

# Monitoring of Hydraulic Structures: Long-Term Testing of Inclination Sensors

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## ABSTRACT

Structural health monitoring of massive hydraulic structures is becoming increasingly important in Germany due to the age structure and condition of the infrastructure necessary to ensure safe shipping. A survey within the Federal Waterways and Shipping Administration (WSV) has shown that inclination sensors are most frequently used in the monitoring systems of massive hydraulic structures. However, inclination sensors are prone to drift, which can lead to misinterpretation of measurement data, especially over long measurement periods. The potential of the inclination sensors on the one hand and their deficits on the other hand show the necessity to examine their behavior under long-term testing conditions. Eight potentially suitable inclination sensor models are tested under typical and comparable environmental conditions. Since each sensor is unique, three identical single-axis inclination sensors of each model are tested. The test rig is designed for long-term stability. So far, the 24 inclination sensors have been measuring for almost 2 years in a closed concrete block under the open sky to replicate typical environmental conditions (temperature, solar radiation, etc.). Various temperature sensors installed in the concrete block ensure compensation for temperature effects. An automatic and a manual reversal measurement are used as references because they detect and eliminate their own linear sensor drift. In addition to explaining the design of the test rig, an interim result is presented that identifies the inclination sensor models that show the lowest sensor drift and sufficient long-term stability.

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## PROBLEM AND APPROACH

The transport infrastructure associated with federal waterways in Germany is, to a large extent, of considerable age. Approximately 50 % of ship locks and weirs were constructed before 1950, and around 30 % date back to before 1920 [1]. Unlike in other infrastructure sectors, these structures are generally not bypassable, and their failure would often result in the closure of entire waterways. Due to this particularity, the age structure of the solid components and the poor state of maintenance in some cases, it is often necessary to inspect the existing structures in order to ensure the safety of shipping traffic. To evaluate structural capacity, the guideline most commonly applied is the **BAW**Merkblatt "Load-bearing capacity of existing massive hydraulic structures (TbW)" [2], which ensures the reliability level required for existing structures in accordance with DIN EN 1990 [3].

The necessity for automatic structural monitoring typically arises from structural or computational deficiencies that are relevant to load-bearing capacity. The TbW guideline provides the possibility to compensate for such safety deficits through a structural monitoring system with an alarm function, allowing continued operation of the structure. This, however, requires the presence of sufficiently ductile structural behavior, ensuring that any failure is preceded by a detectable warning [2].

Although structural monitoring, as described above, is becoming increasingly important and technological advances allow for its general use, it is currently mainly used in hydraulic engineering for dams due to their high hazard potential. The monitoring system includes a customized solution for each dam. Broader implementation of structural health monitoring in waterway infrastructure requires standardized procedures and systems. Therefore, the Network of Experts of the Federal Ministry for Digital and Transport (BMDV) is currently developing a guideline with recommendations regarding appropriate system components [4].

A survey within the WSV regarding existing monitoring systems revealed that inclination sensors are used in most systems (see Figure 1, left). These do not require a fixed reference, line of sight or connecting elements and offer the potential to be used underwater. However, inclination sensors are prone to drift, which can lead to misinterpretation of structural deformations. For example, Woschitz demonstrated this in an extensive study on the static properties of inclination sensors [5].

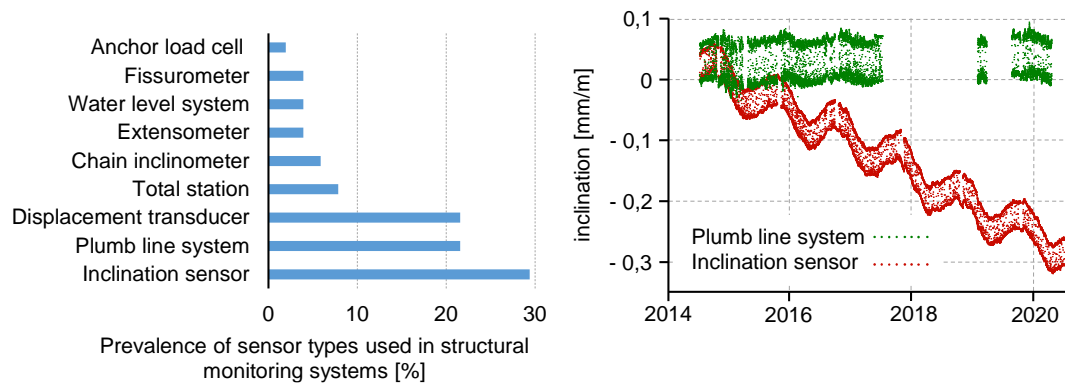


Figure 1. Type of sensor used in hydraulic structures of the WSV (left), values of a drifting inclination sensor at the Eibach lock (right) [4]

