INCREASING ACCURACY OF TILT MEASUREMENTS

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We have proposed few effective methods of increasing accuracy of tilt measurements to be performed under quasi-static conditions by means of miniature tilt sensor (built of MEMS accelerometers). They ensure increase of the accuracy of ca. 50 %. The methods can be also useful while measuring tilt by means of accelerometers manufactured with application of conventional technologies.

Key words : *tilt sensor, accelerometer, accuracy, MEMS*

1. Introduction

While building modern mechatronic devices, it is often required to apply sensors having miniature dimensions and featuring high reliability and accuracy. In some applications a tilt sensor is to be employed. It can be proven that in many cases measurements of tilt does not have to be performed under dynamic conditions. Then, structure of the tilt sensor can be significantly simplified.

A good example can be here a mobile articulated microrobot that was built at the Institute of Micromechanics and Photonics, Warsaw University of Technology [1]. Its mechanical snake-like structure consisted of identical modules having dimensions of about 25 mm. In the considered application, the tilt sensor had to meet the following technical requirements : two-axial detection of tilt over 360°, overall dimensions not exceeding the size of the microrobot module, accuracy of indications of about 1°, operation under quasi-static conditions (i.e when no constant accelerations, except for the gravitational one, are affecting the sensor). As a similar application, other robots of this type may be suggested here, presented e.g. in [2,3].

Once preliminary research on various types of such sensor (mercury sensors, contact sensors, sensors with tuning forks or with optoelectronic elements) had been completed, it was possible to indicate the most advantageous solution that turned out to be a sensor employing measurement of three Cartesian components of the gravitational acceleration. This is one of the methods of determining the tilt, whose advantage is a possibility of applying commercial accelerometers and a capability of realizing two-axial detection of tilt over 360°.

Operation principle of such sensor is presented in Fig. 1 [4]. It consists of three constituent accelerometers. Their basic structural member is a seismic mass suspended on a flexible element. A component of the gravitational force affects position of the seismic mass. Value of the operating acceleration is determined by measuring strain of the flexible elements.

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The presented sensor consists of three flat springs 2 having two strain gauges 1 bonded at each side, so that the Wheatstone bridge would respond to strains resulted by bending only. A seismic mass 3 is attached at the end of the spring. Each of the springs is a cantilever beam being bent by a component of the gravitational force, acting along the axis denoted by the arrows and characters x, y, z. So, beam A indicates component force in y axis, beam B in x axis, and beam C in z axis. Since weight of the seismic masses 3 is known and constant, components of the gravitational force may be identified with components of the gravitational acceleration.

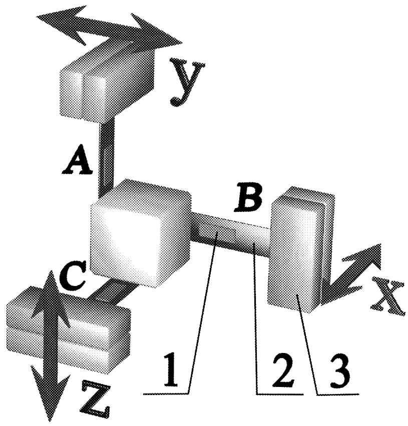

Fig.1: Schematic of the mechanical structure of the tilt sensor [4]
1 – strain gauge, 2 – flat spring, 3 – seismic mass

It is noteworthy that Micro Electro-Mechanical Systems (MEMS) accelerometers usually operate according to a similar principle, although they employ different kinds of detection – piezoresistive, capacitive or tunneling [5] – of the strain of the elastic elements supporting the seismic mass. Various technologies are used for fabricating them; the most common are surface and bulk micromachining, and less popular, LIGA process [6]. These sensors feature miniature dimensions what in the considered application is very important. For this reason, the authors have built few models of the tilt sensor employing just MEMS accelerometers. The best performance has been achieved in the case of a physical model built of two dual-axis devices – commercial accelerometers ADXL 202E manufactured by Analog Devices Inc. [7], oriented perpendicularly with respect to one another [8]. Promising results have been also obtained in the case of another model of tilt sensor, described in [9], built of a single multi-axial accelerometer presented in [10].

