MEMS Accelerometer as a Sensor of Geometric Quantities

Typical applications of MEMS accelerometers are measurements of linear acceleration and vibration. Mathematical processing (integration or differentiation) of the output accelerometer signals makes it possible to sense other physical quantities: linear displacement, velocity, jerk, jounce and higher-order derivatives of position vector. Single- or dual-axis tilt measurements under static or quasi-static conditions are also well-known. Appropriate positioning of an accelerometer makes it possible to sense angular velocity. Linear displacement may be also determined using the pedometer principle. Nevertheless, the paper describes and illustrates other sensing methods and instruments using MEMS accelerometers, which make it possible to measure some geometric quantities like: parallelism of datum axes (and thus axial run-out), angular displacement, tilt under specific dynamic conditions. Even though processing of the measurement signals is not as simple as in the typical applications, it seems that due to unique attributes of MEMS sensors, the proposed measurement methods are interesting and promising. The considerations are referred to latest patents pending and publications. Advantages and shortcomings of these untypical applications of MEMS accelerometers are discussed.

Keywords: *MEMS, accelerometer, tilt, axial run-out*

Introduction

The basic quantity measured by means of accelerometers is acceleration. As far as MEMS accelerometers are concerned, we can measure both constant acceleration (e.g. gravitational acceleration) as well as variable acceleration (e.g. vibration), what is a very advantageous feature. The typical bandwidth of MEMS accelerometers reaches few kHz, the measuring range can be as small as few tenths of g ($g \approx 9.81$ m/s^2), e.g. as presented in [1], or as high as few hundred g.

However, using integration or differentiation of the signals obtained from the accelerometer, many other physical quantities can be determined. By integrating the acceleration measured by the accelerometer we can calculate the value of linear velocity and displacement (distance/length), while performing the reverse operation (with the accuracy to a constant), we obtain the following: jerk, snap (jounce), crackle and pop.

Table 1. *Physical Quantities obtained by Mathematical processing of Acceleration*

Geometric Quantity	**Mathematical Operations**
displacement	↑ Integration Differentiation ↓
velocity	
acceleration	
jerk	
snap (jounce)	
crackle	
pop	

Measuring values specified in the middle of the table allows us to determine a wide range of geometric quantities without the need to repeatedly perform complex mathematical operations, what considerably reduces calculation time and minimizes the related errors.

As aforementioned, modern MEMS accelerometers can measure accelerations in a wide range and at high frequencies, and while integrated with modern computing units, their output signals can be transmitted in real time to various control or safety systems. Other advantages of MEMS accelerometers are low cost, robustness, high reliability and shock survivability, low power consumption, compact size, hermetic packaging [2].

Indirect Processing of the Acceleration Signal

Because of the errors resulting from mathematical processing, especially while integrating the acceleration signal, many indirect methods of determining velocity and displacement have been proposed.

Figure 1. *Device mounted on a car wheel*

Source: https://doi.org/10.3390/s21041327.

One example of such approach is a method of determining linear displacement and velocity of a vehicle, presented in [3]. A device attached to the wheel of a test car containing a MEMS accelerometer collects data, which are then processed to eliminate disturbing components of acceleration (e.g., wheel rotation, gravitational acceleration, vertical vibration, vibration transverse to the direction of motion) and then determine the vehicle displacement and velocity by integration of the acquired signals.

An interesting idea is to use MEMS accelerometers to determine angular velocity of a rigid body. Such concept is proposed e.g. in [4], and consists in application of few accelerometers, whose spatial arrangement makes it possible to sense angular velocity owing to different indications of particular accelerometers.

Another example of a device employing indirect measurements is a pedometer [5,6]. Most of us carry a MEMS accelerometer integrated in a smartphone or a smartwatch. Regardless of whether it is a smart device with built-in fitness functions that allow us to count the steps traveled during the day by the holder of the device or the accelerometer attached directly e.g. to clothing for research purposes, the principle of measurement is the same. When a person moves, vibrations are generated and collected by the accelerometer. The collected signals also include the gravity acceleration, which tells us about the orientation of the accelerometer. After filtering out the components resulting from the gravity acceleration, we are able to obtain the velocity or displacement from various parameters of the signal - such as period and frequency, we can determine the step length or gait irregularity. In addition to applications in recreation or sports, these data may be useful for medical or rehabilitation purposes [7].

