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Dynamical system of measuring of small inclination angles

This paper presents a new method of measuring of small inclination angles. The method consists in application of a pendulum with a diaphragm coworking with an optoelectronical barrier. Results of studies of the constructed device are also presented, they focused on determination of drift of the measured inclination angles as well as variation of the period of the complete oscillation of the pendulum for positive and negative angles of inclination. Variation of mean errors of the studied magnitudes for all test measuring series were analyzed graphically.

1. *Introduction*

Engineering objects frequently need to be monitored in respect to the shape or displacements, during construction as well as under conditions of full exploitation. The observations may be carried permanently or periodically. Sometimes there may arise a task to study deflection from horizontality of the monitored object. One possible way to fulfill this geodetic task is to perform a direct measurement of inclination angles of a chosen part of the object with use of devices designed specially for accurate determinations of small inclination angles.

Measurements of small inclination angles may be carried out with application of various methods, beginning with the simplest, which depend upon classical liquid levels and their modifications (resistant, capacitive or photoelectric levels) through typical electronical levels, which principal of operation relies e.g. upon variation of inductance of a coil in the Maxwell bridge caused by oscillations of a pendulum suspended and hanging down freely in the housing of the device (Niveltronic level). Also, there can be distinguished photoelectric measuring systems with a proper, freely hanging pendulum that simultaneously plays a role of diaphragm to a set of photoresistors arranged as the Wheatstone bridge. Also devices being modification of the accelerometer may be applied to detect deflections from horizontality. Characteristic feature of such a solution (e.g. Schaevitz inclinometer) is that a pendulum deflects from its initial position after applying acceleration to the device. The paper describes elaborated method of determination of small inclination angles through time measurements of a swinging pendulum coworking with photoelectric sensor. It should be emphasized here that the method was originally elaborated by the author.

2. *Concept of the measuring method*

The concept of the method for determination of small inclination angles is connected with a pendulum system. The pendulum may be driven with power or electricity. If the photoelectric barrier 3 (Fig. 1), coupled with the base 7 of the inclinometer through the element 4, is attached vertically to the diaphragm 5, connected to the pendulum 2 which plays the role of optical interrupter for the light beam, then we have:

$$T = T_1 + T_2 \qquad (1)$$

and

$$T_2 - T_1 = 0 \qquad (2)$$

where T – oscillation period of the pendulum.

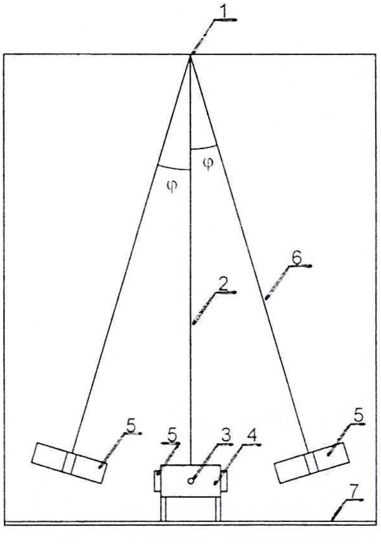


Fig. 1. Scheme of location of the optoelectronical barrier and optical interrupter coupled with the pendulum of the inclinometer: 1 – point of pendulum suspension, 2 – pendulum with optical interrupter, at free position, with inclination angle of the base equal to 0, 3 – element of the optoelectronical barrier, 4 – carrier of the optoelectronical barrier, 5 – optical interrupter, coupled rigidly with the pendulum, 6 – extreme position of the pendulum, after its deflection by angle φ, at inclination angle of the base equal to 0, 7 – base of the inclinometer

If the base of the instrument is deflected from its horizontal position by an angle α, then the pendulum with the optical interrupter (at free sag) will not coincide with the axis of the electronical barrier. Time intervals T_1 and T_2, determined with movement of the optical interrupter will not be equal. The difference $T_2 - T_1$ depends on value of the angle and may take positive or negative values in dependence on the inclination angle α. The value of the inclination angle α, determined from one full period of pendulum oscillation may be computed using the following formula:

$$\alpha = (T_2 - T_1)\,k = \Delta T \times k \tag{3}$$

where:

α – angle value given in seconds of arc,

ΔT – difference between the two time intervals T_1 and T_2 in milliseconds,

k – coefficient given in seconds of arc per one millisecond.

