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MEMS-based Accelerometers - The Quest for Low Frequencies and Weak Signals

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SUMMARY

Accelerometers based on a Micro Electro Mechanical System (MEMS) deliver accurate and linear measurements of the ground motion over a large bandwidth (0-800Hz). Such performance has been obtained by using a closed-loop function that minimizes the displacement of a tiny inertial mass to a few nanometers. To improve the signal-to-noise towards the very low frequencies at which the instrument noise increases, a new MEMS has been developed - it provides a significantly lower noise floor (at least -10dB) and thus a higher dynamic range (+10dB). This performance has been tested in a silo that previously housed nuclear missiles and displays high acoustic shielding. This new MEMS sensor will even further ease the detection of low frequencies and of weak signals like those coming from deep targets or from micro-seismic events.

Introduction

In the search for oil and gas in frontier areas, seismic reflection is used to explore deep and complex targets. Successful imaging requires ray paths regularly distributed up to long offsets within a wide range of directions. This is achieved using Single Sensors Single Source (S^4) High Density (HD) Wide AZimuth acquisition (WAZ). In parallel definition of an accurate velocity model requires the preservation of an adequate signal-to-noise ratio at the low frequencies. Accelerometers based on a Micro Electro Mechanical System (MEMS) have been developed to fulfill these requirements both from an operational and geophysical point of view. MEMS sensors are easily integrated with the electronics. A receiver point may consist of a single device (e.g. the Digital Sensor Unit, DSU) the weight of which being about half that of a single geophone connected to a digitizer. This obviously eases the deployment of a large number of channels as required by S^4 HD-3D. For recording, MEMS sensitivity to external perturbations (e.g. temperature & EM pickup) is one order of magnitude less than seen in geophones: MEMS delivers a digital signal only within very tight specifications. In particular, MEMS response to a constant acceleration varying in frequency is constant from DC (0Hz) to 1kHz, both in phase and in amplitude which is optimal to capture low frequencies.

However, the instrument noise of MEMS accelerometers increases significantly towards the lowest frequencies (< 5Hz) and it may become apparent while recording in a very quiet environment. This limitation to record a weak signal may be compensated by a denser spatial sampling, but this would require using a significant amount of MEMS accelerometers. A more obvious but more challenging solution is to decrease the noise floor. This is what has been achieved recently as describe hereafter.

Architecture of a MEMS accelerometer

The sensing part of a MEMS accelerometer is based on the same principle as a coil geophone: it is an inertial mass with a set of springs. One difference is that the mass is a tiny piece of silicon which is 10^4 smaller than the suspended mass in the geophone (1mg instead of 10g). In the DSU MEMS, this mass is surrounded by several combs of very thin electrodes (Figure 1) which are interleaved with the corresponding combs of the frame in order to create a capacitor. The typical gap between every finger of the mass and of the frame is a few micro-meters. Any capacitance variation related to a relative motion of the inertial mass with respect to the frame will be detected and compensated for immediately in order to keep the displacement very small. Combs of electrodes are distributed in different compartments each ensuring a different function (Figure 1): two are to compensate for the ground motion (seismic); another is to compensate for the gravity (tilt & offset correction), and the last for the auto-tests (gain & distortion). Each compartment comprises at least a pair of combs for the upward and downward motions. At each end of the MEMS axis, two springs enable a motion of the mass that is only of a few nanometers compared to millimeters in the geophone.

