"MEMS based seismic and vibration sensors in Building & Structural Health Monitoring systems"

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Abstract

Structural Health Monitoring systems are increasingly being installed throughout the world most especially in areas vulnerable to high levels of seismic activity but also within large structures subject to sub-surface landslip, mining, or externally induced stress and vibration. Strong Motion seismic sensor technology is evolving in respond to these emerging demands with traditional Electromechanical FBAs being increasingly displaced by more cost effective, more robust Micro-electromechanical (MEMS) based sensors. Barriers to accelerating the rate of adoption of SHM systems are varied but include product marketing, the ability to offer a true value proposition, improvements in value for money dominated by cost of wired installations, validation of system reliability, and more simply user friendly interfaces to end users. Sensor costs are seen as a cost limiting factor but low power consumption, higher quality sensors remain as the key challenge today. This paper summarises the world from the point of view of manufacturers of MEMS based seismic sensors, looking upwards into the diverse number of market applications, end user demands, assessing what generic products and trends have emerged to-date and summarising a view of why MEMS technologies could dominate in the coming years. Most importantly many of these capabilities exist today in Europe and are not just the futuristic visions of some large global Corporation

Keywords: MEMS, Sensors, Seismic, Strong Motion

1. Market structure and application drivers

For those working day-to-day in the fields of Building and Structural Health Monitoring (SHM) the diverse structure of the market applications, the international, national, and regional standards are relatively well known. However for someone designing and manufacturing seismic sensors for this and other applications it is difficult to understand the nuances of many of the applications, the minefield of differing standards and relatively conservative attitudes towards adopting new technology that exists in many places today.

Seismic sensors have been implemented for well over half a century and most prevalently as geophones in Oil/Gas Seismic imaging used extensively today for Oil/Gas discovery and more recently Oil/Gas reservoir monitoring. Driving forces in this market sector have driven many of the key MEMS based technical developments in recent years, driving forward 'Full Wave' systems using both P and S wave sensing to allow both deeper and finer resolution imaging of key sub-surface lithology.

In parallel MEMS accelerometers have become major players in multi-media and automotive applications driving forward significant improvements in volume low cost manufacture and high product operational reliability.

The growth of SHM systems in many regions of the world is driven by both the costly repair / insurance of unquantifiable 'subjective' ageing of many nations' large structures such as dams, bridges, high-rise building, and the increasing pressure on many governments to provide effective civil intervention/protection and control system post major earthquake and as seen quite recently for example in Haiti, Chile and Southern China. It has been reported that earthquakes are responsible for some 60% of all deaths caused by natural disasters.

The proliferation of sensors purported to be used in the latest generation systems has drawn the attention of many of the world's sensor technology suppliers and specifically MEMS manufacturers who are forever looking for new major applications for their new products.

Countering this market pull are several barriers to the increased adoption of SHM systems. Firstly, at the end user level, SHM systems are sold independently of many other Building Monitoring and Security systems. Building owners are confused as to the added value of such systems and have difficulty to understand how they add value independently of the other Building/Security systems, already a pre-requisite in many cases for new buildings.

Secondly, many questions arise in relation to 'value for money'. The total cost of the system is still predominantly driven by cost of installation in part due to conservative attitudes in retaining fixed wire systems. Technically there are many challenges to solve including the need to optimise wireless sensor placement to ensure required levels of connectivity, data synchronization [1][2] and the challenge to provide useable information to a system operator and not just technical data. Governmental regulation demanding such systems clearly helps in this regard but awareness needs to be increased amongst the building owners and insurance community if the systems can truly sell on a true stand alone basis.

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1.1. Sensors within SHM

A relatively narrow family of sensors are currently deployed within SHM systems namely velocity (broadband and strong motion), strong motion acceleration, tilt, strain, positional/displacement, curvature and corrosion. These sensors must comply with a host of national and regional standards often historically driven by their wide adoption in Geotechnical and Geophysical research.

Systems suppliers have also traditionally tended to be masters of sensor integration, and in many cases suppliers also of sensors themselves. Access to key sensor technology has often been a differentiating factor in their success as system providers.

With the emergence and increasing adoption of MEMs based Strong Motion sensors these traditional relationships are being revisited.

1.1.1. Sensor Standards

Many nations have guarded there own standards in regard to Building Codes and specifically standards for sensors used within Structural Health Monitoring systems. Whilst for example sensor specifications vary from place to place and form application to application, a sensor supplier is seeking to establish standard products thereby allowing the market and themselves to benefit from scalability and access to maximal 'Total Available Market'. To this extent sensor suppliers are driven to adopting the most challenging of parameters within a specification as the new 'standard'. The advantage of establishing international standards is clearly the ability to provide higher volume 'standard' products at low cost.