Figure 1 (right) shows measurements from an inclination sensor installed at Eibach Lock, indicating a trend of approximately 0,45 mm/m per year. This trend is attributed to sensor drift, as redundant measurements obtained with a plumb line system detected trend-free structural behavior [4]. The potential of inclination sensors on the one hand, and their limitations on the other, highlight the need for an in-depth investigation of their behavior within a long-term test environment.

## EXPERIMENTAL SETUP

The aim of the test rig described in this article is to determine the drift of potentially suitable inclination sensors under typical and comparable environmental conditions. The sensor drift is a slow change in the output variable with a constant input variable due to the ageing process of the sensor. In order to investigate the sensor drift, a long-term stable plane is provided under typical ambient conditions so that the ageing process can take place realistically. As the input variable temperature changes over the year, these changes must be compensated for in the drift evaluation.

The test setup is shown in Figure 2 and briefly explained below. It is installed on a one-meter-deep foundation with compacted subsoil to provide a stable long-term base. The concrete block stands on three precision levelling wedges made of stainless steel, which allow continuous and highly precise inclination adjustments of the concrete block. The precision levelling wedges are protected from the weather and direct sunlight by covers. A  $670 \times 670 \times 15$  mm stainless steel plate is mounted stress-free on three threaded rods within the concrete block using spherical washers. The sensors measure over several years in the closed concrete block, located outdoors on the premises of the Federal Waterways Engineering and Research Institute (BAW) (see Figure 3, left).