A unique situation, when no acceleration is sensed by a triaxial accelerometer (i.e. free fall), provides also a basis for calculation of linear velocity and displacement, assuming that the motion takes place at a uniform acceleration equal to 1*g*. Then, while sampling the acceleration signal over time, the parameters of the motion can be easily determined using the time-stamping. It should be mentioned that detection of a free fall has been commonly used for protection of magnetic hard disk drives for laptops, where MEMS accelerometers can be used also for compensation of vibration of the head [8].

It can be foreseen that in the nearest future MEMS accelerometers with a small sub-g measurement range (below 0.1 *g*) will be introduced to the market. Then, another geometrical quantity could be sensed: level, meant as a horizontal position determined with a high precision of at least 0.01°.

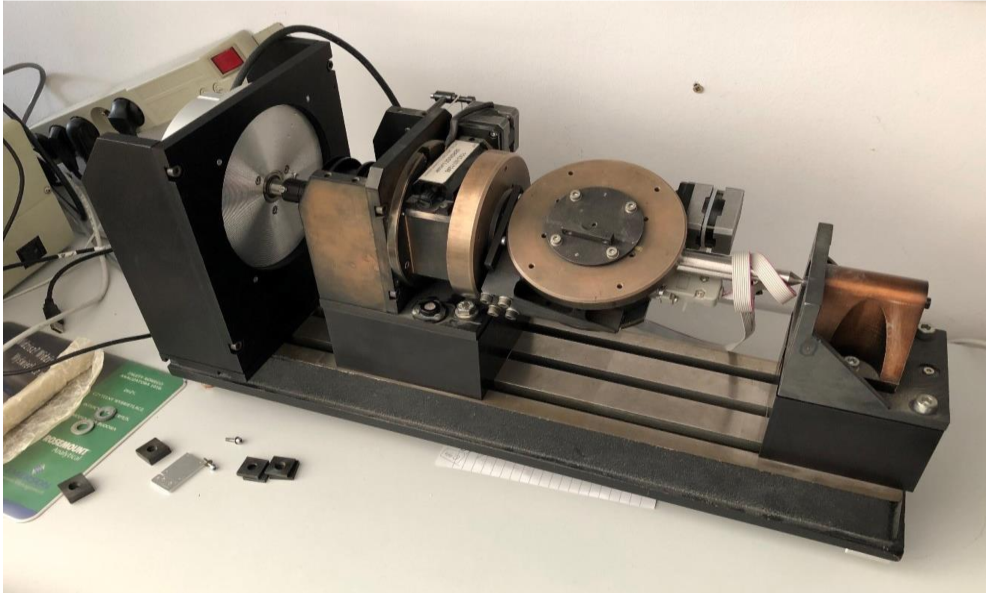
Tilt as a Geometric Quantity

Another example of the use of low-cost accelerometers to measure geometric quantities is determination of tilt under static conditions, which is one of typical applications of accelerometers [9]. The Cartesian components of the gravitational acceleration in a local coordinate system (frame) must be first determined and then transformed by means of trigonometric functions. In this way, component tilt angles can be determined: pitch and roll [10].

Whether the considered tilt takes place within one (pitch) or two (pitch and roll) determined planes or within an arbitrary plane (axial pitch) is quite an important issue.

Dual-axis tilt within two determined planes can be applied e.g. by means of a test rig presented in Figure 2, whose main units are two rotary stages, whose rotation axes are perpendicular.

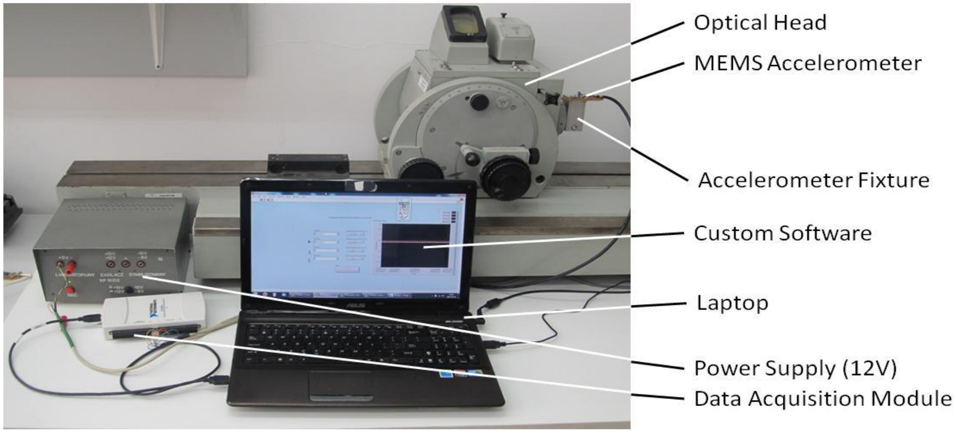
Figure 2. *Computer-controlled dual-axis test rig for studying tilt sensors*



Source: our own research

We use the test rig to apply any arbitrary angular position within the full solid angle (2 × 360°) with accuracy of 0.02°. In the case of more demanding experimental studies, we use the optical head presented in Figure 3 to apply angular position with high precision of 0.0008°, however about one rotation axis only.

