Inertial MEMS Testing

New Challenges in Motion Simulation

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Symposium Gyro Technology 2009

Karlsruhe, Germany

Abstract

As MEMS inertial sensors have a completely different value chain and fabrication, many questions about testing and characterisation need to be answered. ACUTRONIC tries herewith to outline one approach. Manufacturing processes from the semiconductor industry also bring new players and a new culture onto the market place of inertial sensing. The demand is driven by lower cost and specific testing throughout the complete value chain. The trends are continuing towards higher performance and smaller form factors. Yet another enabler that has facilitated integration, adaptability and configurability has been the integration of mixed signal electronic functions in an ASIC[1]. Implementing DSPs[2] or MCUs[3] provide the possibility to follow the way from partial to full IMU[4] with extensive firmware contents. As MEMS inertial sensors need to measure the same values under the same circumstances as their classical predecessors, we have to raise the question whether testing is changing or not. Distinctive aspects in Inertial MEMS Testing are volume / test capacity, accuracy and whether throughput or the maximum accumulation of data is desired (inline / online). Since fabs are built up along black boxes we are functionally breaking down the tasks for a turnkey testing solution. New approaches and conceptual innovations need to be taken into account and as certain requirements naturally remain the same, other specific characteristics of MEMS enable testing in new ways.

[1] *ASIC: Application Specific Integrated Circuit*

[2] *DSP: Digital Signal Processor*

[3] *MCU: Micro Controller Unit*

[4] *IMU: Inertial Measurement Unit*

1 Introduction

The advent of inertial MEMS may be described as the substitution of manufacturing processes for known instruments. No additional features or functions are being obtained. Thus no differences in testing and calibrating should be expected. Widely true at a first glance, the statement does blind out important aspects. This paper wants to light them up and spark a lively debate about testing of inertial MEMS. The statements are of a general nature and do include accelerometers and the various types and forms of miniature coriolis vibratory gyroscopes.

2 MEMS Inertial Sensors - General Trends

Despite sustainable mistrust and against many predictions, MEMS inertial sensors are challenging, complementing and replacing the classical instruments more and more. Once driven by the military and related industries, such instruments were often kept as secrets and its utilisation was limited to few people - probably for a reason (this Symposium is and was an exception, of course). Fortunately, due to and with the new possibilities of manufacturing such devices in larger numbers, small and cheap, we are experiencing a fascinating rebirth of motion sensing. And now it is available for all of us. Some say, there is a revolution going on with a bigger impact than the introduction of the computer mouse. The processes from the semiconductor industry also bring new players and a new culture onto the market place of inertial sensing. How about testing and calibrating? Suitable testing can be both technically challenging and expensive. The devices and designs are very diverse and the (additional) market is still fragmented - a nightmare for a test equipment supplier! Although outsourcing in general and foundries in particular are established meanwhile, many market participants suffer from the lack of standards, best known methods (BKM) and procedures.

2.1 Market Drivers and Enablers

From a test/characterisation point of view, the navigation/guidance application domains related to avionics/aerospace have been the technology drivers that required high performance dynamic testing from 1 to 6 degrees of freedom. Defense customers - with the ability of spending money for Research and Development - again set the pace not only in accuracy, but more importantly in size and thus portability. The increasing usage of such instruments has created new demands in terms of testing throughout the entire value chain. Needless to say, it is driven by lower cost. With big Semiconductor players entering the scene, civil applications and wide-spread supply to everyone became possible. The nature of the market has therefore changed significantly. We can observe a rapid transition from a technology-push situation to a market-pull environment. It happened not only because of the lower prices, but also due to a more fertile market place and information exchange. The big players may not have been part of the classic inertial community so far, but marketing-wise they are certainly way ahead of them. Yet another circumstance is deriving out of that involvement - it's the expectations of investors, venture capitalists and the public during economically difficult times.

	Pressure	Temperature	Vibration	Rotation/Motion	Light	Sound	Other
RF MEMS							
Bio MEMS Microfluidics		✓					
MOEMS					✓		
Gyroscopes		✓		✓			
Accelerometers		✓	✓	✓			
Silicon Microphones						✓	
Pressure Sensors	✓	✓					
Inkjet Heads							✓

Table 1 MEMS and their different stimuli

2.2 New markets and applications

The use of inertial sensors is no longer limited to their classical fields of application. Controlling via motion sensing is much more natural and ergonomic. Frankly speaking, our communication with machines/computers has been fairly limited in the last 40 years. An alphanumerical keybord is not really the most convenient way of interaction. Inertial sensors now allow this interface to become more natural.

