Development of low-cost inclination sensor based on MEMS accelerometers

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Abstract. Rapid development of Micro Electro Mechanical Systems (MEMS) and the minimization of sensor cost, size and energy consumption in the last two decades leads to an effort to replace traditional sensors with their MEMS alternatives. The power consumption is one of the key problems, due to necessity to provide long term device power supply. Therefore a newly developed device was designed with the accent to low power consumption, to be able to operate with one small internal battery at range several months to years. The main goal was to develop a wireless monitoring system capable of continuous stability monitoring of various building structures. The sensor is designed to measure slow inclination variations or changes and in combination with variant designed for high frequency monitoring should represent complete solution of real time structure health monitoring. The STATOTEST compact measurement system is mainly composed of triaxial MEMS accelerometer as a sensing unit, motherboard containing IOT modules and battery, all placed in single waterproof box. The raw signal measured by MEMS accelerometer is preprocessed inside the unit and the data are sent to the cloud via LoRaWan, NBLoT or satellite. The results can be displayed, managed and exported through the web application. This paper presents current state of sensor development, refer to number of problems, which were solved during the process and deals with estimation of its accuracy characteristics in the laboratory conditions. During the laboratory experiment, small defined changes of inclination were performed and compared with values registered by the inclination sensor. The testing was performed before and after calibration procedures. After eliminating of accelerometers production errors, the accuracy of the unit measurement RMSE is less than 0.002° for the step change of 0.09°, tested in six different orientations of the sensor. One measurement is mean of 1000 measurements and its residual random error for one measurement is 2°x10^-5. Series of laboratory tests proved high short-term device accuracy in stable conditions. It is well known, that MEMS accelerometers strongly depend on the sensor temperature. To perform temperature compensation, we built own climate chamber, which is able to change automatically temperature of the several devices at once in specified ranges. Temperature compensation was then performed by using of polynomial approximation to obtain the field measurement accuracy close to laboratory conditions. This task is challenging because it is necessary to improve the proper material composition between the MEMS and the monitored structure and the device fixing methods.
1. Introduction

Automation in all fields of human activity is the trend of today and it is no difference in geotechnical engineering. Automatic data collection and its transmission to the user in real time is often becoming a basic requirement. This is especially true when long-term monitoring is required - traditional methods that depend on the work of a skilled operator are not only prohibitively expensive, but also make continuous monitoring at higher frequencies virtually impossible. Aging infrastructure is a common problem in developed world, and monitoring requirements can be prohibitively expensive. Many different parts of a single structure are often required to monitor. The solution is to use a larger number of low-cost sensors [1, 2]. This phenomenon also affects inclinometer measurements, with conventional inclinometers are replaced with MEMS accelerometers. Their advantages are low power consumption, low cost and digital output. The main disadvantage is the dependence of the measurement on temperature.

The aim of this work was to develop a comprehensive monitoring system comprising relatively inexpensive sensors widely applicable in a comprehensive building monitoring system. A system that allows monitoring of both slow structure deformations and high-frequency tilt changes (vibrations). We offer a variant for monitoring slow tilt changes in this paper. The aim was to eliminate the shortcomings of the accelerometer. So that the state of the structure could be monitored continuously.

2. Description of the device

The inclinometer is part of the STATOTEST system, which is primarily aimed to structure-health monitoring. The monitoring system consists of individual inclinometer sensors that transmit data to the cloud or directly to the user via IoT networks. The data in the cloud is then continuously reported and can be visualized and controlled via a web interface (figure 1). In addition to inclinometers, the system uses other types of sensors, which all are capable to measure temperature which is a major environmental factor influencing structures:

- high frequency accelerometers to measure the vibration of the structure,
- resistance or inductive dilatometers to measure distance, dangerous dilatation,
- strain gauges to measure deformation,
- temperature of the structure,
- weather stations to measure temperature, relative humidity, wind speed and precipitation.