Figure 3. *Manually controlled test rig for studying tilt sensors*



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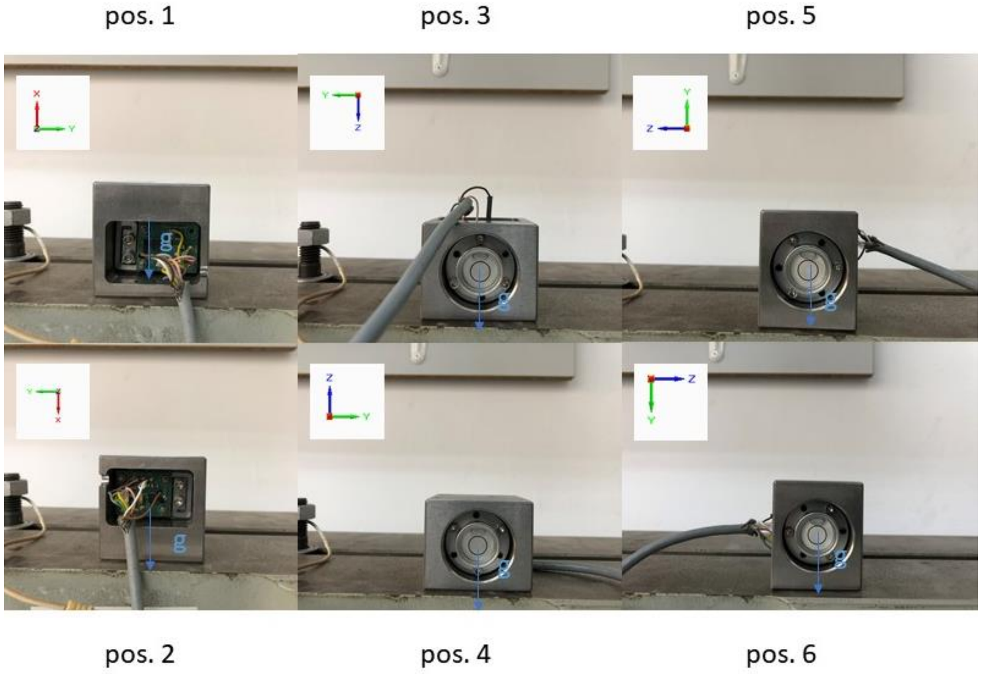
Both test rigs are used mainly to calibrate MEMS accelerometers, using the gravitational acceleration ±1*g* as the reference.

Precise Dual-axis Tilt Sensor

The necessity of cyclic calibration of the tested MEMS sensors motivated us to design a special housing for our tilt sensors employing MEMS accelerometers. The housing makes it possible to calibrate triaxial MEMS accelerometers using the same idea as presented in [11].

Illustration of the calibration process of a triaxial MEMS accelerometer is presented in Figure 4. For each of the three sensitive axes, two extreme orientations are applied (pos. 1 and 2 for *x*-axis; pos. 3 and 4 for *z*-axis; pos. 5 and 6 for *y*-axis). Then, the sensor under static conditions senses maximum and minimum reference values representing acceleration ±1*g*.

Figure 4. *Six positions of the housing while calibrating the accelerometer*



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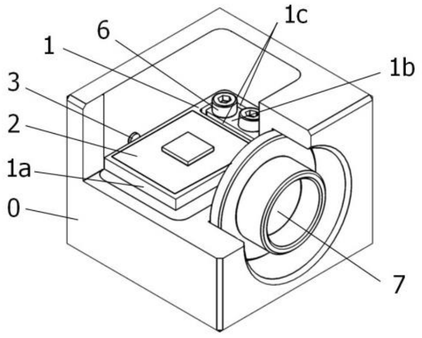
However, when tilt measurements are perfomed, precise calibration of the MEMS accelerometer is not the only issue. The same due diligence must be exercised with respect to alignment of the accelerometer sensitive axes. Any misalignment of the accelerometer with respect to the housing will affect both the calibration process as well as tilt measurements.

