Terrestrial Applications of a Nano-g Accelerometer

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Abstract:

The ultra-sensitive accelerometer, developed for NASA to monitor the microgravity environments of Space Shuttle, free orbitors and Space Station, needed to measure accelerations up to 10 mg with an absolute accuracy of 10 nano-g (10^{-8} g) for at least two orbits (10^{4} seconds) to resolve accelerations associated with orbital drag. Also, the accelerometers needed to have less than 10^{-9} F.S. off-axis sensitivity; to be thermally and magnetically inert; to be immune to quiescent shock, and to have an in-situ calibration capability.

Multi-axis compact seismometers designs that have twelve decades of dynamic range will be described. Density profilometers, precision gradiometers, gyros and vibration isolation designs and applications will be discussed. Finally, examples of transformations of the accelerometer into sensitive anemometers and imaging spectrometers will be presented.

NANO-G ACCELEROMETER

Under a NASA advanced technology development contract a nano-g accelerometer was developed in collaboration with Northeastern University[1,2]. The intended use of the accelerometer was the tri-axial measurement of orbital drag on the Shuttle and Space Station which required an acceleration range of 10^{-2}-10^{-8} G over a frequency range of 0.0001 - 25 Hertz.

Silicon micromachined devices reported by others have not achieved the necessary sensitivity. These devices have been based on either piezoresistive or capacitive position sensing elements. The resolution of accelerometers is directly proportional to the position detection capability and the square of the fundamental frequency of the mechanical structure. Our accelerometer design is motivated by the need for small size and high sensitivity. For a low mass system this dictates ultra sensitive position detection such as that of an electron tunneling tip with an extreme spatial resolution of less than $0.001 \text{Å}Hz^{0.5}$.

Three distinctively different dice are fabricated and subsequently assembled using a 'zero' thickness bonding technique. Hermetic sealing and electrical connections between the different dice are also accommodated during this bonding operation. The accelerometer is controlled by electrostatic force plates above and below the proof mass. The lower electrode has a dual role. In operation, it provides a necessary control electrode, and when not in operation, it is used to immobilize the proof mass to protect the flexures and particularly the tunneling tip.

The active element (proof mass) of the accelerometer can be electrostatically suspended at the null position in a gravitation field by electrostatic levitation. The voltage to accomplish this is a function of the acceleration imposed upon the proof mass. This results in the elimination of one of the most serious difficulties in static and dynamic earth calibrations of micro-g accelerometers. The same levitation feature permits the accelerometer to be nulled in a wide variety of conditions. The force actuation can provide an alternating excitation of the sensor to dynamically calibrate it over the frequency range of interest. In addition to both ground and in flight calibrations, this feature permits health monitoring, coefficient correction and sensor characterization over long term space flights.

A further important design issue for accurate tri-axial acceleration measurement is the minimization of off-axis sensitivity. This was accomplished by insuring that the proof mass and spring design was symmetric, weak in the compliant direction, and operated with the tunneling tip in close proximity to the unperturbed proof mass. As a consequence of a zero deflection flexure, thermal sensitivity is reduced. Thermal mismatched stress is also eliminated by fabricating the entire die out of mono-crystalline silicon and bonding these die together directly (i.e. no interface material). Figure 1 shows a not to scale cross section of the accelerometer indicating the important features of the four dice structure. The tip die (the top die in the figure) has an approximately 3.75 μm high tunneling tip at its center. Two identical proof mass dice are rotated by 180° and bonded together to form the 'proof mass'. The net weight of the proof mass is 0.18 gm which is held to the surrounding frame by a set of springs referred to as 'crab legs' and located in the exact center of the structure with the tunneling tip designed to just touch the unperturbed proof mass.