![Figure 1. Scheme of the STATOTEST monitoring system](image)

The inclinometer itself consists of triaxial MEMS accelerometer, IoT hub, ADXL 355 MEMS accelerometer [3], 3.6 V /5800 mAh battery all integrated in one plastic box. IP67 degree of protection ensures sufficient protection against dust and water. Communication with the cloud is carried out via networks LoRa, NBiot or satellite. Newer versions of the device versions support two-way communication. Interval of measurements can be typically set from several minutes to days. One reading of the inclinometer is represented by average of 1000 readings of the MEMS accelerometer. Basic corrections and computations are made inside the device. Consequently, measured data and computed
values are sent to the cloud. The system operates fully autonomously and alerts via SMS, when tilt limits are exceeded.

3. Laboratory testing and calibration
The basic accuracy characteristics of the inclinometer were determined under laboratory conditions to verify the inclinometer applicability to monitor small changes in tilt. Testing was performed in six basic device orientations (figure 2). Values characterizing the repeatability, accuracy and precision of the measurements were determined. The experiments were performed under stable temperature conditions.

![Figure 2](image.png)

**Figure 2.** Six orientation of the device during the testing and calibration

3.1. Repeatability
In general, accelerometer measurements are affected by relatively large random errors [4]. These errors are compensated by repeating the measurements. In case of slow deformations and low measurement frequency $f < 1 \times 10^{-2}$ Hz, it is possible averaging of large numbers of measurements. In this case, 1000 MEMS accelerometer readings are averaged directly in the device. The aim of the test was to verify whether a given number of repetitions is sufficient to reduce random measurement errors so that they do not affect the accuracy of the sensor measurement. For this purpose, a simple experiment was performed where several sensors were measured under stable conditions.

The sensor was placed in stable conditions and constant temperature. During 16 minutes, 100 inclinometer readings were taken. Tilt values were registered for each of the 6 basic orientations of the instrument (figure 1). The standard deviation without sensor movement were similar for all sensor orientations with $s = 2.3° \times 10^{-5}$, which is valid for the average of 1000 readings of an accelerometer.

Averaging 1000 sensor readings is sufficient. The residual random error is ten times less than the standard deviation of the measured tilt (section 3.2) and therefore will not affect the accuracy of the sensor determined tilt.

3.2. Precision and accuracy
The main purpose of the inclinometer is to monitor tilt changes, so the orientation of the device is not important, only the accuracy of tilt change. The orientation in space is rather informative, giving an idea of the direction of the space movements. The key is maximum accuracy at minimum tilt changes. During the experiment, the device was mounted on Leica TC1610 total station telescope (vertical direction accuracy is $0.0005g$ i.e. $0.00045°$). The telescope was in approximately horizontal position (figure 3).
Small tilts of the sensor were induced by fine rotation in vertical plane. The angle of vertical tilt was calculated from the difference of two vertical directions. The accuracy of the tilt induced in this way is significantly higher than the accuracy of the total station over the whole range. In the case of small changes in the vertical direction, its accuracy is practically equal to the accuracy of the vertical circle reading, i.e. 0.0001g and 0.00009° respectively. The assumed accuracy of the tilt measured by the accelerometer was 0.001°. Due to the order of magnitude higher accuracy of the total station, the inclinations induced by the rotation of the total station telescope were considered as nominal and deviations from these inclinations were treated as true errors. The magnitude of the induced tilt was 0.1g i.e. 0.09°. This value corresponds to a deflection of 1.57 mm/meter. The assessment was made both on the accuracy (the degree of agreement between the magnitude of the measured tilt and its nominal value) and on the precision characterizing the degree of dispersion of the measured values.

The test results indicate high accuracy and precision of the instrument. The standard deviations of the measured inclinations were mostly within $2° \times 10^{-3}$. However, a significant systematic error in the magnitude of the measured tilt can be observed in some inclinometer orientations (table 1). In such cases, there is a significant decrease in measurement accuracy. The sensor has to be calibrated even for very small inclination measurements.