In order to make sure that the accelerometer is correctly oriented within the housing, a special aligning unit is used, which allows the accelremeter orientation to be corrected with respect to all the three Cartesian axes. The housing and the aligning unit are shown in Figure 5 and 6.

Figure 5. *Precise tilt sensor: 0 - housing; 1 - aligning unit; 1a - supporting section of the aligning unit; 1b - mounting section of the aligning unit; 1c - grove in the aligning unit; 2 - accelerometer PCB; 3 - aligning screw; 6 - clamping screw; 7 - spirit level*



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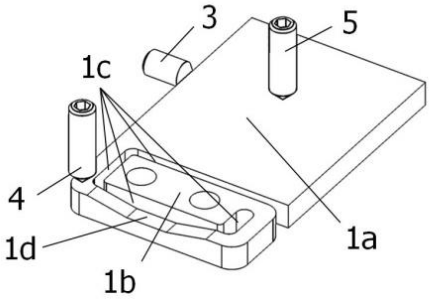
More detailed illustraction of the alligning unit is presented in Figure 6. By means of the three aligning screws (3, 4, 5) it is possible to precisly set the angular position of the acceelrometer PCB attached to the unit about three Cartesian axes. Referring to Figure 3, aligning screw 3 sets the angular position about *z*-axis, aligning screw 4 sets the angular position about *y*-axis, and aligning screw 5 sets the angular position about *x*-axis.

Figure 6. *Aligning unit: 1a - supporting section; 1b - mounting section; 1c - grove; 1d - relief; 3, 4, 5 - aligning screws*



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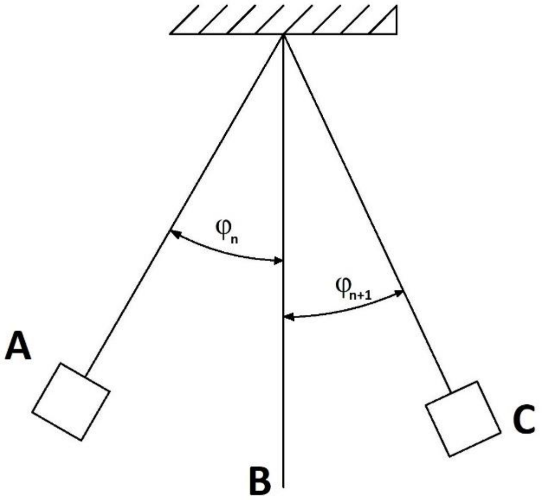
Tilt under Dynamic Conditions

Even though tilt measurements realized by means of accelerometers are restricted to static and quasi-static conditions, we managed to propose a tilt measurement principle under specific dynamic conditions, which occur while the accelerometer performs oscillating motion, like a pendulum illustrated in Figure 7. An example of an industrial application of the proposed measurement principle can be monitoring of the tilt of a lifted load (in particular, suspended on a cable).

Analyzing the oscillating motion, it can be assumed that static conditions take place at the positions of maximal tilt, i.e. positions A and C in Figure 7. Then standard mathematical formulas can be used for determining the maximal value of the tilt, just as in the case of operation under static or quasi-static conditions.

Moreover, the position at the midpoint (B) can be also used for measurement purposes. The position can be easily determined since the accelerometer output signal is then maximal, because the full gravitational acceleration and maximal centripetal acceleration are sensed on the vertical sensitive axis of the accelerometer. Applying formulas presented in [14], tilt of the lifted load can be evaluated.

Figure 7. *The Measurement Positions in Oscillating Motion*

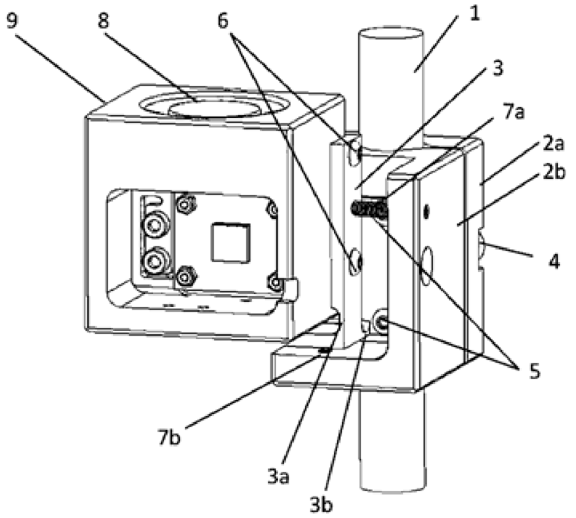


Source: our own research

Sensor for Monitoring Tilt under Dynamic Conditions

Addressing the presented idea of monitoring tilt of a lifted load, we designed a special instrument and applied for a patent [15]. We proposed a method of attaching a tilt sensor having a cuboidal housing, like our tilt sensor presented in Figure 5, to a crane cable in such a way as to make it possible to correct the orientation of the sensor housing with respect to the cable, on which the monitored object (load) is suspended. The device is presented in Figure 8, and uses the same aligning principle as the aligning unit presented in Figure 6.

