MEMS-BASED INERTIAL SYSTEMS

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Key words: MEMS-sensors, inertial systems, systems in package, gyro sensor, acceleration sensor, MEMS technology, fail-safe electronic systems.

Abstract: MEMS-based inertial systems are one of the fastest growing application segments of the micro-sensor market. The applications range from consumer to personal navigation and automotive systems, where they are used for rollover detection and stability control. This paper presents an overview of MEMS-based inertial systems composed of acceleration and gyro sensors, ASIC for driving the sensor and sensing the signals, packages to house the sensors and ASICS and software for controlling and fail-safe operation of the system. To produce such systems, several technologies are needed, such as IC and MEMS technologies, packaging, calibration tests, etc. The driver for technology is the automotive industry, which requires as little volume and power consumption as possible, as good a performance as possible for as small price as possible. Following this rule, a number of inertial systems have been developed for automotive ranges from 75°/s to 300°/s, programmable band from 10 to 200Hz, noise floor of 0.02(°/s)/√Hz, single supply voltage of 5V, linearity better than 0.1%, automotive temperature range and probability of undetected errors smaller than 10^{-9}/h.

Inercijski sistemi na osnovi MEMS tehnologije

Kjučne besede: MEMS senzorji, Inercijski sistemi, sistemi v ohišju, giroskop, senzor pospeškov, MEMS tehnologija, varni elektronski sistemi

Izvleček: Inercijski sistemi, ki bazirajo na MEMS tehnologijah so najhitreje rastoče področje trga senzorskih sistemov. Uporaba sega od potrošnih, osebnih navigacijskih do avtomobilskih sistemov, kjer se uporabljajo za zaznavo stabilnosti in prevračanja ter pri merjenju pospeškov. Članek obravnava pregled integriranih inercijskih sistemov, ki so sestavljeni iz senzorja pospeška, senzorja vrtenja, ASIC vezja, ki skrbi za krmiljenje senzorjev in detekcijo šibkih signalov, mikrokontrolerja in programov za krmiljenje in upravljanje varnega sistema ter ohišja. Za učinkovito gradnjo takšnega sistema potrebujemo različne tehnologije kot so: tehnologija integriranih vezji, MEMS tehnologije, pakiranje, kalibracija, testiranje itd. Glavni razlog za razvoj novih tehnologij je avtomobilska industrija, ki zahteva inercijski sistem z majhnim volumnom, težo, majhno porabo moči, avtomobilskimi specifikacijami in čim nižjo ceno. V preteklih letih je bilo razvitih nekaj takšnih sistemov, ki delujejo v avtomobilskem področju od 75°/s do 300°/s, programabilno pasovno širino od 10 do 200Hz, šumom, ki je manjši od 0.02(°/s)/√Hz, linearnostjo boljšo kot 0.1% pri napajalni napetosti 5V in delujejo v avtomobilskem temperaturnem področju. Poleg tega avtomobiski standardi zahtevajo veliko zanesljivost delovanja, kjer mora biti verjetnost za neodkrito napako manjša kot 10^{-9}/h.

1 Introduction

MEMS inertial systems, consisting of MEMS accelerometers and gyro sensors, ASIC that drive the sensors and sense the signals, package and embedded software are very important parts of silicon-based smart sensor-systems. The technology driver is the automotive industry, because it requires more and more "smart-sensor systems" to be built into the vehicles. Applications of automotive inertial systems include stability control, rollover detection, acceleration detection for the airbags and add-on for the GPS navigation system. Other applications are biomedical, sport, industrial and robotic, military and consumer like picture stability control in cameras, 3D mouse and virtual reality devices, etc. Common requirements for all these applications are appropriate performances, low price, low volume and low power consumption. These factors are the most important drivers for further technological development of MEMS inertial systems, composed of sensors, analogue and digital signal-processing hardware and embedded algorithms.

The paper is organized as follows: Section 2 covers basic principles of operation of both sensors; in Section 3 historical background is presented, while in Section 4 the most important automotive requirements are shown. Section 5 describes MEMS inertial measurement system used in automotive applications. The introduction of MEMS technology is presented in Section 6, together with a description of the most important sensing and actuation principles (electrostatics in MEMS). In section 7, possible implementations of the MEMS accelerometer and gyro sensors are presented with an electro-mechanical model of the gyro sensor. Section 8 explains possible implementation of electronic systems able to drive the sensors and sense weak signals coming from the sensors.

2 Principles of operation

2.1 Accelerometer

Generally, an accelerometer consists of a proof mass suspended by springs connected to a fixed frame. Figure 1 shows a general accelerometer sensor structure and its simplified model.

When accelerating, according to Newton's second law, the proof mass is moved from its rest position and the displace-

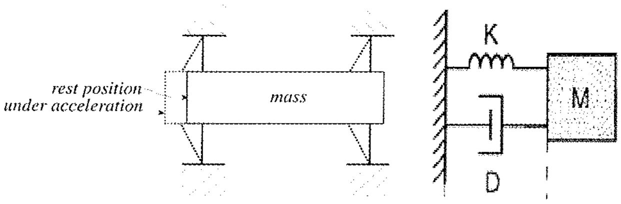


Fig. 1: Accelerometer sensor and its simplified model

ment can be sensed. The acceleration sensor has proof mass *M*, effective spring constant *K* damping factor β and can be approximately described by second order differential equation (2.1):

$$M x'' + \beta x' + Kx = Ma \quad (2.1)$$

The displacement is approximately proportional to $x_s = \frac{g}{\omega_0^2}$. The linear mechanical transfer function of the device can be described by the second order system (2.2):

$$H(s) = \frac{1}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} \quad (2.2)$$

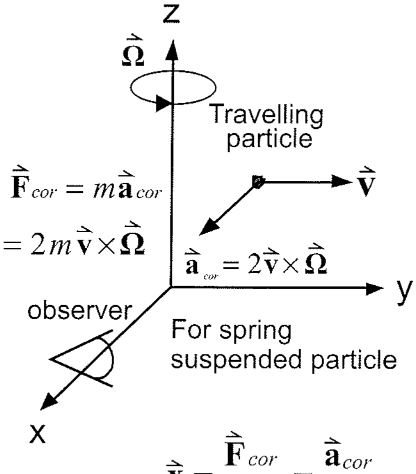
where resonance frequency of the system is $\omega_0^2 = \frac{K}{m}$, quality factor of a system in resonance is proportional to $Q = \frac{\sqrt{KM}}{\beta}$. If proof mass is very small as in MEMS, then Brownian motion of the air can disturb the operation of the sensor creating random force $F_B = \sqrt{4k_B \beta T}\left[N/\sqrt{Hz}\right]$, which presents the lower resolution limit of the acceleration sensor (2.3):

$$g_n = \frac{1}{g}\sqrt{\frac{4k_B T\omega_0}{MQ}}\left[\frac{g}{\sqrt{Hz}}\right] \quad (2.3)$$

To reduce noise level a sensor can be placed in a vacuum. In that case, the lower limit is defined by the noise generated in the electronic sensing circuitry.