For one measuring cycle, the time intervals T_1 and T_2 are fulfilled with standard clock impulses of a period T_Z, of number N_1 and N_2 respectively:

$$T_1 = N_1 \times T_Z \tag{4}$$

and

$$T_2 = N_2 \times T_Z \tag{5}$$

The difference between the two intervals (ΔT) derived from the most left and right positions with respect to the optoelectronical barrier amounts to:

$$\Delta T = T_2 - T_1 = T_Z\,(N_2 - N_1) \tag{6}$$

3. *General description and block diagram of the electronical system of the inclinometer*

The electronic inclinometer, in its model version, consists of four individual devices:

- photoelectric sensor,
- stabilized feeder of the photoelectric sensor,
- counting device, provided with a system of measurement results digital display,
- quartz generator of standard frequency.

The photoelectric sensor is composed of a pendulum provided with an optical interrupter, electronic elements of double optoelectronical barrier, consisting of, among others, light-emitting diodes and phototransistors. The pendulum is driven with a spring clock-work. Since there is a possibility of disturbance of the optoelectronical barrier work with changeable external illumination, the inclinometer sensor was isolated from the disadvantageous influences through application of a lightproof housing. The photoelectric sensor is electrically connected with the standard frequency generator as well as with the counting device. The counting device contains, among the others, forming system – transforming the signal from the optoelectronical barrier receiver into its digital form, and steering system – generating signal which enables correct work of the counter and the register. The counter works bidirectionally during the measurement of the time difference. The system of register, decoder and counter makes it possible to give result of one individual measurement or result of averaging of 100 measurements onto the display.

The block diagram of the electronical system of the inclinometer is given in Fig. 2. On the display of the device there are given at the same time value of the oscillation period (T) and results of measurements of the time differences (ΔT), dependent, among the others, on the angle of inclination of the instrument. Since the measurement results in the model device change in every 1-2 sec., it is possible to switch on an averaging system. The latter allows to obtain mean values from 100 time differences (ΔT) and 100 periods of pendulum oscillations (T). In such a case, the averaged values are kept on the display for about 2 minutes.

