Accelerometer

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An **accelerometer** is a device that measures proper acceleration; proper acceleration is not the same as coordinate acceleration (rate of change of velocity). For example, an accelerometer at rest on the surface of the Earth will measure an acceleration due to Earth's gravity, straight upwards (by definition) of $g \approx 9.81\ m/s^2$. By contrast, accelerometers in free fall (falling toward the center of the Earth at a rate of about $9.81\ m/s^2$) will measure zero.

Accelerometers have multiple applications in industry and science. Highly sensitive accelerometers are components of inertial navigation systems for aircraft and missiles. Accelerometers are used to detect and monitor vibration in rotating machinery. Accelerometers are used in tablet computers and digital cameras so that images on screens are always displayed upright. Accelerometers are used in drones for flight stabilisation. Coordinated accelerometers can be used to measure differences in proper acceleration, particularly gravity, over their separation in space; i.e., gradient of the gravitational field. This gravity gradiometry is useful because absolute gravity is a weak effect and depends on local density of the Earth which is quite variable.

Single- and multi-axis models of accelerometer are available to detect magnitude and direction of the proper acceleration, as a vector quantity, and can be used to sense orientation (because direction of weight changes), coordinate acceleration, vibration, shock, and falling in a resistive medium (a case where the proper acceleration changes, since it starts at zero, then increases). Micromachined accelerometers are increasingly present in portable electronic devices and video game controllers, to detect the position of the device or provide for game input.

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Physical principles

An accelerometer measures proper acceleration, which is the acceleration it experiences relative to freefall and is the acceleration felt by people and objects. Put another way, at any point in spacetime the equivalence principle guarantees the existence of a local inertial frame, and an accelerometer measures the acceleration relative to that frame.[1] Such accelerations are popularly denoted g-force; i.e., in comparison to standard gravity.

An accelerometer at rest relative to the Earth's surface will indicate approximately 1 g *upwards*, because any point on the Earth's surface is accelerating upwards relative to the local inertial frame (the frame of a freely falling object near the surface). To obtain the acceleration due to motion with respect to the Earth, this "gravity offset" must be subtracted and corrections made for effects caused by the Earth's rotation relative to the inertial frame.

The reason for the appearance of a gravitational offset is Einstein's equivalence principle,[2] which states that the effects of gravity on an object are indistinguishable from acceleration. When held fixed in a gravitational field by, for example, applying a ground reaction force or an equivalent upward thrust, the reference frame for an accelerometer (its own casing) accelerates upwards with respect to a free-falling reference frame. The effects of this acceleration are indistinguishable from any other acceleration experienced by the instrument, so that an accelerometer cannot detect the difference between sitting in a rocket on the launch pad, and being in the same rocket in deep space while it uses its engines to accelerate at 1 g. For similar reasons, an accelerometer will read *zero* during any type of free fall. This includes use in a coasting spaceship in deep space far from any mass, a spaceship orbiting the Earth, an airplane in a parabolic "zero-g" arc, or any free-fall in vacuum. Another example is free-fall at a sufficiently high altitude that atmospheric effects can be neglected.

However this does not include a (non-free) fall in which air resistance produces drag forces that reduce the acceleration, until constant terminal velocity is reached. At terminal velocity the accelerometer will indicate 1 g acceleration upwards. For the same reason a skydiver, upon reaching terminal velocity, does not feel as though he or she were in "free-fall", but rather experiences a feeling similar to being supported (at 1 g) on a "bed" of uprushing air.

Acceleration is quantified in the SI unit metres per second per second (m/s^2), in the cgs unit gal (Gal), or popularly in terms of standard gravity (*g*).

For the practical purpose of finding the acceleration of objects with respect to the Earth, such as for use in an inertial navigation system, a knowledge of local gravity is required. This can be obtained either by calibrating the device at rest,[3] or from a known model of gravity at the approximate current position.

Structure

Conceptually, an accelerometer behaves as a damped mass on a spring. When the accelerometer experiences an acceleration, the mass is displaced to the point that the spring is able to accelerate the mass at the same rate as the casing. The displacement is then measured to give the acceleration.

