

Low-Shock Manipulation and Testing of Micro Electro-Mechanical Systems (MEMS)

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1. Introduction

A MEMS (Micro Electro-Mechanical System) is a block of different miniaturized components (mechanical, electric and electronic) integrated on a silicon layer. This kind of semiconductor system is able to combine the computational skills of microelectronics with the perception and control capabilities of micro sensors and micro actuators, with the main advantage of making the system compact. After the sensors gather information, the electronics processes the data and issues commands for a desired outcome or purpose.

Since MEMSs can perform optical, chemical, thermal, electronic, mechanical and biological functions, they can operate as inkjet heads, accelerometers, gyroscopes, pressure sensors, microphones and micro-fluidic systems, with the possibility of combining more than one function in the same MEMS. They are employed in several fields, such as automotive, electronics, consumer goods, high technology. As Fig. 1 shows, the MEMS market is increasing, with a change in the types produced. In fact, even if the currently most produced ones are inkjet heads for printers, market forecasts highlight that microphones for telephone market and accelerometers for multimedia consoles are going to be the main business in the next few years.

MEMSs require a high level of fabrication and design knowledge, in order to create compact and functional components. In this direction, a dedicated research is being carried on with the aim of improving fabrication and testing processes. Unlike electronic components made with integrated circuits, mechanical ones are fabricated selectively etching away or adding parts of the silicon substrate (Lindroos et al, 2010). Almost all kinds of MEMSs are built on wafer (thin films) of silicon like ICs, but there are other several different processes. Besides silicon and gallium arsenide commonly used in semiconductor industry, other materials as quartz, piezoelectric materials, Pyrex, polymers, plastics and ceramics are utilized (Gad-el-Hak, 2001). Essentially there are 3 building steps: deposition of thin film of material on a substrate; application of a patterned mask on top of the films by photolithographic imaging, and etching of the films selectively to the mask (Hsu, 2008). Normally the deposition methods are classified in 2 big groups: using chemical reactions or physical reactions. The lithographic process typically consists in the transfer of a pattern to a photosensitive material by selective exposure to a radiation source such as light. Finally, in order to form a

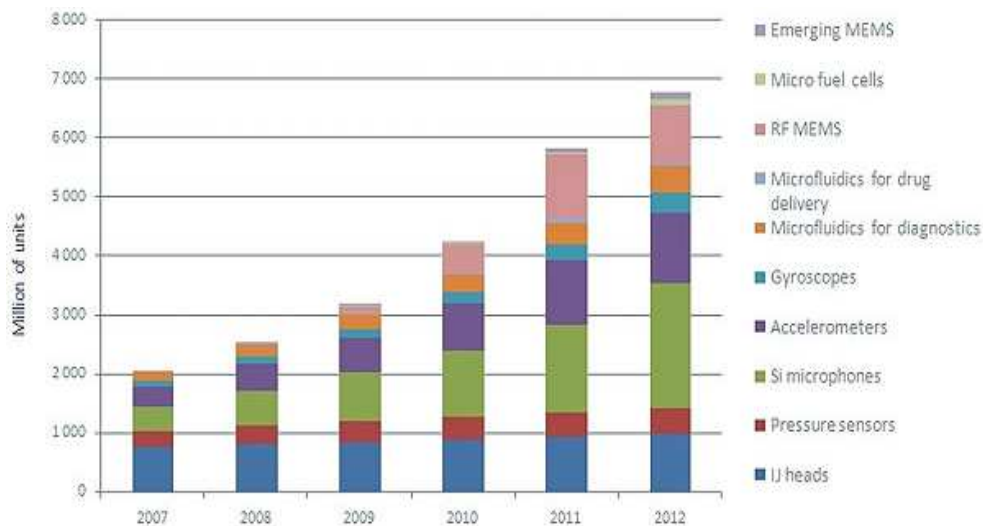


Fig. 1. 2007-2012 MEMS market forecast (millions of units) (Yole Développement, 2009)

functional MEMS structure on a substrate, it is necessary to etch thin films previously deposited. These processes consist in removal of material from desired areas by means of physical or chemical techniques and they are classified as wet or dry. However, each manufacturer uses their own technology, and consequently also the building process is quite particular. Moreover, MEMSs can differ for shape and types of contact (Fig. 2).

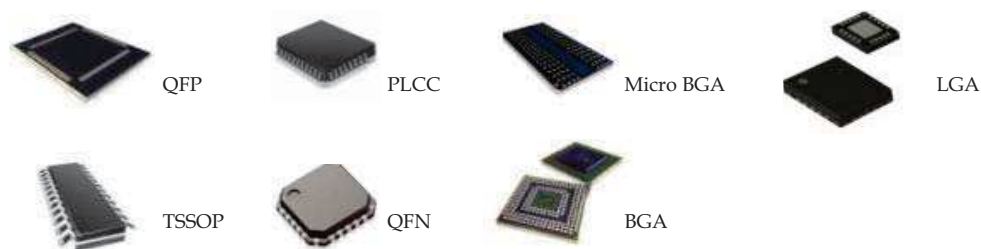


Fig. 2. Different types of MEMSs tested with SPEA Test Cells

Since MEMSs are manufactured using batch fabrication techniques like other electronic devices, fabrication and material costs must be maintained relatively low. For this reason, in order to keep functional test costs as low as possible, those tests are done by specific MEMS Test Cells (MTC).