2.2 Gyroscope

A gyroscope is a device that can sense rotation of an object in space: it measures the angular velocity of a system with respect to the inertial reference frame. Different physical mechanisms can be used for sensing the rotation; Coriolis Effect is most commonly the used. Coriolis force is apparent force that arises in a rotating reference frame. If an observer is sitting on the *x* axis observing moving object with velocity vector $\vec{v}$ (Figure 2) and if the coordinate system is rotating together with the observer with angular velocity $\vec{\Omega}$ then the observer thinks that the particle is changing its path in the direction of *x* axis with acceleration $\vec{a} = 2\vec{v}\times\vec{\Omega}$: this is a Coriolis effect, according to French scientists.



$$\vec{x} = \frac{\vec{F}_{cor}}{K} = \frac{\vec{a}_{cor}}{\omega^2}$$

Fig. 2: The Coriolis effect

The effect can be observed in nature because of the earth's rotation: the winds and ocean currents in the northern hemisphere are deflected towards the right while in the southern hemisphere they are deflected towards the left. Another example is that north-flowing Arctic rivers cut faster into their right banks (from the perspective of looking upstream) than their left ones, etc.

In the past, gyroscopes were built by means of a rotating wheel, as suggested in Figure 3. Angular momentum $\vec{L}=\vec{I}\vec{\omega}$ is the result of a rapidly spinning wheel with angular velocity ω, which keeps its direction in space. If the outside frame changes, as on the right side of Figure 3, then angular momentum tries to keep the direction in space and, as a result, the precession with angular velocity $\vec{\Omega}_p$ starts ($\vec{I}$ is momentum of inertia, $\vec{L}$ is angular momentum, $\vec{\tau}$ is torque and $\vec{\Omega}_p$ is precession angular velocity).

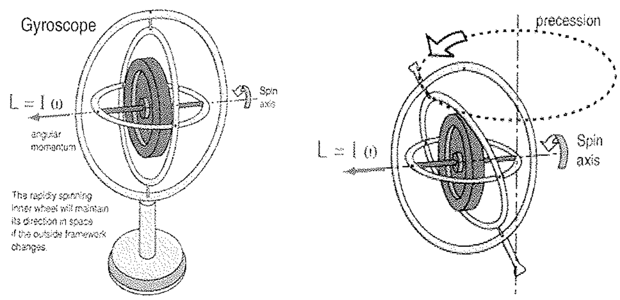


Fig. 3: Mechanical rotating gyroscope

$$\vec{\tau} = \frac{d\vec{L}}{dt} = \vec{I}\vec{\alpha} = \vec{\Omega}_p \times \vec{L} \quad (2.4)$$

Most mechanical gyroscopes built in the past used this principle. It was possible to build high precision gyroscopes in this way but volume, mass, power consumption and price of such implementations are prohibitively high for most applications. Introduction of MEMS technologies enables mass production of cheap and high quality sensors.

3 Historical background

Very little is known about applications of acceleration sensors before 1924 /1/. The effects of Coriolis force were used through spinning-tops for ceremonies (Chinese, Greeks, Romans, Maori). In 1740, Searson noted that the spinning-top has a tendency to remain level even when the surface was tilting. In an experiment in 1851 the French scientist Foucault proved the rotation of the earth by building a pendulum in Paris's Pantheon. He used a pendulum with 28kg mass, suspended on 67m long wire (Figure 4). The plane of oscillations of the pendulum changes during the 24-hour because of the Coriolis Effect produced by the earth's rotation.

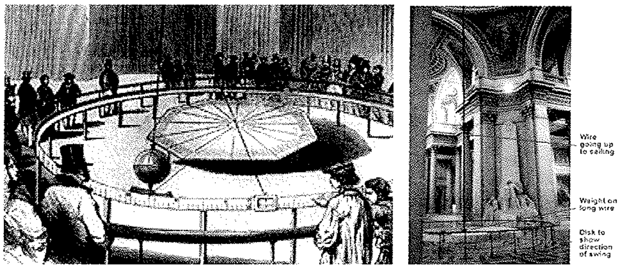


Fig. 4: Foucault's pendulum in the Pantheon, Paris

Johann Gottlieb Friedrich von Bohnenberger designed the first modern mechanical gyroscope around 1800, while in the mid-19th century the spinning-top acquired the name gyroscope (though not through its use as a navigation tool). Figure 5 shows one of the first operational gyrocompasses used for navigation purposes around 1908.

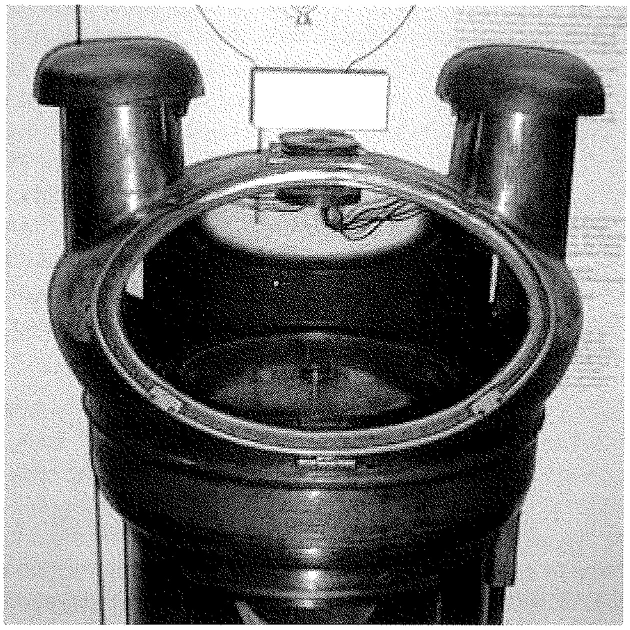


Fig. 5: Gyrocompass

During the 20th century many different implementations of gyro sensors appeared, mainly for space navigation and military applications. They used mechanical, optical or ring laser principles. They are all accurate and stable but very expensive, bulky, consume a lot of power and are therefore not very useful for automotive applications. Some of the historical implementations are described in /2/.

4 Automotive requirements

Typical characteristics for different applications of accelerometers are listed in Table 1. The data are taken from /2/.

