MEMS Based Digital Geophones with Onboard Sigma Delta Modulator

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Summary

This paper presents an overview of the design & operating principles of Micro-Electro-Mechanical Systems (MEMS) Digital Geophones being introduced in seismic data acquisition.

Seismic reflection is a powerful technique for under ground exploration which depends upon on the existence of distinct and abrupt seismic velocity and /or mass density changes in the sub surface. The change in density or velocity is known as acoustic contrast. Ground motion can be measured as displacement, velocity, or acceleration. Conventional geophone is velocity sensitive which has limitation about frequency response, noise etc.

MEMS based accelerometer with onboard Sigma Delta Modulator can be used as digital geophones for seismic data acquisition. The advantages over conventional geophones are that digital geophones provide a direct digital output signal in the form of a pulse density modulated bit stream, broad bandwidth, less sensitive to planting tilt, 3 component seismic data acquisition from a single point geophone, etc.

Capacitive accelerometers which measure acceleration below their fundamental resonance can be thought as digital geophones with very high sensitivity, no DC output, no drift bias stability and lowest noise floor. Micromachined geophones can offer size and weight advantage over conventional geophones.

Introduction

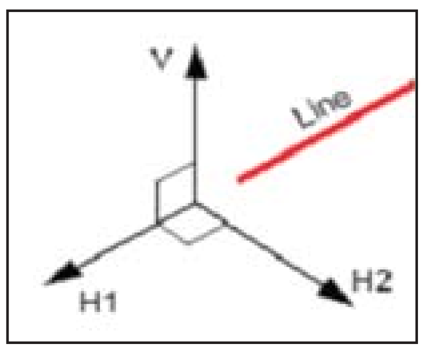
Exploring marginal oil fields is the challenging task & requires state of the art technology in exploration for seismic data acquisition. Geophones (Sensors) play an important role in acquiring quality seismic data .

Emerging technology, MEMS accelerometer with on board suitable electronics may be used as digital geophones in seismic exploration for oil & gas. MEMS digital geophones may provide low noise and dynamic range to be applicable to seismic data acquisition. Accelerometer, embedded with Sigma Delta Modulator (ÓÄM) have potential to provide broader bandwidth, and lesser sensitivity to planting tilt. This technology is likely to be introduced in oil industries for seismic exploration. This paper is intended to give an overview to those who have little background of accelerometer & sigma delta modulator. It would be easier to understand digital sensors if first understand the basics of conventional geophones, MEMS, Sigma delta converter, noise shaping , over sampling, quantization noise etc.The package also provides the facilities to extract the values of the elevation, static corrections and coordinate values from SPS data under the menu Data Extraction.

Conventional geophones (velocity sensitive)

Geophones are highly sensitive ground motion transducers that have been used for decades. In the electromagnetic geophone the magnet is coupled to the ground and for practical purposes moves with it, while the suspended coil tend to remain stationary.

The relative movement between the coil and the magnet causes a voltage to be generated across the windings of the coil. This voltage is proportional to the rate at which the coil cuts the magnetic flux, i.e. to its velocity with respect to the magnet. This is the reason the geophone is classified as velocity sensitive.



Conventional geophone is used for frequency (4Hz-400Hz) seismology experiments because its resolution degrades at low frequency. The poor low frequency (10 mHz-1Hz) performance arises because the output is proportional to the velocity of the proof mass.

The area of interest for getting digital output signal from the geophone & 3 component signal from a single geophone is not served from the conventional geophones.

Micro-Electro-Mechanical Systems (MEMS)

Micro-Electro-Mechanical Systems (MEMS) represent one of the fastest growing areas for miniature electronics. MEMS have a wide variety of applications, including environmental sensors, biomedical sensors, transducers , motion detectors etc.

The traditional MEMS depend on the function of many minute mechanical parts. Most MEMS currently require large number moving parts. Due to the extremely small size of these moving parts , the problems are associated with the mechanical parts , friction, damage etc.