Currently, there are two ways of testing MEMSs:

- On strips (components physically joint together as they come from the manufacturing process)
- As singulated components (already diced and finished)

The former approach is normally applied at the end of the manufacturing process just before dicing, while the latter is done on single MEMSs. Obviously, both ways of testing have pros and cons: diced MEMSs imply more issues for manipulation; in the case of strip test, MEMSs

damaged during the subsequent dicing cannot be detected. Some MEMS manufacturers opt for testing single components, after which they can directly pack the products for customers. This strategy requires a testing and packing process that does not damage the MEMS. During handling and testing, MEMSs undergo different stresses (inertial forces, collisions, negative pressure). Some typologies, e.g. low- g accelerometers and gyroscopes, are particularly sensible to shock and acceleration. Datasheets declare maximum acceptable acceleration (e.g. $10000\ g^1$ for 0.1 ms) to avoid permanent mechanical damage, but practical experience shows that MEMSs could be troubled by lower stresses lasting longer, for instance losing calibration. For this reason, the handling process needs to be designed to guarantee low shock manipulation, or in other words low mechanical impacts and accelerations. There are few studies and data on these phenomena, therefore the aim of this work was also to evaluate forces and accelerations on the MEMS during the whole test cycle (from its entrance in the MEMS Test Cell to its exit) and to highlight the most critical phases. Automatic Test Cells for single MEMS have different architectures and every kind of MEMS needs different tests, even if some phases (feeding, handling, etc.) are common. Without loss of generality - as much as possible - the study has been done referring to MEMS Test Cells produced by SPEA S.p.A. for low- g accelerometers and gyroscopes.

2. Types and structure of a MEMS Test Cell (MTC)

The MEMS Test Cell for testing single components is based on several modules with different functions. Mainly, the entire test cell is composed of five modules (Fig. 3):

- Feeding equipment
- Handler unit
- MEMS Physical Stimulus
- Tester
- Unloading equipment

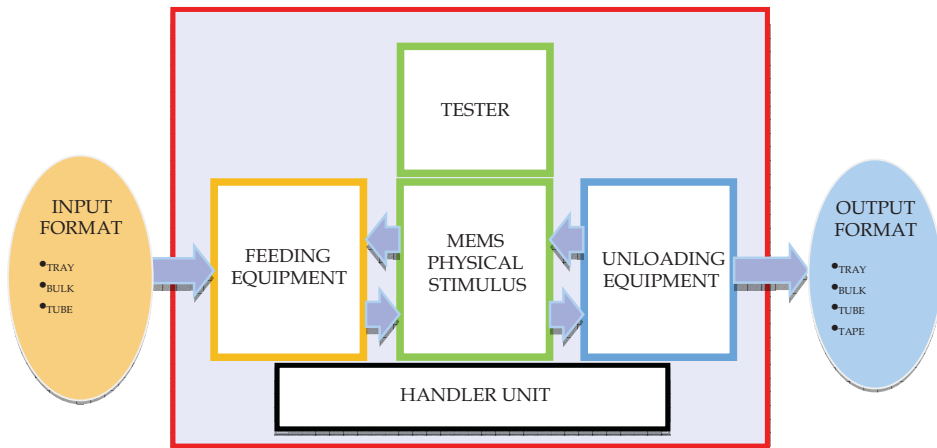


Fig. 3. Block scheme of MTC for singulated MEMS

¹It is common use to indicate accelerations with reference to the acceleration of gravity g . This Chapter uses the same notation wherever applicable.

Before and after the test, MEMSs can be stocked and carried in different ways. The most common one is the use of a tray: a specific plate in plastic material with proper pockets. It is specific to every kind of MEMS, but it is standardized following the semiconductor laws. Hereinafter the five modules are presented.

2.1 Feeding equipment

The main function of the feeding equipment is to prepare the MEMSs to be picked by the handler unit. MEMSs are carried to the final test by tray, bulk or tube. Obviously these ways influence the feeding equipment since they need to be customized using quite different technologies. Since during the test MEMSs have to be contacted univocally, their orientation is an issue to solve. Tray and tube contain orientated MEMSs since they are prepared in advance, while in bulk they come unoriented.

SPEA's feeding equipment for tray is called TSL (Tray Stack Loader) and consists in a module with the function of tray storage. An opportune mechanical device permits preparing a tray filled with MEMS, in order to be ready for the picking phase (Fig. 4a). This approach guarantees a high throughput, since a high number of MEMSs can be quickly picked up by the handler unit. The bigger constraint is the predetermined pitch, influencing all the equipments downstream.