Table 1: Typical characteristics of acceleration sensors

Parameter \ Application	Automotive airbag	Automotive stability systems	Navigation	Micro-gravity	Military
Range	±50g	±2g	±1g	±0.1g	±10000g
Band	400kHz	400Hz	100Hz	1Hz	>50kHz
Resolution	50-200mg	1-2mg	4μg	1 μg	0.1g
Off-axis sensitivity	<3%	<5%	<0.1%		
Non-linearity	<2%	<2%	<0.1%		
Shock in 1ms	>2000g	>2000g	>10g		
Temp. range	-40 to 125	-40 to 125	-40 to 80		
TC of offset	<50 μg/°C	<5 μg/°C	<0.5 μg/°C		
TC of sensitivity	<900ppm/°C	<100ppm/°C	<5ppm/° C		

Different applications require different characteristics regarding sensitivity, range, frequency response, resolution, non-linearity, off-axis sensitivity, shock survivability, etc. The most demanding are, of course, accelerometers used in micro-gravity measurements. The requirements for automotive applications as regards resolution, sensitivity, stability, etc. are not as demanding as for navigation and micro-gravity, and have a smaller range compared with ballistic and impact-sensing applications: for automotive applications, the price, volume and power consumption must all be as low as possible. This can be achieved only if MEMS integration technology is used.

Table 2 shows typical characteristics of gyro sensors for different applications. Many different implementations are possible, each covering its own application area. Automotive requirements (rollover detection and stability control) are not as demanding as navigation requirements regarding stability, noise and range, however, the price, volume and power consumption must be much lower, which is possible to implement only by integration. Additional automotive requirements equally important for the proper operation of inertial measurement systems are:

- Allowed mechanical shock during operation: ≤1500g
- Allowed mechanical shock un-powered: ≤2000g
- Mechanical vibrations A=0.75mm, 10g, 55Hz to 2000Hz ..., 24h
- EMI requirements (0.1MHz to 400MHz)
- EMI Emission: 0.15 ... 200MHz, E< 30dBμV/m
- Lifetime: 15000 hours in 17 years
- Probability of undetected error: $<10^{-9}$/h

Table 2 Typical characteristics of gyro sensors

Applications / Parameter	Rate (Automotive) MEMS	Tactical (Fibre -optics, MEMS	Inertial (Ring -laser optical)
Full scale Range [°/s]	50-1000	>500	>400
Noi se dens. [°/s/√Hz]	0.01 -0.03	0.001	0.0001
Scale factor accur.[%]	0.1 to 2	0.01 to 0.1	<0.001
Bias error [°/s]	<2	0.1 -1	<0.01
Angle rand. walk [°/√h]	Unimportant	0.05 to 0.5	<0.001
Bandwidth [Hz]	10 -25-70	100	10
Max. shock in 1ms [g]	10^3	10^4 - 10^5	10^5
Temp. range [°C]	-40 to 125	-40 to 125	-40 to 125
Power cons. [W]	<0.1	>10	>10
Price	<10EUR	High	Very high

MEMS gyro sensors are mechanical sensors so they are sensitive to mechanical shocks and vibrations. Robustness against mechanical shocks is in contradiction with sensitivity and scale factor. A special design of sensor and control electronics is therefore needed to overcome these conflicting requirements. In addition, MEMS accelerometers and gyro sensors are usually capacitive sensors using very small capacitances: they have very high impedance, so they are very sensitive to external electro-magnetic fields; appropriate packaging, shielding and fully differential electronics could solve problems. The hardest requirement is reliability regarding probability of undetected error, which can be achieved only by running so-called fail-safe system, which measures important parameters of the system in real-time.

5 MEMS inertial measurement unit

An automotive application of a MEMS inertial measurement unit with 6 degrees of freedom is shown in Figure 6. It is composed of x, y and z acceleration sensors to be able to measure longitudinal, lateral and vertical acceleration and 3 gyro sensors capable of measuring rotation about each axis: yaw rate about z-axis, pitch rate around y-axis and roll rate around x-axis. MEMS IMU includes sensors and electronics for driving all sensors and processing all signals from the sensors.

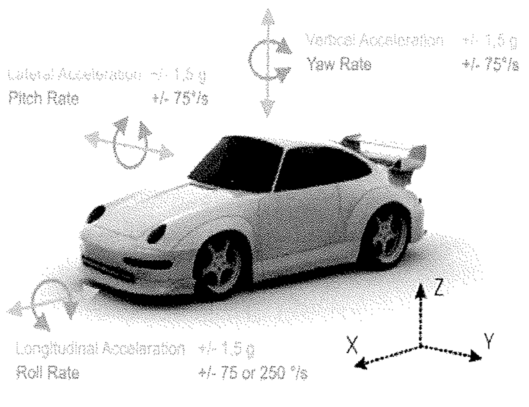


Fig. 6: MEMS inertial measurement unit

Required ranges for all sensors for rollover detection and stability control (ESC) are shown in Figure 6. Currently it is not possible to integrate all six elements into the same ASIC: this is not, however, a distant dream. At present, it is possible to integrate two acceleration sensors and two gyro sensors on top of the ASICs, which includes all necessary electronics to get System in Package (SiP). An integrated z-axis gyro is still awaiting implementation.

IMS (Inertial Measurement System) is in reality a system where sensors are only one part. Other equally important parts are: low noise analogue signal-processing hardware, digital signal-processing algorithms and hardware, micro-controller with embedded software running fail-safe algorithms, package, calibration and built-in self-test. Integration of all these elements in a single chip or as SiP provides an opportunity to reduce price, increase reliability and robustness and reduce power consumption.

6 MEMS technologies

To reduce fabrication cost and increase reliability, the sensors must be scaled down by borrowing fabrication technologies from IC technology. In this way, the dimensions are reduced (millimeter down to tenths of nanometer range) and batch-processing of thousands of devices in parallel is possible, thus reducing the price considerably. To be able to scale mechanical structures, special micro-fabrication technologies have been developed /6/. The related field is called Microsystems technology and the systems built in this way are called Micro-Electromechanical Systems (MEMS). Micromachining in combination with standard IC processing steps (doping, deposition, photolithography and etching) forms the technological base for the implementation of today's micro-electromechanical sensors and systems. Usually a MEMS sensor is just one of the elements of an intelligent sensor system, which also includes ASIC for driving and processing signals from the sensors, package, software, calibration, testing, etc. To reduce further the number of external passive or active components, different techniques and technologies have been developed: SoC (System on Chip), SSoC (Sensing System on Chip) and SSiP (Sensing System in Package). Their implementation depends on available technology, physical requirements and required price.

Micromachining is used to produce three-dimensional mechanical structures (cantilevers, bridges, membranes, springs, etc.) /7/, (Figure 7). using different etching techniques: bulk micromachining is used to etch silicon substrate, while surface micromachining (Figure 8) is used to release a cantilever, beam or plate deposited on top of a sacrificial thin film layer. The critical technology step is etching and most promising is anisotropic deep reactive ion etching (DRIE), which can produce very high aspect ratio micro-structures (Figure 9) needed for inertial sensors.