Picture 1 Some consumer applications

2.3 Increased miniaturisation and integration

The trend is continuing towards higher performance and smaller form factors. The integration of 6 degrees of freedom on one single die is still the ultimate goal.

But the smaller the systems, the lower the accuracy, and, manufacturing defects hugely influence the performance. There are 2 types of errors we can categorise: deterministic failures and stochastic ones. Whereas the deterministic and systematic failures are relatively easy to find and fix, the stochastic ones remain hard to understand. Investigating and testing in and for the latter is often like stepping in the dark.

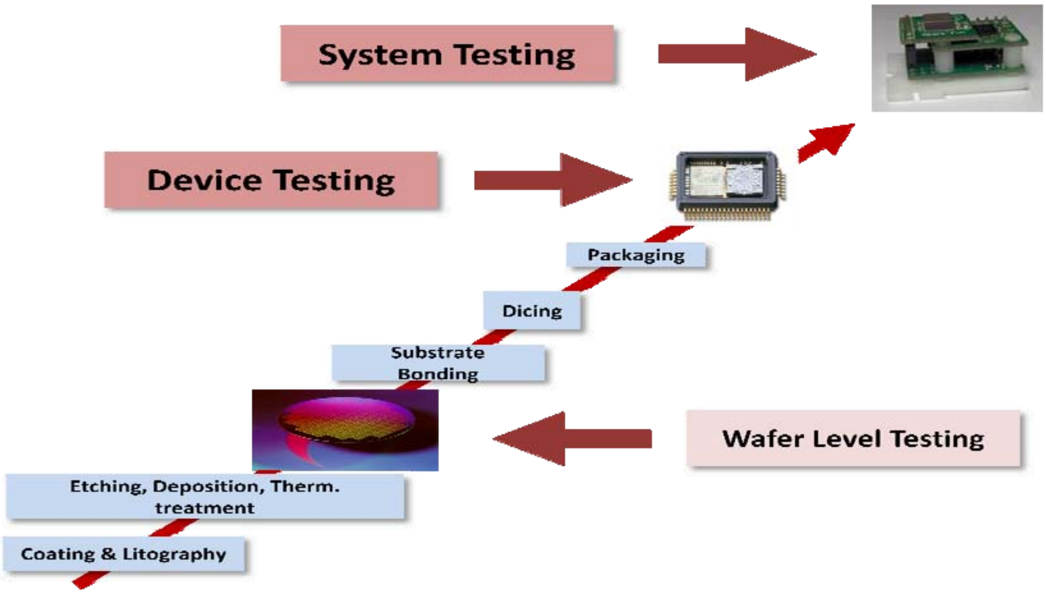
2.4 Signal processing implementation

Yet another enabler that has facilitated integration, adaptability, and configurability has been the integration of mixed signal electronic functions in an ASIC. Implementing DSPs or MCUs provide the possibility to follow the way from partial to full IMU with extensive firmware contents. Depending on the implemented principle, many different parameters and measurands need to be observed. They need to be treated in the right manner to get the relevant information. Examples are characterisation with bias and offset, multi point linearity corrections for thermal influences and so on. Models and algorithms are being developed and run to overcome the failures and compensate various effects. With sophisticated firmware the inherent imperfections of the microstructures may be bypassed.

3 Inertial Sensor Testing

There is a wide range of different grades of performance for any application. From robustness to different bandwidths, from accuracies to lifetimes and reliabilities, the respective test procedures are mirroring this great variety.

Testing of any device is naturally related to the questions 'when' and 'what'. The 'when' refers to the production step and thus at what stage or stages the sensor will be accessible. Depending on that stage, different types of testing may be applied. Along the value chain of micro-machined devices, we can identify 2-3 possible entry points to apply motion in order to excite the structures and also measure responses.



Picture 2 The value chain of MEMS and IMUs

3.1 Module / IMU characterisation

At this stage an entire functional module is tested. Rate linearity with or without speed, cross-axis misalignment, temperature drifts and so on are characterised dynamically. Nothing new, we all know what's needed.