If MEMSs are carried in bulk, a bowl feeder is used to load them in the MTC (Fig. 4b). Since MEMSs come disorderly, this module is able to orientate and to convey them to a station representing the input for the next module. This equipment must be customized according to the test cycle.

Finally, tubes containing a defined number of MEMSs are also used to carry them. Its feeding equipment is based on gravity to extract the MEMSs from the tube, implying some issues due to impact shocks.

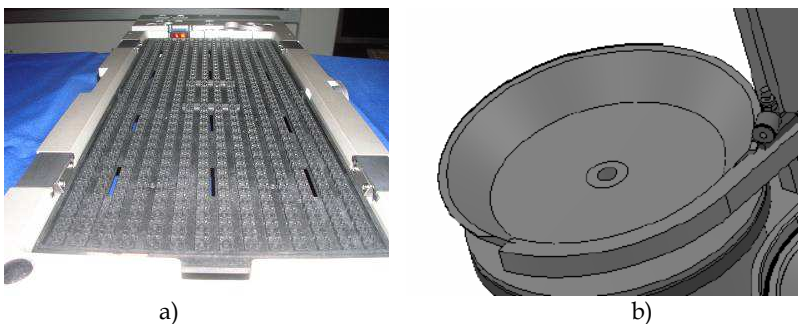


Fig. 4. Feeding equipments: a) TSL, b) Bowl Feeder

2.2 Handler unit

This unit is fundamental for the testing of single MEMSs. In fact, it permits to pick the MEMSs prepared on the feeding equipment and to place them in the test cell, ready to be tested. Sometimes, the same handler unit permits to pick MEMSs in the test cell and to take them to the unloading equipment. This module can be made using different technologies. SPEA uses a head (Fig. 5), moving along an horizontal work plane (XY), with picking tools (pick-up) moving along the Z axis. Such devices, thanks to a movement in the Z-direction done by pneumatic actuators, achieve the grasp of MEMSs.



Fig. 5. SPEA's head (handler unit)

2.3 Physical Stimulus Unit

The test cell is based on a stimulus unit aimed at testing the MEMSs with an adequate stimulation, depending on their typology and contacting technology. In order to be tested, MEMSs need to be inserted in a specific contacting unit with electric pins. These pins permit to acquire the electric signals from the MEMSs under test and to transmit them to the tester, stating if the test result is pass or fail. As an example, the stimulus unit used for low-*g* accelerometers and gyroscopes consists of a board, with a defined number of pockets where the MEMSs are lodged, mounted on a system of orthogonal axes. This system permits 2 angular degrees of freedom (roll and pitch), or 3 (roll, pitch and yaw), in order to turn the board as needed.

2.4 Tester

This unit acquires signals from the MEMSs under test and, after an elaboration, it declares the results of the test as pass or fail.

2.5 Unloading equipment

Finally, the unloading equipment permits to sort the MEMSs in proper packages, ready to be sold to customers. Normally, this equipment allows to separate defective MEMSs from valid ones, according to the different failures that may have occurred. Some MEMS manufacturers stock the semiconductor components in tape on reel (Fig. 6). The tape presents specific pockets where MEMSs are individually stored and closed by a thin film. This way to carry MEMSs is not commonly used during the manufacturing process, since it permits a limited throughput. On the contrary it is quite common after the final test.



Fig. 6. Tape on reel

3. Manipulation techniques

As presented in section 2, the handler unit of the MTC has the main role of carrying MEMSs from a module to another. This phase could be done by using a pick-and-place device which manipulates MEMSs. Even if MEMSs are of millimetric size, their very low mass permits to assimilate their manipulation to micro manipulation.

Micro manipulation is based on physical laws and principles different from those of large scale mechanics. In fact, in this field, some forces which are negligible in the large scale (electrostatic, Van der Waals, surface tension) become dominant; on the contrary, gravitational and inertial forces are not so significant. For this reason, the manipulation assumes an irreversible nature and the unloading of the component becomes the most critical phase in the whole process (Tichem et al., 2004). In fact, the bigger issue is the detachment of the micro component from the actuator. This section presents the state of the art of current technology for micro component handling, and a brief classification of physical principles useful in this field.

Micro manipulation can be classified in two main categories: with or without contact. The former category is the most used and well known. It includes the use of forces of mechanical, fluidic or molecular nature.

The most common grasping technique is based on suction. A suction pad or a sucker touches the object, and then the suction is created between the two parts. This technique is widely used for pick-and-place phases, because it allows short grasping and releasing times. In Fig. 5 SPEA's handler unit is shown. It has eight picking tools using suction and operating in parallel.

A further method is the use of grippers (Ansel et al., 2002). Fig. 7 shows the two basic principles of functioning.