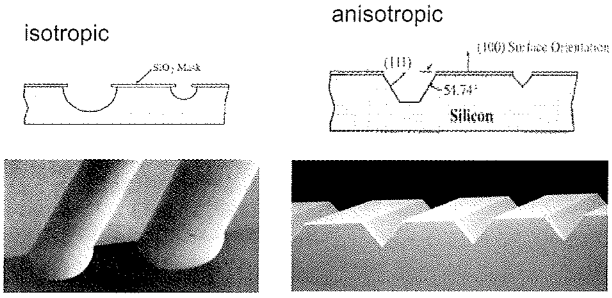


Fig. 7: Bulk micromachining

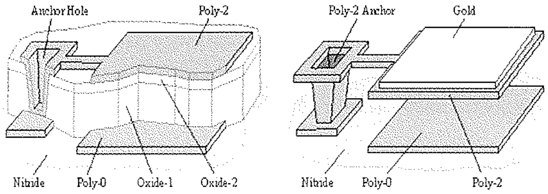


Fig. 8: Surface micromachining

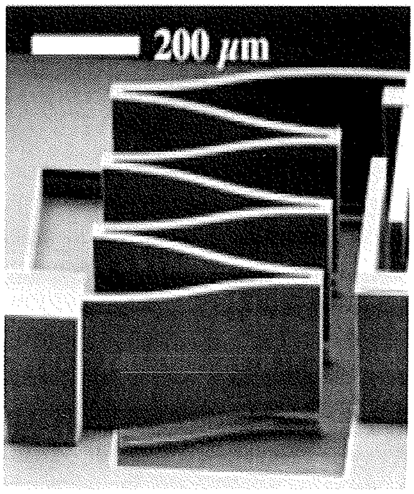


Fig. 9: DRIE example

If MEMS structures are to be integrated in the same silicon substrate as the ASICs, then a number of constraints are imposed on the micromachining steps so as not to detract from the performance of the electronics. Most important limiting factors are temperature of post-processing steps and/or contamination of the ASICs substrate and surface. Companies have developed several strategies for the integration: Pre-CMOS micromachining, Intra-CMOS micromachining and Post-CMOS micromachining /9/. Figure 10 shows dimensions of MEMS elements compared to different physical structures.

Despite miniaturization, all classical physical laws are still valid for most of the MEMS sensors. The reduction in size, however, has the following important consequences: surface/volume ratio is drastically increased, so surface properties dominate and surface charges become very important, friction is greater than inertia, heat dissipation is greater

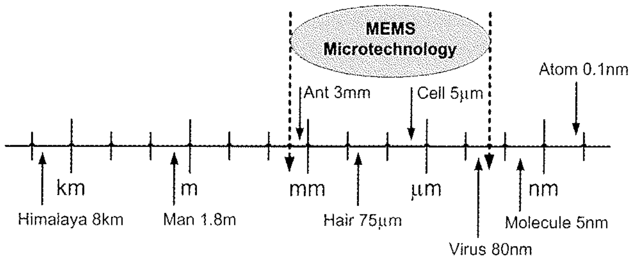


Fig. 10: MEMS technology element sizes

than heat storage, electrostatic force is greater than magnetic force and finally new phenomena negligible at macro-scale can be observed. To be able to design and produce reliable MEMS sensors it is essential to model the device and technology as good as possible and to control the MEMS process as good as possible. Thorough testing is also part of successful production.

During production of MEMS structures, several critical issues may corrupt the performances of the sensor. Two of the most damaging are: Stiction (Figure 11) and surface stress (Figure 12).

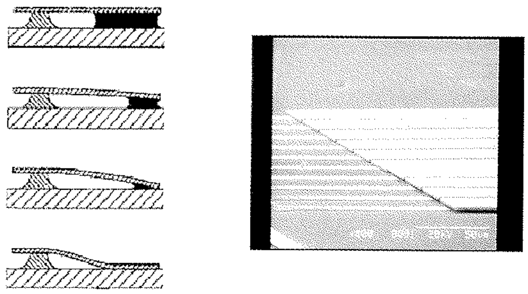


Fig. 11: Critical Issue: Stiction

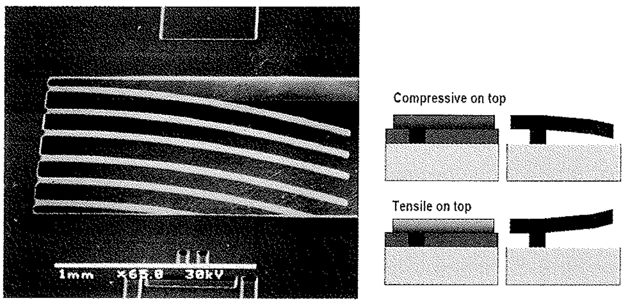


Fig. 12: Critical Issue: Surface stress

Stiction is caused by different mechanisms. The consequences for accelerometer and gyro sensors are disastrous since sensors with short circuits do not operate correctly. It is therefore important that we remove the possibility of stiction by appropriate etching and/or release techniques or by using anti-stiction coating of the structure and/or pulsed laser post-processing.

Another critical problem is surface stress, which causes bending of mechanical structures in an unwanted direction. The consequence is again disastrous for the operation of MEMS inertial sensors: it is especially dangerous for gyro sensors, where surface stress may cause prohibitively high quad-bias. It may become several orders of magnitude bigger than the bias signal and may saturate the measurement channel. It is very important to prevent surface stress during processing by choice of appropriate materials, appropriate device design, annealing after process steps and customized deposition and etching processes.

7 Electrostatics in MEMS

In MEMS, electrostatic force is bigger than magnetic force. In addition, sensing capacitance can be more accurate than sensing magnetic field or resistance because of noise. If we place inertial sensors in a vacuum, then Brownian motion of the air or gas does not define the resolution limit of the sensor any longer: the noise generated in the first stages of analogue signal-processing electronics dictates the resolution limit. Electrostatic force can be used for actuation and capacitance as a measure of mechanical displacement. Two different shapes of capacitances are possible in MEMS: plate capacitor (Figure 13) and comb capacitor (Figure 14).