Another issue should be addressed here also. As tilt sensors, accelerometers can operate not only under quasi-static conditions (when possible vibration can be filtered off) but also under specific dynamic conditions. If vectors of external accelerations acting upon the tilt sensor are know (as they are usually generated by fully controlled actuators), they can be regarded while analyzing indications of the sensor, and thus determination of the tilt will remain true. Even if the exact parameters of the acting accelerations are not known, they can still be eliminated – using a so-called pseudo-inertial approach – provided their character is specific. In such a case, application of relatively simple algorithms ensures correct indications of the tilt sensor.

A spatial arrangement of the components of the gravitational acceleration and the corresponding tilt angles is shown in Fig. 2. An arbitrarily oriented tilt angle φ has been additionally represented by two component angles : pitch angle α and roll angle β. Such a way of defining the tilt has been commonly accepted in the related literature.

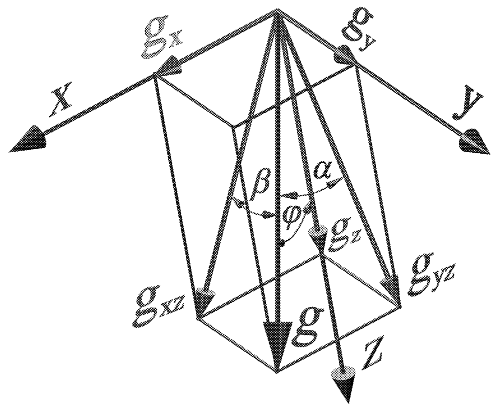

Fig.2: Distribution of the gravitational acceleration

Denotations used in Fig. 2 have the following meaning : g_x, g_y, g_z – Cartesian components of the gravitational acceleration, g_xz, g_yz – geometric sums of the corresponding pairs of the component accelerations, g – gravitational acceleration, φ – arbitrarily oriented tilt angle, α – pitch angle, β – roll angle.

Basic relations between the tilt angles and the components of the gravitational acceleration, determined on the basis of the sensor indications, are well known and can be expressed as follows [11] :

$$\alpha_1 = \arcsin \frac{g_\mathrm{x}}{g} \ , \tag{1}$$

$$\beta_1 = \arcsin \frac{g_\mathrm{y}}{g} \ . \tag{2}$$

Nevertheless, other relations are also valid here [8] :

$$\alpha_2 = \arccos \frac{g_\mathrm{yz}}{g} = \arccos \frac{\sqrt{g_\mathrm{y}^2 + g_\mathrm{z}^2}}{g} = \arccos \sqrt{\left(\frac{g_\mathrm{y}}{g}\right)^2 + \left(\frac{g_\mathrm{z}}{g}\right)^2} \ , \tag{3}$$

$$\beta_2 = \arccos \frac{g_\mathrm{xz}}{g} = \arccos \frac{\sqrt{g_\mathrm{x}^2 + g_\mathrm{z}^2}}{g} = \arccos \sqrt{\left(\frac{g_\mathrm{x}}{g}\right)^2 + \left(\frac{g_\mathrm{z}}{g}\right)^2} \ . \tag{4}$$

Angles α_1 and α_2 are meant as pitch and have the same value, just as β_1 and β_2 that are meant as roll, however they are determined according to different formulas. The additional subscripts have been introduced in order to allow us to unequivocally distinguish between these two cases in the further part of the article.

A physical model of the sensor presented in Fig. 1 has been manufactured with application of a conventional technology. Then, it has been subjected to experimental studies [4]. The obtained results proved usability of the sensor for the intended application.

The same was true in the case of physical models of the sensor, which were built of MEMS accelerometers [8, 9].

2. Measurement of the tilt angles

A significant shortcoming of determining the tilt angles by measuring components of the gravitational acceleration is a difficulty of achieving a satisfactory accuracy of the pitch and the roll angle. However, a relevant method that consists in converting three Cartesian components of the gravitational acceleration into the tilt angles has been proposed in [8]. The method, illustrated in Fig. 3, significantly increases the mentioned accuracy. Its principle is to use two different formulas for determining the tilt angles, depending on their values.

Further considerations have been limited to determining the roll angle β (nevertheless, analogous proceeding relates to the pitch angle α as well). In the case of each of the three accelerometers, which constitute the whole tilt sensor, the full range of their indications may be obtained while tilted within the range of $-90° \div 90°$ (as sine and cosine function is periodic). Because of a symmetry of these indications within that range, further considerations may be limited to a sub-range of $0° \div 90°$.

The mentioned method of determining the roll angle (and analogously the pitch angle) consists in using formula (2) for the roll within a range of $0° \div 45°$, whereas formula (4) for roll values within a range of $45° \div 90°$ [8].