The opening and the closure of the gripper, corresponding to grasping and releasing the object, can be done through different actuations: shape memory alloys (Zhong & Yeong, 2006), MEMS (Mayyas et al., 2007; Skidmore et al., 2003), piezoelectric (Agnus et al., 2003) and chemical (Randhawa et al., 2008) actuators. As an example Fig. 8 shows a MEMS micro gripper.

Another solution is to use a passive gripper, characterized by the absence of any type of direct actuation for the manipulation of the object (Tsui et al., 2004).

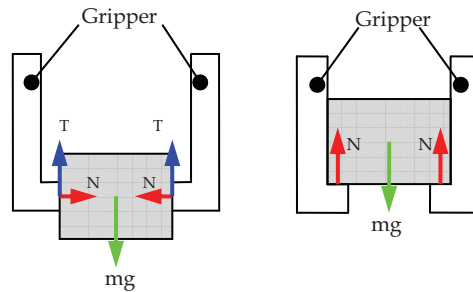


Fig. 7. Gripping by friction (left) and form closure (right).

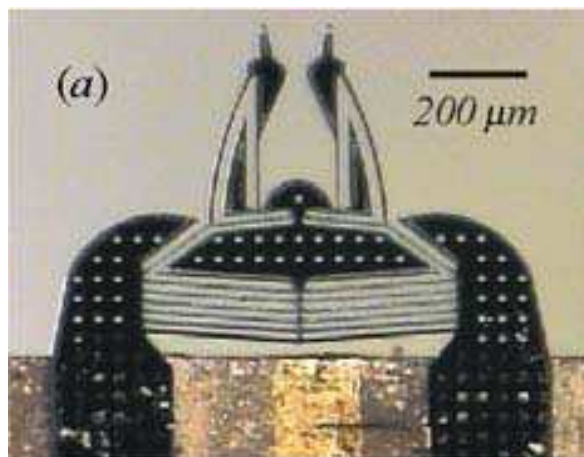


Fig. 8. MEMS micro gripper.

Other interesting manipulation techniques use forces of fluidic nature.

Some possibilities are sketched on Fig. 9. Fig. 9a shows a surface tension method. This method utilizes a low viscosity fluid that evaporates without leaving residuals. For small objects with limited weight, the capillarity force and the surface tension of a liquid between the grasping equipment and the object are sufficient to guarantee the grasp without any damage to the component (Bark et al., 1998). Moreover, using an appropriate shape of the gripping tool, the surface force is able to orient the component.

Fig. 9b shows the principle of micro holes heating. This method is based on the pressure variation inside micro holes on the actuator surface due to a temperature change (Arai & Fukuda, 1997). In detail, before the contact between the picking tool, the temperature is increased. After the tool touches the component, temperature is decreased again, so the pressure inside the hole decreases. In this way, vacuum is created inside the holes, allowing the picking of the object. Finally, the release is done by heating again. The actuator heating can be realised in different ways: a laser beam, a micro heater on the actuator, conduction.

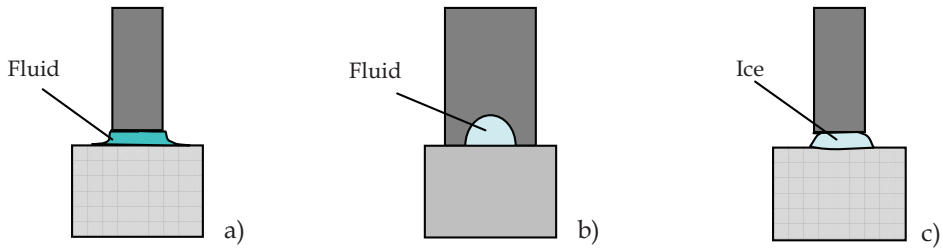


Fig. 9. Manipulation with fluidic forces: a) surface tension, b) micro holes heating, c) cryogenic.

Fig. 9c shows the cryogenic method. The grasp using the adhesion property of ice consists on freezing a small quantity of liquid between the picking tool and the object (Liu et al., 2004, Ru et al., 2007). The release of the object is done by breaking or melting the frozen material.

In addition to cryogenic grippers working in air, some submerged freeze microgrippers working in water have been developed in order to avoid issues due to capillarity force (Walle et al., 2007).

Forces of molecular nature such as Van der Waals force can be used for manipulation (Feddemma et al., 2001). The main issue of this method is the difficulty to control it, in particular during the release phase that must be done by skewing the actuator tip in order to decrease the adhesion force.

The second category, without contact between the tool and the manipulated object, includes the use of magnetism, electrostatic, ultrasonic pressure, optical pressure, fluidic principles (Vandaele et al., 2005). They present various advantages such as the fact that surface forces can be completely neglected, friction is reduced, it is possible to manage breakable and delicate objects, surface contamination is completely avoided. They are less known and currently not reliable, but they could possibly represent the future of micro manipulation.

