LOW-RANGE TILT SENSING WITH MEMS ACCELEROMETERS

Sergiusz Łuczak, Dariusz Kołodziej

Abstract:

Ways of adjusting MEMS accelerometers for tilt measurements over a small angular range of few degrees arc or less are considered with regard to achieving a possibly high accuracy. The paper describes some additional mechanical structures applied to overcome the problem of incompatibility between the large measuring range of MEMS accelerometers and the expected small angular measuring range.

Keywords: *MEMS, accelerometer, tilt, accuracy.*

1. Introduction

One of the most common applications of MEMS accelerometers are tilt measurements. The typical low-range of the commercial MEMS accelerometers is of ±1÷2 g, which is adjusted quite well to tilt changes of ±90°. In such a case, the user may achieve related accuracy of tilt measurements up to ca. ±0.2° [1]-[3].

However, in many cases, the angular range of tilt measurements is quite small, i.e. of a few degrees arc or less (e.g. while levelling, aligning, or in astronautics), and sometimes the above accuracy may not be sufficient. So, the typical solution would be application of MEMS accelerometers featuring a lower measuring range. The advantages of such approach are discussed by the author in [4]. However, no such devices are commercially available. A once available accelerometer with the smallest measuring range (according to the knowledge of the author) was a MEMSIC MXA6500E with the range of ±0.5 g [5]. Yet, its accuracy was no better than its competitors' featuring a larger measuring range. In the opinion of the author, the reason for not manufacturing MEMS accelerometers with a measuring range much below ±1 g is probably the noise level (being usually of ca. 1 mg what corresponds to a tilt of ca. 0.1° at best), which makes it useless to decrease the measuring range, as the accuracy, dependent on the noise level, cannot be improved.

So, at the time being, it is rather impossible to acquire an accelerometer with a measuring range that is adjusted to detection of tilt angles as small as few degrees arc. However, there are still some ways of adjusting the measuring range of the considered device to the range of the tilt angles to be sensed.

2. Mechanical Gears

The first approach to solve the problem of measuring tilt over a small angular range is to apply a special mechanical gear, operating e.g. as a compliant mechanism, that would increase the measuring angular range up to ±90°. Then, the problem becomes a typical tilt measurement over a large measuring range, referred to e.g. in [1]. However, such mechanism must feature very small plays and kinematic errors, otherwise accuracy of the related measurements would be significantly affected. So, the most promising solution are mechanisms based on separate elastic elements (like springs or membranes) or integrated compliant mechanisms.

An example in the first group mentioned above may be a twisted torsional suspension spring having a tape-shape. This elastic element was commonly applied in mechanical measuring instruments, like a microkator or an optikator [6]. It can provide a high ratio of movement conversion, e.g. displacement of ca. 0.03 mm can be transformed into a rotation of 180° [6].

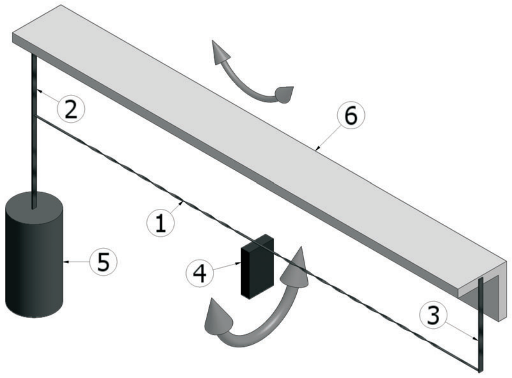

Fig. 1. Mechanism with a tape-shape spring.

The basic element of the mechanism presented in Fig. 1 is a twisted spring 1 having a tape-shape, which rotates as it gets tensed. A MEMS accelerometer 4 is fixed to the spring in the middle of its length, while its ends are attached to two flat springs 2 and 3, secured in a frame 6. The first spring is loaded with a seismic mass 5.

When the whole structure gets tilted (see the thin arrow), the seismic mass 5 keeps its vertical position, and so deflects the flat spring 2, what tenses the tape-shape spring 1, and thus causes its rotation along with the accelerometer 4 (see the thick arrow). Crucial parameters of the mechanical structure (material and dimensions of all the springs, weight of the seismic mass) should be selected in such a way, as to ensure rotation angle of the accelerometer of ±90° while tilted at the maximum value of the measured angle.