In commercial devices, piezoelectric, piezoresistive and capacitive components are commonly used to convert the mechanical motion into an electrical signal. Piezoelectric accelerometers rely on piezoceramics (e.g. lead zirconate titanate) or single crystals (e.g. quartz, tourmaline). They are unmatched in terms of their upper frequency range, low packaged weight and high temperature range. Piezoresistive accelerometers are preferred in high shock applications. Capacitive accelerometers typically use a silicon micro-machined sensing element. Their performance is superior in the low frequency range and they can be operated in servo mode to achieve high stability and linearity.

Modern accelerometers are often small *micro electro-mechanical systems* (MEMS), and are indeed the simplest MEMS devices possible, consisting of little more than a cantilever beam with a proof mass (also known as *seismic mass*). Damping results from the residual gas sealed in the device. As long as the Q-factor is not too low, damping does not result in a lower sensitivity.

Under the influence of external accelerations the proof mass deflects from its neutral position. This deflection is measured in an analog or digital manner. Most commonly, the capacitance between a set of fixed beams and a set of beams attached to the proof mass is measured. This method is simple, reliable, and inexpensive. Integrating piezoresistors in the springs to detect spring deformation, and thus deflection, is a good alternative, although a few more process steps are needed during the fabrication sequence. For very high sensitivities quantum tunneling is also used; this requires a dedicated process making it very expensive. Optical measurement has been demonstrated on laboratory scale.

Another, far less common, type of MEMS-based accelerometer contains a small heater at the bottom of a very small dome, which heats the air inside the dome to cause it to rise. A thermocouple on the dome determines where the heated air reaches the dome and the deflection off the center is a measure of the acceleration applied to the sensor.

Most micromechanical accelerometers operate *in-plane*, that is, they are designed to be sensitive only to a direction in the plane of the die. By integrating two devices perpendicularly on a single die a two-axis accelerometer can be made. By adding another *out-of-plane* device three axes can be measured. Such a combination may have much lower misalignment error than three discrete models combined after packaging.

Micromechanical accelerometers are available in a wide variety of measuring ranges, reaching up to thousands of *g*'s. The designer must make a compromise between sensitivity and the maximum acceleration that can be measured.

Applications

Engineering

Accelerometers can be used to measure vehicle acceleration. Accelerometers can be used to measure vibration on cars, machines, buildings, process control systems and safety installations. They can also be used to measure seismic activity, inclination, machine vibration, dynamic distance and speed with or without the influence of gravity. Applications for accelerometers that measure gravity, wherein an accelerometer is specifically configured for use in gravimetry, are called gravimeters.

Notebook computers equipped with accelerometers can contribute to the *Quake-Catcher Network* (QCN), a BOINC project aimed at scientific research of earthquakes.[4]

Biology

Accelerometers are also increasingly used in the biological sciences. High frequency recordings of bi-axial[5] or tri-axial acceleration[6] allows the discrimination of behavioral patterns while animals are out of sight. Furthermore, recordings of acceleration allow researchers to quantify the rate at which an animal is expending energy in the wild, by either determination of limb-stroke frequency[7] or measures such as overall dynamic body acceleration[8] Such approaches have mostly been adopted by marine scientists due to an inability to study animals in the wild using visual observations, however an increasing number of terrestrial biologists are adopting similar approaches. This device can be connected to an amplifier to amplify the signal.

Industry

Accelerometers are also used for machinery health monitoring to report the vibration and its changes in time of shafts at the bearings of rotating equipment such as turbines, pumps,[9] fans,[10] rollers,[11] compressors,[12][13] or bearing fault[14] which, if not attended to promptly, can lead to costly repairs. Accelerometer vibration data allows the user to monitor machines and detect these faults before the rotating equipment fails completely.

Building and structural monitoring

Accelerometers are used to measure the motion and vibration of a structure that is exposed to dynamic loads.[15] Dynamic loads originate from a variety of sources including:

- Human activities – walking, running, dancing or skipping
- Working machines – inside a building or in the surrounding area
- Construction work – driving piles, demolition, drilling and excavating
- Moving loads on bridges
- Vehicle collisions
- Impact loads – falling debris
- Concussion loads – internal and external explosions
- Collapse of structural elements
- Wind loads and wind gusts
- Air blast pressure
- Loss of support because of ground failure
- Earthquakes and aftershocks

Under structural applications, measuring and recording how a structure dynamically responds to these inputs is critical for assessing the safety and viability of a structure. This type of monitoring is called Health Monitoring, which usually involves other types of instruments, such as displacement sensors -Potentiometers, LVDTs, etc.- deformation sensors -Strain Gauges, Extensometers-, load sensors -Load Cells, Piezo-Electric Sensors- among others.