4. Experimental detection of shocks during the test cycle

As above described, the automatic test cycle is generally composed of the following phases: MEMSs are loaded on trays (or bowl feeder), then a pick-and-place robotic head carries the MEMSs to the test area where it undergoes the test. After the test, another (or the same) pick-and-place unit carries the MEMSs to different destinations, according to the test results (pass or fail). Usually a code reader is placed between the loading area and the test area.

Each phase shows specific circumstances that are potentially critical from the shock point of view.

The careful analysis of the whole test cycle leads to the identification of three critical situations, requiring in-depth examination:

1. during the pick phases, there could be an impact between pick-up and MEMS; in particular the pick-up of the robot head could collide with the MEMS during its downward motion, depending on the shape and the calibration of the device;
2. when the MEMS is already picked, it undergoes possibly dangerous accelerations during the head movement;
3. before the test phase, MEMS is clamped to the socket board; generally the clamp is controlled by means of a single-acting pneumatic cylinder, in which the spring causes the clamp impact on MEMS.

4.1 Pick-up force measurement

The contact force during the pick phase is strongly dependent on the pick-up typology. In a first case (Fig. 10a) the pick-up end is provided with a seat shaped to allocate the MEMS, at the end of the descent stroke the pick-up hits the tray surface, so avoiding a direct contact with the component; the grasping is operated by the subsequent suction, sparing any shock.

A second solution is shown in Fig. 10b. In this case the pick-up directly hits the MEMS surface; this solution is less expensive and therefore very diffused but, since the contact force may be critical, an accurate analysis of the operating condition is usually necessary. In the following such analysis, both experimental and analytical, is described.

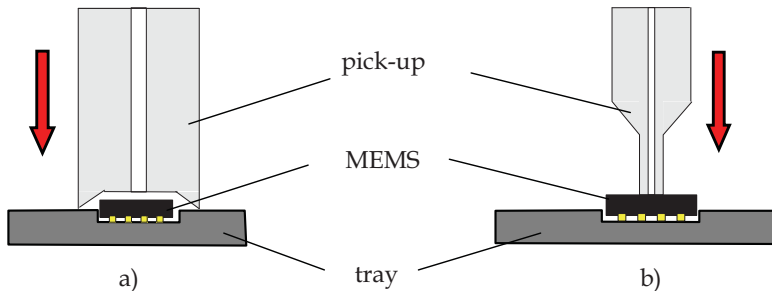


Fig. 10. Pick-up typologies a) without impact on MEMS, b) with impact on MEMS

A load cell (Brüel & Kjør Load Sensor, 0- 5000 N, resolution: 0.001 N) replaced the MEMS to be hit by the pick-up, as the MEMS is during the pick-and-place operation. The main difference between the real situation and the experimental layout was the replacement of the tray with an adequate aluminium support for the load cell.

The load cell support was positioned on the test machine and a setup was made to repeat the pick-up spring compression of 1.5 mm that was measured with a speed cam on real test cycle. The test was repeated using all 8 pick-up's from the same robot head and using two springs with different stiffness inside the pick-up. Fig. 11 shows the experimental test setup.

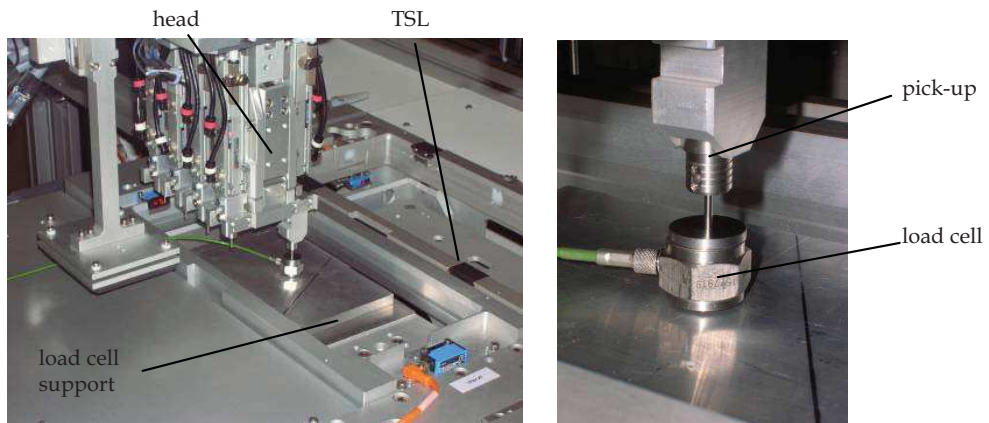


Fig. 11. The experimental test setup

Fig. 12 shows the results of the test performed using the 8 different pick-up's from the same head. The impact force peak is about 5 N. The results of tests performed using springs with different stiffness do not show a significant dependence of the force peak value on spring type. Performing the test again in the same conditions with the same pick-up demonstrated a good repeatability.