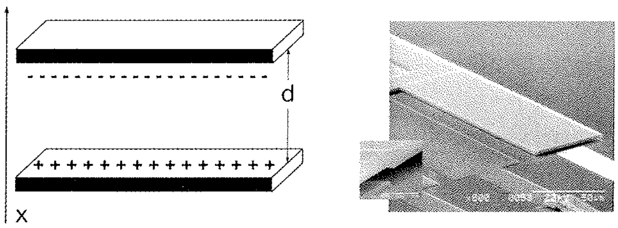


Fig. 13: Plate capacitor

Plate capacitance as a function of displacement x if we neglect fringe capacitance is (6.1).

$$C(x)=\frac{\varepsilon_r\,\varepsilon_0 A}{(d-x)}\cong C_0\left(1+\frac{x}{d}\right) \tag{6.1}$$

For small movements the relation is approx. linear. If one plate is anchored, the capacitance is a measure of a displacement assuming negligible fringe capacitance and no bending. If voltage V is connected between the plates, then the attractive force between the plates is (6.2)

$$F(x)=-\frac{\varepsilon_r\varepsilon_0 A}{2(d-x)^2}V^2 \tag{6.2}$$

We can see that the force is in quadratic relation to the applied voltage and inversely quadratic in displacement x. Only attraction force is possible. In addition, applying a sine wave signal to produce oscillatory movements causes a second harmonic component, which must be carefully considered. Electrostatic force can be used for driving and for electrostatic trimming.

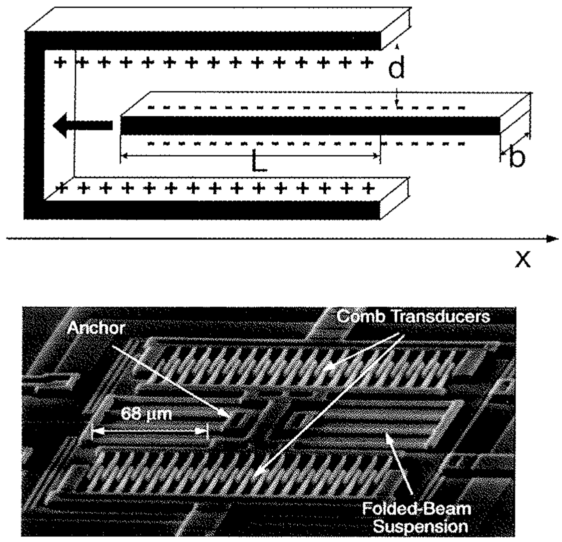


Fig. 14: Comb capacitor

For comb capacitors (Figure 14), the capacitance is proportional to the position x of the inner plate even for large displacement. Assuming that fringe capacitances are much smaller than comb capacitances than the capacitance as a function of x is (6.3):

$$C(x)=2\frac{\varepsilon_r\,\varepsilon_0 b}{d}(L-x) \tag{6.3}$$

Applying voltage V to the structure gives a force proportional to the square of the applied voltage (6.4): in this case, a force is linearly related to distance d and independent of the position L. Again, we tactically assumed no bending and no fringing field. In reality, this is not the case and fringing fields cause a different non-linear relation between position and capacitance, unwanted coupling between neighboring structures, and additional forces not covered by equations above, such as levitation effects, etc. Here we will not cover these effects in detail.

$$F(x)=-\frac{\varepsilon_r\,\varepsilon_0 b}{d}V^2 \tag{6.4}$$

Figure 15 shows the effect of ground plate capacitance: any voltage difference between moving structures and ground plates causes bending owing to the presence of electrostatic force, which changes the resonance frequency of the structure in z direction.

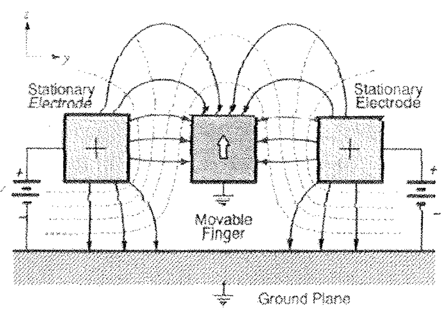


Fig. 15: Levitation effect owing to parasitic capacitance towards substrate

8 MEMS acceleration and gyro sensors

8.1 MEMS acceleration sensors

Many possible transduction mechanisms can be used for acceleration and gyro sensors and many were tested in the past: piezo-resistive, electromagnetic, piezoelectric, ferroelectric, optical, tunneling and capacitive. An extensive reference list of possibilities is given in /2/. Capacitive accelerometers are popular because it is relatively easy to measure very small capacitance changes. In addition, for carefully processed MEMS capacitors the actuation voltage is low, which is an additional advantage.

Lateral capacitive MEMS accelerometer is presented in Figure 16. In the presence of external acceleration, the support frame moves from its rest position; plate capacitance between proof mass and support frame changes. The sensor has good DC response, good noise performance, low drift, low temperature sensitivity, low power dissipation and relatively simple structure. Capacitive sensors are, however, sensitive to mechanical shock and vibrations and to electromagnetic fields so appropriate design and shielding are necessary.

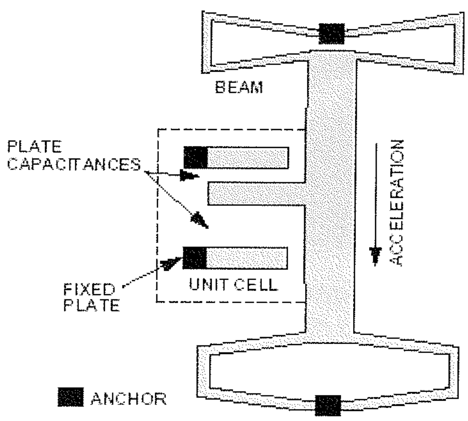


Fig. 16: Simplified view of lateral acceleration sensor under acceleration

The challenge is finding appropriate interface circuitry, where low noise and low drift readout/control circuitry with high sensitivity and large dynamic range are needed. Electronic readout/control circuit requirements for acceleration and gyro sensor systems are very similar, therefore, both are treated in subsection 9.1.

8.2 MEMS gyro sensor and its model

Almost all reported MEMS gyro sensors are vibratory type devices: in this case, no rotational elements are needed and miniaturization and batch fabrication are possible. The most important specifications are:

- Resolution: defined by the random noise of the sensor and electronic given in $\left[(°/s)/\sqrt{Hz}\right]$. In the absence of rotation, the output signal is random, composed of white noise and slowly varying function; the white noise part defines the resolution.
- Drift: peak-to-peak value of the slowly varying noise component defines short and long-term stability expressed in $[°/h]$.
- Scale factor: is defined as the amount of change in the output per unit change of rotation rate and is expressed in $\left[V/(°/s)\right]$.
- Bias: is zero rate output and is the output when there is no rotation; it is given in $[°/s]$. It can be digitally compensated if changes because of ageing and temperature drift are small.

