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Measurements of Acceleration as a Basis for Designing New Devices

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New applications of acceleration measurements are discussed, with a focus on employing microelectromechanical system accelerometers for this purpose (due to their outstanding advantages). Some examples of such applications are presented and discussed in the paper. They are mostly related to single- or dual-axis tilt measurements under static or quasi-static conditions. The paper describes and illustrates examples of such measurements in various fields, like scuba diving and freediving or motorcycle riding, where the application of microelectromechanical system accelerometers is closely related to human safety. The considerations regard both successful commercial implementations and some of the latest patents pending.

topics: microelectromechanical system (MEMS) accelerometer, tilt, diving, motorcycle

1. Introduction

Even though acceleration was discovered more than four centuries ago and has been measured ever since, new applications of such measurements are constantly being proposed. For instance, in modern physics, gravitational acceleration is measured while studying various particles [1], and new types of piezoelectric sensors were developed to measure vibration parameters [2]. Prospects for new applications emerge while the measurements are performed using *microelectromechanical system* (MEMS) accelerometers that can sense linear acceleration, both uniform and variable. These sensors employ technology developed for microsystems, which involves the fabrication of miniature structures and components on a silicon chip. MEMS accelerometers have several advantages over conventional accelerometers, such as small dimensions — currently even less than 1 mm — low cost, low power consumption, high sensitivity and reliability, as well as easy integration with other sensors and electronics, high shock-resistance and high reliability, making them the best option to be used in measurement and safety systems for many applications.

Over the recent years, novel applications of MEMS accelerometers have emerged in various fields, such as structural monitoring, diving, automotive (motorcycle) safety, biomedical devices, consumer electronics, and aerospace engineering. These applications require novel designs, fabrication platforms, optimization, and testing of MEMS accelerometers and help improve human safety in recreation, transportation, and some specific tasks where information about spatial orientation is very important.

2. Some new applications

2.1. Wheel odometers and pedometers

Accelerometers developed in MEMS technology are not only used to monitor and record acceleration, velocity, and displacement of vehicles and people, but can also be employed in enhanced versions of such measurement systems. An accelerometer-based wheel odometer for kinematics determination [3] is one of them, as it employs MEMS accelerometers to determine the angular velocity of a rigid body. In such case, the following equation is true [3],

$$a = g\cos(\omega t \pm \phi) + R\omega^2, \tag{1}$$

where a is measured acceleration; g — gravitational acceleration; ω — angular rate; φ — geometrical phase shift; R — radius at which the accelerometer is mounted; t — time.

Such a concept has also been proposed in, e.g., [4], where a series of accelerometers was applied due to their low weight and small size. The appropriate spatial arrangement of MEMS accelerometers makes it possible to sense angular velocity owing to different indications of particular accelerometers

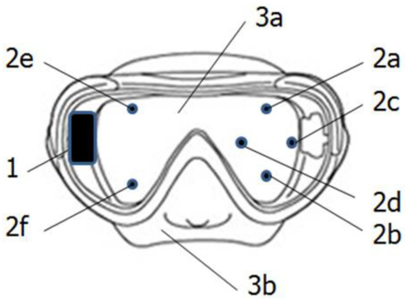

Fig. 1. Diving mask with tilt/orientation LED indicators: 1 — electronic system with accelerometer; 2a–2f — light sources; 3a — glass faceplate; 3b — flexible skirt.

when their geometrical configuration is known accurately. The low cost of modern devices makes it also more cost-efficient than some time ago.

2.2. Diving (scuba diving and freediving)

The experience that has been gained in this field so far has already been used in more unusual areas of human activity.

For instance, the main risks while diving are the following: dangerous marine species, malfunction of diving equipment, asphyxiation, decompression sickness, nitrogen narcosis, and oxygen toxicity. Even nowadays, despite using modern diving computers, accidents do happen. The causes of the accidents are most often the diver's lack of attention and insufficiently effective alarm systems. An accident may often also be caused by a lack of information about the spatial orientation of the diver, which is not provided by a standard diving computer.