The variety of markets where seismic sensors in their various forms are supplied to date is shown in Fig 1, differentiating between the legacy Geoscientific and Civil Protection markets, the dominant Energy markets and the emerging SHM and Civil Engineering markets.

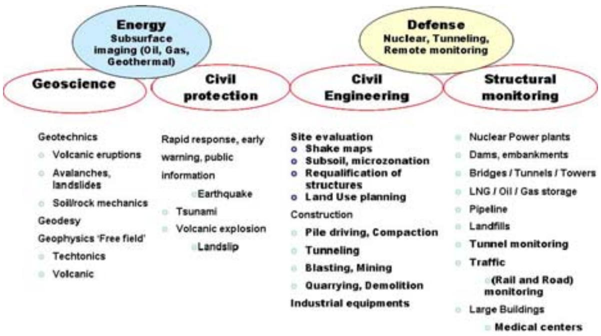

Fig 1 Markets and applications for Seismic sensors

As a starting point for Strong Motion Sensors the USGS and ANSS standards (13 June 2007)[1] and the State of California standards [2] are commonly seen as representative of driving forward the latest technology requirements. They are not however all embracing and each national and regional standard needs to be tracked in the context of new systems architectures, data storage protocols and communication standards.

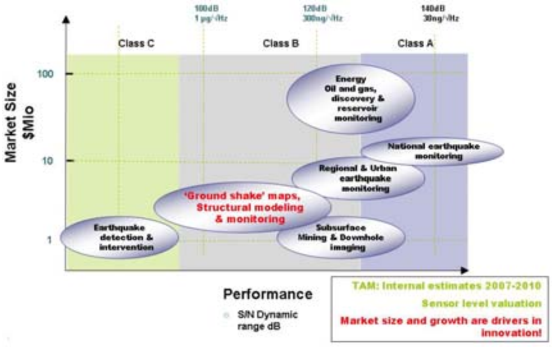

Fig 2 Estimated strong motion seismic market size depending on application.

2. Strong Motion accelerometers

2.1. Classifications

Strong Motion accelerometers are sub-classified into grades Class A, B, C and D. The specifications of Class A and Class B sensors are summarised in the USGS & ANSS documents [3][4]

The key parameters differentiating performance in the differing categories are Full Scale g range; dynamic range/noise levels across key frequency bands; linearity and power consumption.

Class C sensors are most commonly fulfilled today by a range of open loop capacitive MEMs based sensors deriving their functional performance from developments in the automotive and more recently multi-media applications, benefiting consequentially from good reliability, low power consumption and lower cost. Noise performance limits / signal resolution constrains their use to acting largely as ambient noise sensors; applications where ambient noise levels are relatively high; providing rapid earthquake *event detection* and subsequent early warning *protection* such as to switch down infrastructure e.g. elevators, gas and electricity supply; or to act as 'wake up' sensors for power sensitive sensor systems.

Class B sensors are today extensively used in Structural Health & Building Monitoring applications giving high level (>18bit) signal resolution in frequency 0.02-100Hz. The high dynamic range is required as comparative pre and post event data is required so as to accurately and safely *monitor* relative changes / damage to the structure. Demand for Full Scale g ranges have progressively increased to ±5g reflecting actual recorded levels of 3 to 4g in buildings from amplification throughout the building (Fig.3).

Fig. 3 Amplified signal from floor to roof

Linearity levels are targeted at approximately 1% at Full Scale. Traditionally these sensors have been supplied by Force Balance Accelerometers (FBAs) based on servo loop large electromechanical structures. In the past decade servo loop 'closed loop' Micro-electromechanical (MEMS) sensors have come to be adopted as a preferred technology offering lower cost, higher robustness, small size and lower power consumption. However battery powered systems are still often required especially when 'energy harvesting' is not practicable driving an increasing demand for reduced sensor power consumption

Class A sensors are characterised in particular by their very high signal resolution (20-24bit) and high dynamic range and in particular at very low frequencies. They are most typically used throughout the Geoscientific and Civil Protection applications but with relatively low uptake to date in SHM due to high power consumption, excessively low dynamic range and above all their significantly higher cost.