The new micromachined technology has made possible to eliminate problems associated with the mechanical parts. The position of mechanical structure above surface of wafers enables sensors to move in all the three axis, x, y and z. Motion sensing is usually implemented with a differential capacitance structure which has the advantage that change in capacitance for given displacement is 1st order linear for small deflection, simplifying the signaling conditioning task. Differential plates may work as an actuator by causing a flexible structure to move back and forth. Thus motion can be sensed and induced. The ability to sense tiny changes in capacitance and onboard signal conditioning circuitry may reduce interference from the noise.

MEMS Accelerometer

Accelerometers are the stars of the MEMS devices with integral electronics that offer readout and self-test capability, and cost far less than accelerometers of decades ago. The type of MEMS accelerometers are capacitive, electromagnetic, piezoelectric, ferroelectric, optical, etc. The most successful types are based on capacitive transduction; the reasons are the simplicity of the sensor element itself, low power consumption, and good stability over temperature. Although many capacitive transducers have a nonlinear capacitance vs. displacement characteristic, feedback is commonly used to convert the signal to a linear output. The output can be analog, digital, or any of various types of pulse modulation. Sensors with digital output are convenient when the data is transmitted without further noise degradation.

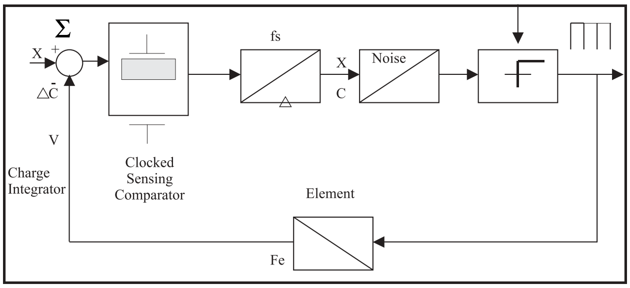


Fig. 1: Block diagram of an accelerometer embedded in a SD Modulator force feedback control loop

Micromachined inertial sensors are often incorporated in closed loop force feedback structures; a particularly advantageous approach is based upon the inclusion of the sensing element in a sigma-delta modulator (SDM) type control structure. The order of the SDM, and hence the noise shaping properties, is usually limited by the dynamics of the mechanical sensing element and may be insufficient for high performance applications.

A major design parameter for such an electro-mechanic ΣΔ Modulator is the signal to quantization noise ratio (SQNR). The quantization noise should be made small enough so that it does not limit detectable signal of the sensor. The SQNR is mainly determined by the transfer function of mechanical sensing element which can be approximated by a second order mass damper spring system and can be regarded as analogous to the cascaded electronic integrator commonly used in electronic ΣΔ Modulator A/D converter.

Since the damping of typical micromechanical sensing element can be very high (due to squeeze film effects), the equivalent DC gain of the integrator function is considerably lower than compared with electronic counterparts. This leads to a much lower SQNR for electromechanical ΣΔ Modulator compared with an electronic implementation.

Among the specifications to consider when choosing an accelerometer are bandwidth, noise, cross-axis sensitivity, drift, linearity, dynamic range, shock survivability, and power consumption. Resonant frequency is also important because the sensor's upper useful frequency range is usually some fraction of its resonant frequency, which also determines its sensitivity and displacement per g of acceleration.

$$d_g = \frac{Mg}{K_{sp}} = \frac{g}{\omega_o^2}$$

where

dg = displacement per g

M and Ksp = mass and spring constant of the device

g = 9.8 m/ s^2

ω_o = angular resonant frequency

the displacement of a sensing element is an essential part of the sensing process, and dg is the part of open loop gain of the sensor, so there tends to be a strong inverse relationship between sensitivity and band width for any class of sensors.

Noise

There are many contributors to noise in an accelerometer—the sensor itself, the readout electronics, mechanical damping, and all electrical resistances. MEMS sensors are so small that the Johnson noise of the devices' mechanical resistance must be considered, while it is usually ignored in larger sensors. Just as Brownian motion agitates bacteria and dust motes, it can be a large force on a tiny MEMS component. The Brownian force is

$$F_B = \sqrt{4kTD}\left(\frac{N}{\sqrt{\text{Hz}}}\right)$$

which causes Brownian motion of the proof mass, x_B:

$$x_B = \frac{\sqrt{4kTD}}{k_{sp} + j\omega D - \omega^2 M}\left(\frac{M}{\sqrt{\text{Hz}}}\right)$$

where:

D = damping coefficient of proof mass *M* supported by spring constant k_ω

Solving for the acceleration that generates the same motion, x_B, and substituting:

$$Q = \omega_0 M / D$$
$$\omega_0 = \sqrt{k_{sp} / M}$$
$$g = 9.8 \text{ m/s}^2$$

gives the Brownian equivalent acceleration noise in g/ Hz:

$$g_{n,B} = \frac{\sqrt{4kTD}}{Mg} = \frac{1}{g}\sqrt{\frac{4kT\omega_0}{MQ}}\left(\frac{g}{\sqrt{\text{Hz}}}\right)$$

From equation, we see that a large mass and a high Q (low damping) help achieve a low noise floor. To achieve a large mass in a micro machined sensor typically requires a wafer-thick proof mass carved out of the sensor chip. For absolute minimum noise, the damping constant must be reduced by suspending the proof mass in a vacuum from purely elastic springs. Feedback prevents the sensor from ringing at its resonant frequency.

Accelerometer embedded with ΣΔ modulator

Sigma Delta Modulator

The key feature of sigma delta modulators is that they provide high dynamic range and flexibility in converting low bandwidth input signals.

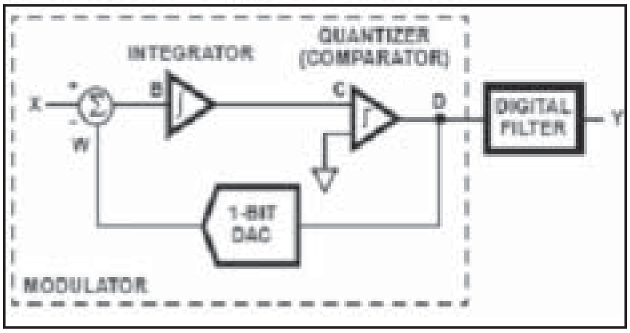


Fig. 2 : First order sigma delta ADC

The input signal X comes into the modulator via a summing junction. It then passes through the integrator which feeds a comparator that acts as a one-bit quantizer. The comparator output is fedback to the input summing junction via a one-bit digital-to analog converter (DAC), and it also passes through the digital filter and emerges at the output of the converter. The feedback loop forces the average of the signal W to be equal to the input signal X. A quick review of quantization noise theory and signal sampling theory will be useful before diving deeper into the sigma delta converter.

Signal sampling

The sampling theorem states that the sampling frequency of a signal must be at least twice the signal frequency in order to recover the sampled signal without distortion. When a signal is sampled its input spectrum is copied and mirrored at multiples of the sampling frequency fS. Figure 2A shows the spectrum of a sampled signal when the sampling frequency fS is less than twice the input signal frequency 2f0. The shaded area on the plot shows what is commonly referred to as aliasing which results when the sampling theorem is violated. Recovering a signal contaminated with aliasing results in a distorted output signal. Figure 2B shows the spectrum of an oversampled signal. The oversampling process puts the entire input bandwidth at less than fS/2 and avoids the aliasing trap.