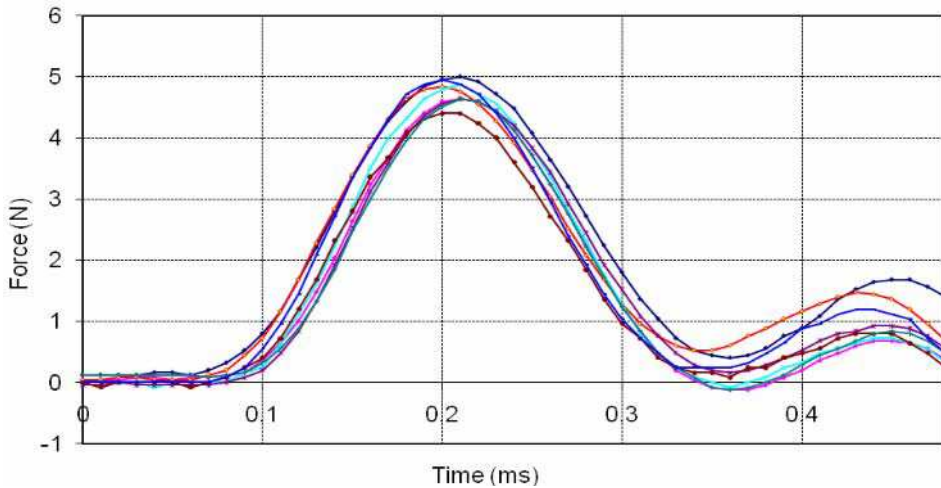


Fig. 12. Impact force in pick phase, using the 8 different pick-up's from the same head

4.2 Pick-up acceleration measurement

Measurements of pick-up acceleration during its descent and back were performed in order to investigate on the possibly dangerous accelerations during the head movement. The X and Y axis movement are operated by electro-mechanical drives on pneumostatic slides so that their acceleration is well known and controllable, whereas the Z-axis movement (vertical) is operated by a pneumatic cylinder. Its acceleration is unknown and not controlled. Therefore the first step is to investigate on these values in order to evaluate its possible effects and to consider the need to limit or control the Z-axis movement.

The pick-up was replaced with an accelerometer (Silicon Design 2210, ± 100 g) and the pick-up movement along Z-axis was reproduced, recording the results. Fig. 13 shows the experimental setup.

The mass difference between the pick-up and the sensor is about one gram, but considering that there are also other masses on movement like the piston and the piston rod, this variation is not significant. The test was repeated using 3 cylinders on the same head.

Fig. 14 shows an example of the test results. In Fig. 14a, the stroke time is about 110 ms and the acceleration peak is around 100 g. Therefore the machine design and set up needs a direct attention to the required compromise between the operation velocity and the possible component shock. If the MEMS needs a smoother manipulation it is possible to adjust the pneumatic circuit in order to obtain lower velocity and, consequently, lower acceleration. As an example, Fig. 14b shows a test result with the same pick-up and head conditions, with different pneumatic resistances of the circuit obtained by properly varying the diameter of intake and exhaust throats. In this case, the acceleration peak decreases to about 40 g, with a stroke time increasing to 140 ms.