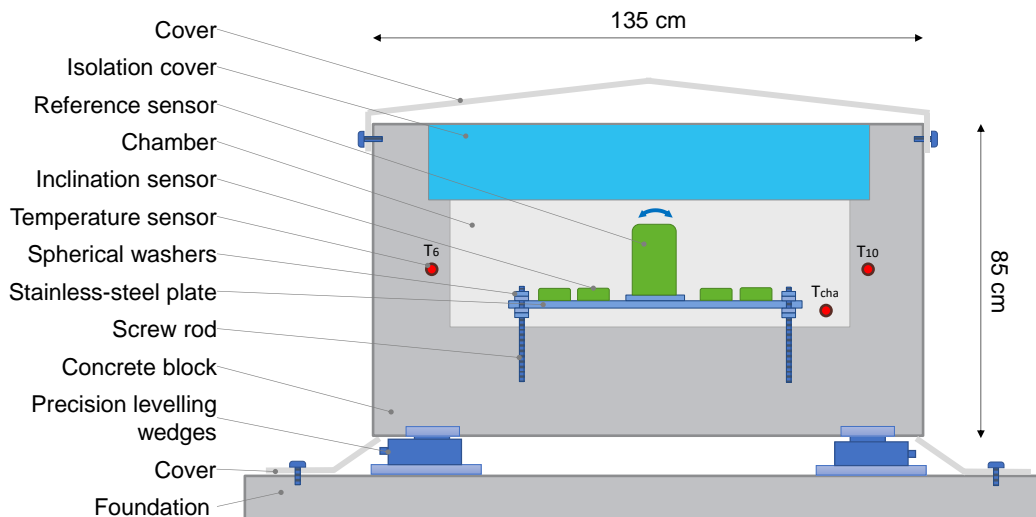


Figure 2. Sketch of the long-term test rig for inclination sensors

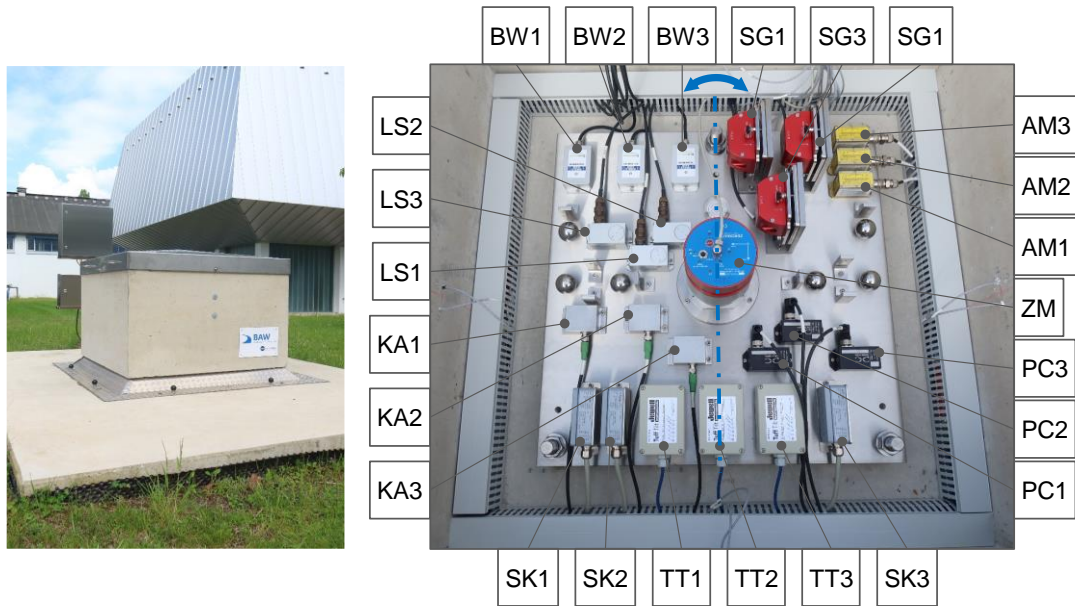


Figure 3. Long-term test rig for inclination sensors from the outside (left) and from the inside (right) with shortcuts, measuring direction and symmetry axis (blue)

Eight different models of inclination sensors are being investigated. Since each sensor is unique, three identical single-axis inclination sensors of each model are tested. The inclination sensors are mounted on the stainless-steel plate (see Figure 3, right). To compensate for temperature effects, ten temperature sensors are embedded in the concrete, and one sensor is placed freely inside the chamber. Additionally, two DAkkS-calibrated reference sensors are integrated into the setup to detect any potential inclination of the test rig. These include an automatic reversal measurement with the Zeromatic 2/1 and a manual reversal measurement with the BlueLevel, both from Wyler AG. These reference systems can detect and compensate for their own linear sensor drift. The question of why automatic reversal sensors are not used as a standard can primarily be answered by the high acquisition costs. For example, the Zeromatic 2/1, including the required additional equipment, costs around €12000. In addition, the precision mechanics integrated into the sensor can lead to significantly higher maintenance demands. For this reason, the Zeromatic 2/1 performs a reversal measurement only once every 24 hours to compensate for its own drift.

Table I lists the inclination sensors tested in the experimental setup. All technical specifications of the sensors are taken from the data sheets. The selection of inclination sensors was based on models already used by BAW, as well as additional sensors that meet defined criteria. These include a measurement range of approximately  $\pm 17,5 \text{ mm/m}$  ( $\pm 1^\circ$ ), an analog output signal of 4 – 20 mA, and a protection class of at least IP65. Procurement-related constraints and unanswered quotation requests further limited the selection. All technical specifications of the sensors are taken from the data sheets.

TABLE I. TESTED INCLINATION SENSORS

Sensor model Manufacturer or distributor	Abbr.	Measuring range	Repeatability	Output signal	IP	Price
AIM 70 AMOS Sensoren & Meßtechnik	AM	± 17,5 mm/m	0,00035 mm/m	4 – 20 mA	65	€2550
BWH 518 Wuxi Bewis Sensing Tech. LLC	BW	±17,5 mm/m	0,08727 mm/m	4 – 20 mA	67	€242
KAS211-41A a.b. Jödden GmbH	KA	± 26,2 mm/m	0,17453 mm/m	4 – 20 mA	67	€374
LSOC-1 Sherborne Sensors	LS	± 17,5 mm/m	0,01400 mm/m	4 – 20 mA	65	€1916
PC-IN1-1° Position-Control	PC	± 17,5 mm/m	0,10472 mm/m (accuracy at 20°C)	4 – 20 mA	65	€1588
SBS1U SEIKA Mikrosystemtechnik GmbH	SB	± 17,5 mm/m	Not specified	± 5 V	65	€1275
OS541MA0202 Sisgeo S.R.L.	SG	± 43,6 mm/m	0,06981 mm/m (max. peak error)	4 – 20 mA	67	€410
Tuff Tilt 801 Jewell Instruments	TT	± 8,7 mm/m	0,00349 mm/m	± 5 V	65	€1330