2.2. Sensor supply benchmarking

Depending on sensor classification of number of global competitors exist today. Amongst the Class C Strong Motion sensor suppliers several 'open loop' MEMS suppliers have emerged including several 'automotive/consumer' vendors - including but not limited to VTI, ADI, ST – and a variety of specialist vendors such as MSI, Colibrys each offering a trade-off of performance and price. Hewlett Packard has also recently announced its intention to enter into this market but no specific data or commercial products have as yet been announced.

Class B sensors suppliers are as of today relatively few. Colibrys offers both the SF2006 and SF1500 sensors. SDI offers a capacitive based metal MEMS sensor; Endevco offers a piezo-sensor. Not forgetting derated FBAs from Kinemetrics as an example. All products are differentiated largely by g-range, dynamic range/noise (Fig 4), power consumption, linearity – see spider graph comparative performance Fig 5.

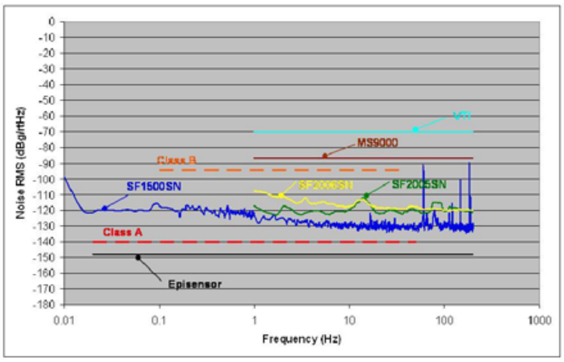

Fig 4. Dynamic range specifications for Class A/B/C sensors

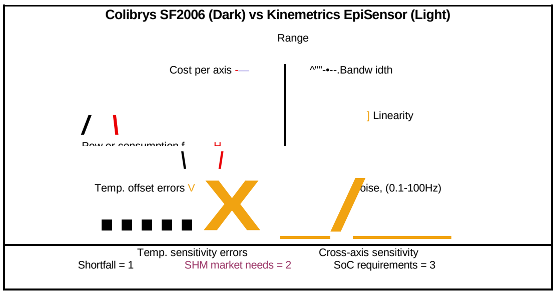

Fig 5. Comparison of Class B compliance to State of California requirements

The market for Class A sensors has been historically dominated by Nanometrics and Kinemetrics/Metrozet with the 'Episensor' often referred to as the benchmark product. All suppliers to date base their products on Electromechanical Force Balance Accelerometers with prices typically ranging from $700 to $3000 per axis depending on volumes and specifications. In Japan Kokusai has been it seems the market leader although in the past year Harbin University has started selling FBAs in limited volumes at $500-600 per axis.

2.3 Future technological trends

Specifically within the world of Strong Motion accelerometers, it is still foreseen that Structural engineers will continue to prefer to use single axis sensors wherever possible giving optimal freedom for sensor placement within the building but also avoiding generation of redundant data and reducing power consumption.

It is anticipated that open loop MEMS sensors will improve their signal dynamic range as more sophisticated signal processing architectures are adopted permitting maybe a better power/dynamic range trade-off

Another trend will be towards reducing power consumption. Class B sensors today use some 70mW per axis and this represents some 3% of total available power in many stand alone systems. Energy harvesting will become relevant in some systems but will more often be done at systems and not sensor level. Many SHM systems will not however have the option to deploy photovoltaic, airflow or vibration based energy scavenging systems. Some innovative sensor manufacturers are evaluating also the possibility for sensors to be developed with in-built 'wake up' capability thereby reducing significantly the mean power consumption.

Research has also recently been published on developments of MEMS based 'closed loop' Class A sensors aimed at offering lower power, improved robustness but most importantly lower cost[5]. Commercialization of such products is projected starting 2011-12.

Conclusions

The future growth of the Structural Health Market is depending on many things including;

- Collaboration with Building and Security Monitoring providers.
- Offering information to end user not data.
- Increased awareness amongst insurance companies / building owners of the added value of SHM systems
- Replacement of cable / wired systems by reliable wireless system reducing significantly installation costs and delays.
- Reduced current consumption to improve life time of battery powered systems.
- Emergence of lower cost MEMS based seismic sensors

Many established volume suppliers of MEMS capacitive sensors are exploring this market to expand or diversify their existing business base. Colibrys is already an established leader in supply of Class C and Class B sensors to this market. In the coming years it is hoped to launch new lower cost, lower power consumption Class A and Class B sensors based on latest MEMS sensor and closed loop electronics designs and start to establish market share for supply of Class A sensors also [3].

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