According to the guidelines of the International Organization for Standardization, a combined standard uncertainty of a given quantity is to be estimated with geometric sum of its partial derivatives with respect to all the input variables multiplied by standard uncertainty of the respective variable [12]. So, while determining a combined standard uncertainty of the roll angle, calculated according to formula (2) or (4), we may use the following general formula:

$$u_{\mathrm{c}}(\beta) = \sqrt{\left(\frac{\partial\beta}{\partial g_{\mathrm{x}}}\,u(g_{\mathrm{x}})\right)^2 + \left(\frac{\partial\beta}{\partial g_{\mathrm{y}}}\,u(g_{\mathrm{y}})\right)^2 + \left(\frac{\partial\beta}{\partial g_{\mathrm{z}}}\,u(g_{\mathrm{z}})\right)^2 + \left(\frac{\partial\beta}{\partial g}\,u(g)\right)^2} \tag{5}$$

where $u(g_{\mathrm{x}})$, $u(g_{\mathrm{y}})$, $u(g_{\mathrm{z}})$ – standard uncertainties related to the measurement of the Cartesian components of the gravitational acceleration g, $u(g)$ – standard uncertainty related to determining value of the output signal of the accelerometer, which corresponds to the gravitational acceleration g (obtained during a calibration process of the tilt sensor), $u_{\mathrm{c}}(\beta)$ – combined standard uncertainty of the roll angle.

It is reasonable to assume that the tilt sensor will be built of accelerometers of the same type, thus featuring the same metrological parameters. So, it has been assumed that the uncertainties related to the measurement of the components of the gravitational acceleration $u(g_{\mathrm{x}})$, $u(g_{\mathrm{y}})$ and $u(g_{\mathrm{z}})$ are equal. In order to simplify further considerations, it has been also assumed that they are significantly bigger than the uncertainty of determining value of the output signal of the accelerometer, which corresponds to the gravitational acceleration $u(g)$, i.e.:

$$u(g_{\mathrm{x}}) = u(g_{\mathrm{y}}) = u(g_{\mathrm{z}}) \gg u(g)\ . \tag{6}$$

The above assumption can be justified in the following way. Indication of the accelerometers that corresponds to the gravitational acceleration is determined in the process of calibration of the tilt sensor (which requires performing much more measurements than in the case of determining component accelerations during a standard operation of the sensor). This suggests that the related uncertainty $u(g)$ will be much lower than the uncertainties of measuring components of the gravitational acceleration $u(g_x)$, $u(g_y)$ and $u(g_z)$ at a given angular position of the sensor. Value of these standard uncertainties related to measurements of acceleration is dependent on the quality of a particular accelerometer.

The calibration process is often performed in the case of commercial accelerometers, since it also allows us to eliminate other systematic errors of accelerometer indications (e.g. temperature errors, errors caused by changes of the voltage supplying the electronic transducer embedded within the sensor, etc.). The problem of calibrating accelerometers used for measuring tilt angles has been discussed more thoroughly in [13, 14].

Assuming that relation between the standard uncertainties may be expressed by formula (6), it has been accepted that value of the gravitational acceleration is constant. Thus, we disregard variations resulted from changing position of the sensor on the earth or its altitude, interactions of the celestial bodies (especially the moon), etc. Such approach results in a necessity of calibrating the sensor at the location where it will be used. It is also possible to introduce an appropriate corrections while knowing values of the gravitational acceleration at the exact location (and in the time) where (and when) the sensor was calibrated, and where (and when) the sensor would be used.

Using the general equation defined by (5), the combined standard uncertainty of the roll angle calculated according to (2) and (4) can be determined by means of the following formulas, respectively:

$$u_c(\beta_1) = \frac{u(g_y)}{|g|}\,\frac{1}{\cos\beta_1}\ , \tag{7}$$

$$u_c(\beta_2) = \frac{u(g_y)}{|g|}\,\frac{1}{\sin\beta_2}\ . \tag{8}$$

A graphical illustration of formula (7) and (8) is presented in Fig. 3. Numbers at the y axis refer to the combined standard uncertainty of determining the roll angle β, by a unitary value of the relative standard uncertainty of determining the component of the gravitational acceleration $u(g_y)/|g|$ (the first term of formula (7) and (8) at the right). Terminal values of the illustrated graphs have been omitted (in the case of formula (7) values for angles of $80° \div 90°$, and in the case of formula (8) for angles of $0° \div 10°$) as they grow to infinity.