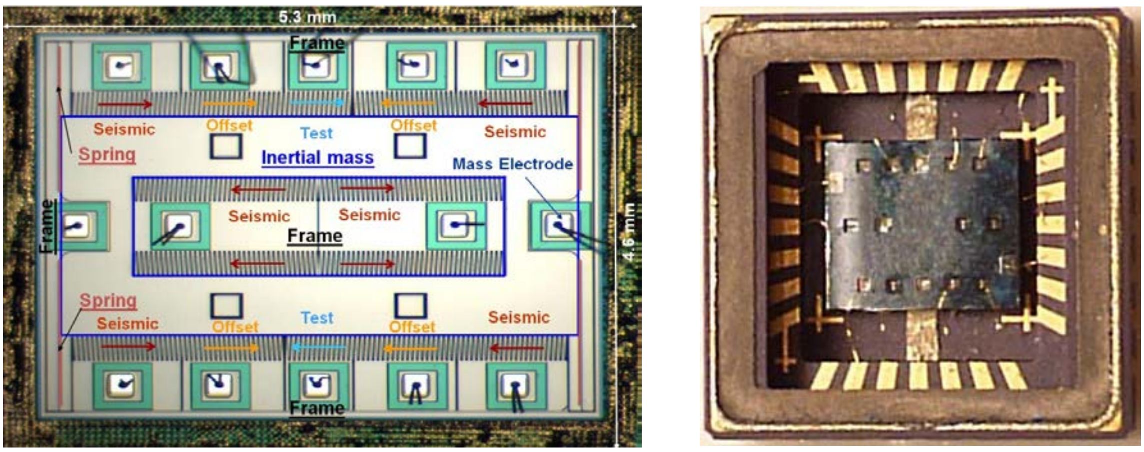

***Figure 1** DSU MEMS architecture as seen by microscope (left) and MEMS in its open ceramic case used to maintain a strong vacuum (right).*

The frame-inertial mass assembly is directly engraved on a large silicon plate (the wafer) from which hundreds of MEMS are manufactured simultaneously. Each one is encapsulated within a ceramic case to be able to maintain a strong vacuum between the electrodes. Such vacuum is mandatory to reduce the Brownian Motion noise which results from the impact of any remaining gaseous molecules against the mass. In addition, all the manufacturing process must be performed in a very clean environment to avoid any microscopic dust to be inserted between the electrodes.

MEMS closed-loop functioning

To develop a capacitance MEMS with a flat response over a larger bandwidth (typical 0-800Hz) while keeping a high sensitivity and a low noise floor, a closed-loop configuration has to be selected. By minimizing displacements the non-linearity of the spring-mass assembly has no effect on the output signal. What matters is the feedback force measured by the electronics which behavior is not frequency dependent at least up to 1kHz. This electrostatic force is based on the activations of two sets of electrodes (for upward & downward motions; Figure 1) by a reference voltage coming from an Application Specific Integrated Circuit (ASIC) the MEMS companion electronics.

The ASIC also manages the offset actuator that is able to compensate for gravity to preserve the performance of the sensor whatever its tilt. As a result, the MEMS accelerometer is omni-tilt, but it is a directional sensor that only measures the projection of the ground motion along its axis. This directivity results from the 80dB ratio between the sensitivity in the MEMS axis versus that in the cross-axis. In case of a 3C assembly of MEMS, the tilt is accurately detected by the two horizontal components with respect to the gravity vector. Since the full wavefield has been captured the measurements can be compensated for tilt in order to get the data that would have been obtained if the sensor had been planted vertically. With respect to a reflected ray emerging vertically, this ensures an optimal separation between the PP and the converted PS wave.

MEMS noise floor attenuation

The DSU MEMS of the current recording system (428XL) has a noise floor (40ng/sqrtHz from 10 to 200Hz) that has been set to be lower than the ambient noise in most of the surveyed areas. However, this noise increases towards the low frequencies, particularly below 5Hz where it may exceed ambient noise. Below 55Hz, it becomes higher than that of a single geophone connected to a digitizer (Figure 2, left). This difference increases if a higher gain is applied by the digitizer or if a higher sensitivity is obtained by connecting geophones in series. Even if processing data recorded from closely spaced MEMS accelerometers was able to mitigate this gap, it became important to put the MEMS noise floor at a level similar to that of the geophone, particularly for low frequencies and weak reflections recording. For that, significant changes in the MEMS and associated ASIC were required.

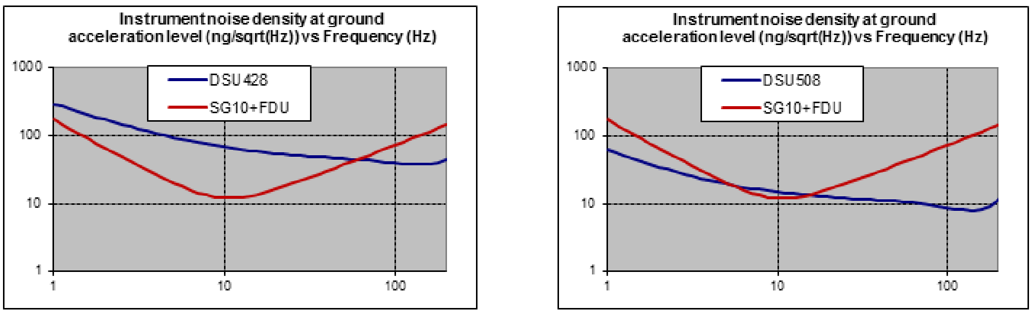

Figure 2 *Comparison in acceleration of the noise floor from different sensors: DSU MEMS 428 (left) & 508 (right) vs. a SG-10 geophone connected to a Field Digital Unit (FDU).*