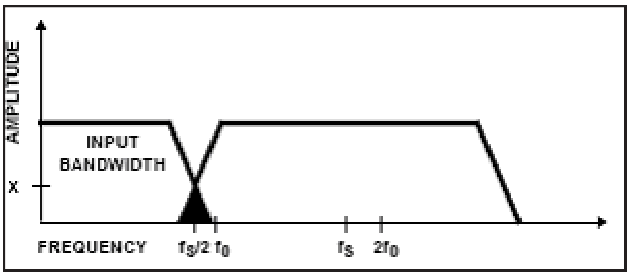


Fig. 2a : Undersampled signal spectrum

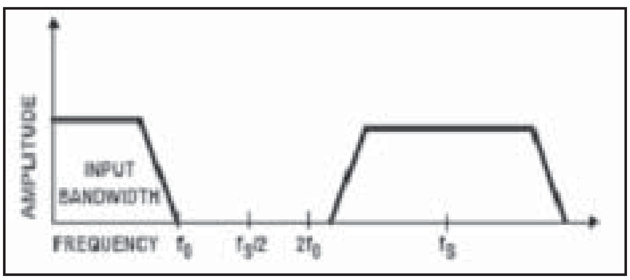


Fig. 2b : Oversampled signal spectrum

Quantization noise

Quantization noise (or quantization error) is one limiting factor for the dynamic range of an ADC. This error is actually the "round-off" error that occurs when an analog signal is quantized. For example, Figure 3 shows the output codes and corresponding input voltages for a 2-bit A/D converter with a 3V full scale value. The figure shows that input values of 0V, 1V, 2V, and 3V correspond to digital output codes of 00, 01, 10, and 11 respectively. If an input of 1.75V is applied to this converter, the resulting output code would be 10 which corresponds to a 2V input. The 0.25V error (2V - 1.75V) that occurs during the quantization process is called the quantization error. Assuming the quantization error is random, which is normally true, the quantization error can be treated as random or white noise. The quantization noise power and RMS quantization voltage for an A/D converter are given by the following equations

$$e^2_{RMS} = \frac{1}{q}\int_{-\frac{q}{2}}^{\frac{q}{2}} e^2 \, de = \frac{q^2}{12} \quad (V^2) \qquad \text{—— (i)}$$

$$e_{RMS} = \frac{q}{\sqrt{12}} \quad (V) \qquad \text{—— (ii)}$$

where q is the quantization interval or LSB size

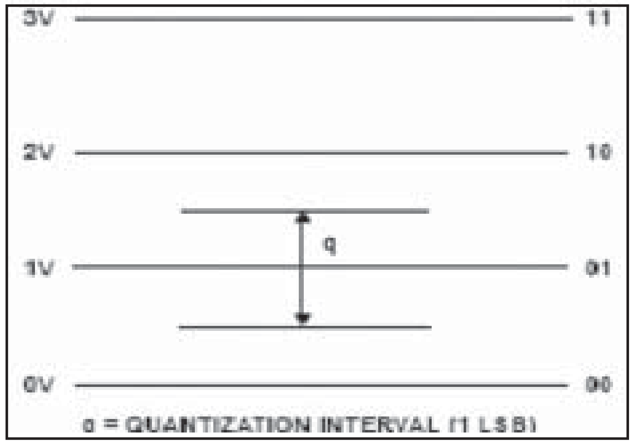


Fig. 3 : Code example of a 2 bit A/D converter

As an example, the RMS quantization noise for a 12-bit ADC with a 2.5V full scale value is 176µV. A quantized signal sampled at frequency fS has all of its noise power folded into the frequency band of $0 \le f \le fS/2$. Assuming once again that this noise is random, the spectral density of the noise is given by

$$E(f) = e_{RMS}\left(\frac{2}{f_S}\right)^{\frac{1}{2}} \quad \left(\frac{V}{\sqrt{Hz}}\right) \qquad \text{—— (iii)}$$

Converting this to noise power by squaring it and integrating over the bandwidth of interest (f0), we get the following result:

$$n_0^2 = e^2_{RMS}\left(\frac{2f_0}{f_S}\right) \quad (V^2)$$

$$n_0 = e_{RMS}\left(\frac{2f_0}{f_S}\right)^{\frac{1}{2}} \quad (V) \qquad \text{—— (iv)}$$

where n_0 is the in-band quantization noise, f0 is the input signal bandwidth, and fS is the sampling frequency. The quantity fS/2f0 is generally referred to as the oversampling ratio or OSR. It is important to note that equation (iv) above shows that oversampling reduces the in band quantization noise by the square root of the OSR.

Sigma Delta modulator quantization noise

The results of the above sampling and noise theory can now be used to show how a sigma delta modulator shapes quantization noise. Figure below shows the sampled data equivalent block diagram of a first order sigma delta modulator.

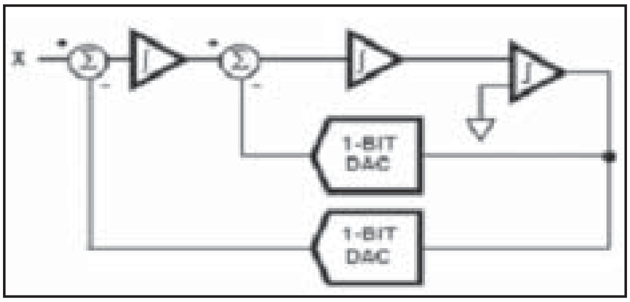


Fig. 4 : Second order sigma delta modulator

The sigma delta converter shapes the quantization noise. In the first order sigma delta converter if sampling frequency fs is increases by a factor 2, the in band noise shall be decreases by 9 dB. In the second order sigma delta converter, if fs is increases by a factor of 2 , the in band noise decreases by 15 dB.

