MEMS for Geophysicists

Jon Tessman, Bruce Reichert, Jim Marsh, Jeff Gannon, Howard Goldberg
Input / Output Inc., Stafford, Texas, USA

Summary

Input/Output, Inc. has developed a MEMS accelerometer to use as a seismic sensor for oil and gas exploration. Currently, moving coil inductive geophones are used as seismic sensors. Geophone design and performance have evolved for more than 50 years to the point that modern geophones are small, rugged, highly sensitive to motion, and produce minimal background noise. Achieving performance superior to a modern geophone with a MEMS accelerometer has been a significant technical challenge, but other benefits enabled by MEMS and accelerometer technology, such as direct digital output at the sensor, inherent high *vector fidelity*, and superior low-frequency response, justify the effort.

This paper provides a general overview of MEMS technology, describes Input/Output's MEMS fabrication facility and reviews the technical principals and challenges of the VectorSeis™ 3C MEMS accelerometer. This paper will address the following main points:

- What is MEMS technology?
- How does the Input/Output MEMS sensor work?
- How is the Input/Output MEMS sensor manufactured?
- What are the benefits of a MEMS sensor for seismic sensing?
- Analysis of field test data.

General MEMS Technology and Industry Overview

MEMS is an acronym for Micro Electro Mechanical Systems. MEMS are miniaturized mechanical devices that can be electronically sensed or actuated. MEMS devices can be mass produced at comparatively low cost with semiconductor-like manufacturing methods. MEMS devices are widely used today in automotive applications (i.e., airbag sensors and engine manifold pressure sensors) and computer components (e.g., inkjet printer nozzles, hard disk drive heads).

There is an important distinction between three different MEMS manufacturing processes:

- *Surface micro-machining* is an "additive" process that involves depositing several thin layers of different materials on a single side of a single-wafer substrate. These layers can be selectively etched to produce raised structures. Through the use of sacrificial layers, these layers are transformed into movable mechanical structures that are suspended above the substrate. The mechanical structures are typically made out of deposited polysilicon layers. Surface micro-machining is very similar to Complementary Metal-Oxide-Silicon (CMOS) processes used in IC production.

- *Bulk micro-machining* is a "subtractive" process that involves the removal of material to form holes, grooves, membranes, and complex 3D structures. The subtractive processes involve removing material from the substrate. The substrates are typically single-crystal silicon or glass/quartz materials. Bulk micro-machining processes can occur on both sides of single-wafer or bonded multiple-wafer substrates. Bulk micro-machining uses many unique process steps and has less in common with IC production than surface micro-machining.

- *Hybrid micromachining* is our definition for a process that involves using bulk micro-machining techniques on silicon-on-insulator (SOI) substrates to form surface micro-machined-like structures. The typical bulk micro-machining process used is dry silicon etching to form the mechanical structures. This technology is somewhat compatible with integrating MEMs and electronics on the same substrate.

MEMS technology is at least twenty years old. For years MEMS has been viewed as a promising technology that would provide the "interface" to the digital world and create an industry equal in magnitude to semiconductors. However, only recently has the commercial success of MEMS technology and products begun to be realized. Today, MEMS devices are enabling breakthrough products in new MEMS markets like telecommunications and biomedicine. In the first nine months of year 2000 more than $5 billion was spent by telecommunications equipment companies on acquisitions of MEMS related start-up companies. The 2004 MEMS market is forecast to grow to between $8 billion to $18 billion for the 1999 level of between $3 billion to $4 billion.

The Input/Output MEMS Sensor

The Input/Output MEMS sensor has two principal components, a bulk micro-machined, capacitive accelerometer, and a custom mixed-signal, closed-loop, force-feedback application specific integrated circuit (ASIC). Each component is subsequently described.