3.2 Device level testing

One or more dies (sensor with, or sensor plus ASIC) are put together in a package. Flipping, aligning, soldering, bonding and sealing are summarised as 'back-end' or 'packaging'. Interestingly, the costs for packaging are among two thirds of the total cost of a device! Packaged devices are completely different compared to dies, but closer to what we know from classical instruments. As the functions of the microstructures largely depend on the environmental conditions and the mechanically induced effects like stress, it is more than worth to test devices at that stage. Here, of course, motion or acceleration is the stimulus to apply. Dynamic testing, calibration, accelerated life-time testing and FMEA[1] tests are performed.

3.3 Wafer-level probing

The above stated large contribution of packaging to the costs of a device is a big waste in the case of a bad device. Increasing the yield is one path to follow, and sorting bad dies out before the costly

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[1] *FMEA: Failure Mode and Effects Analysis*

process steps is the other possibility. The latter has recently enjoyed much interest. Well known are static testing of capacitance, leakage behaviour, sticking and others. Some of these values are indications for malfunctions later on and are tested with the known probers and equipment. Due to the large impact of the following production steps it is admittedly difficult to create stimulation comparable to the final working point. Nevertheless, stimulating the die dynamically is desired and also done. Like this, measurands like resonance frequency f_r, damping ratio, -3dB frequency f_{-3dB} and Q-factor are obtained.

4 Crucial question

Out of chapter 3 we learn that state-of-the-art motion simulation cannot be avoided from device level. It leads directly to the crucial question:

Out of the test equipment manufactures perspective, is it really necessary to distinguish between classical and MEMS sensors?

4.1 No, it's not

The same values to measure, same stimuli to be applied and the appropriate systems are available on the market.

End of the story.

But,

4.2 Yes, it is

Firstly, the physical properties like size and mass have an impact on how to handle the UUTs. Different dimensions require special alignment and fixturing. Smaller drives and actuators can be used. The sheer amount of UUTs demands shorter cycle times and thus higher throughput. Increasing batch sizes or one-piece-flows largely influence the interfaces of the test equipment and different ways of excitation than electromechanical drives scan be used. To reach the working point as fast as possible in the case of temperature is a must and temperature chambers may not always satisfy these requirements.

Not to underestimate is the change in the general market nature. Different target group, different customers and much more end-users in daily business want to be served. Less restrictions, open communication and private use of inertial devices have increased the fertility of the market place. Innovation and progress are enabled.

Although the market will most probably consolidate similar to what happened in the semiconductor industry, there is still a lot of start-ups and smaller companies. In such dynamic conditions not all of them do have the possibility of spending money, time and resources for testing. Outsourcing or collaborating seems to be the solution to their problems. Luckily, there is a company making both equipment and testing expertise available for them! While data security is guaranteed, anyone can rent the facilities and operational personnel in order to refine, finish or improve their development. We call it Test Services and it is a new business model complementing ACUTRONIC's range of offerings.

Picture 3 Systems in the testing facility (ACUTRONIC Angular Vibration Table AC150 and Two-axis Motion Simulator with Temperature Chamber AC277-TCG)

5 Distinctive aspects in Inertial MEMS Testing

Aiming to put things in a certain order we describe testing using the following criteria:

5.1 Volume / test capacity

Capacity requirements are defined primarily by the volume of UUTs, achievable cost savings and last but not least quality requirements. Technical feasibility of customer-specific ways of testing plays an important role, too.

The estimated production levels for each application domain are as follows:

- Few thousands units per year in Aerospace and Defense
- Avionics in the range of 10k units per month
- For industrial use few 100k units per month
- More than 1M units per month are going into consumer applications
- Up to 1M units per month for the Automotive

We therefore categorise the volume:

- Low (up to 10k units per month)
- Medium (up to 100k units per month)
- High (> 100k units per month)

Cycle time is crucial for high volume applications. Every second counts. Strips, reel handling, single components are tested alone or in batches on trays. All movements in the necessary handling steps can be used to stimulate as well. Increase accelerations to supply the demand to quicker establish the needed rate. The size and thermal mass of the UUTs might question the use of temperature chambers to save time and energy. In low and medium volume testing a modular system concept enables flexibility for different testing procedures. Not to forget is the economic price range of such products suited for this category.

Picture 4 simex^{TM}ONE, the one-axis member of ACUTRONIC's modular simex^{TM}-series

5.2 Accuracy

The test equipment's requirements hugely vary with the accuracy of the UUT. High-end or tactical grade is still represented by Aerospace, Avionics, Military and few industrial applications. Moreover, MEMS inertial sensors are much more sensitive to their environment in comparison with their 'clockwork'-ancestors. This is given by their sheer size, very small thermal mass and imperfections. It must be taken into account when it comes to handling and fixturing. This is delicate and can have significant impact on the test itself, and - in order to avoid it - on the testing system accordingly. Undefined mechanical interfaces represent a dangerous reason for not achieving a result to trust in. Further issues can also derive from a basic weakness of batch testing. It is the different geometrical position of the UUTs that creates variation in exposure to the motion.