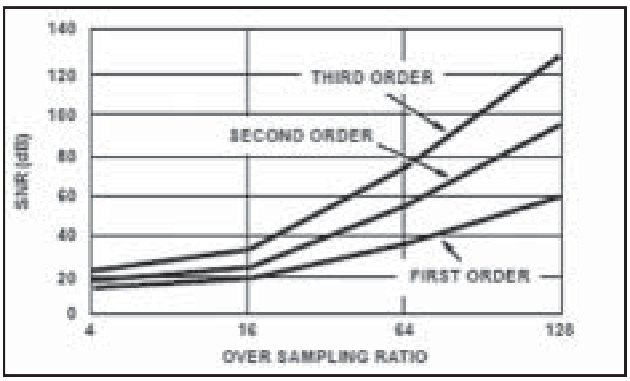


Fig. 5 : Shaping attribute of sigma delta modulator

The noise shaping attributes of the sigma delta modulator can be shown graphically as in Figure 5. Figure 5A shows the quantization noise spectrum of a typical Nyquist type converter and the theoretical SNR of such a converter. Figure 5B shows the effects of oversampling. fS/2 is much greater than 2f0 and the quantization noise is spread over a wider spectrum. The total quantization noise is still the same but the quantization noise in the bandwidth of interest is greatly reduced. Figure 5C illustrates the noise shaping of the oversampled sigma delta modulator. Again the total quantization noise of the converter is the same as in Figure 7A, but the in-band quantization noise is greatly reduced.