While using the method of determining tilt proposed in [8], a maximal value of the combined standard uncertainty $u_c(\beta)$ reaches $1.41\,u(g_y)/|g|$, so it increases only by 41 % compare to the relative standard uncertainty related to determining the component of the gravitational acceleration $u(g_y)/|g|$, which characterizes indications of each of the constituent accelerometers.

3. Methods of improving tilt measurements

The works on the tilt sensor that have been carried out hitherto have allowed us to notice various ways of improving its parameters, especially increasing accuracy of measuring the tilt. At the same time, it has been assumed that we still strive after minimizing dimensions of the sensor and its cost. The most important methods are presented below.

In order to solve the problem regarding miniaturization of the size of the tilt sensor it should be fabricated in a technology designed for MEMS. Here, the simplest solution

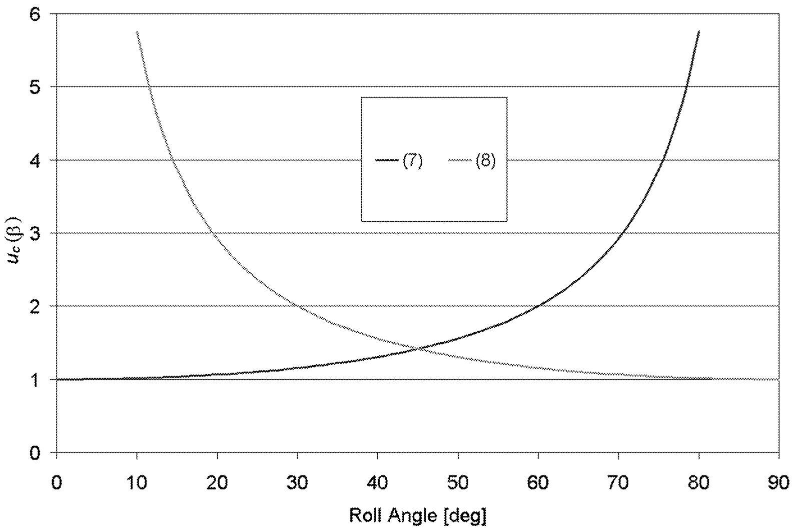

Fig.3: Graphs of formula (7) and (8)

is to use commercially available accelerometers, preferably multi-axial ones. At present, single- and dual-axis accelerometers are commonly available, e.g. ADXL 103, 202, 213 or 322 by Analog Devices, having dimensions of 5×5×2 mm or smaller. In this case, while measuring the tilt it is required to apply three or two (as presented e.g. in [8]) sensors, respectively. It is well known that accelerometers having three and more sensitive axes have been already built [9, 10, 16, 17], yet serious problems with their reliability and availability are not uncommon.

However, application of MEMS accelerometers results in significant difficulties connected with obtaining the required accuracy of the tilt sensor. In this case, it becomes necessary to develop appropriate ways of proceeding, which ensure obtaining satisfactory metrological parameters of the sensor. The works that have been realized hitherto allow us to point out few methods that make it possible to reach this goal. It should be noted that the methods presented below do not exclude each other, so while using them simultaneously we can achieve significant increase of the accuracy of measuring the tilt.

3.1. Using indications of all the constituent accelerometers simultaneously

The simplest way of decreasing uncertainty of indications of the tilt sensor is to simultaneously process indications of all its constituent accelerometers. This method may be applied while using any kind of accelerometers, and it consists in determining the roll angle (and analogously the pitch angle) as a weighted average of values of the angles β_1 and β_2, calculated according to the equation (2) and (4) respectively. The average is defined as:

$$\beta_4 = w_1\,\beta_1 + w_2\,\beta_2\ . \qquad (9)$$

The only disadvantage of such procedure is a necessity of performing additional numeric calculations, what in some cases may result in difficulties related to realizing a real-time control or a necessity of applying more advanced electronic circuits processing the output signals of the tilt sensor and thus increasing the cost of the whole device.