The MEMS sensor is composed of a moving inertial mass, the proof mass, suspended by springs from a surrounding frame structure. By manipulating the spring constants the resonant frequency of the sensor has been moved into the kilohertz range (out of the seismic band). Designed to operate below its resonant frequency, the sensor behaves as an accelerometer. Moving coil sensors (geophones) are also suspended mass systems but for mechanical reasons (size, weight, cost) they are designed to have their resonant frequency below the seismic band (ie. 10hz). A substantial amount of engineering effort has been put into tuning the sensitivity of the MEMS sensor to match the seismic industry's requirements (ie. 2.0×10^{-1} to 3.0×10^{-8} g ±1g static)

The upper and lower surfaces of the proof mass have metal deposited on them to create conductive surfaces. Upper and lower wafer caps also have deposited metal to create a variable capacitance between the proof mass and the cap wafers. The MEMS assembly is formed from four individual silicon wafers, each wafer etched to form component structures and then collectively bonded to form the final die assembly. Figure 1 shows a schematic of the MEMS accelerometer cross-section. Figure 2 is a photograph of a de-capped MEMS accelerometer die.

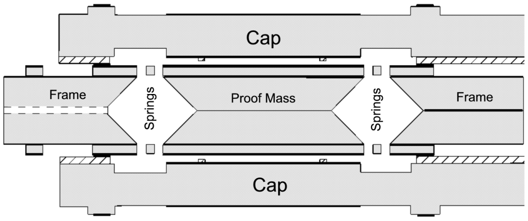

Figure 1. Cross-section of the MEMS accelerometer.

Figure 2. Photograph of the MEMS accelerometer die (without cap wafer).

Achieving the extremely low sensor noise performance required for seismic applications was a significant technical challenge. Two controllable parameters that have a major effect on inherent thermodynamic sensor noise include the mass of the proof mass (the smaller the mass, the greater the noise) and the damping of the resonant structure (greater damping results in greater noise). To fabricate the MEMS accelerometer bulk micromachining was chosen over surface micromachining for several reasons including ability to fabricate larger proof masses. To reduce the damping of the resonant structure the sensor die is packaged in a high vacuum to produce an evacuated internal cavity containing the proof mass.

Considerable engineering effort was involved in the MEMS spring design in order to achieve a desirable resonant frequency (nominally 1,000 Hz) while avoiding undesirable higher order vibrational modes, which contribute to noise and stability problems.

The MEMS accelerometer die is capable of being used as a stand-alone capacitive accelerometer, but to achieve the performance required for use as a seismic sensor necessitated the development of the custom mixed-signal ASIC.

The ASIC serves several important functions. First, the MEMS accelerometer is operated in a closed-loop, force feedback mode. As changes in capacitance are sensed by the ASIC, a restoring electrostatic force is applied to maintain the proof mass in a central (neutral) position. Second, the acceleration response, as measured by the feedback force, is digitized by an internal 5th order sigma-delta A/D converter. The output of the MEMS accelerometer is an oversampled (128 kHz) digital bitstream. The ASIC contains approximately 40,000 integrated transistors. Figure 3 is a photograph of the packaged ASIC.

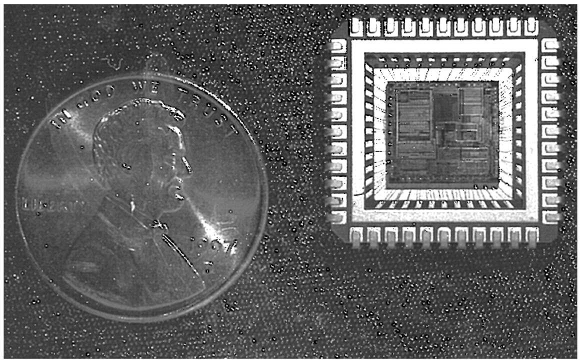

Figure 3. Photograph of the MEMS accelerometer ASIC.

Considerable systems integration modeling and analysis was required to optimize both the MEMS accelerometer and ASIC design parameters to achieve high performance and robust stability. Commercial third-party modeling and analysis tools were adequate for component design and capable of parametric systems design screening, but achieving optimum systems performance required developing custom simulation tools to understand higher order component response effects on overall systems performance. This effort alone was a considerable undertaking but has proven essential in refining the design and optimizing the system performance.

The Input / Output MEMS Manufacturing Facility

The MEMS accelerometer is being produced at Input / Output's state-of-the-art six inch wafer fabrication facility. This facility possesses MEMS process capabilities that are unique in a high-volume production environment, including: double-sided lithography; deep reactive ion etching; precision multiple wafer registration and bonding; wet etching to support bulk micro-machining; vacuum packaging.

A significant effort was put into optimizing the equipment automation and design, process design and sensor design to achieve the high yields and high-volume production capability required for this complex MEMS device.