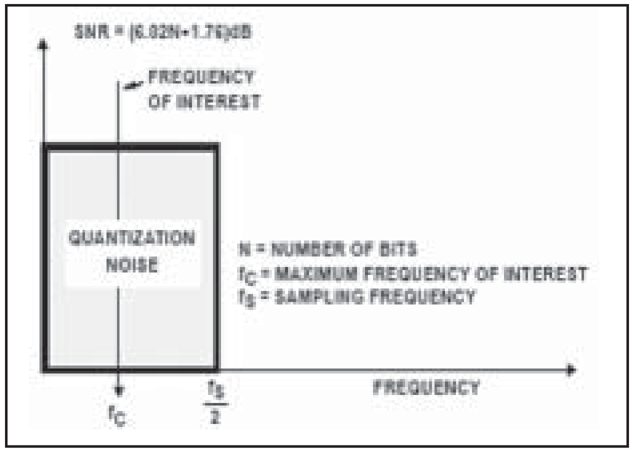


Fig. 5a : Nyquist converter quantization noise spectrum

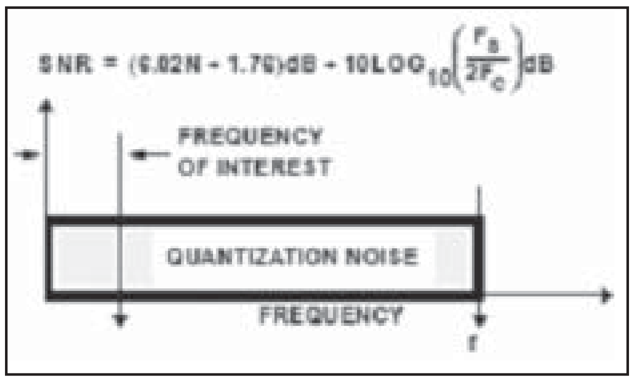


Fig. 5b : Oversampled converter quantization noise spectrum

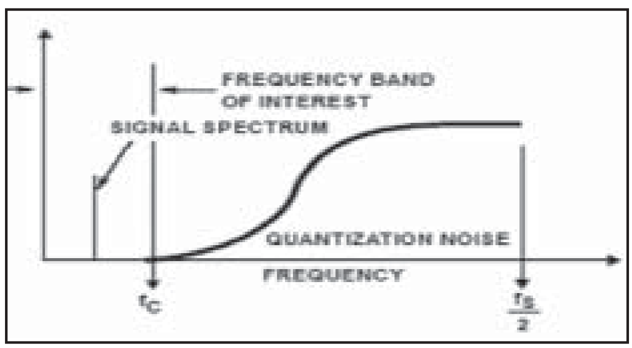


Fig. 5c : Oversampled 1st order sigma delta quantization noise spectrum

Accelerometer as digital geophones

Capacitive accelerometers, which measure acceleration below their fundamental resonance can be thought as Geophones with very high sensitivity and no DC out put requirement. With no drift of bias stability, geophones design can be optimized to give lowest noise floor. Micromachined sensors can offer size and weight advantages over conventional sensors as well asdigital output which is transmitted noise free.

To achieve the maximum sensitivity, the spring constants (and resonant frequency) are reduced so that the maximum acceleration is 0.2 g over a frequency range of 0–800 Hz. Minimum resolvable acceleration is $30ng/\sqrt{Hz}$ for a dynamic range of 115 dB. To avoid saturating the A/D converter, the device must be oriented such that the sensitive axis is horizontal. The noise floor of device is about 66 times lower than that of most "high-resolution" surface micro machined accelerometers.

A MEMS accelerometer is a tiny silicon chip for which size (~1 cm) and weight (< 1 gm) is much less than the ones of a coil based sensor (3 cm long & 76 gm cartridge). For some crews in the Middle East that handle 55 tons of geophone strings, this difference may be of importance!

The main advantage of MEMS accelerometers is their broadband linear phase & amplitude response that may extend from 0 (DC) to 800 Hz within 1 dB. With MEMS, low frequencies recording (< 10 Hz) are not prevented by the resonant frequency that is far above the seismic band pass (1 kHz). This makes it possible to record the Direct Current (DC) related to the gravity acceleration that provides a useful reference for sensitivity calibration and tilt measurement. Since acceleration increases with frequency (at constant velocity), accelerometers fit well with high frequency measurements. In this domain (> 40 Hz) also the electric noise of the MEMS is less than the one of the coiled geophone .

These broadband capabilities offer potential for a dramatic improvement in the vertical resolution of seismic data, which depends on the ratio 2n between the minimum and maximum frequencies (Fmax / Fmin = 2n, n being the number of octave). It is also particularly suited for recording low frequency signal (4-5 Hz) that is reflected at the main lithological contrasts between geological formations (interest for seismic inversion without log based initial model). The distortion in the acceleration domain is less with a MEMS (-90 dB) than with a geophone (-70 dB). Finally, if we consider the amplitude calibration of a point receiver and its stability over aging and temperature variations, the overall performance of a digital sensor, where MEMS are integrated with the station electronic in a single housing, is better than the one of a geophone that is connected to different station units during a survey.

Advantages of digital geophone

The benefits of MEMS technology in the development of digital geophone are,

- Direct digital output at the sensor
- Wide Bandwidth to resolve reservoir details
- High vector fidelity enable acquisition of data of unparalleled clarity
- Superior low and high frequency response
- Enable acquisition of cost effective multi component data
- Increased Operational efficiency
- Provides information about tilt against the vertical axis
- Achievement of in pact – 3C digital geophone in a single housing

A comparison of a typical * MEMS based digital geophone and conventional geophone

Sl. No	Parameter	* Digital Geophone	Conventional Geophone
1	Harmonic Distortion	0.0027 %	0.1 – 0.15 %
2	Vector Fidelity	46 dB	29 dB
3	50/ 60 Hz pick up	No	Yes
4	Analog Leakage	No	Yes
5	Amplitude Response	Flat	Lower response below fn
6	Phase response	Flat	± 90º centred on fn
7	Frequency Response	0 -500 Hz	10 - 240 Hz
8	Tilt Limits	None	± 10º

* Typical parameters of I/O make VectorSeis ™ geophone (courtesy: Published Technical literature).

Conclusion

The micromachined technology is reliable and scalable and has potential to add into the data quality in seismic exploration.

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Views expressed in this paper are that of the author(s) only and may not necessarily be of ONGC.

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