Values of the weight coefficients w_1 and w_2 must be found within the interval of $\langle 0, 1\rangle$ and satisfy the following equation:

$$w_1 + w_2 = 1 \; . \tag{10}$$

Assuming that the weight coefficients are constant (and neglecting thus their uncertainties), the combined standard uncertainty of the roll angle may be calculated as follows:

$$u_c(\beta_4) = \sqrt{\big(w_1\, u_c(\beta_1)\big)^2 + \big(w_2\, u_c(\beta_2)\big)^2} \; . \tag{11}$$

Regarding formula (7) and (8), equation (11) may be expressed the following way:

$$u_c(\beta_4) = \frac{u(g_y)}{|g|} \sqrt{\frac{w_1^2}{\cos^2\beta_1} + \frac{w_2^2}{\sin^2\beta_2}} \; . \tag{12}$$

At this point, the issue is to determine such values of the coefficient w_1 and w_2, that the combined standard uncertainty of the roll angle reaches a minimal value.

Besides, as we have already learned (see Fig. 3), one of the angles, determined in the previous steps according to (2) or (4), is more accurate. Therefore, it is more advantageous to use that angle instead of the two. So, while determining values of the considered coefficients a variable β_3 has been introduced. As it results from Fig. 3, this variable can be determined as follows:

$$\beta_1, \beta_2 \in \langle 0°, 45°\rangle \Rightarrow \beta_3 = \beta_1 \; , \tag{13}$$

$$\beta_1, \beta_2 \in \langle 45°, 90°\rangle \Rightarrow \beta_3 = \beta_2 \; . \tag{14}$$

Regarding formula (10), (13), (14), equation (12) can be transformed in the following way:

$$u_c(\beta_4) = \frac{u(g_y)}{|g|} \sqrt{\frac{w_1^2 - 2\,w_1\,\cos^2\beta_3 + \cos^2\beta_3}{\sin^2\beta_3\,\cos^2\beta_3}} \; . \tag{15}$$

The combined standard uncertainty $u_c(\beta_3)$ reaches a minimal value, when its derivative with respect to w_1 equals zero, so when the following condition is met:

$$2\,w_1 - 2\,\cos^2\beta_3 = 0 \; , \tag{16}$$

and hence:

$$w_1 = \cos^2\beta_3 \; , \tag{17}$$

$$w_2 = \sin^2\beta_3 \; . \tag{18}$$

Courses of the weight coefficient w_1 and w_2 are presented in Fig. 4. For an instance, at three characteristic values of the roll angle β_4: 0°, 45°, 90° (see Fig. 3), the coefficients will be respectively: $(1, 0)$; $(0.5, 0.5)$; $(0, 1)$.

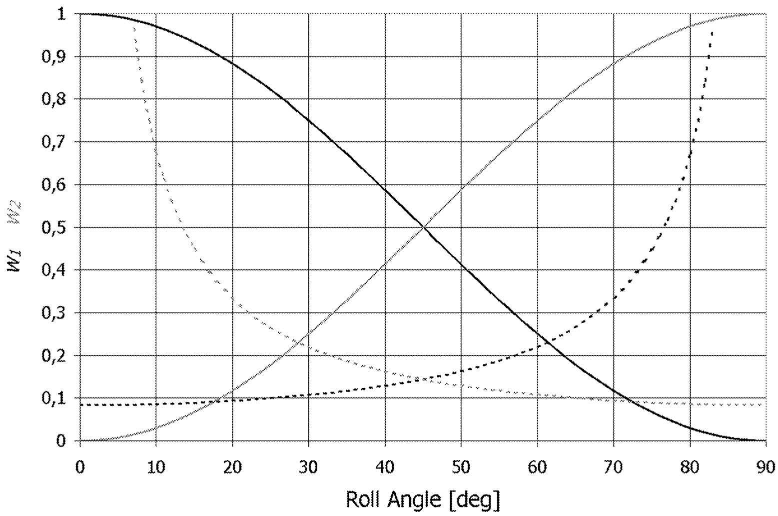

Fig.4: Graphs of formula (17) and (18)

The black course in Fig. 4 corresponds to coefficient w_1, whereas the gray course refers to coefficient w_2. In order to compare the courses with the previous considerations, two curves drawn with dashed lines (corresponding to formula (7) and (8), as in Fig. 3) have been added. As can be clearly observed, in the case of determining smaller values of the roll angle, where the uncertainty of β_1 is small also, coefficient w_1 is bigger than w_2, whereas for bigger values of this angle vice versa.