The MEMS accelerometer in closed loop configuration is subject to five sources of noise. To reach the target specification (10-12ng/sqrtHz) for a new generation of MEMS accelerometers it has been necessary to work on all sources of noise to preserve the best noise-to-power consumption ratio:

- (N1) the Brownian noise related to the MEMS sensor. Increasing the level of vacuum reduces it;
- (N2) the electronics noise related to the readout of the mass position. A new architecture of the ASIC lowers it;
- (N3) the jitter which affects the edges of the voltage pulses applied to the sets of electrodes. Each sensor has now its own clock generator to reduce it;
- (N4) the electronics noise in the voltage reference used by the feedback actuator. Each ASIC has its own very low noise reference and uses a new architecture to generate the pulses;
- (N5) the aliased noise related to the parasitic modes of the mass which are excited by the quantization noise of the Sigma-Delta loop. This noise has been reduced by about 20dB.

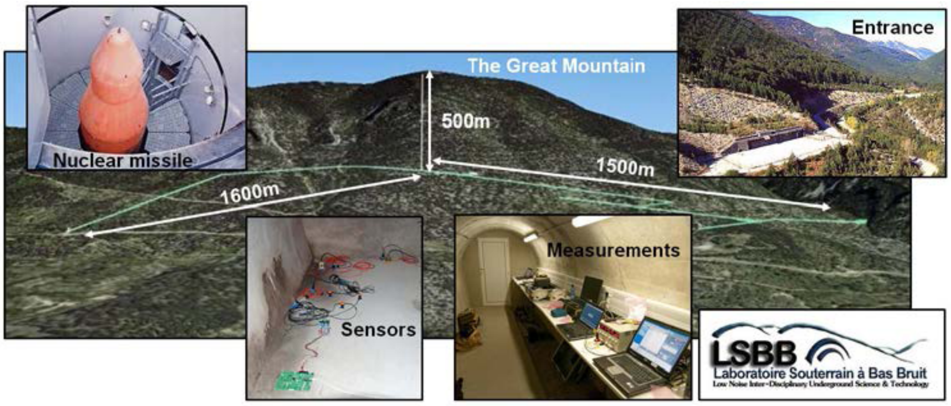

Figure 3 *The LSBB underground facility, that previously housed nuclear missile, where very low noise measurements are made possible thanks to its high acoustic shielding.*

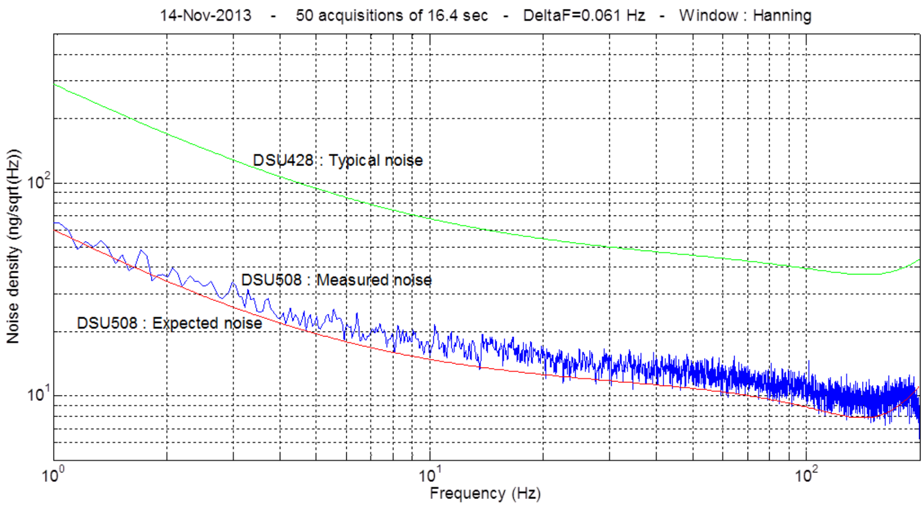

Figure 4 *Noise floor comparison of the vertical MEMS of the DSU-428 & -508: up to -12dB (/4) improvement is noticed in a large frequency range including the lowest frequencies.*