Figure 2 shows a portion of the top view of the proof mass and springs and Figure 3 shows a top view of the force plate die where the metal platen is covered with an oxide layer (0.5 μm) to prevent an electrical contact between the proof mass and the force plate when the proof mass is being electrostatically clamped. Figure 4 shows the tip die complete with access ports for external connection. Zero thickness referenced bonds are essential to maintain the tight spatial tolerancing and thermal insensitivity required of this accelerometer. The low temperature (< 400° C) eutectic bonding, sealing and inter-connection procedure was developed where etched channels were created in the bond regions on which a spreading layer of metal was deposited and patterned in the channels. Finally the bond metal was deposited and patterned on top of the spreading layers in such a way that it protruded above the wafer surface and was narrower than the spreading layer such that

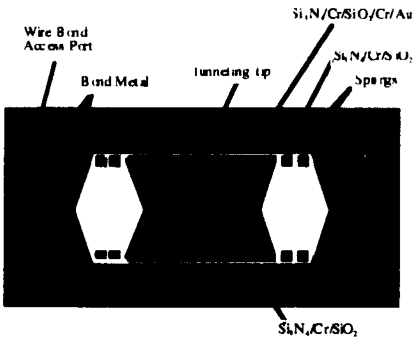

Fig. 1 Accelerometer Cross Section

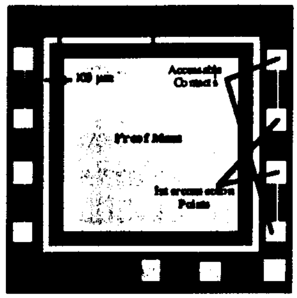

Fig. 2 Top View of Proof Mass

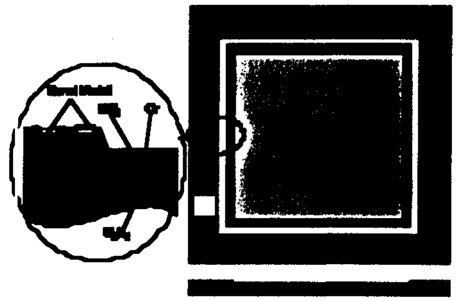

Fig. 3 Top View of Force Plate

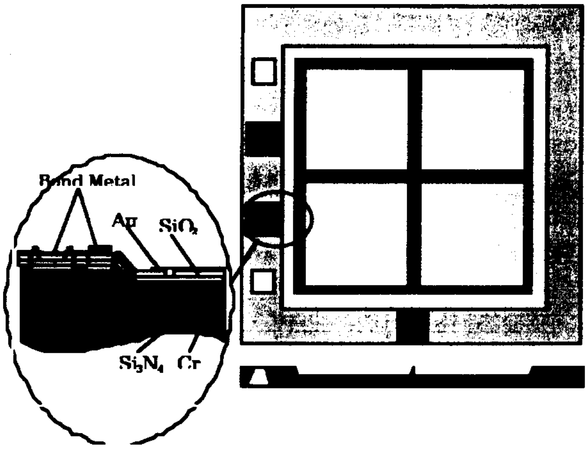

Figure 4 Tip-Plate Die

it's volume was less than the volume of the channel. When two dice prepared in this way are brought in contact and heated, the bond metal melts and spreads by wicking and capillary forces reducing the spacing between the wafer surfaces to zero.

The sensitivity of this sophisticated accelerometer was determined to be sub micro-G and superior to the best of the commercial micro-G accelerometers (QA3000). Thermal dependence was not discernible and stability and accuracy were below the noise floor of the test system and believed to meet it's design criteria of 10^{-2}-10^{-8} G over a frequency range of 0.0001 - 25 Hertz.

Aside from interest in the accelerometer by the international space faring community the largest market is in sensitive seismometery and geological density gradient survey applications particularly down deep bore holes.