![Figure 3. The inclinometer fixed on Leica total station (left)](image)

**Table 1.** Characteristics of precision ($s_p$) and accuracy ($s_a$) of the measured inclination change before calibration

| Position 1 | Position 2 | Position 3 | Position 4 | Position 5 | Position 6 |
|------------|------------|------------|------------|------------|------------|
| $s_p$ (°)  | $s_a$ (°)  | $s_p$ (°)  | $s_a$ (°)  | $s_p$ (°)  | $s_a$ (°)  |
| 0.0008     | 0.0010     | 0.0011     | 0.0010     | 0.0008     | 0.0009     |

3.3. Calibration process

A static calibration method has been used to adjust measurement of the MEMS accelerometer using modified 12-parameter calibration model [5]. Compensated measurements $W$ were obtained as product of the matrix of measurements $w$ and matrix of 12 calibration coefficients $X(1)$ [6]. It was used a steel orthogonal fixture to quickly adjust the sensor to 6 defined positions (figure 2, figure 5 right).

\[ W = w \cdot X \]  

(1)
During the calibration matrix of calibration coefficients are obtained using least squares method, where \( w \) is matrix containing measurements in 6 orthogonal static positions and matrix \( Y \) consists of 6 normalized Earth gravity vectors (2).

\[
X_{(4,3)} = (w' \cdot w)^{-1} \cdot w' \cdot Y
\]  

where:

\[
w^{(6,4)} = \begin{pmatrix}
x_1 & y_1 & z_1 & 1 \\
x_2 & y_2 & z_2 & 1 \\
x_3 & y_3 & z_3 & 1 \\
x_4 & y_4 & z_4 & 1 \\
x_5 & y_5 & z_5 & 1 \\
x_6 & y_6 & z_6 & 1
\end{pmatrix}
\quad \text{and} \quad
Y_{(6,3)} = \begin{pmatrix}
1 & 0 & 0 \\
-1 & 0 & 0 \\
0 & 1 & 0 \\
0 & -1 & 0 \\
0 & 0 & 1 \\
0 & 0 & -1
\end{pmatrix}
\]

Table 2. Characteristics of precision (\( s_p \)) and accuracy (\( s_a \)) of the measured inclination change after calibration

| Position 1 | Position 2 | Position 3 | Position 4 | Position 5 | Position 6 |
|------------|------------|------------|------------|------------|------------|
| \( s_p \) (°) | \( s_a \) (°) | \( s_p \) (°) | \( s_a \) (°) | \( s_p \) (°) | \( s_a \) (°) | \( s_p \) (°) | \( s_a \) (°) | \( s_p \) (°) | \( s_a \) (°) |
| 0.0008     | 0.0007     | 0.0007     | 0.0010     | 0.0010     | 0.0007     | 0.0007     | 0.0007     | 0.0007     | 0.0010     |

The calibration procedure eliminated systematic errors in the scale of the measured inclinations, as seen in the table above (table 2). The standard deviation of the measured inclinations after calibration did not exceed 0.001°. Maximal registered deviation of measured acceleration from nominal 1g was \( 8 \times 10^{-2} \) before calibration and after calibration it decreased to \( 8 \times 10^{-4} \).

3.4. Influence of the temperature

It is well known that MEMS accelerometers are significantly affected by temperature [7, 8]. This is not such a problem for high frequency measurements or for measurements of rapid changes in tilt, vibration. However, for slow deformation measurements it plays a major role. The measurements of used MEMS accelerometers are corrected by using correction factors supplied by the manufacturer. These partially compensate for the influence of temperature, but differences between the individual sensors remain. A thermal chamber was used to experimentally determine the effect of temperature on the STATOTEST sensors. In order to simulate the extreme conditions that can occur in field use. The sensors were exposed to temperature fluctuations from -30 to +60 °C for several days (figure 4). The extreme conditions proved to have no effect on the operation of the device, but the accelerometer measurements were significantly correlated with temperature, as expected.
The use of a climate chamber to estimate thermal drift proved to be problematic. This was due to the considerable vibration of the equipment during operation and also to the deformation of the chamber caused by the thermal expansion of the steel. For this reason, a custom climate chamber was constructed to allow automated changes in sensor temperature without unwanted vibration. The sensors were placed in the chamber in such a way to avoid their inclination changes due to expansion and contraction of the chamber (Figure 5 left).