Figure 8. *Device for mounting the tilt sensor on a rope: 1 - rope; 2a and 2b - two-part housing, 3 - aligning fixture; 3a and 3b - constriction; 4 and 5 and 6 - clamping screws; 7a and 7b - aligning screws; 8 - spirit level; 9 - housing of the tilt sensor*



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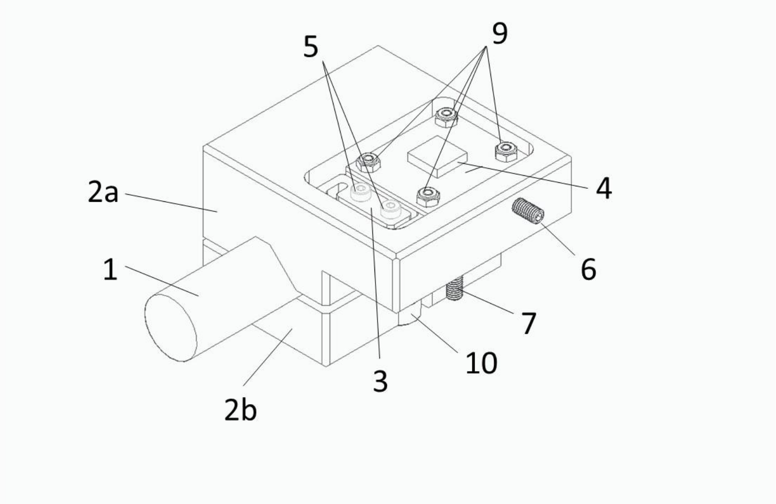
The two-part housing makes it possible to easily attach the sensor to a cable having diameter within a specified range. Position of the compliant aligning fixture with two constrictions is controlled by means of two aligning screws. In this way, orientation of the housing of the tilt sensor can be set as vertical (what is indicated by the spirit level) when the rope has also a vertical position.

Axial Run-out Sensor

While performing experimental studies of MEMS accelerometers using the presented test rigs, we always strive for minimizing the related misalignment errors, which occur when a particular sensitive axis of the tested accelerometer is not parallel (or perpendicular) with respect to the rotation axis of the test rig. However, we discovered that variations of the accelerometer output signal associated with the misaligned sensitive axis that can be observed while rotating the accelerometer, may be used not only in the aligning process, as discussed in [16], but also to determine the maximal value of the misalignment angle, which in this case may be considered a kind of axial run-out or, more precisely, the measure of the angle between the sensitive axis of the accelerometer and the rotation axis of the test rig.

We patented the mechanical structure of the sensor [17], which uses the same principle of fixing the sensor on the tested shaft as the sensor presented in Figure 8, and the aligning unit similar to the one presented in Figure 6 (yet without aligning screw 5, which is not used in this case).

Figure 9. *Axial run-out sensor: 1 - tested shaft; 2a and 2b - two-part housing; 3 - aligning unit; 4 - accelerometer PCB; 5 - clamping screws; 6 and 7 - aligning screws*



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Summary

Even though MEMS accelerometers were introduced to the market long time ago (over 30 years ago), and their applications have been proposed in great numbers so far, it is still possible to build novel sensors of geometric quantities employing these microsystems. Much more demanding measurement needs can be addressed while fusing signals generated not only by MEMS accelerometers, but also MEMS gyroscopes, pressure sensors and magnetometers. All these sensors can be integrated within one packaging: Inertial Measurement Unit (IMU), offering to R&D teams and original equipment manufacturers (OEM) a powerful measuring instrument at a relatively low price.

We presented and discussed original sensors employing a single MEMS accelerometer: 1. precise dual-axis tilt sensor, 2. tilt sensor for application under specific dynamic conditions, 3. axial run-out sensor. All these sensors feature a special mechanical housing and a mechanical unit for aligning the accelerometer sensitive axes.

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