A number of vibratory MEMS gyro sensors have been developed in the past: tuning fork, piezoelectric, gimbals-vibratory, etc. Usually, micro-machined gyro sensors rely on coupling of excited vibration mode into a secondary mode owing to Coriolis acceleration. The magnitude of secondary movement is proportional to input angular velocity and driving speed and is perpendicular to the primary motion, as suggested for the tuning fork gyro example shown in Figure 17. Driving could be electrostatic or electromagnetic and sensing could be electrostatic or piezoelectric. One such example is explained in /**13**/.

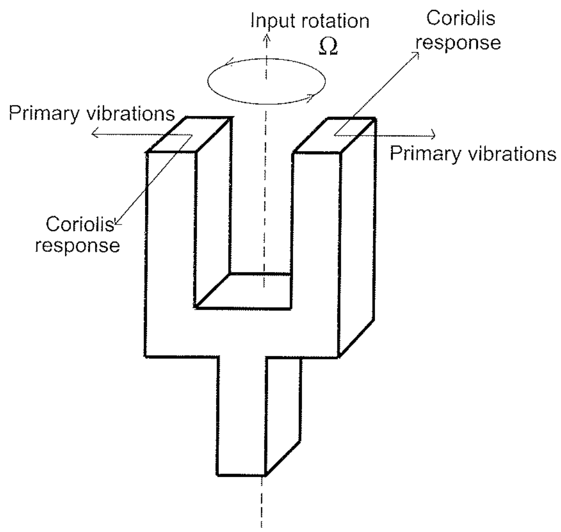


Fig. 17: Tuning fork gyro principle

Many other implementations have been demonstrated and their explanations are collected in /2/, for example, one from Samsung /14/ and one from Bosch /16/. The principle of operation of a gyro sensor presented in /14/ is suggested in the left part of Figure 18. If the mass M is suspended from the suspended frame and is vibrating in a vertical direction as suggested, then because of Coriolis acceleration the inner frame is vibrating perpendicular to the direction of the vibration of the mass M: this vibration is sensed by comb capacitors (sense fingers). Because of imperfections, part of the driving vibrations is transferred to the sense direction and produce output even without

Coriolis acceleration (ZRO). This transferred movement is in quadrature to the Coriolis movement: part of it can be removed by electrostatic trimming. Unfortunately, remaining quad-bias increases the demand for already high dynamic range in the measurement channel and produce cross-talk from driving to the sensing mode. In addition, mechanical shocks and vibrations can seriously corrupt the operation of such sensors and reduce their usefulness, especially in safety critical systems like automotive. Companies have improved robustness by using a fully differential sensor that reduces the influence of vibrations and shocks by order of magnitude.

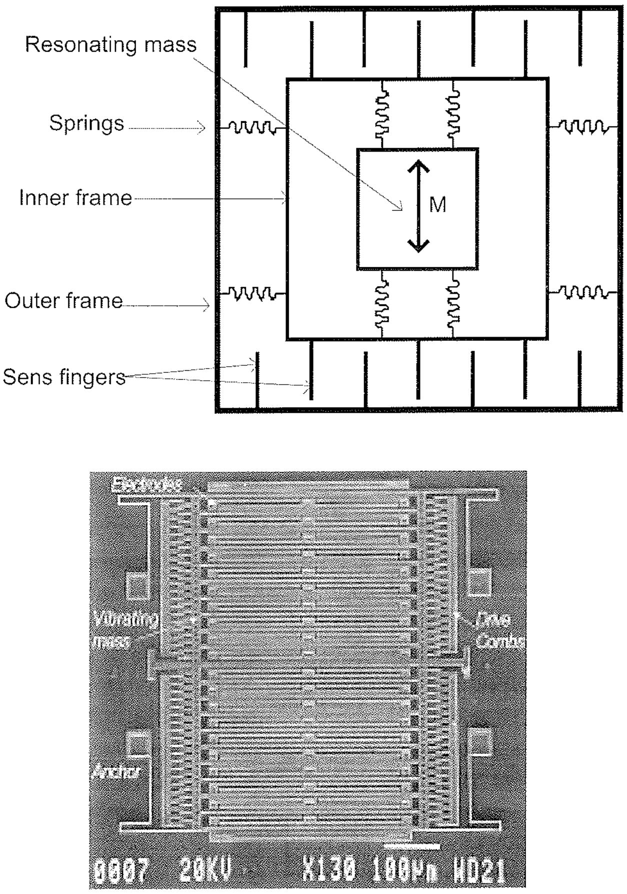


Fig. 18: Schematic presentation of Samsung gyro and its photomicrograph

Further improvements are possible by mechanical decoupling of drive and sense vibrating modes implemented in gyro sensors produced by Bosch /16/ (Figure 19) and further improved in other implementations (Figure 20). The operation of the sensor presented in Figure 20 is as follows.

Driving electrostatic force applied to blue comb capacitors causes the sensor to start oscillating around z-axis. Red comb capacitors sense the rotation of the sensor around z-axis. When no Coriolis acceleration is present, the sensor is ideally vibrating around z-axis with no displacements in z direction. Coriolis acceleration around y-axis causes the ring to start moving vertically: these movements are transferred to the plate capacitors through the springs that are stiff in z and y direction; Plate capacitance change is a measure of the Coriolis acceleration around y-axis.