MULTI-AXIS SEISMOMETER

The architecture of the accelerometer is such that large static or slowly varying accelerations can be electrostatically compensated allowing nano-g resolution in one-g fields (i.e. earth) with seven decades of dynamic range. The acceleration sensitivities of these micro-machined accelerometers are proof mass selectable. If accelerometers are designed to measure full-scale accelerations of one g and one Kilo-g, with accuracies of micro-g and mili-g respectively, their co-location provides an acceleration measuring instrument that spans nano-g to Kilo-g. An orthogonal triad of these three accelerometers (10^{-9}-10^{-3}g, 10^{-6}-10^{0}g and 10^{-3}-10^{3}g) would provide a three-axis seismometer with 12 decades of dynamic range.

If bonded to a silicon cube the accelerometers are thermally inert and their proof masses can be electrostatically levitated to null static fields (i.e. earth or planet gravity). A 'smart' three-axis accelerometer/seismometer is realized by the integration of an ultra precision voltage reference (temperature-controlled zener diode), precision DACs, and a three-decade overlap in accelerometer scalings.

Deployed as a terrestrial seismometer this single unit could replace the dual Streckeisen and low-g seismometers used for earthquake mapping. The extremely small size, thermal insensitivity, and robustness (electrostatic 'caging' protecting from shock loading and quiescent handling) makes these systems ideal sensors for use down bore holes and for planetary seismometry.

TOLERANT GRADIOMETER

NASA has an interest in an accurate (< 1 milligal) gravity field measuring instrument for deployment on the Shuttle, or a 'free flyer', to map the global earth gravity field. Such an instrument would enable geophysicists to understand plate dynamics, plumes and mantle structure and provide oceanographers with a precise geoid for determining ocean currents and other ocean phenomena.

The component micro-G accelerometers required for such a gradiometer are single axis devices that exhibit very low cross-coupled interference. The alignment of a cubic array of 81 such accelerometers to the gradiometer structure (arranged in 27 vector triads) will be a major activity, as will the empirical determination of each accelerometer's vector relative to the orthogonal axis of the gradiometer. While in principle only four such triads are sufficient, the extra measurement permit the removal of all the most serious errors - self gravity, gain, alignment mismatch, and vibration rectification. The instrument would consist of a solid cube of less than 10 cm dimension.

In space applications the main advantage of such a gradiometer, over existing designs, is its much greater tolerance for spacecraft shortcomings, including free propellants and other moving masses, and vibrations from articulated components. Thus, the spacecraft need not be designed around the gradiometer, and other payloads may be more easily accommodated. Also, the extra accelerometers mean that performance degrades quite gracefully should individual accelerometers fail.

It has long been known that gradiometers actually measure components of an "intrinsic tensor" - a combination of the gradient and various angular velocity and acceleration terms. The direct removal of these terms by practical gyros, or other attitude measurements, is not done to sufficient accuracy. However, dynamic estimation based on the rotational and translational equations of motion of the free floating gradiometer and the spacecraft attitude measurements greatly improve gradient estimation.

All accelerometers and gradiometers are subject to attraction of local masses and masses fixed in instrument coordinates generally cause an output bias that is indistinguishable from bias from other sources, and irrelevant for geophysical purposes. However, propellant motions, articulated objects, outer drag free motion, and thermal distortions may cause signals with power spectra similar to the earth or planetary gravity tensor signal. This is self-gravity which, except for propellant motions, are all measurable, and can be removed by calculation. In differencing gradiometers, accelerometer gain mismatch and input axis misalignment both yields errors proportional to the common acceleration. In the proposed instrument error calibration and the ensemble of accelerometers should greatly improve the detection and removal of these scale factor errors.

Vibration rectification results from compliance in the accelerometer mounting structure in a differencing gradiometer leading to a DC signal even if the vibration frequency lies outside the pass band of the accelerometers. However by including a three-dimensional model of the accelerometer mounting structure and redundant accelerometers (81 verses 27) a clear signature of the gradients is expected in spite of rectification.