Noise floor measurement

To verify the noise floor of the new generation MEMS (DSU-508), testing necessitated the use of a very quiet area to enable the measurement of such low levels of noise. The facility selected is located in the South of France, in a missile silo that was decommissioned in 1997 to be used for scientific measurements requiring great isolation. The core facility of the "Laboratoire Souterrain à Bas Bruit" (LSBB an i-DUST lab) is buried down 500m depth below a mountain in a rural area far from industrial activity, roads and railways (Figure 3). The extremely weak anthropic impact as well as the thermic isolation and the acoustic shielding allow reaching a threshold of noise close to the minimum terrestrial noise (0.4ng/sqrtHz from 1 to 100Hz; Peterson NLNM model).

Measurements were done on both a vertical (Figure 4) and horizontal MEMS accelerometer. From 1Hz to 1kHz they show a good fit between the expected noise floor and the actual one. From 60ng/sqrtHz at 1Hz noise reaches 20ng/sqrtHz at 6Hz and is below 10ng/sqrtHz at 70Hz. The performance is even better on the horizontal component that does not require gravity compensation. From 30ng/sqrtHz at 1Hz noise reaches 20ng/sqrtHz at 3Hz and is below 10ng/sqrtHz at 70Hz. In both cases the gap with the typical instrument noise of the previous generation MEMS (DSU-428) is of -10 to -12dB. If we compare the new noise floor with that of a single geophone connected to a digitizer for most frequencies, except around 10Hz, it is lower (Figure 2, right).

Interests of low noise floor MEMS for seismic acquisition

Though its noise floor has been significantly lowered, the full scale of the new MEMS is still identical to the previous one (0.5g) and it is constant in the acceleration domain. The total dynamic range of the MEMS accelerometer is the ratio of the RMS values of this full scale over the noise floor. In the 10-100Hz frequency range corresponding to a 4ms sampling rate, the amount of noise is about 100ng and the dynamic range reaches 131dB. With respect to the dynamic range of the previous DSU-428 MEMS (120dB @4ms) this is a significant improvement. In desert areas and for the lowest frequencies, the noise floor may be the limiting factor to record weak signals because it gets higher than the ambient noise. In such conditions, a 10dB (/sqrt10) drop corresponds to an improvement of the signal-to-noise that would have been only obtained with the previous MEMS by using ten times more recording channels or by increasing by ten the sweep length!

When the instrument noise is above the ambient noise, the number of weaker signals that may be identified are significantly reduced. Assuming that this noise has a Gaussian distribution, the vertical component of the new DSU will be able to detect a non-coherent signal (e.g. a micro-seismic event) that is more than three times lower amplitude than with the previous DSU. In a bandwidth of 100Hz, the magnitude in acceleration of a non-coherent events of three times the RMS noise that is detected with a probability of 99.7% would be: - for DSU-508: 12ng*sqrt(100)*3 = 360ng;
- for DSU-428: 40ng*sqrt(100)*3 = 1200ng.

In the case of a coherent signal detection like for that of a vibrator, we can get from the new MEMS the same signal-to-instrument noise ratio using a stack order or a sweep length ten times lower.

Conclusions

MEMS accelerometers exhibit many favorable characteristics making them the sensor of choice for broadband Single Sensor Single Source High Density 3D. The previous generation MEMS sensors (DSU-428) provided many successful examples of projects in which the vertical resolution of the sections was increased thanks to broader band frequency content. However, at low frequency and for the deeper and weaker events, the improvement was not significant unless the survey was recorded with much higher trace density. Today, a new MEMS sensor generation (DSU-508) has been developed that displays a significantly lower noise floor (at least -10dB) and thus a higher dynamic range (+10dB). Considering that MEMS sensor response is linear in the acceleration domain down to DC, there should be no attenuation and sufficient signal-to noise ratio towards the low end of the spectrum. These are the ideal conditions to record the very low frequencies (down to 1Hz) as emitted by heavy vibrators using a low dwell sweep. This should fulfill the frequency requirement for the latest inversion methodologies (e.g. FWI). 3C MEMS accelerometers become also a sensor suited to the passive monitoring of the weak microseismic events like those generated by hydraulic fracturing.

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