We proposed a diving mask with a simple head-up display [5, 6] that provides information about dual-axis tilt (pitch and roll) or upward/downward orientation (single-axis tilt [7]) to the diver, as illustrated in Fig. 1.

Pitch and roll are to be determined according to the following formulas,

$$\alpha = \arctan\left(\frac{g_x}{\sqrt{g_y^2 + g_z^2}}\right), \tag{2}$$

$$\gamma = \arctan\left(\frac{g_y}{g_z}\right), \tag{3}$$

where g_x, g_y, g_z are the Cartesian components of the gravitational acceleration; α — pitch; γ — roll.

The diving mask consists of a faceplate (no. 3a) or two lenses, made of tempered glass or plastic, around which a flexible skirt (no. 3b) is spread, forming the inner space of the mask covering the eyes and nose of the diver or his whole face.

In the inner space of the mask, an electronic system (no. 1) with a MEMS-type accelerometer is fixed. It is connected to a light-signaling system consisting of:

- four light sources (nos. 2a–2d) fixed to the faceplate (or the left lens) that indicate tilt, where (no. 2a) and (no. 2b) represent pitch angle, and (no. 2c) and (no. 2d) represent roll angle,

and

- two light sources (nos. 2e–2f) fixed to the faceplate (or the right lens) that indicate upward (no. 2e) or downward (no. 2f) orientation.

All the light sources (pitch-up (no. 2a), pitch-down (no. 2b), roll-left (no. 2c), roll-right (no. 2d), orientation-upward (no. 2e), orientation-downward (no. 2f)) are contained in the inner space of the mask and are fixed to the glass; they emit the light towards the inside of the mask.

Light sources (nos. 2a–2d) are arranged in a quadrilateral configuration. They are designed mainly for freediving, helping the diver to precisely keep vertical attitude while descending without a guide line. The light sources emit light in two colors. If the pitch or roll angle are smaller than 2 degrees arc, no light is emitted (the diver keeps approximately a vertical attitude — no alert is necessary). If any of the angles is in the interval from 2 to 5 degrees arc, appropriate light source emits yellow light, and if any of the angles exceeds 5 degrees arc red light is emitted.

Light sources (nos. 2e–2f) are designed mainly for scuba-diving, helping the diver to distinguish between downward/upward orientation. Such information may be helpful, or even life-saving while in an emergency situation (e.g., middle ear barotrauma or diving within a large fish shoal). Each light source emits light in one color only, however different. If the orientation is downward light source (no. 2f) shines blue and if it is upward light source (no. 2e) shines green.

It is also possible to build the mask as having only one set of indicators: either (nos. 2a–2d) for freediving or (nos. 2e–2f) for scuba diving, as suggested in the relevant patents pending [5, 6].

Such mask eliminates the risk of an alarm or other important information going unnoticed. In addition, improved version of the mask can be fitted with light-emitting diode (LED) numeric displays to aid spatial orientation based on signals from MEMS accelerometers. The light weight and small size of this type of accelerometer fabricated as microsystems, along with its low power consumption, make it possible to integrate the entire measurement system into a sealed, waterproof mask. This type of solution will help to eliminate some of the main causes of diving accidents.

Furthermore, accelerometers can be used not only by the diver himself but also by those watching him (rescuers, lifeguards, instructors, and sports referees). Signals generated by a set of MEMS accelerometers, processed by computing units, allow real-time recording and observation or reconstruction of movements, position, and orientation of the diver, when his visual observation may be difficult due to external conditions and human perception (refraction of light on the water surface, tight corners of the area, e.g., during rescue searches or repetitions at sports competitions) [8, 9].