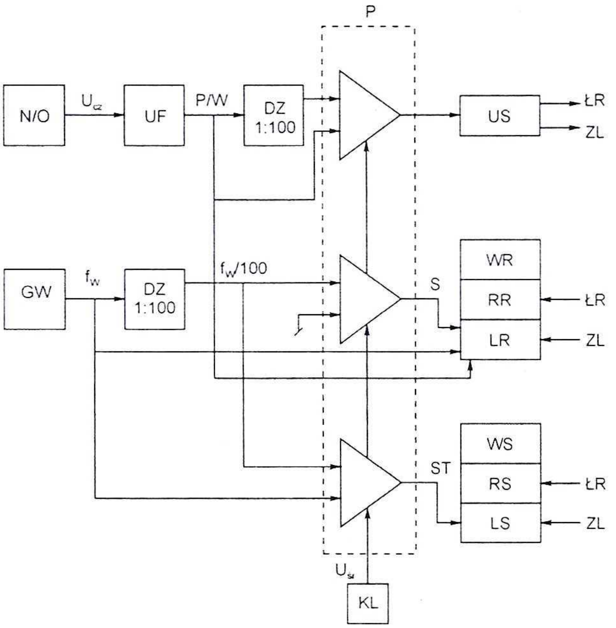


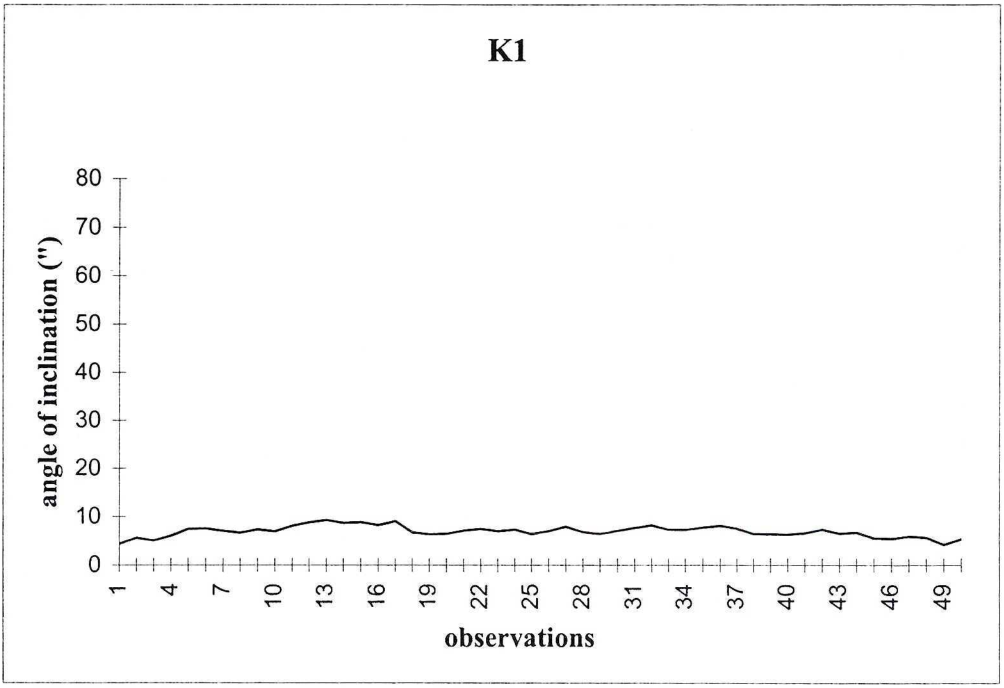
Fig. 2. Block diagram of the electronic inclinometer: *N/O* – transmitter/receiver (of the optoelectronical barrier), U_{cz} – voltage from the sensor, *UF* – forming system, *DZ* – divider 1:100, *P* – switch, *US* – control systems, *ŁR* – signal "load the register", *ZL* – signal "set the counter to zero", *GW* – standard frequency generator, *WR* – display of the difference, *RR* – register of the difference, *LR* – counter of the difference, *WS* – display of the sum, *RS* – register of the sum, *LS* – counter of the sum, *KL* – keyboard, f_W – standard frequency, *P/W* – signal "ahead" or "back", $f_W/100$ – frequency 100 times smaller, *S* – input signal of the counter of differences, *ST* – driving signal of the counter of the sum, $U_{śr}$ – averaging

4. *Testing investigations of the electronical inclinometer*

The testing investigations of the electronical inclinometer were performed taking advantage of a level examiner, on which the sensor of the inclinometer was mounted. Averaged values of 100 time differences (ΔT) and according averaged (from the same number of determinations) values of the periods of the pendulum (T) were automatically recorded, at a given angle of inclination. One measuring series, performed at the given inclination angle, enclosed 50 couples of observations. The studies were carried for positive and negative inclinations, from $-780''$ to $+720''$ at $60''$ changes of the angle between the measuring series. In the model device there was applied a modified, doubled optoelectronical barrier, with the light interrupter accommodated to it.

5. *Results of testing*

Elaboration of the test measurements made it possible to prepare plots of drifts of the measured inclinations (denoted in Fig. 3, 4, 5 by K) as well as plots presenting variation of the periods of the pendulum oscillations (denoted in the Fig. 3, 4, 5 by T). Also, plots giving variations of mean inclination errors (m_K) and of the mean errors of oscillation period of the pendulum (m_T) for all the measuring series (Fig. 6).