Can low-end products be tested using low-end equipment?

Maybe, but the more accurate and smooth the rate, the faster and better the result. You have the possibility of rotating less than a full 360° instead of averaging over a couple of turns.

Accurate equipment is smart equipment!

5.3 In / off-line

To distinguish between IN-LINE and OFF-LINE is important. One can imagine that high volume production is trimmed for yield and throughput in order to minimise cost. Every second and penny are squeezed out IN-LINE during 24/7. Not really comfortable to most of us, but that's the rude portion of the relationship with the semiconductor industry. The failure models and neuralgic points are known and actual measurements are the feedback in order to control the production line. Statistical process control is the keyword.

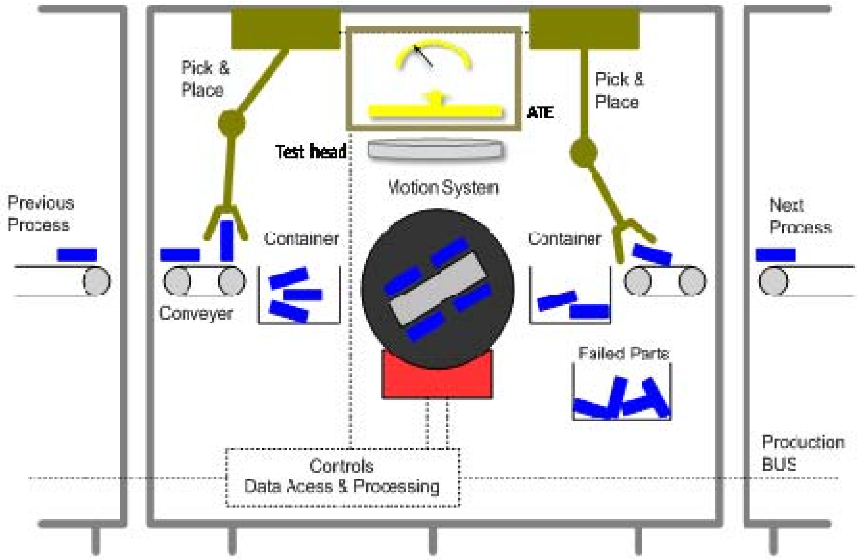
IN-LINE testing is therefore based on the knowledge about cause and effect. Prior to production the interactions and relationship of parameters must be understood. OFF-LINE characterisation and measurements at an early stage of development have to be carried out. R&D departments and (educational) institutions are typical examples for this group.

IN-LINE needs throughput, automated handling, fast processes, short test cycles and means to achieve the test condition very fast. Fast cooling and heating, fast acceleration, fast deceleration, fast pick-and-place are mandatory.

Offline testing for process and production control can involve manual labour and might take a little longer, although automation of test to a certain degree could still be advantageous.

6 Example Basic functionality requirements

Applying the elaborated statements we can make a concept example for of high volume turnkey tester, designed for low to medium accuracy devices and modules. It fits within the existing production line and is a typical IN-LINE setup.



Picture 5 Conceptual look at a turnkey testing system

Located between sequential black boxes we would like to functionally breakdown the basic tasks of a turnkey testing solution:

- Handling — Receiving, orienting, sorting
- Stimulus — Excitation of the sensor using less common principles of actuation
- ATE[1] — Measuring, acquiring and managing data, Calculation and evaluation, to determine the characteristics of the sensors, e.g. linearity, bias, etc. Calculate correction factors and write back to the device
- Fab[2] Interface — Connect the system to the fab net for statistical process control

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[1] *ATE: Automated Test Equipment*

[2] *Fab: Semiconductor fabrication plant*

7 Conclusion

It's not about reinventing the wheel, but dealing differently with both UUTs and customers! We must address the MEMS community in a specific way. The distinctive aspects are lined out and possible approaches can be derived. It is nothing but fair if ACUTRONIC does not line out the complete recipe for its prosperous future on a silver plate in this conclusion. Instead we would rather invite all interested people to get in touch with us.

References

Market volumes are refined out of reports from market researchers

(YOLE, isuppli, Frost&Sullivan, Cabrillo)