Medical applications

Zoll's AED Plus uses CPR-D•padz which contain an accelerometer to measure the depth of CPR chest compressions.

Within the last several years, several companies have produced and marketed sports watches for runners that include footpods, containing accelerometers to help determine the speed and distance for the runner wearing the unit.

In Belgium, accelerometer-based step counters are promoted by the government to encourage people to walk a few thousand steps each day.

Herman Digital Trainer uses accelerometers to measure strike force in physical training.[16][17]

It has been suggested to build football helmets with accelerometers in order to measure the impact of head collisions.[18]

Accelerometers have been used to calculate gait parameters, such as stance and swing phase. This kind of sensor can be used to measure or monitor people.[19][20]

Navigation

An inertial navigation system is a navigation aid that uses a computer and motion sensors (accelerometers) to continuously calculate via dead reckoning the position, orientation, and velocity (direction and speed of movement) of a moving object without the need for external references. Other terms used to refer to inertial navigation systems or closely related devices include inertial guidance system, inertial reference platform, and many other variations.

An accelerometer alone is unsuitable to determine changes in altitude over distances where the vertical decrease of gravity is significant, such as for aircraft and rockets. In the presence of a gravitational gradient, the calibration and data reduction process is numerically unstable.[21][22]

Transport

Accelerometers are used to detect apogee in both professional[23] and in amateur[24] rocketry.

Accelerometers are also being used in Intelligent Compaction rollers. Accelerometers are used alongside gyroscopes in inertial navigation systems.[25]

One of the most common uses for MEMS accelerometers is in airbag deployment systems for modern automobiles. In this case the accelerometers are used to detect the rapid negative acceleration of the vehicle to determine when a collision has occurred and the severity of the collision. Another common automotive use is in electronic stability control systems, which use a lateral accelerometer to measure cornering forces. The widespread use of accelerometers in the automotive industry has pushed their cost down dramatically.[26] Another automotive application is the monitoring of noise, vibration, and harshness (NVH), conditions that cause discomfort for drivers and passengers and may also be indicators of mechanical faults.

Tilting trains use accelerometers and gyroscopes to calculate the required tilt.[27]

Volcanology

Modern electronic accelerometers are used in remote sensing devices intended for the monitoring of active volcanoes to detect the motion of magma[28]

Consumer electronics

Accelerometers are increasingly being incorporated into personal electronic devices to detect the orientation of the device, for example, a display screen.

A *free-fall sensor* (FFS) is an accelerometer used to detect if a system has been dropped and is falling. It can then apply safety measures such as parking the head of a hard disk to prevent a head crash and resulting data loss upon impact. This device is included in the many common computer and consumer electronic products that are produced by a variety of manufacturers. It is also used in some data loggers to monitor handling operations for shipping containers. The length of time in free fall is used to calculate the height of drop and to estimate the shock to the package.

Motion input

Some smartphones, digital audio players and personal digital assistants contain accelerometers for user interface control; often the accelerometer is used to present landscape or portrait views of the device's screen, based on the way the device is being held. Apple has included an accelerometer in every generation of iPhone, iPad, and iPod touch, as well as in every iPod nano since the 4th generation. Along with orientation view adjustment, accelerometers in mobile devices can also be used as pedometers, in conjunction with specialized applications.[29]

Automatic Collision Notification (ACN) systems also use accelerometers in a system to call for help in event of a vehicle crash. Prominent ACN systems include OnStar AACN service, Ford Link's 911 Assist, Toyota's Safety Connect, Lexus Link, or BMW Assist. Many accelerometer-equipped smartphones also have ACN software available for download. ACN systems are activated by detecting crash-strength accelerations.

Accelerometers are used in vehicle Electronic stability control systems to measure the vehicle's actual movement. A computer compares the vehicle's actual movement to the driver's steering and throttle input. The stability control computer can selectively brake individual wheels and/or reduce engine power to minimize the difference between driver input and the vehicle's actual movement. This can help prevent the vehicle from spinning or rolling over.

Some pedometers use an accelerometer to more accurately measure the number of steps taken and distance traveled than a mechanical sensor can provide.