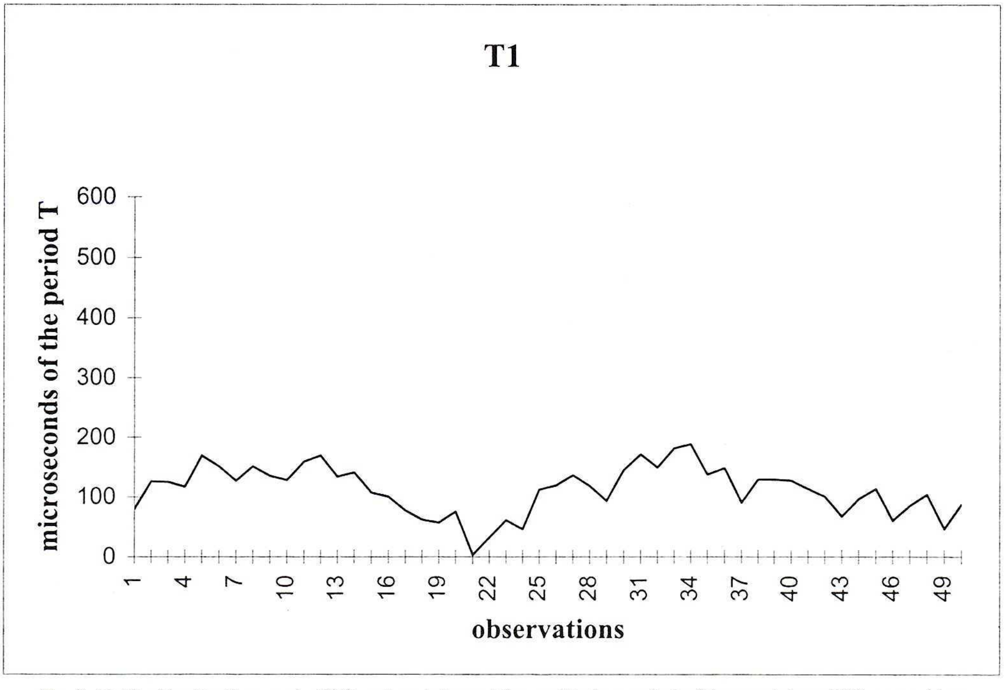
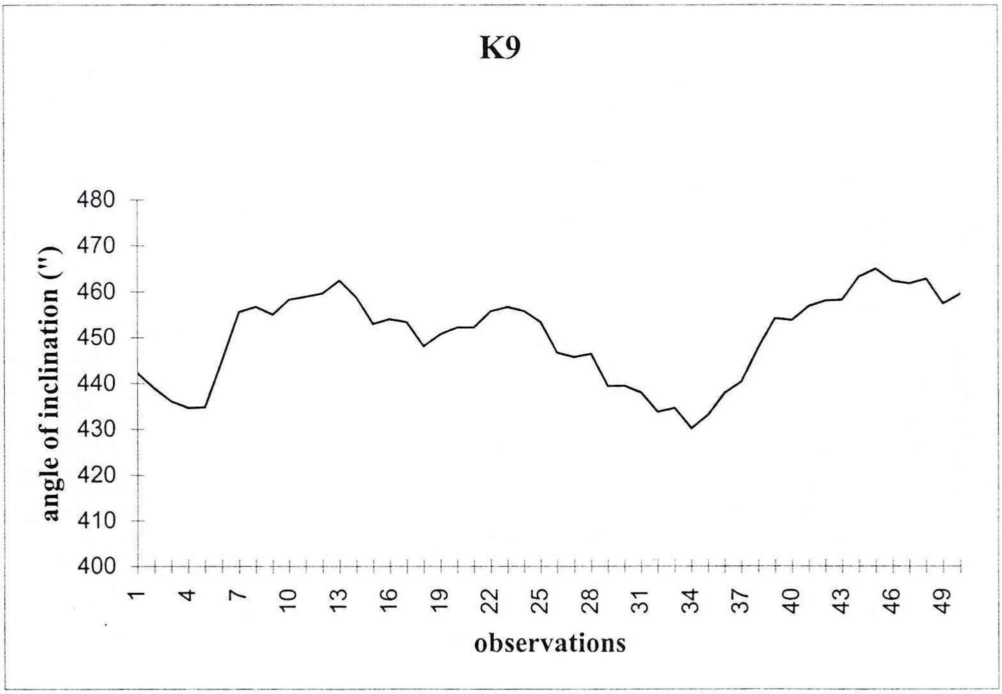