The wafer fabrication processes are performed in a 6,500 square foot Class 100 clean room. MEMS accelerometer packaging and test processes are performed in a 3,000 square foot Class 100,000 clean room. Each packaged MEMS accelerometer die is tested before final assembly in the MEMS accelerometer package. Figure 4 shows the wafer fabrication clean room.

6,500 square foot Class 100 wafer fabrication clean room.

The ASIC is fabricated and packaged at a commercial, third-party CMOS foundry. ASICs are tested at Input / Output with a Teradyane A567 advanced mixed-signal IC tester before assembly in the MEMS accelerometer package.

Benefits of a MEMS Accelerometer for Seismic Sensing

The MEMS accelerometer has undergone extensive laboratory and field testing to validate its performance. Ambient sensor noise, dynamic range, harmonic distortion, and cross-axis rejection are all important performance characteristics for seismic applications.

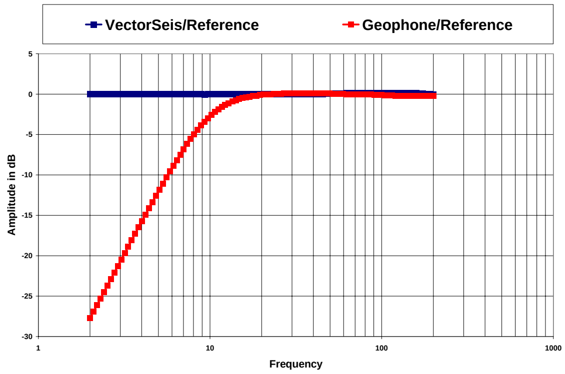

Figure 4. Frequency response of MEMS accelerometer and 10 hz. Geophone. The 2Hz low frequency restriction on the plot is due to limitations of the shake table used in the measurement.

Figure 4 is a plot of the amplitude spectra of the MEMS sensor and a critically dampened 10hz geophone. Both sensors have been normalized to a reference sensor. Note the customary roll-off associated with the geophone below its natural frequency. MEMS sensors do not exhibit this roll-off and in fact are linear to DC. The ability to preserve frequencies below 10Hz will greatly interest those geophysicists routinely working with seismic inversion. Tests have indicated that it is possible to maintain frequencies down to 3Hz on final migrated stack data using MEMS sensor technology.

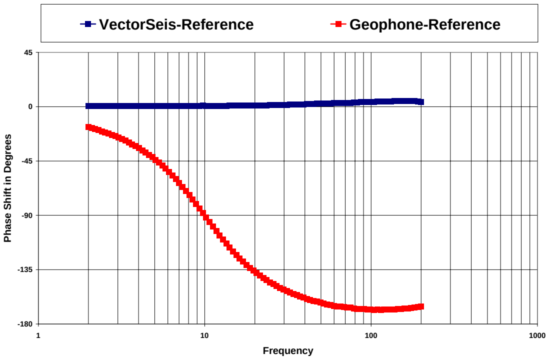

Figure 5. Phase response of MEMS accelerometer and 10 hz. Geophone. The 2Hz low frequency restriction on the plot is due to limitations of the shake table used in the measurement.

Figure 5 is a plot of the Figure 4 data in the phase domain. Note the characteristic 180° phase change associated with the geophone data. Again, the MEMS sensor does not exhibit the same response but has only 6° of deviation at 200hz. Stable phase response will result in better deconvolution performance in the processing of MEMS data.

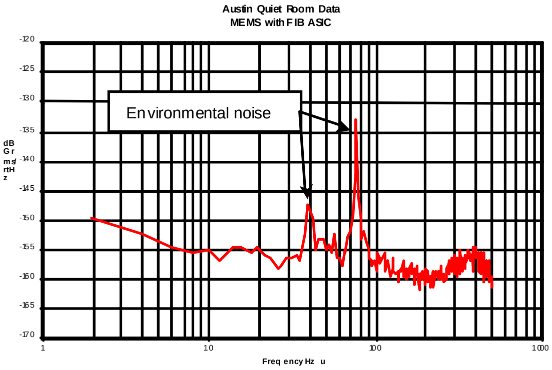

Figure 6. MEMS accelerometer noise floor.