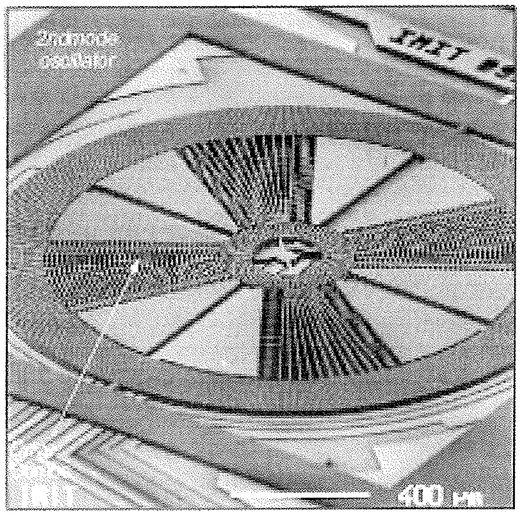


Fig. 19: x-axis vibratory gyroscope by Bosch

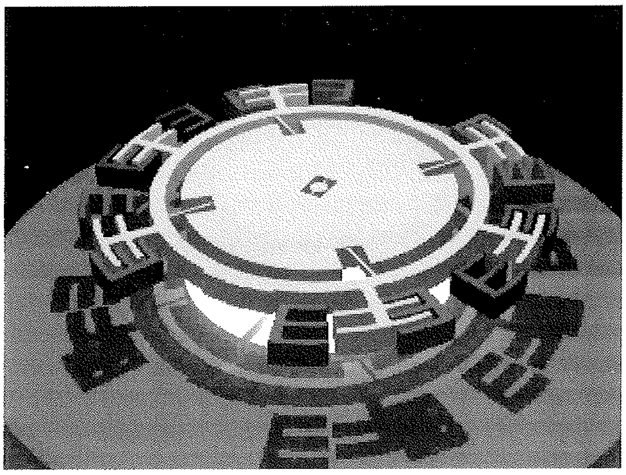


Fig. 20: Vibratory gyro with decoupled primary and secondary motion

Driving frequency must be precisely controlled using appropriately-tuned PLL, while amplitude of oscillation in the resonance is controlled by the AGC: the scale factor is proportional to the velocity of the drive mode and therefore to the amplitude; it is constrained by material, gaps between combs, reliability of operation, good S/N ratio, etc. The coupling from drive mode to the sense mode owing to Coriolis force is weak and must be amplified mechanically by operating in the resonance if possible. Drive and sense mode could be approximately described by 2^{nd} order transfer function modeling a mass-dumping-spring system, where the dominant dumping factor comes from the movement in the air. If proof mass is vibrating in a vacuum, then very high Q could be realized (several 10000) and if driving and sensing frequencies could be matched, the coupling would be amplified by the Q factor. Unfortunately, drive and sense resonance frequencies are different and it is almost impossible to match them precisely, even by using electrostatic trimming and electronic tuning, which is suggested in experimental implementation /**17**/. Here, reported performances are considerably better than any other MEMS gyro sensor reported up to now, as far as bias stability and noise floor are concerned. Mode matching causes higher sensitivity and greater scale factor, but the sensor becomes a very narrow band and sensitive to vibrations and shocks. A compromise between sensitivity, bandwidth and robustness is always necessary. Another concern is quad-bias signal: it happens because part of the driving movement is transferred to the sensing mode owing to imperfections in the mechanical structure; it corrupts the sensing channel. Fortunately, it is in quadrature with bias signal and it can be almost completely removed by appropriate signal-processing. Quad-bias signal could be orders of magnitude bigger than bias signal, so linearity and SnR requirements of the measurement channel are very demanding.

9 Electronic systems concepts and system integration

Electronics system concepts for accelerometers and gyro sensors are very similar. The gyro sensor, however, requires electronic with much better performances because of weaker signals, Most high performance MEMS gyro sensors operate in a vacuum to reduce the influence of Brownian motion of the molecules of the air and thus reduce the noise floor of the sensor. Consequently the noise floor for that kind of device is limited by the noise floor of the sensing channel of the ASIC and by analogue and digital signal-processing of driving and sensing signals. Simulation for efficient design of inertial system require accurate modeling of sensor and electronics.

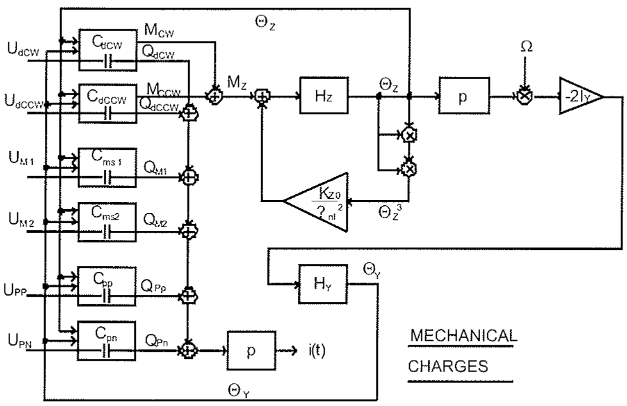


Fig. 21: Simplified model of a gyro sensor.

Figure 21 shows simplified coupled mechanical-electrical model of a gyro sensor. The sensor is driven in resonance by sine wave-like signals generated in the ASIC PLL: amplitude of oscillations is maintained by the use of AGC. Rotation of the sensor is sensed through measurement of capacitors C_{ms1} and C_{ms2} (Figure 23) using HF sensing voltages U_{M1} and U_{M1}. Sensing voltages U_{PN} and U_{PP} are used to sense plate capacitances. One plate of each capacitor of a sensor is connected to the common node and thus all charges from driving, motor sensing and plate capacitors are added together: to distinguish individual contributions, different sensing frequencies can be used.

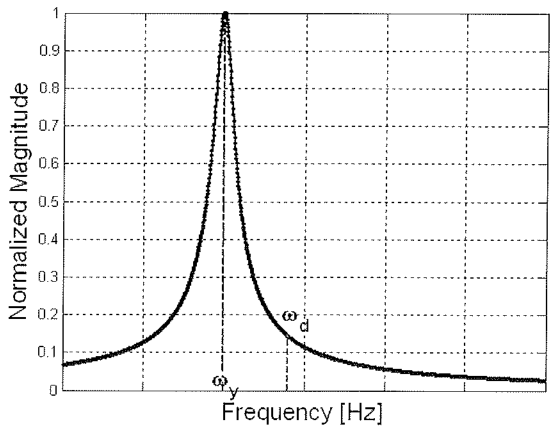


Fig. 22: Characteristics of Gyro sensor

Figure 22 shows resonance characteristics of a sensor. Sensing dynamics for constant rate can be described by (6.5). For matched modes, the highest sensitivity could be achieved but with very small bandwidth and very poor robustness against vibrations, while for mismatched modes the sensitivity is smaller but the bandwidth is bigger, and robustness is increased.

$$y + 2\xi\omega_y y + \omega_y^2 y = 2\Omega\omega_d x_o \sin(\omega_d t) \qquad (6.5)$$

A simplified electrical model of a sensor is presented in Figure 23.

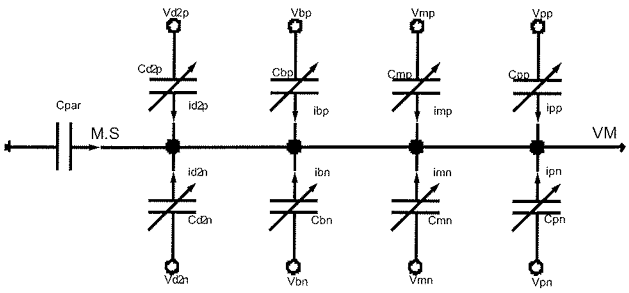


Fig. 23: Simplified electrical model of a sensor

Approximate capacitances for sensor presented in Figure 20 are given in (6.6):

$$\begin{aligned} C_{par} &\cong 5-10\,pF \\ C_{dx} &\cong 0.1\,pF \\ C_{mx} &\cong 0.2\,pF \\ C_{bx} &\cong\sim 0.05\ pF \\ C_{px} &\cong 2\,pF \\ \Delta C_p &\cong 0.05\,aF\ \left(\Omega = 0.1\ {}^o/s\right) \end{aligned} \qquad (6.6)$$

We can see that the biggest capacitor is parasitic capacitance C_{par}. Sensor capacitances are much smaller while changes owing to Coriolis acceleration are extremely small: electronics must resolve capacitance changes smaller than $0.05aF$ at angular speed of $\Omega = 0.1°/s$ in as big a bandwidth as possible, which requires the dynamic range of a measurement channel in a range of more that $150dB$.