Fig. 3. Drift of inclination angle (K1) and variation of the oscillation period of the pendulum (T1), at positive inclination angle



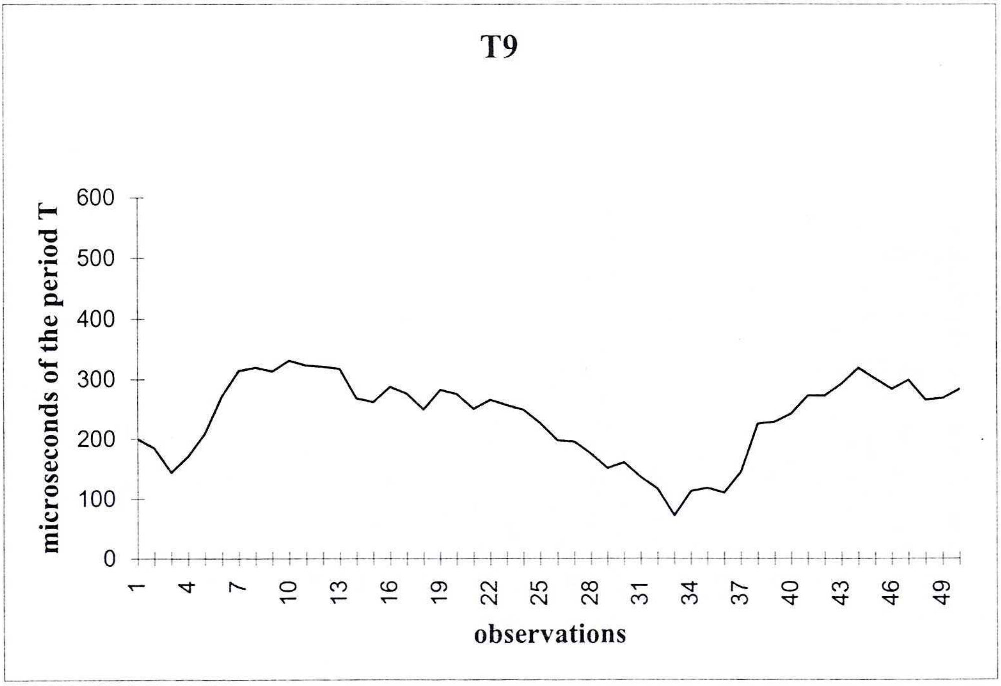


Fig. 4. Drift of inclination angle (K9) and variation of the oscillation period of the pendulum (T9), at positive inclination angle