VIBRATION SUPPRESSION

There are two dynamic means of mitigating disturbances that may be applied to microgravity payloads on board the Shuttle or Space Station. One means, an active isolation system, takes the approach that the platform to be isolated be allowed to "float" or "sway" to a certain extent within some sway space. Active Isolation uses dynamic control to improve its performance by deploying microgravity measuring accelerometers mounted on the isolated platform to calculate the necessary forces to be applied through a set of co-located actuators to cancel the forces that are transmitted to the isolated platform through the stiffness, damping, and frictional effects inherent in the coupling and umbilical cables. An adversarial effect of active isolation is that the motion of the isolated platform has a reciprocal and amplification effect on the motion of the host structure (i.e. will aggravate environment of neighbors). Also if multiple experiments are installed on a single isolated platform, servicing one experiment will disturb all the others.

Conversely a Vibration Suppression System (VSS) consists of a set of linear proof mass actuators mounted to a payload or structure that apply the forces required to cancel the effects of disturbances. Because the primary cause of large accelerations is the amplification of disturbances by the lightly damped structural modes of a Shuttle or Space Station, a system that produces forces that cancel the excitations due to disturbances effectively increases the damping of structural modes and significantly reduce the structure's response. A Vibration Suppression System does this by sensing the **(acceleration)** response at an optimized set of locations and driving momentum actuators (linear motors) to null the sensed response.

The advantages of this approach over active platform isolation are that the entire environment is improved throughout the structure, not just that of the platform. While the platform disturbances are attenuated the rest of the structure is too, through improved damping and reduction of settling time following transient disturbances and excitation of structural modes. VSS essentially mimics freestanding shock absorbers. Small VSSs could be placed at the extremities of flimsy panels (i.e.. solar panels) to attenuate transient disturbances and prevent the excitation of their structural modes. The mass of VSS could potentially be less than the mass savings represented by more flimsy panels. For microgravity experiments all disturbances above the sub-Hertz frequencies will be eliminated but not at the expense of a neighbor or contributing to the excitation of the hundreds of structural resonances of space vehicle.

While the microgravity experimenters would be the immediate beneficiaries of VSS it would be of global benefit when applied to large structures (terrestrial as well as in space) and potentially be a saving technology for Space Station Alpha.

DERIVATIVE MEMS

These two derivative devices utilize the zero thickness bonding, encapsulation, wiring, micro flexures and electrostatic caging technologies spawned by the nano-g accelerometer development. The electrostatic 'caging' innovation also spawned the concept for an electrostatic peristaltic pump, and inter wafer eutectic wiring spawned techniques for implementing ultra dense electronic circuit fabrication.

Active Optical Filter

The first derivative device under development is an active optical filter manufactured as an assembly of micromachined silica wafers. The wafers carry stationary and movable mirrors that form a reflective Fabry-Perot cavity. To make the device feasible the mirrors must be aligned and keep their alignment. The position of the mirrors has to be controlled and measured while the geometry of the filters must not change with time or the environment.

In the reflective Fabry-Perot interferometer the proof mass and spring flexures of the accelerometer are used as a mirror platform to maintain surface parallelism accurately and constrain the cross-axial location of the movable mirror to the sub-μm level. The accelerometer tunneling tip is removed from the center quad plate (Figure 4) and the metal platens are covered with a thin insulation layer to facilitate 'caging' of the mirror. A thin metal layer is deposited on the lower surface of an optically flat transparent substrate followed by a dielectric mirror coating. The quad plate die, two proof mass dice and thin spacing dice are bonded together to form the adjustable cavity. Figure 5 illustrates how the dielectric coated mirror is placed over this cavity to produce a reflection Fabry-Perot cavity with the facing surface of the movable mirror (proof mass). The electrostatic platens on either side of the 'proof mass' face electrostatic platens on the quad die and behind the dielectric mirror enabling monitoring and control of the spacing of the optical elements via capacitance measurement and force feedback through electrostatic actuators.