Figure 6 is a plot of the ambient sensor noise, recorded in an isolated quiet chamber. The sensor maintains a noise floor of less than –150 dBg^2/√Hz (less than 30 nano-g) throughout the seismic frequency range, nominally 3 Hz to 200 Hz. Rotating machinery within the area of the quiet chamber causes the two spikes that appear in the plot. The maximum sensor input (before A/D saturation) is nominally 0.2 g peak, providing a dynamic range exceeding 115 dB.

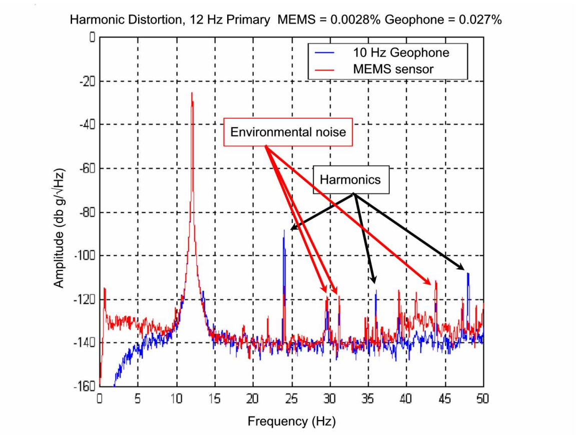

Figure 7. MEMS accelerometer vs. geophone: Harmonic distortion.

Figure 7 shows the frequency response to a 12Hz sine wave input signal. The total harmonic distortion in the seismic frequency range is less than 0.0028%. Distortion within the vibration table limits the distortion measurements. Analysis predicts a total harmonic distortion of 0.0001%

Vector Fidelity

"Multicomponent data are said to have vector fidelity if a unit impulse, directionally aligned with a given component yields the same impulse response function on that as for the same impulse directed along any other component, and zero response on all other components"

- Leon Thomsen, BP Upstream Technology

Input / Output has set a goal of measuring true earth motion ± 1% using MEMS technology. This goal implies a vector fidelity of 40dB. A number of sensor and manufacturing parameters determine the overall vector fidelity of a multicomponent system. The following play a key role in achieving the goal of 40dB vector fidelity;

Precision vibration table measurement have established the MEMS accelerometer itself has cross-axis rejection exceeding –60 dB.

Internal orthoganality of the sensors mounting during manufacturing of VectorSeis™ is nominally 0.3°.

Variation in component to component sensitivity is 0.3% after factory calibration.

total angular error in the measurement system cannot exceed 0.57° (1% cross-axis noise = $\sin^{-1}$ (0.01)). This applies to both tilt (θ) and azimuth (ϕ).

It is the final requirement that proves to be the biggest challenge during field operations. Under normal circumstances this would imply that we need to measure the orientation (ϕ) and the verticality (θ) in the field within a 0.6° accuracy. The MEMS based sensor offers an alternative method of addressing the vertical orientation (VOR) issue.

Since the sensor can measure acceleration to DC, it is possible to determine the true gravity vector by analyzing the magnitude of G each sensor is operating under. The results of this analysis are stored with the trace data as direction cosines and describe the tensor rotation required to recover the signals as if the sensor were deployed at true vertical orientation. Application of VOR is done in the processing center before any other processes. Azimuthal alignment (ϕ) within this requirement can be achieved using a variety of commercial instrumentation with little or no impact on crew operations.

Field Tests & Results

During the month of August 2000, two field tests were conducted in eastern Alberta. At these sites, a small number of MEMS VectorSeis™ sensors (1st and 2nd generation sensors with differing noise floors) were co-located with both conventional geophone arrays (6 elements over 20m) and a single conventional 3C geophone (four sensor types total). The resultant data underwent identical processing flows in an attempt to produce comparable datasets to evaluate sensor performance.

This processing effort resulted in a total of 7 unique datasets for each survey. Four compressional (P-P) and three converted wave (P-S) volumes. Selected lines will be analyzed (P-P & P-S) for differences in the data that may be accounted for due to the inherent properties of MEMS based 3C sensor technology.

The discussion will conclude with a comparison of actual maps produced from both a conventional 3C geophone dataset and MEMS based datasets. These examples are drawn from the first commercial project acquired with VectorSeis™. Here the tangible effects of vector fidelity can be demonstrated along with the benefits of multicomponent interpretation.

Acknowledgements

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