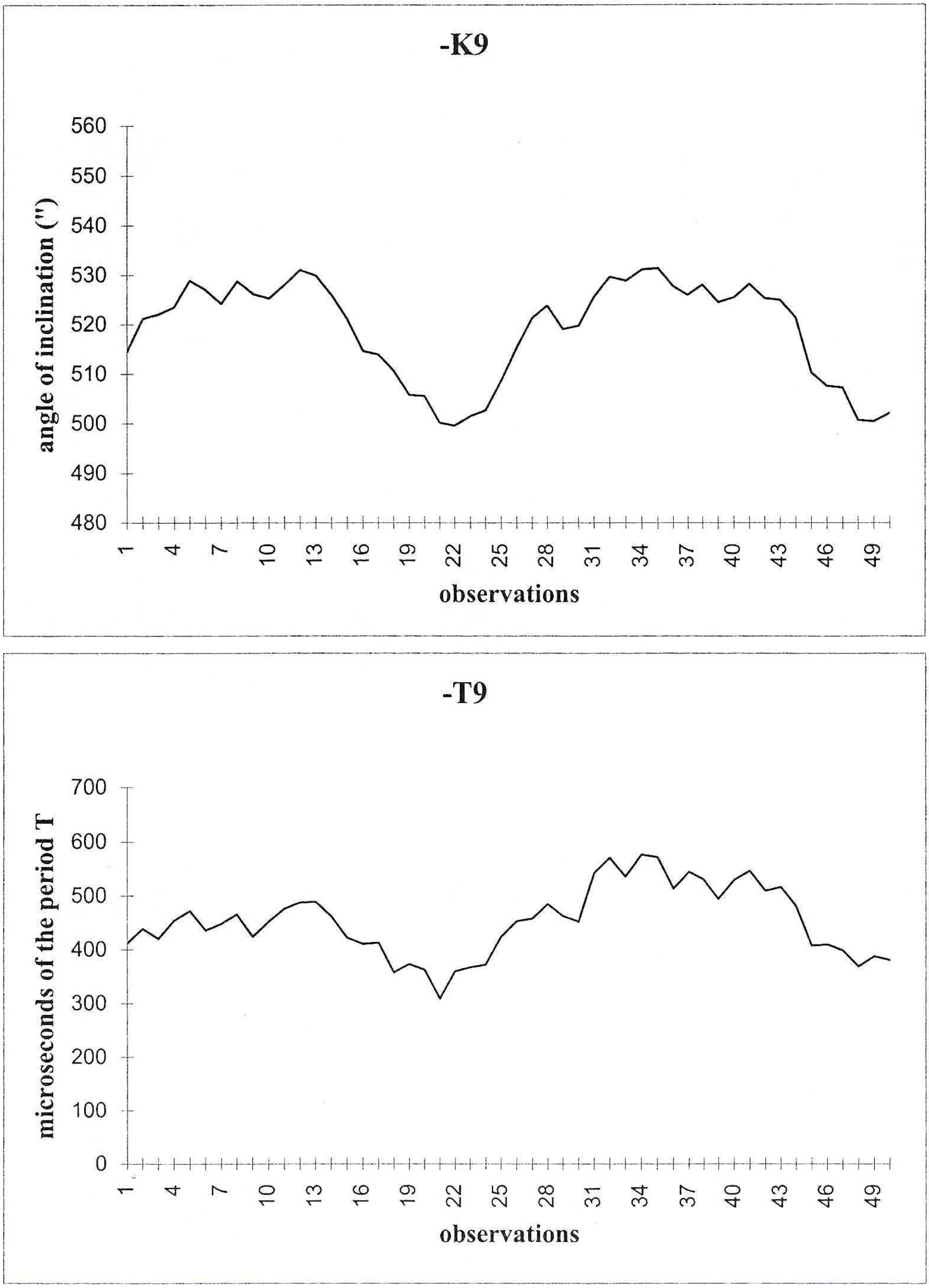
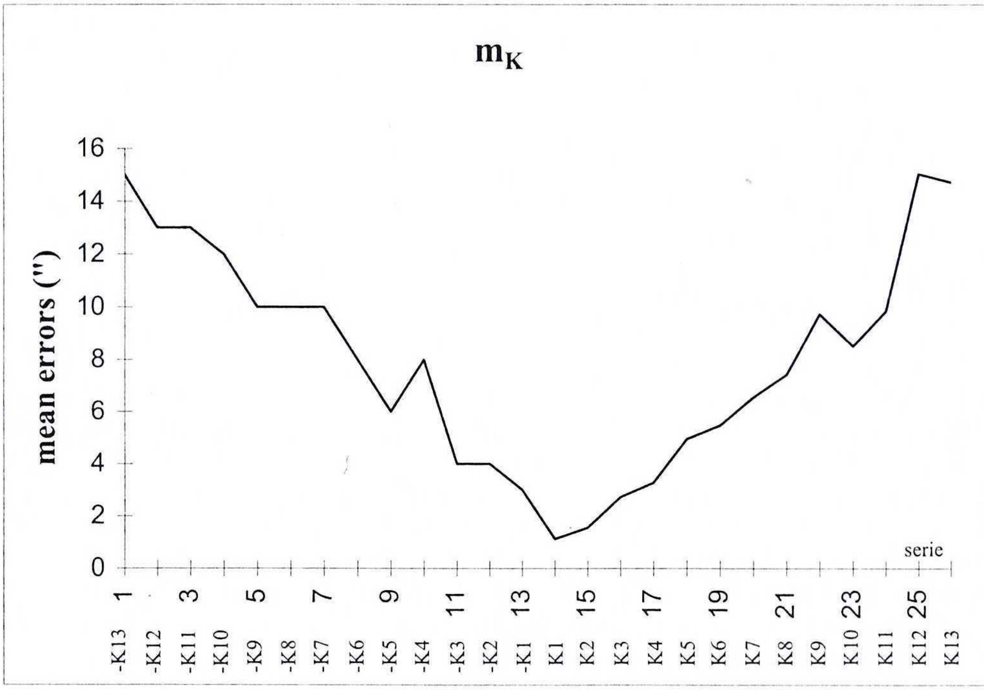