Since we have already known values of the coefficient w_1 and w_2, we can finally determine value of the roll as:

$$\beta_4 = \beta_1 \cos^2 \beta_3 + \beta_2 \sin^2 \beta_3 \; . \tag{19}$$

Assuming that uncertainties of the weight coefficients may be neglected, regarding formula (17) and (18), equation (15) may be reduced to the following form:

$$u_\mathrm{c}(\beta_4) = \frac{u(g_\mathrm{y})}{|g|} \; . \tag{20}$$

Hence, it results that the combined standard uncertainty of the roll angle (and analogously the pitch angle) will have a constant value equal to the relative standard uncertainty of determining the component of the gravitational acceleration $u(g_\mathrm{y})/|g|$, which, on the other hand, characterizes indications of each of the constituent accelerometers. Compare to the method of determining the tilt presented in section 2, the maximal decrease of the uncertainty of determining the roll angle equals 30 % (for the roll angle of 45° – see Fig. 3).

3.2. Increasing the number of the constituent accelerometers

Application of a tilt sensor built of at least four single-axis accelerometers makes it possible to decrease the uncertainty of determining the tilt angles. However, we must take into account that dimensions of the sensor will increase, what may be unacceptable in some cases. A more advantageous idea is to apply one multi-axial accelerometer. Such solution is proposed in [9], where an accelerometer with four sensitive axes has been applied for determining the tilt.

In order to prove the advantage of using multi-axial accelerometers, the mentioned four-axis accelerometer will be considered. Its sensitive axes do not form a Cartesian co-ordinate system. Therefore, the first step is to calculate the Cartesian components of the gravitational acceleration. Owing to this operation it is possible to determine the tilt angles according to the methods presented in the prior sections.

The accelerometer has four sensitive axes consisting of a silicon spring-mass system shown in Fig. 5 [10] (each one is rotated by 90° around the vertical axis). The spring, which suspends the mass, makes an angle of 54.7° with the accelerometer surface (this angle results from a special etching technology, employing crystallographic features of the silicon, used for fabrication of the accelerometer). Deflection of the mass takes place only in orthogonal direction with respect to the spring, thus each mass is sensitive to acceleration in two of the three Cartesian directions.

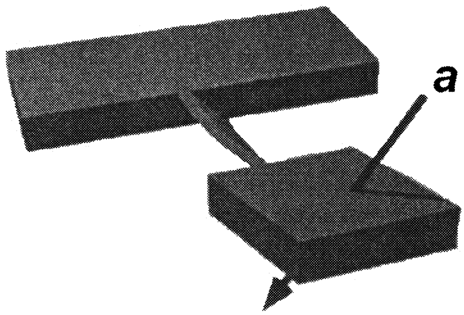

Fig.5: Geometry of the four-axis accelerometer [10]

The Cartesian components of the acceleration measured by the considered four-axis accelerometer may be determined according to the following formulas [10]:

$$a_{\rm x} = \frac{1}{2\,\sin 54.7^\circ}\,(a_1 + a_3)\ , \tag{21}$$

$$a_{\rm y} = \frac{1}{2\,\sin 54.7^\circ}\,(a_2 + a_4)\ , \tag{22}$$

$$a_{\rm z} = \frac{1}{4\,\sin 54.7^\circ}\,(a_1 + a_2 + a_3 + a_4) \tag{23}$$

where $a_{\rm x}$, $a_{\rm y}$, $a_{\rm z}$ – Cartesian components of the acceleration vector, a_1, a_2, a_3, a_4 – projections of the acceleration vector onto the sensitive axes of the sensor (indicated by the accelerometer).

As all the sensitive axes consist of a system having identical mechanical structure, formed during one fabrication process, it is reasonable to assume that indications of each sensitive axis feature the same metrological parameters. So, analogously to (6), we may accept that the standard uncertainties of determining projections of the acceleration onto the sensitive axes of the accelerometer are equal, i.e.:

$$u(a_1) = u(a_2) = u(a_3) = u(a_4) = u(a)\ . \tag{24}$$

Then, the combined standard uncertainties of the Cartesian components of the measured acceleration can be determined according to the following formulas:

$$u_{\mathrm{c}}(a_{\mathrm{x}}) = \sqrt{\left(\frac{\partial a_{\mathrm{x}}}{\partial a_1}\,u(a)\right)^2 + \left(\frac{\partial a_{\mathrm{x}}}{\partial a_3}\,u(a)\right)^2}\ , \tag{25}$$

$$u_{\mathrm{c}}(a_{\mathrm{y}}) = \sqrt{\left(\frac{\partial a_{\mathrm{y}}}{\partial a_2}\,u(a)\right)^2 + \left(\frac{\partial a_{\mathrm{y}}}{\partial a_4}\,u(a)\right)^2}\ , \tag{26}$$