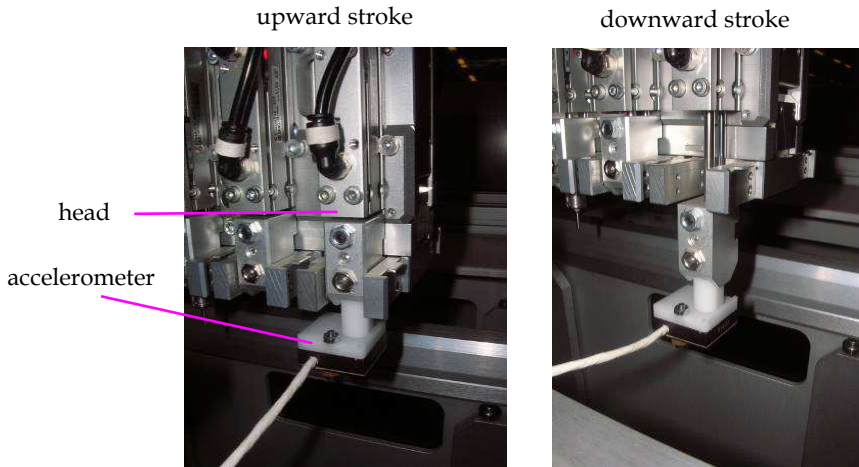


Fig. 13. Experimental setup for the pick-up acceleration measurements

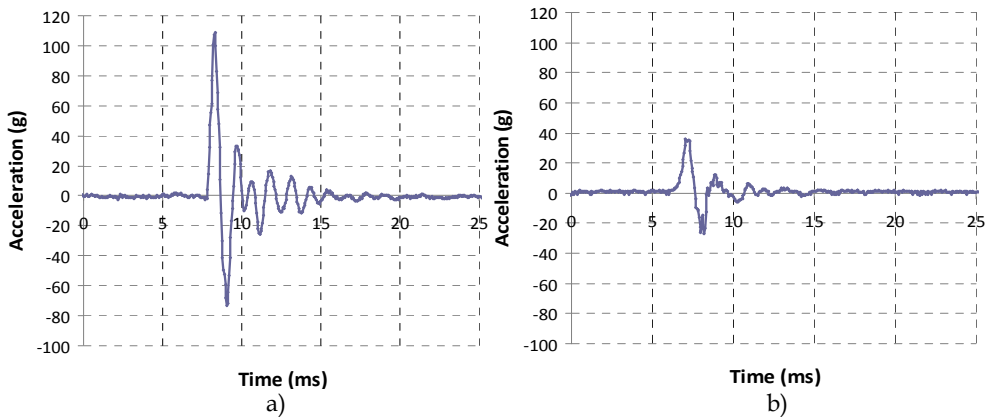


Fig. 14. Examples of the pick-up acceleration

4.3 Clamping force measurement

There are different socket types, but generally each of them has a clamp device aiming at constraining the MEMS during the test. A commonly used device is the turret socket, which includes clamps operated by pneumatic cylinders. Fig. 15 shows a functional scheme: the opening of the clamp is done by the air supply, the clamp closure is passively carried out by springs exerting force on the upper face of the cylinder when the compressed air is exhausted. The clamp moves downwards and hits the MEMS, which is positioned on an elastic support, thus generating a potentially critical phase in the manipulation cycle.

The force exerted by the clamp could be critical for the MEMS, therefore an investigation has been carried out in order to quantify the impact force.

Since there are many difficulties in equipping the Test Cell with sensors without altering the system, a separated test setup was designed and realised.

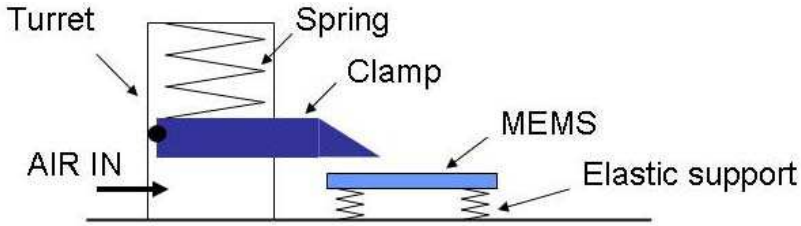


Fig. 15. Functional scheme of the clamping

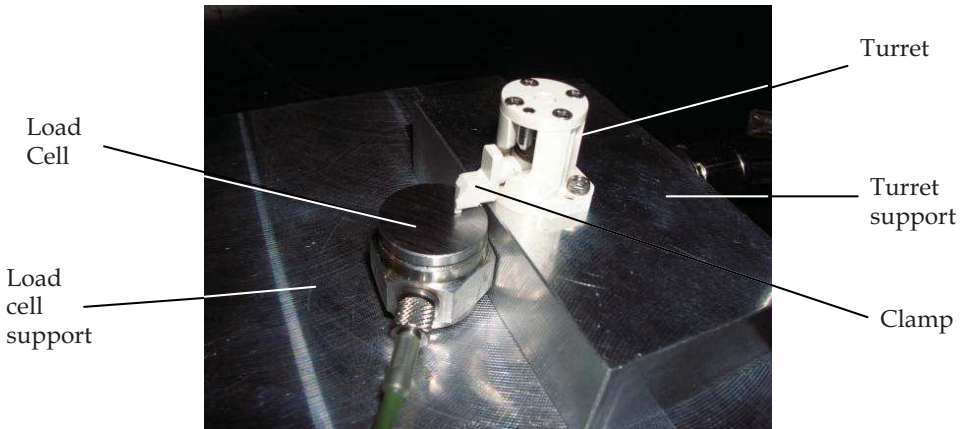


Fig. 16. Experimental setup for clamping force measurement

The experimental test setup is shown in Fig. 16: the MEMS is replaced with a load cell with the aim of evaluating the impact force during the clamp closure dynamics, with a rigid load cell support.

The turret is from a SPEA MEMS Test Cell. The load cell is a Brüel & Kjær (Range: 0-5000 N; Resolution: 0.001 N).

Similarly to the real situation, the clamp hits the load cell 0.3 mm before its total stroke. On the other hand, there are some important differences between the actual situation and the test setup. In the real application the MEMS support has a significant compliance and the air supply to the 8 turrets is given by proper channels calibrated by adequate pneumatic throats; on the contrary, in the test setup the load cell support is practically rigid and the turret is supplied by a short and direct duct.

Tests are repeated using three different supply pressures, with or without an outlet silencer and inserting different throats on the line.

Fig. 17 shows experimental test results for different supply pressures. Each curve is the average of at least three tests. There was a good repeatability and the supply pressure influence on peak value is almost negligible. The impact force peak is between 20 and 27 N.