The inclination sensors were initially tested over a one-year period to identify defective units, verify calibration functions, establish data logger connectivity, and detect any potential interactions. During this preliminary phase, one LS-sensor was found to be defective and was replaced. No interactions due to electrical or magnetic fields were observed.

## DATA EVALUATION

The measurement series currently covers the period from 29 May 2023 to 12 May 2025. The sampling rate of the measurements began with a measurement every minute and was reduced to every 5 minutes after one year. In a first step, gross measurement errors such as outliers and abrupt jumps are removed. The prepared dataset is shown in Figure 4.

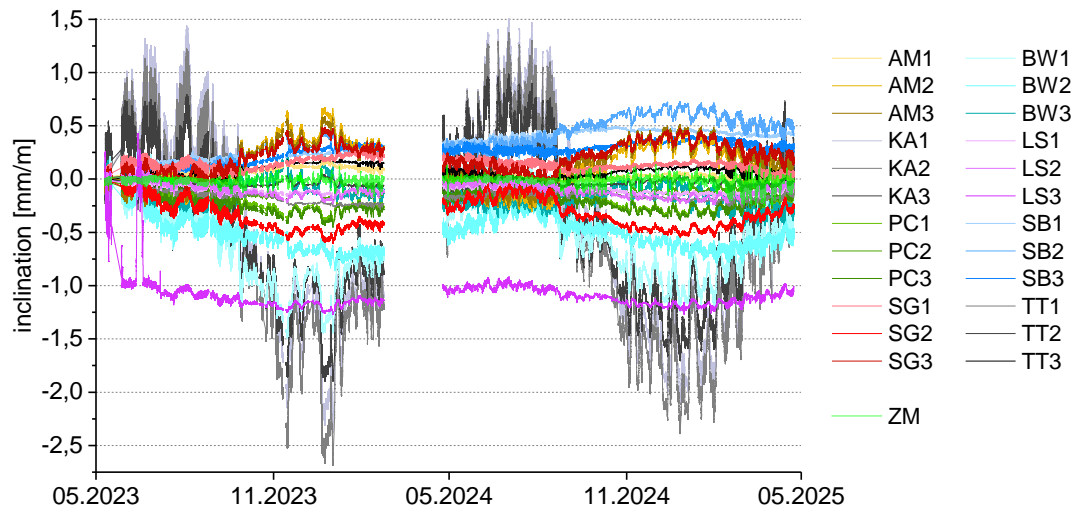


Figure 4. Prepared measurement results of all inclination sensors

All inclination sensors start at zero mm/m. A major data gap from March to May 2024 was caused by a power outage, which necessitated repair of the data logger. All measured temperatures are shown in Figure 5. The temperature sensors are connected to a separate data logger, which did not require repair, resulting in a smaller gap in the temperature dataset.

The reference sensor ZM shows a slight trend in the inclination values (Figure 4, light green), which can be interpreted as an uncertainty in the drift determination. Although all inclination sensors are mounted on the same stainless-steel plate and measure in the same direction, they sometimes give significantly different inclination values. This discrepancy is primarily due to varying thermal influences on the individual sensors as well as differences in measurement accuracy. The thermally induced deformations of the following three components significantly affect the inclination measurements: the concrete block, the stainless-steel plate and the individual sensor itself. To quantify sensor drift, a multiple linear regression is applied using the following regression model:

$$\alpha(T_{cha}, \Delta T_{block}, t) = c_{cha} \cdot T_{cha} + 0,009 \frac{mm}{m} \frac{1}{K} \cdot \Delta T_{block} + D \cdot t + c_0 \quad (1)$$

with the dependent variable  $\alpha$  the inclination, the independent variables  $T_{cha}$  the temperature in the chamber,  $\Delta T_{block}$  the temperature difference of the concrete block, the time  $t$  and the regression coefficients  $c_{cha}$ ,  $c_0$  and  $D$  representing the drift, which is the primary result sought from this long-term experiment.