$$u_{\mathrm{c}}(a_{\mathrm{z}}) = \sqrt{\left(\frac{\partial a_{\mathrm{z}}}{\partial a_1}\,u(a)\right)^2 + \left(\frac{\partial a_{\mathrm{z}}}{\partial a_2}\,u(a)\right)^2 + \left(\frac{\partial a_{\mathrm{z}}}{\partial a_3}\,u(a)\right)^2 + \left(\frac{\partial a_{\mathrm{z}}}{\partial a_4}\,u(a)\right)^2}\ . \tag{27}$$

Having performed necessary calculations, we obtain the following equations:

$$u_{\mathrm{c}}(a_{\mathrm{x}}) = u_{\mathrm{c}}(a_{\mathrm{y}}) = 0.866\,u(a)\ , \tag{28}$$

$$u_{\mathrm{c}}(a_{\mathrm{z}}) = 0.865\,u(a)\ . \tag{29}$$

Therefore, it may be assumed that uncertainties of determining the Cartesian components of the measured acceleration will approximately be equal, i.e.:

$$u_{\mathrm{c}}(a_{\mathrm{z}}) \approx u_{\mathrm{c}}(a_{\mathrm{x}}) \approx u_{\mathrm{c}}(a_{\mathrm{y}})\ . \tag{30}$$

As formula (28) and (29) indicate, uncertainty of determining the Cartesian components of the measured acceleration is smaller by ca. 13 % compare to the uncertainty of determining projections of the acceleration. The decrease of the uncertainty results from a redundancy of the information provided by the sensor indications. If a further decrease of the considered uncertainty is striven for, the number of the sensitive axes should be increased and an appropriate spatial arrangement of the axes ensured. Yet, that would require to design and fabricate a completely new accelerometer.

3.3. Other solutions

The proposals discussed above have a general character and can be easily applied. The authors have suggested in [15] other ways of increasing accuracy of tilt measurements. Some of them, like eliminating the temperature errors of the applied accelerometers, optimizing their calibration process and selecting their appropriate spatial arrangement, have also a general character, however cannot be applied so easily. Other, like modifying mechanical and electronic structure of the existing designs of the MEMS accelerometers, are difficult to implement and can be considered only in a very specific cases. However, if it turned out that despite effectiveness of the methods discussed in section 3.1 and 3.2, the required improvement of the metrological properties of the tilt sensor had not been ensured, in order to reach this goal we could use the other ways just mentioned. These ways also open out new perspectives for further research on increasing accuracy of tilt measurements.

4. Summary

The presented considerations referring to tilt measurements have been focused on a possibility of miniaturization of the relevant tilt sensor as well as increasing accuracy of its indications.

The authors have proposed a new theoretical approach to determining tilt over the steregon, as far as metrological issues are concerned. The accepted idea of using components of the gravity vector for this purpose allows us to apply a tilt sensor of miniature overall dimensions built of MEMS accelerometers, whereas the proposed method of determining the tilt angles as a weighted average of the three Cartesian components of the gravitational acceleration ensures detection of tilt angles with increased accuracy.

The initial experimental results proved the presented theoretical considerations to be correct, and allowed us to estimate values of accuracy of determining the tilt angles at ca. few tenths of a degree arc [8, 9]. Yet, in order to provide more reliable data, more detailed tests must be performed.

The considerations presented above can be useful while undertaking engineering tasks connected with the problem of measuring tilt. It seems that implementation of the proposed method of determining the tilt angles on the basis of simultaneous processing of three Cartesian components of the gravitational acceleration measured by means of a multi-axial accelerometer is very interesting and effective. It should be noted that it can be realized while using standard elements, so it is not costly neither laborious.

Further progress in development of miniature tilt sensors is still possible. Application of new MEMS triaxial accelerometers, presented e.g. in [16, 17], can decrease dimensions of the sensor. Even more interesting are multi-axial accelerometers, presented e.g. in [9, 10], as they provide a possibility of increasing accuracy of the sensor due to redundancy of the information. Besides, a rapid progress in the main technologies used for fabrication of MEMS accelerometers, i.e. surface and bulk micromachining [6], will result in even better metrological parameters of the fabricated accelerometers, whose performance is at the time being still much worse compare to the conventional devices.

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