As in the case of the previous applications, the small size and low weight of the device, allowing the diver to keep his mobility, are of great importance here. An even more important aspect is the energy efficiency of the sensors, as the multiplication of the number of sensors translates into an increase in energy consumption by the measurement system. On the other hand, in the case of real-time systems, the feature that makes it possible to use MEMS accelerometers for this type of measurement is the satisfactory speed of their operation.

2.3. Motorcycle safety and aerospace technology

Roll angle is the angle about the longitudinal axis of a motorcycle. It is also known as lean angle or bank angle, and it is a key parameter for the stability and maneuverability of a motorcycle. Roll angle is determined by the balance of forces and moments acting on the motorcycle, such as gravity, centrifugal force, friction, aerodynamic drag, and steering torque.

New BMW superbikes are equipped with the *motorcycle stability control* (MSC) system. It is an *inertial measurement unit* (IMU) including a MEMS accelerometer and gyroscope. The motorcycle display indicates in the racing mode the current and maximum values of left- and right-side rolls. MSC system constantly monitors the rotational speed of the wheels, acceleration, braking pressure, and other physical quantities [10]. This data allows the system to recognize critical situations and then intervene.

The value of lean angle can be helpful not only as information for the driver on a racing track or for the safety systems, but it can be used to improve skills and counter-steering techniques in the case of casual drivers. It can also help monitor tire wear and grip level by comparing their lean angle with the tire profile and condition. The skills of the driver and the condition of the tires are essential for the safety of motorcycle driving.

Specially prepared IMUs find application not only in road transport but also in air transport. Research has been started aimed at improving the type of this unit that enables stabilization and flight testing of *unmanned aerial vehicles* (UAVs) [11], which are used not only for recreational purposes but also in various types of research or military operations, and perhaps soon in autonomous air transportation.

2.4. Axial run-out sensors

Particular attention has been given to minimizing errors related to non-perpendicularity or misalignments of the accelerometer sensitive axes with respect to the rotation axes of the frame of the end device. Elimination of these errors has a significant impact on the results of the measurements, especially in the case of conducting experimental tests of MEMS accelerometers. However, a correlation between accelerometer output signals and the misalignment of the accelerometer sensitive axis with respect to the axis of its rotation has been discovered [12]. The maximal value of the misalignment, which is the axial run-out of the rotating shaft to which the accelerometer is mounted, can be determined as follows

$$\beta = a\sin\left(\frac{\max(a) - \min(a)}{2g},\right) \quad (4)$$

where a is acceleration measured within one rotation of the tested shaft and β — axial run-out.

On the one hand, it is possible to observe the generation of signals due to misalignments while rotating the accelerometer and then use the signals for precise alignment. On the other hand, finding the maximum value of the misalignment angle between the accelerometer sensitive axis and the axis of rotation of the test rig can be interpreted as a measure of the axial run-out.

A patented mechanical design of the device measuring axial run-out [13] that meets the above assumptions is shown in Fig. 2. By means of its two-part housing ((no. 2a) and (no. 2b)), the device can be easily fixed on the tested shaft (no. 1) that rotates. Due to the aligning unit (no. 3), the accelerometer sensitive axis can be precisely aligned with respect to the rotation axis of the shaft. Then, any tilt of the shaft can be easily detected, provided that its orientation is approximately horizontal. The angular value of the tilt can be converted into linear value of the detected axial run-out of the shaft.

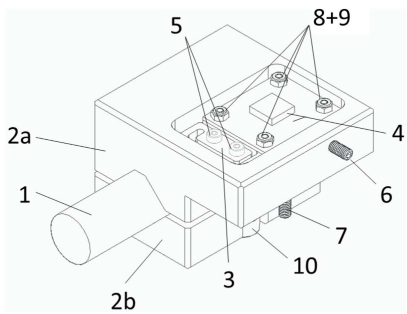

Fig. 2. First axial run-out sensor: 1 — tested shaft; 2a, 2b — two-part housing; 3 — aligning unit; 4 — accelerometer printed circuit board (PCB); 5, 10 — clamping screws; 6, 7 — aligning screws, 8, 9 — screws and nuts securing the PCB.