To capture the thermally induced deformation of the concrete block, the temperature difference

$$\Delta T_{block} = T_6 - T_{10} \quad (2)$$

is considered, as shown in Figure 5. The temperature difference  $\Delta T_{block}$  is selected with  $T_6$  and  $T_{10}$  in such a way that the difference leads to a deformation of the concrete block, which correlates with the measured inclinations (see Figure 2). This thermally induced deformation affects all inclination sensors equally and is therefore uniformly accounted for in the regression model using a fixed coefficient of 0,009 mm/m/K, as determined by the reference sensor ZM.

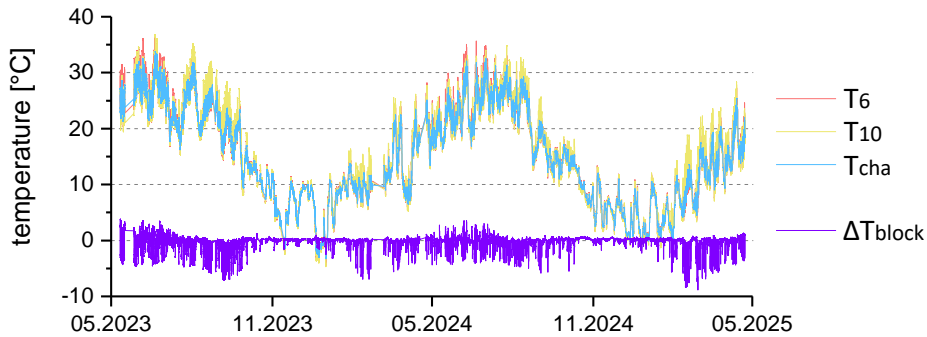


Figure 5. Temperature measurements in the long-term test rig

Thermal influences on the stainless-steel plate and the individual sensors themselves are captured by the chamber temperature  $T_{cha}$ . The coefficient  $D$  represents the drift, which is the target result of this long-term experiment.

## RESULTS

The results of the regression model (1) are summarized in Figure 6. On the left-hand side of the figure, the identified drift  $D$  for each sensor is shown. The coefficient for the temperature dependence in the chamber  $c_{cha}$  (red) is shown in the middle of Figure 6 and the coefficient of determination  $R^2$  (gray) is shown on the right.

The results show that the drift results differ considerably in some cases, even within one sensor model. The reference sensor ZM shows a drift of 0,01 mm/m per year and represents the uncertainty of the drift estimation. The temperature in the chamber has little influence on the measurement results of the ZM sensor, which is probably due to its central position on the stainless-steel plate and effective internal temperature compensation. As a result of these minimal dependencies, the  $R^2$  value is correspondingly low. The same applies to sensor SG1, and particularly to sensor TT2, whose measurement values closely match those of the ZM sensor. As shown in Figure 3, sensors TT1 and TT3 are located to the left and right of sensor TT2 and exhibit an antimetric temperature dependence  $c_{cha}$  on each other. This constellation indicates a symmetrical thermal deformation of the stainless-steel plate. Notably, the highest  $c_{cha}$  values are observed for the KA sensors, indicating a high temperature sensitivity of this sensor model. Since the thermal influence of the stainless-steel plate cannot be clearly separated from the temperature dependence of the sensor itself, a quantitative evaluation is not possible here. In Figure 4, the LS3 sensor shows significant changes in inclination, particularly at the beginning of the test period, and then reaches a stable level at around -1 mm/m. As there is no significant correlation with other sensors, the correlation coefficient of sensor LS3 is correspondingly low.