Fig. 5. Drift of inclination angle (−K9) and variation of the oscillation period of the pendulum (−T9), at negative inclination angle



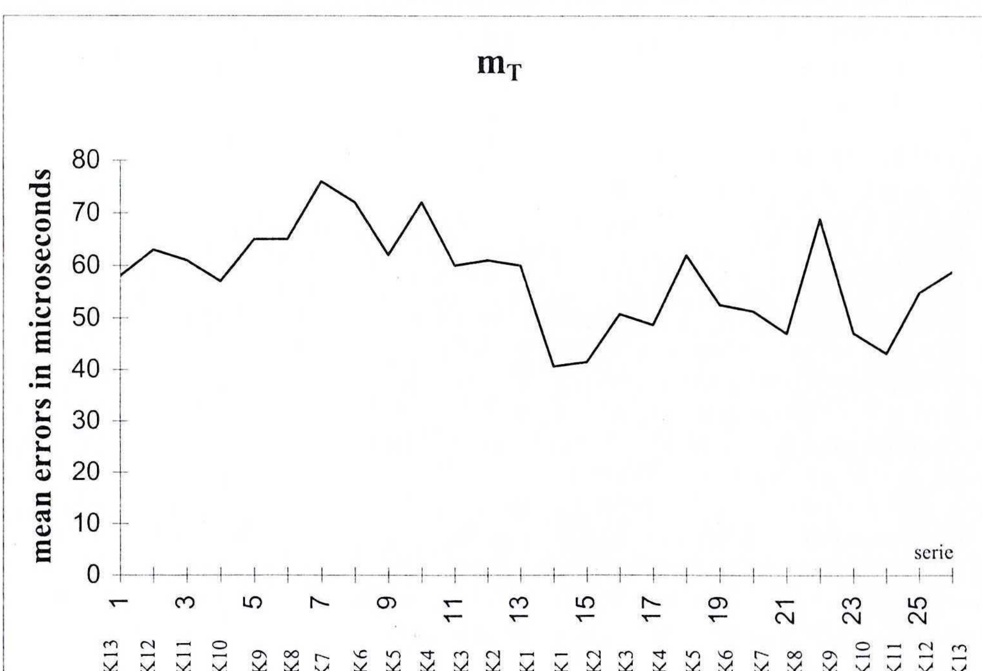


Fig. 6. Variation of mean errors of inclination angles (m_K) and oscillation period of the pendulum (m_T) in measuring series

