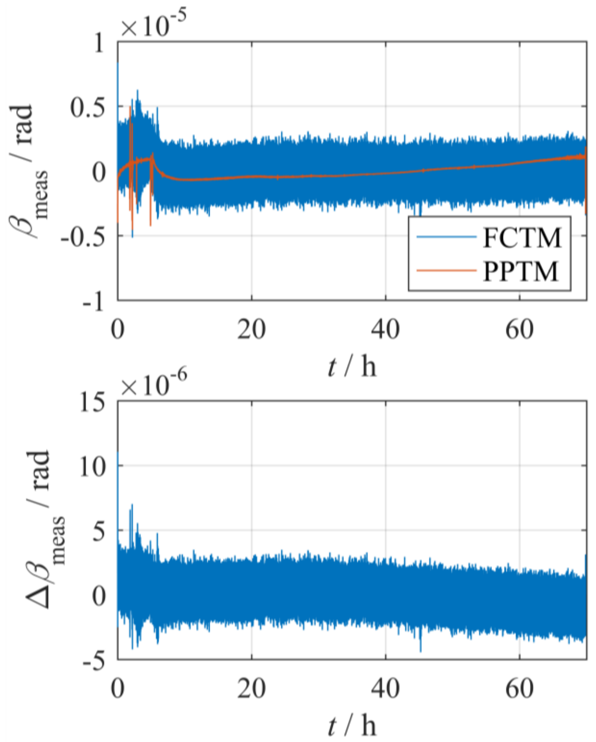

Figure 7: Long-term measurement of the FCTM in closed-loop operation with DSP system and PPTM

In this closed-loop operation, there is approximately a by factor 20 higher noise in the signal of the FCTM signal compared to the PPTM signal. Therefore, the difference of both signals, which is shown in the lower graph of Figure 7, shows even in a shorter timescale a peak-to-peak noise of up to 4 µrad. Furthermore, there appears a long-term drift relative to the signal of the PPTM.

The long-term drift is even better visible in the comparison of the FCTM-OL and the PPTM that is shown in Figure 8. The data was acquired overnight under calm environment conditions, while approximately after 16 hours the mechanical noise in the laboratory increased. Apart from the drift of approximately 5 µrad relative to the PPTM signal, the short-term noise of the FCTM is reduced significantly compared to its closed-loop operation.

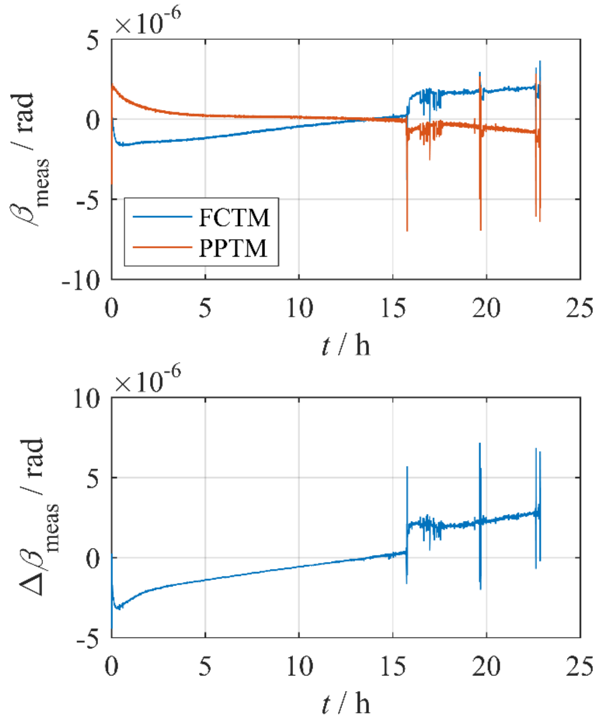

Figure 8: Long-term measurement of the FCTM in open-loop operation and PPTM

In order to further investigate the noise in the measurement signal, a timespan of five hours of unfiltered measurement data with calm environment conditions was used to determine the Fourier transform of the difference between the FCTM and PPTM signals. The amplitudes of this noise spectrum are shown in Figure 9.

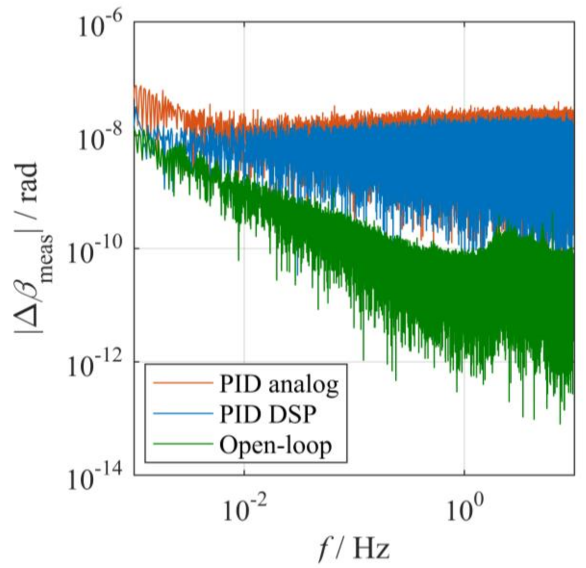

Figure 9: Noise spectrum of the difference of the FCTM relative to the PPTM for different operation modes

The noise of the signal in the open-loop operation mode is especially smaller in the higher frequency range, but also at the lowest shown frequencies, which represent the drift behaviour, the amplitude is slightly smaller. The standard deviations of the tilt signals within a time of 120 s were 0.011 µrad (FCTM-OL) and 2.23 µrad (FCTM, PID DSP) respectively. Partly, these effects are produced by the necessary amplification of the controller in the feedback loop, but also the additional number of involved devices like the DSP system and the UIC can be possible sources of additional noise.

In a further experiment, the DSP system was replaced by an analog PID controller circuit board, which increased the noise slightly. Within a 120 s time span the standard deviation was 3 µrad. In this case it must be mentioned, that the chosen P amplification was 10 times higher compared to the digital PID. In a further development, the UIC needs to be optimised and also the possible appearance of ground loops due to the controller connection should be investigated.

5. SUMMARY

A novel EMFC tiltmeter was developed and initial tests were performed, showing that on a very short timescale a resolution of 1 µrad can be achieved with a response time of 0.5 s. In an open loop configuration, a standard deviation of the short term signal of 0.011 µrad was achieved, which shows the potential of the system resolution.

In long-term experiments, the observed deviations increased to 4 µrad, but nonetheless, further investigations need to be done, focusing on the long term drift behaviour, the linearity and the mechanical robustness of the system. Additional investigations - preferably using two identical tiltmeters - are also necessary to identify the sources of the remaining noise in the measurement. In addition, the signal processing and electrical measurement system needs to be improved to reduce possible sources of noise and to adapt the ADC more specifically to voltage range and bandwidth that is observed in the instruments signals.

In comparison to existing tiltmeters that were developed at TU Ilmenau, the measurement could be increased and size of the instrument was reduced.

6. ACKNOWLEDGEMENT

The research, presented in this paper, was done within the project “Neigungsmessung in industriellen Mehrachsanwendungen” (ZF4075148PO9). The project was financially supported in the framework “Zentrales Innovationsprogramm Mittelstand“ (ZIM) of the German Federal Ministry for Economic Affairs and Energy. The authors would like to gratefully acknowledge this support.

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