Even though it is possible to build the proposed mechanism using a conventional technology, there are certain problems to be solved:

- at least 4 wires must be led to the accelerometer, and each has a significant stiffness (solution: to integrate the sensor with a wireless transmission unit or a signal encoding unit using only two halves of the twisted spring as wires),
- the accelerometer is actually rolled within a nonvertical plane (solution: to apply a more complicated formula for calculating the tilt),
- the accelerometer may be too heavy for the tape-shape spring (solution: to immerse the whole mechanism in a liquid, and thus improve also its dynamics),
- the seismic mass does not keep exactly vertical position due to a restoring moment generated by all the springs (solution: calibration of the whole system compensating for a linear character of this phenomenon, as indicated by experimental studies performed by the author in the past),
- assembly of the system in a conventional technology of fine mechanics is very complicated and expensive.

As for the second group, many structures may be proposed. A related example is presented in Fig. 2.

The basic element of the mechanism presented in Fig. 2 are two parallel springs 1 and 2 fixed to each other at their ends on one side, and coupled with a MEMS accelerometer 6 right there. On the other side, spring 1 is anchored to a stiff frame 4 while spring 2 is connected with a lever 3, supporting a seismic mass 5 (manufactured as an additional element). Members 1–4 constitute one monolithic structure.

When the whole structure gets tilted (see the thin arrow), the seismic mass 5 keeps its vertical position, and so shifts the flat spring 2, what causes deflection of both springs (the springs operate as a thermostat bimetal element), and thus rotation of the accelerometer 6 (see the thick arrow). Crucial parameters of the mechanical structure (material and dimensions of the springs, distance between them, weight of the seismic mass) should be selected in the same way as in the previous case, striving for the rotation angle of the accelerometer to be as large as possible.

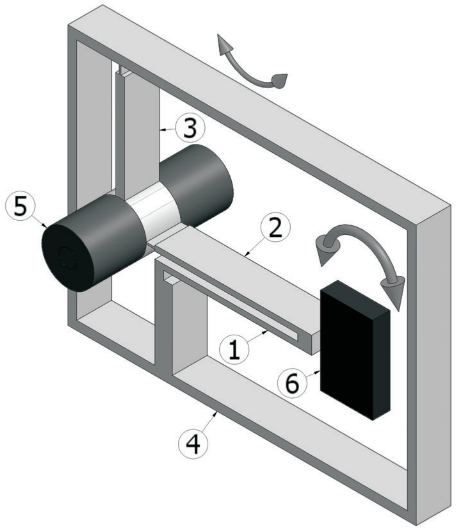

Fig. 2. Monolithic compliant mechanism.

Nowadays, new fabrication technologies, like surface micromachining, bulk micromachining or LIGA process, make it possible to fabricate the proposed mechanism as a monolithic structure of a complicated shape. Regarding its quite large dimensions, exceeding 10 mm, it can be also fabricated using microstructuring of photosensitive glass, a technology developed at the Technical University of Ilmenau, Germany [7]. Quality of such mechanism is much better compare to the traditional approach, where it was to be assembled out of many separate parts. Sometimes, such kind of assembly caused the mechanism to be dysfunctional. A good example may be a constant force escapement designed by Nicolas Dehon for mechanical watches manufactured by the Girard-Perregaux company [8]. As it turned out, only its integrated version manufactured in silicon technology was operating properly.

Apart from the new manufacturing technologies, a powerful toll are new materials, like e.g. Shape Memory Alloys (SMA), that, when appropriately shaped, can provide high stiffness generally, and at the same time high compliancy in a desired direction [9].

Other mechanisms of this kind may be considered also. It may be presumed that one of the following elements playing the substantial role would be applied there:

- levers,
- toothed wheels,
- keys,
- threads,
- springs.

For instance, it seems an interesting idea to apply a harmonic drive operating in a reverse direction (i.e. as a multiplying gear instead of a reduction gear), since ratio of such gear may be even 300 [10]. Its efficiency is reported to be of at least 0.8 [10], what suggests that it will not lock itself by reverse operation. The biggest problem is its resistance to motion, which would require a large weight of the seismic mass, and would result in an increase of the overall dimensions of the whole instrument. Moreover, it also introduces an effect of a restoring moment, as described above.

3. Improvement of Accuracy

In the case of applying an additional mechanism, the accelerometer gets rotated by an angle φ much bigger than the tilt α, what can be expressed as,

$$\varphi = q\alpha \tag{1}$$

where q is the ratio of the mechanism, arbitrarily evaluated to be of 3÷90.