Nintendo's Wii video game console uses a controller called a Wii Remote that contains a three-axis accelerometer and was designed primarily for motion input. Users also have the option of buying an additional motion-sensitive attachment, the Nunchuk, so that motion input could be recorded from both of the user's hands independently. Is also used on the Nintendo 3DS system.

The Sony PlayStation 3 uses the DualShock 3 remote which uses a three axis accelerometer that can be used to make steering more realistic in racing games, such as *MotorStorm* and *Burnout Paradise*.

The Nokia 5500 sport features a 3D accelerometer that can be accessed from software. It is used for step recognition (counting) in a sport application, and for tap gesture recognition in the user interface. Tap gestures can be used for controlling the music player and the sport application, for example to change to next song by tapping through clothing when the device is in a pocket. Other uses for accelerometer in Nokia phones include Pedometer functionality in Nokia Sports Tracker. Some other devices provide the tilt sensing feature with a cheaper component, which is not a true accelerometer.

Sleep phase alarm clocks use accelerometric sensors to detect movement of a sleeper, so that it can wake the person when he/she is not in REM phase, in order to awaken the person more easily.

Orientation sensing

A number of 21st century devices use accelerometers to align the screen depending on the direction the device is held, for example switching between portrait and landscape modes. Such devices include many tablet PCs and some smartphones and digital cameras. The Amida Simputer, a handheld Linux device launched in 2004, was the first commercial handheld to have a built-in accelerometer. It had incorporated many gesture based interactions using this accelerometer, including page-turning, zoom-in and zoom-out of images, change of portrait to landscape mode and many simple gesture-based games.

As of January 2009, almost all new mobile phones and digital cameras contain at least a tilt sensor and sometimes an accelerometer for the purpose of auto image rotation, motion-sensitive mini-games, and to correct shake when taking photographs.

Image stabilization

Camcorders use accelerometers for image stabilization, either by moving optical elements to adjust the light path to the sensor to cancel out unintended motions or digitally shifting the image to smooth out detected motion. Some stills cameras use accelerometers for anti-blur capturing. The camera holds off capturing the image when the camera is moving. When the camera is still (if only for a millisecond, as could be the case for vibration), the image is captured. An example of the application of this technology is the Glogger VS2,[30] a phone application which runs on Symbian based phones with accelerometers such as the Nokia N96. Some digital cameras contain accelerometers to determine the orientation of the photo being taken and also for rotating the current picture when viewing.

Device integrity

Many laptops feature an accelerometer which is used to detect drops. If a drop is detected, the heads of the hard disk are parked to avoid data loss and possible head or disk damage by the ensuing shock.

Gravimetry

A **gravimeter** or gravitometer, is an instrument used in gravimetry for measuring the local gravitational field. A gravimeter is a type of accelerometer, except that accelerometers are susceptible to all vibrations including noise, that cause oscillatory accelerations. This is counteracted in the gravimeter by integral vibration isolation and signal processing. Though the essential principle of design is the same as in accelerometers, gravimeters are typically designed to be much more sensitive than accelerometers in order to measure very tiny changes within the Earth's gravity, of 1 *g*. In contrast, other accelerometers are often designed to measure 1000 *g* or more, and many perform multi-axial measurements. The constraints on temporal resolution are usually less for gravimeters, so that resolution can be increased by processing the output with a longer "time constant".

Types of accelerometer

- Bulk micromachined capacitive
- Bulk micromachined piezoelectric resistive
- Capacitive spring mass system base
- DC response
- Electromechanical servo (Servo Force Balance)
- High gravity
- High temperature
- Laser accelerometer
- Low frequency
- Magnetic induction
- Modally tuned impact hammers
- Null-balance
- Optical
- Pendulous integrating gyroscopic accelerometer (PIGA)
- Piezoelectric accelerometer
- Quantum (Rubidium atom cloud, laser cooled)
- Resonance
- Seat pad accelerometers
- Shear mode accelerometer
- Strain gauge
- Surface acoustic wave (SAW)
- Surface micromachined capacitive (MEMS)
- Thermal (submicrometre CMOS process)
- Triaxial
- Vacuum diode with flexible anode[31]
- potentiometric type
- LVDT type accelerometer

See also

- g-force
- Geophone
- Gyroscope
- Inclinometer
- Inertial navigation
- Accelerograph
- Seismometer
- Shock, Vibration & Acceleration Data Logger
- Degrees of Freedom
- Vibration calibrator

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