Such devices promise significant advantages in instrumentation for space astrophysics and quantitative imaging science in general and may become a major building block of the future optical imaging systems of microspacecraft, probes, and rovers.

One of the many potential applications of such a filter is to augment the Hubble Space Telescope (HST) advanced radial camera (WF/PC-III) spectral filter set. The use of ramp filters on WF/PC-II has demonstrated the advantages of "tunable" filers. Fast moving objects can create very large red shifts. It is nearly impossible to provide a set of fixed filters that would cover all eventualities. The proposed tunable filter can provide complete spectral coverage and simultaneous imaging that is not possible with ramp filters. This capability will enable WF/PC-III to operate as an imaging spectrophotometer. Another major advantage of a micro-machined tunable filter is the lack of blue shift degradation that affects fixed filters.

The Fabry-Perot based filter permits variable bandwidth, continuous tuning and a possibility of self-calibration. It offers low weight, low energy consumption and an extreme thermal stability. The device has numerous commercial applications particularly as a multi color filter for camcorders and digital cameras.

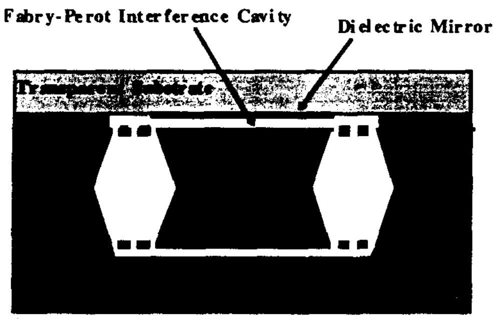

Figure 5 Fabry-Perot Filter Cross Section

Anemometer

The second derivative device under development is a sensitive anemometer for use on Mars to measure wind speeds of the low pressure CO_2 atmosphere. Here the proof mass of the accelerometer and its spring flexures are deployed not as a proof mass but as a large baffle plate that will be presented to the 'wind' and on which the pitot static force will apply.

The tipless quad platen is again used but with the center 50% of each of the quad plates removed. The anemometer is then fabricated out of two baffle plates (proof mass) and two perforated quad dice eutectically bonded together as illustrated in Figure6. Connections are then made to both baffle plates and each set of quad plates from both sides of the assembled unit.

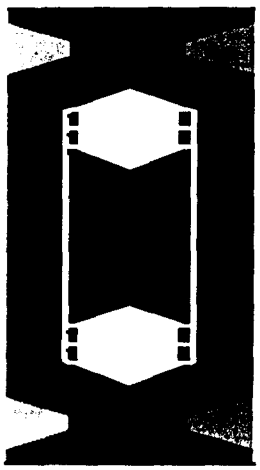

Fig 6 Cross Section of Anemometer {NTS}

During handling, launch etc., the baffle plate is clamped to either of the quad plates by means of a small battery. The separation capacitance's of each quad plate, with respect to its' facing baffle plate, is measured and applied, via a control algorithm, to hold the baffle stationary in the center of the cavity. When the baffle is mounted perpendicular to the gas flow vector of interest the pitot static force (pressure x aperture area) applied from either side of the anemometer is determined from the aggregate voltages on each set of quad plates.

The micromachined anemometer dimensions are less than 2 cm square and 2 mm thick, it does not need to be mounted in a tube and two (or three) of them mounted orthogonaly (60°) will provide wind velocity. A unit mounted horizontally would provide a measurement of vertical drafts. The bi-polar force balanced arrangement of this anemometer provides for a wide dynamic range (10^6) and a bandwidth from sub-Hertz to hundreds of Hertz. The zero flexure deflection design and electrostatic actuator control ensure the anemometer is athermal and the relatively large baffle plates (0.5 cm^2) and compliant suspension ensure high sensitivity.

The market for Martian anemometers would not be commercially compelling, however, the market for sensitive anemometers in industrial and domestic HVAC applications is large.

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