Then, relation between uncertainties $u(\alpha)$ and $u(\varphi)$ of the related angles, determining the resultant accuracy of tilt measurements, can be expressed by the following equation,

$$u(\alpha) = \frac{u(\varphi)}{q} \tag{2}$$

So, the actual tilt angle will be determined q-times more accurate compare to accuracy featured by the accelerometer.

Let us assume, as reported above, that the resultant uncertainty of an accelerometer is of 0.2°, and the ratio is of 90. Then the accuracy of the instrument consisting of the accelerometer and the additional mechanism will be of ca. 10 seconds arc, accepting a 5% kinematic error of the mechanical structure. Such accuracy allows measuring of tilt angles within a rational range of ±2' or wider.

4. Bistable Elastic Elements

Still another approach to the problem of increasing the operating angular range of the MEMS accelerometer in the considered tilt measurements is application of bistable elastic elements. This solution does not provide many advantages, yet in some cases may be a helpful and simple solution.

Two cases can be taken into account:

- a single-axis tilt sensor operates as a limit gauge only,
- a single-axis accelerometer operates as a two-axis tilt sensor.

This principle will allow the output signal to be significantly magnified, however rather for one or few particular angular positions only (being the limits of the allowable range).

5. Conclusions

Low-range MEMS accelerometers are very interesting measuring instruments because of their low price, miniature dimensions, low power consumption and robustness.

Despite the fact that their accuracy does not allow measuring tilt within a small range (of few degrees arc or less), application of the proposed additional mechanical structures makes it possible to sense tilt angles as small as few minutes arc.

It should be noted that the proposed mechanisms operates within one plane only. So, in the case of two-axial tilt measurements, two such mechanisms must be applied, oriented perpendicularly with respect to each other. Additionally, the mechanism with a tape-shape spring (see Fig.1) operates properly only within a vertical plane. So in the considered case of two-axial tilt measurements it should be equipped in an additional support, e.g. two suspension springs.

Even though, at the time being, it seems that application of additional mechanical structures is the only solution while measuring small tilt angles, it should be expected that in the nearest future metrological parameters of MEMS accelerometers will be significantly improved, especially with regard to the noise level determining their accuracy. Then, it may be expected that accelerometers with a very low range, i.e. much below ±1 g, will be commercially available. In such a case there will be no problem in direct realisation of the measurements of small tilt angles referred to.

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References

[1] Łuczak S., "Advanced Algorithm for Measuring Tilt with MEMS Accelerometers" [in] R. Jabłoński *et al.*, *Recent Advances in Mechatronics*, Springer-Verlag: Berlin Heidelberg, 2007, pp. 511-515.

[2] Horton M., Kitchin C., "A Dual Axis Tilt Sensor Based on Micromachined Accelerometers", *Sensors*, vol. 13, no. 4, 1996, pp. 91-94.

[3] Łuczak S., Oleksiuk W., Bodnicki M., "Sensing Tilt with MEMS Accelerometers", *IEEE Sensors J.*, vol. 6, no. 6, 2006, pp. 1669-1675.

[4] Łuczak S., "MEMS Accelerometers in Sensing Small Tilt", *Proc. 6th Polish-German Mechatronic Workshop*, Ilmenau, 2007, pp. 25-30.

[5] "Low Profile, Low Consumption ±0.5 g Dual Axis Accelerometer with Absolute Analog Outputs MXA6500E", MEMSIC Inc., North Andover, MA, 2005.

[6] Ratajczyk E., „Obliczanie przełożenia czujników mikrokatorowych", *Mechanik*, Warsaw, vol. 9, 1968, pp. 502-506 (in Polish).

[7] Preuß R., K. Zimmermann, "Simulation and Experimental Testing of a Microgripper". In: *Proc. 3rd Polish-German Mechatronic Workshop,* Krynica/Kraków, 2000, pp. 166-169.

[8] "The Silicon revolution", *Europa Star*, vol. August-September, 2008.

[9] Oiwa T., Sugimoto T., "Shape Optimization for Flexure Hinges", *J. Jpn. Soc. Prec. Eng.*, vol. 66, no. 60, 2000, pp. 955-959 (in Japanese).

[10] Tryliński W., *Drobne mechanizmy i przyrządy precyzyjne*, WNT: Warsaw, 1978, pp. 437-438 (in Polish).