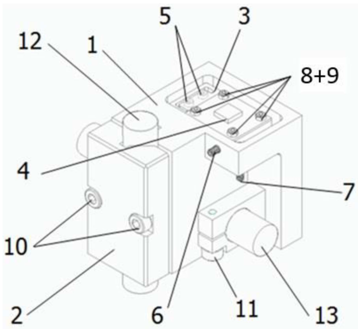

Fig. 3. Second axial run-out sensor: 1, 2 — two-part housing; 3 — aligning unit; 4 — accelerometer PCB; 5, 10, 11 — clamping screws; 6, 7 — aligning screws; 8, 9 — screws and nuts securing the PCB; 12 — tested shaft; 13 — aligning shaft.

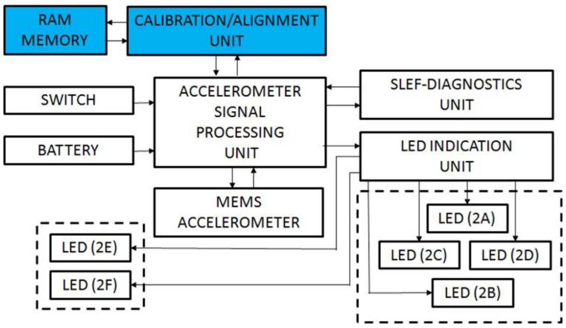

Fig. 4. Block diagram of the control system of the diving mask.

A similar patented device [14] is shown in Fig. 3. It extends the application scope of its predecessor, making it possible to monitor any tilt of the shaft (no. 12) whose orientation is approximately vertical. Additional shaft (no. 13) is used for initial alignment of the accelerometer.

3. Calibration and alignment of MEMS accelerometers

In some cases, it is necessary not only to calibrate the accelerometer itself, for example, in order to increase the accuracy of the measurements [15], but also to align the whole device, mostly because of its specific orientation or due to some misalignments that appear after the installation of the device.

A good example here may be the diving mask with a simple head-up display [5, 6]. Each time the mask is put on the face of the diver, its orientation will be a bit different. So, a special calibration/alignment unit is necessary to compensate for the resultant errors. Such a unit, coupled with a dedicated RAM memory, is presented in Fig. 4 and denoted with a blue color.

4. Conclusions

Acceleration measurements are used in an increasing number of applications, both new, such as the acquisition of additional information that has not been previously available, e.g., diver's orientation or additional parameters improving motorcycle safety, and replacing older technologies, as in the case of testing the strength of buildings or bridges [16, 17]. The acceleration is used directly or its derivative physical quantities are determined (e.g., tilt, pitch, roll, axial run-out).

Miniaturization of acceleration-sensing MEMS devices, along with the reduction in their energy consumption, allows research and development teams to focus on developing technologies that have a tangible impact on society and human safety.

Using low-cost MEMS accelerometers integrated into inertial measurement units (IMU) may help prevent or mitigate the risks of human injury, which is sometimes overlooked by manufacturers due to the lack of direct impact on their profits. Several studies have developed and tested MEMS-based accelerometer sensor systems for various applications and demonstrated their feasibility and reliability [18] at a reasonable price.

The wide range of applications of acceleration measurements has been achieved owing to numerous advantages of MEMS accelerometers, such as fast response, high measurement frequency, high accuracy, high shock resistance, and a wide selection of measurement ranges.

However, there still exist some challenges and limitations related to the discussed measurements that need to be addressed, such as appropriate sensor selection [19], the necessity of its calibration [20] or precise alignment in order to avoid considerable errors [21], noise reduction, data processing, network topology, power management, and system integration. Along with improvements regarding the aforementioned issues, more new applications will emerge in the future.

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