Several temperature cycles were implemented in the range of approximately -20 °C to +60 °C for each sensor. Part of the temperature curve was used for calibration and part for testing the success of temperature compensation. The actual calibration consisted in describing the temperature dependence of the accelerometer measurement by a continuous function, for this purpose a second-degree polynomial was used [9]. The calibration results in the coefficients $a_0,a_1,a_2$ of the thermal function (3). To compensate the accelerometer measurements, a common reference temperature $T_0 = 20$ °C was chosen. The inclinations calculated from the compensated and uncompensated accelerometer measurements are shown in the plots (Figure 6).

$$A(t) = a_2 \cdot t^2 + a_1 \cdot t + a_0$$  \hspace{1cm} (3)

**Figure 4.** Sensors installed in the climatic chamber during the test in extreme temperature conditions at IRSM

**Figure 5.** Climate chamber built for temperature compensation purposes (left); Turned orthogonal fixture made of steel (right)
The standard deviations of the compensated tilts describe the degree of compensation of temperature effects on the inclinometer unit (figure 6). Standard deviations of the tilts above are $s_x = 0.0032^\circ$, $s_y = 0.0112^\circ$, $s_z = 0.0083^\circ$.

4. Results and discussions

For low frequency measurements, the sensor averages 1000 accelerometer readings to compensate for the effect of random errors. This value has proven to be more than sufficient. Comparison of the accelerometer sensor measurement results with nominal (set tilt) values showed that it is appropriate to calibrate the device even for relatively small tilt changes. The use of the turned orthogonal fixture allowing a quick calibration of the sensor in its 6 basic positions proved to be advantageous. Prior to calibration, the sensor measurements showed significant systematic deviations in some of its orientations. After calibration, the systematic errors were well compensated and the standard deviations of measured tilt changes was within 0.001°.

Temperature compensation of sensor proved to be a more complex problem than compensation of sensor production errors. Sensor errors caused by temperature influence are in order of 0.1°. After compensation by using of reference temperature curve (a 2nd order polynomial), the standard deviation of the tilt dropped to 0.01°. We proved that the errors due to temperature changes are roughly in order higher than the manufacturing errors of the accelerometer, so they will be a major limiting factor of the device accuracy. Furthermore, temperature variations do not only affect the accelerometer measurements itself, but may affect the composition of the material between the accelerometer and the measurement object, especially in the case of uneven heating of the inclinometer casing. Therefore, in addition to the implementation of temperature compensation, the thermal influence on the equipment in the field must be minimised as much as possible.

5. Conclusions

The sensor, equipped with a triaxial MEMS accelerometer, is able to register even minimal tilts with high accuracy. The systematic errors of accelerometer and the resulting systematic errors are significant even for small changes of tilt measurements. However, they can be sufficiently eliminated by a simple calibration procedure using an orthogonal fixture. Optimal compensation of the temperature dependence of accelerometer proved to be crucial, causing errors in orders higher than those found under constant temperature conditions. When temperature compensation is used, the standard deviation in the temperature range from -20° to +60° is approximately 0.01°. This value limits the accuracy of long-term inclinometer measurements. However, these variations may be due to some extent not only to the characteristics of the MEMS accelerometer itself, but also to the design of the entire sensor and the design of its attachment to the structure. It will be advisable to consider optimization of the material composition, the inclinometer casing, the mounting method or also possible protection against uneven heating of the device.
Acknowledgements
This research was funded by conceptual development research organisation RVO: 67985891

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