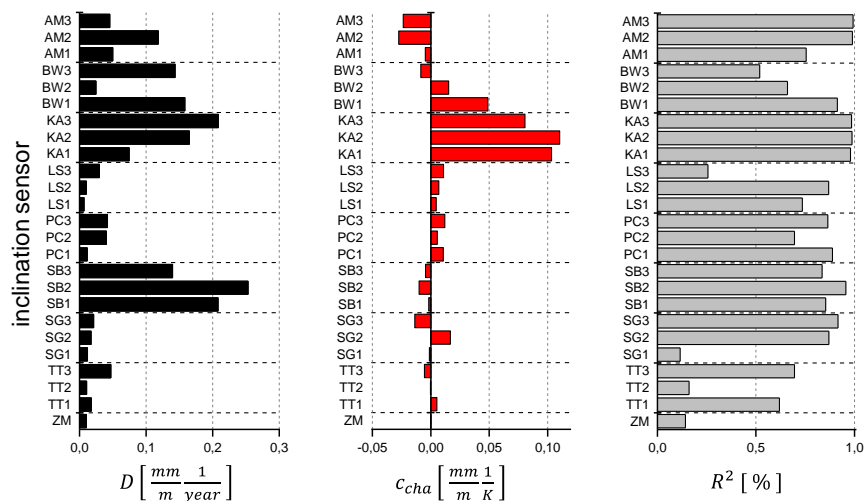


Figure 6. Results of the regression analysis with equation (1) for each tilt sensor: positive sensor drift  $D$  (left, black), dependence on the temperature in the chamber  $c_{cha}$  (middle, red) and coefficient of determination  $R^2$  (right, gray)

## CONCLUSION

Figure 7 summarizes the three available drift results for each sensor model by displaying the median as a bar and the minimum and maximum determined drifts as a span. The upper axis shows the equivalent horizontal displacement for a rigid chamber wall at a height of 10 m after 10 years, which would be misinterpreted due to the drift. With regard to the magnitude of the drift values obtained, the SG, LS, TT and PC sensors currently appear to be the most suitable for long-term monitoring under the given environmental conditions. However, due to a defective sensor delivered for testing and the aforementioned measurement errors associated with LS3, the reliability of this sensor model should be viewed critically.

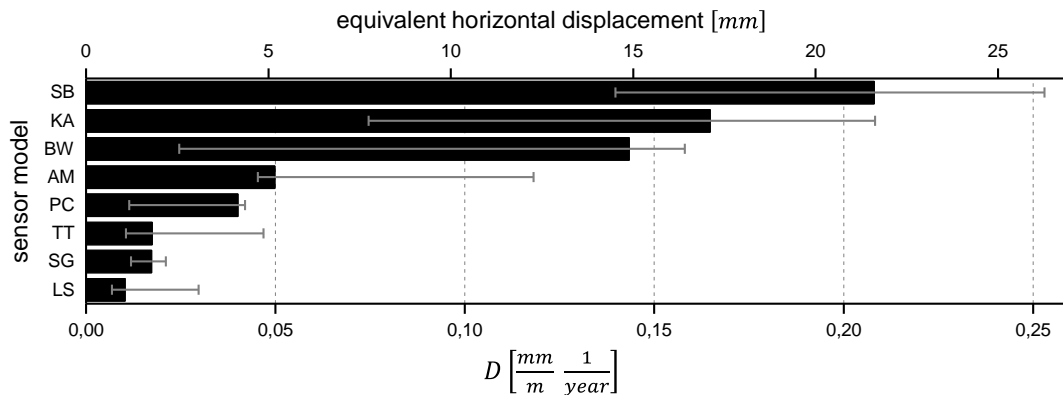


Figure 7. Drift per sensor model (median as bar, min/max as span) and equivalent horizontal displacement at a height of 10 m after 10 years

The test rig provides typical and long-term stable conditions for evaluating the suitability of inclination sensors for monitoring massive hydraulic structures. The different thermally induced deformations of the stainless-steel plate cannot be separated from the temperature influence on the sensors. In order to identify the most long-term stable sensor, the test rig must be operated for a longer period of time.

## REFERENCES

1. Heinzelmann, C., J. Bödefeld, A. Westendarp 2018. "Herausforderungen im Verkehrswasserbau" Bautechnik 95, H. 7, pp. 499-504.
2. Federal Waterways Engineering and Research Institute 2016. BAWMerkblatt "Load-bearing capacity of existing massive hydraulic structures (TbW)"
3. Handbuch Eurocode 0 - Grundlagen der Tragwerksplanung 2011, Version consolidated by DIN. Berlin: Beuth.
4. Kühne, C., C. Stephan 2023. "Monitoring of Hydraulic Structure: Problem and Approach" presented at the European Workshop on Structural Health Monitoring 2022 Palermo, pp. 840-848.
5. Woschitz, H. 2009 "Test of Static Properties of a Variety Tiltmeters" tm - Technisches Messen, H. 10, pp. 465-473.