9.1 Sensing electronics

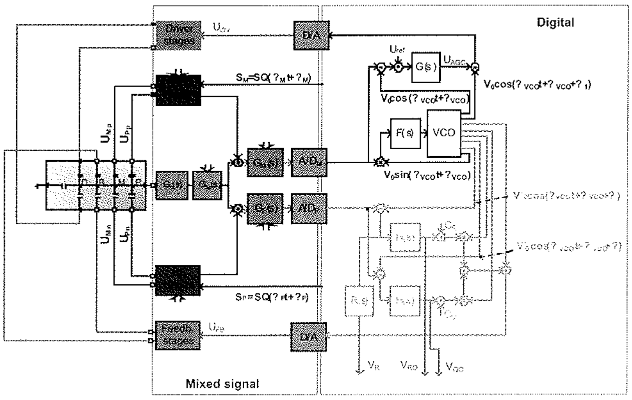


Fig. 24: Analogue and digital signal-processing block diagram

Figure 24 shows a block diagram of analogue and digital signal-processing needed to drive the sensor and sense all charges. Critical element regarding noise is charge amplifier $G_C(s)$, which transforms the spectrum of added HF and LF charges from the sensor into appropriate voltages. Since CMOS transistors are contaminated with 1/f noise this is one of the reasons for using HF sensing signals, as suggested in Figure 25. Sensing components must appear out of 1/f noise to be able to detect very small capacitor changes. A second reason for using high

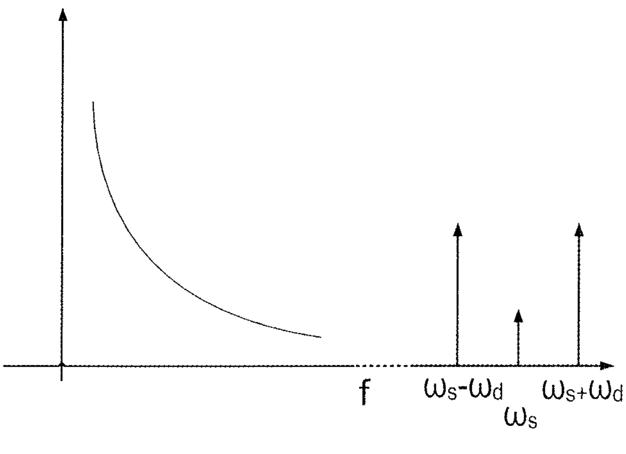


Fig. 25: HF sensing spectrum

sensing frequency is reduction of feedback "resistor" in the charge amplifier, which is needed to keep voltages around reference level and to provide appropriate low impedance virtual ground for the moving structure and common plate of sensors capacitors. Other noise sources of the ASIC may corrupt the measurement channel, so every possible noise source in a system must be carefully analyzed and optimized. The following noise sources were considered: charge amplifier thermal and 1/f noise, input referred noise of programmable gain stages and mixers, quantization and circuit noise of the A/D converters, 1/f and thermal noise of sensing and driving signals, quantization noise caused by different digital signal-processing algorithms, etc. In addition, cross-talk noise coming from on chip digital signal-processing blocks to the sensitive analogue channels were among the hardest problems to solve during the design of the MEMS inertial system.

10 Packaging

MEMS inertial sensors are mechanical elements, so it is very important to reduce any stress during production or during use, because mechanical stress can eventually change the behavior of sensitive mechanical structures. Wafer level packaging provides an appropriate level of vacuum for a sensor. The whole sensor is then placed in an open cavity package or into a plastic package together with the ASIC. Figure 26 shows the gyro sensor and ASIC in an over-molded plastic package. In this case, the main problems are related to mechanical stress because of different expansion coefficients of different materials.

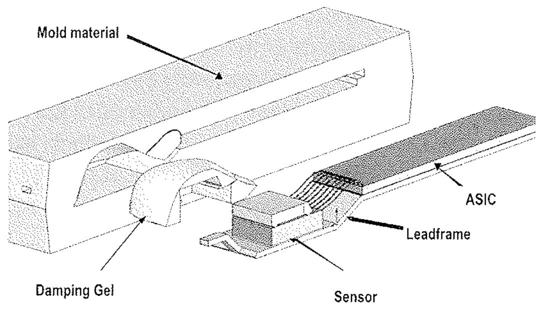


Fig. 26: Gyro sensor in plastic package

11 Calibration and test

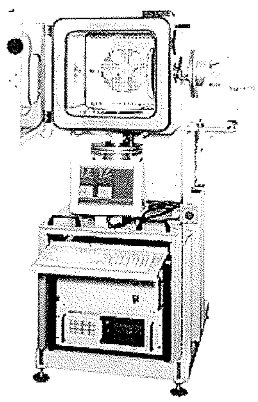


Fig. 27: Turning table in temperature chamber

For efficient production of MEMS inertial systems the calibration and the test are as important as all other activities. During production, every sensor-ASIC pair is carefully calibrated and tested at different temperatures using automated test equipment (Figure 27). Companies like SensorDynamics are working on new equipment for handling accelerated tests and calibration procedures.

12 Conclusions

An overview of MEMS-based inertial systems is presented in the article. The principles of operation of acceleration and gyro sensors have been presented, together with some historical background, followed by specification of important parameters for different applications. The technology driver for inertial systems is automotive industry, which requires reliable precise and cheap systems. MEMS technology is the most appropriate technology at the moment and provides batch-processing possibility like ASICs technology, which is the basis for price reduction. The final goal of integration, however, which has not yet been reached, is a six degrees of freedom inertial system with three accelerometers, three gyros and all signal-processing electronics integrated in a single package or even in a single chip. Basic technology steps needed for the implementation of MEMS inertial sensors are presented, together with possible problems and some basic structures for acceleration and gyro sensors.

The design of MEMS-based inertial systems requires careful modelling of sensor, electronics and package and optimization of inter-related parameters. In vacuum-packed sensors, the resolution is limited by noise of signal-processing electronics, so the HF sensing principle can be used. In addition, all possible noise sources must be carefully analyzed and optimized.

MEMS inertial systems need thorough testing of all electronic blocks and sensors. To meet all specifications in automotive temperature range extensive calibration at different temperatures is necessary.

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