For small inclination angles (about 8″) the plot of the drift for inclination angle measurements for 50 averaged observations does not differ much from the theoretical straight line. There can be seen almost 100% compensation of errors caused by irregular period of pendulum oscillations. Variation of the period of pendulum oscillations at symmetrical position, in respect to optoelectronical barrier axis (the plot T1 in Fig. 3) does not effect substantially the results of angle measurements (plot K1 in Fig. 3). Small deflection of the plot K1 from the straight vertical line can be explained with fluctuations that occur in electronical system of the sensor. At bigger inclination angles (plot K9 in Fig. 4 and plot –K9 in Fig. 5) there can be noticed considerable drift of the results of measurements, and variation of this drift is of near-sinusoidal shape. Also, there can seen shifts of the plots K9 and –K9 below the level of theoretical value of the inclination angle, i.e. 480" and –540". Analyzing corresponding plots representing period of oscillations of the pendulum (plot T9 in Fig. 4 and –T9 in Fig. 5), a distinct effect of irregularity of pendulum period (T) on variation of results of inclination angle measurements can be observed (plots K9 in Fig. 4 and –K9 in Fig. 5). It is clear that the observed minimums on the plot T9 do force minimums on the plot K9, and varied values of pendulum oscillations period cause that inclination angle measurement results also change, in the same direction. Influence of changeable period of oscillations of the pendulum (T) on results of angle determinations is distinct, since at bigger inclination angles the difference following from the formula (2) is considerable, thus compensation of pendulum period irregularity is smaller.

Analyzing the mean errors m_K for all 26 measuring series (plot m_K in Fig. 6) it can be seen that the smallest error occurs at position 14, corresponding to a small inclination angle (about 8″) and it becomes bigger together with the increase of the absolute value of the inclination angle.

6. *Conclusions*

On the basis of performed analysis of the results obtained using the model version of electronical inclinometer constructed at the Institute of Geodesy, University of Warmia and Mazury in Olsztyn, the following conclusions concerning the inclinometer that performs dynamical measurements of small inclination angles can be formulated:

1. Results of determinations of time interval differences (T_2 - T_1) which depend, between the others, on the inclination angle of the basis of the device, at small inclination angles show small drift of angle measurement results.

2. When the angle of inclination increases (towards positive or negative directions) the differences between extreme values obtained from measurements become bigger. The plot of drifts of the measurement results differs more and more from the theoretical straight vertical line, and it takes a near-sinusoidal shape. It is a result of regularly and periodically changeable period of oscillation of the pendulum.

3. Variation of the period of oscillations of the pendulum at bigger inclination angles, has a substantial effect on the shape of the plot of inclination angle results.

4. Minimization of the errors of inclination angle measurements, at bigger inclination angles, can be achieved through application of a special system of stabilization, which provides fixed period of the pendulum oscillations. It will extend the range of correctly measured angles, within admissible, in certain applications, errors of the measurements.

5. Application of this measuring system, completed with automatic recording of the results) can provide continuous and automated control of stability of engineering objects.

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Dynamiczny system pomiarów małych kątów nachylenia

Streszczenie

W pracy przedstawiona jest nowa metoda pomiaru małych kątów nachylenia, oparta na wykorzystaniu wahadła z przysłoną współpracującą z barierą optoelektroniczną. Załączone są również wyniki badań skonstruowanej aparatury, dotyczące dryftu kąta pochylenia i zmienności okresu wahań wahadła dla dodatnich i ujemnych kątów pochylenia. Zobrazowano też zmienność błędów średnich kąta pochylenia i okresu wahań wahadła dla wszystkich testowych serii pomiarowych.

Анджей Ваниц

Динамическая система измерения малых углов наклона

Резюме

В работе представлен новый метод измерения малых углов наклона, который основан на использовании маятника с затвором, сотрудничающим с оптоэлектроническим барьером. Приложены тоже результаты исследований конструированной аппаратуры, касающиеся дрейфа угла наклона и изменений периода колебаний маятника дла положительных и отрицательных углов наклона. Представлены тоже измерения ошибок средних угла наклона и периода колебаний маятника дла всех тестовых серий измерений.