Fig. 18 shows a comparison between a clamping performed by the experimental turret with no throat in the pneumatic line and one performed with a throat of 0.8 mm diameter.

These tests highlight that the impact force may be controlled by a proper selection of the pneumatic circuit parameters.

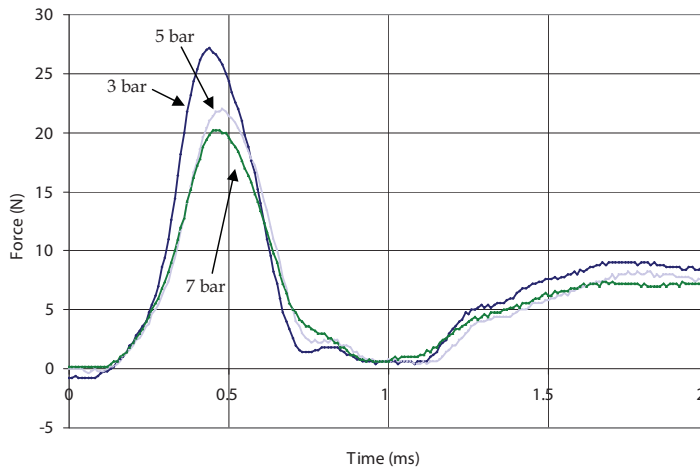


Fig. 17. Impact force of the clamp on the load cell at different supply pressures

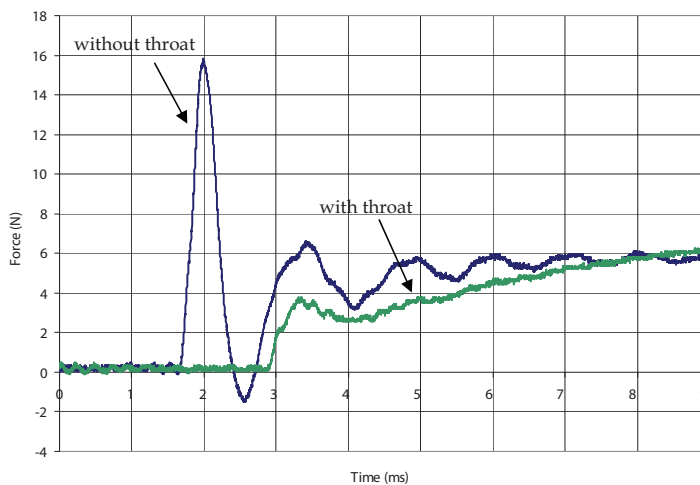


Fig. 18. Impact of the clamp on the load cell with and without throat in pneumatic line

On the other hand, because of the differences between the actual Test Cell and the experimental setup, these results cannot be directly used to evaluate the impact forces exerted on the MEMS during the actual test cycle.

For this reason, a numerical model was realised and validated against the experimental results. Such a model can therefore be used both to verify the MEMS condition during the actual test cycle, and to design future Test Cells.

5. Numerical model of clamping

An AMESim model has been realised to simulate the interaction between clamp and MEMS. Its aim is to analyse the process and find out the parameters which most influence the

strength of the impact and the operation speed. Once the model is complete with all the physical parameters involved and is validated against experimental data, it is possible to simulate a change in one or more parameters in order to mitigate the impact or to increase the operation speed.

This spares the necessity to set up a test bench for that, whilst remaining confident in the validity of the results for application to the real world. The scheme of the model is shown in Fig. 19.

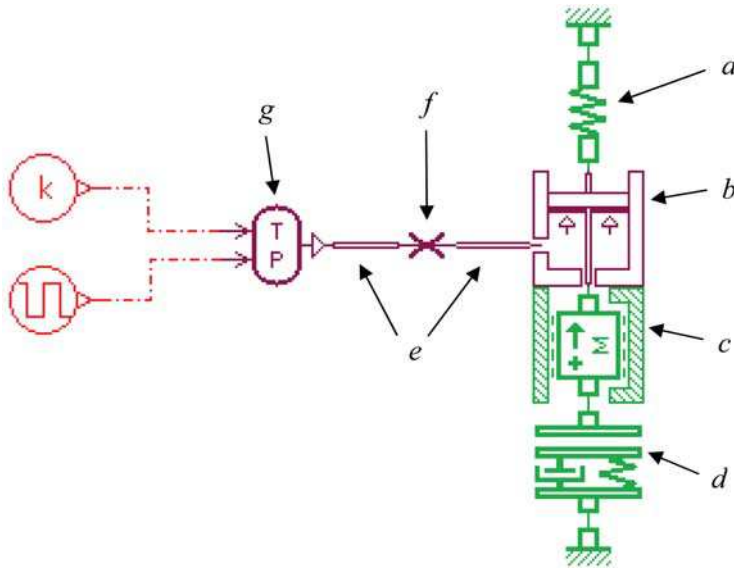


Fig. 19. AMESim model of the clamp-MEMS contact

Each block of the model represents a physical feature of the real device. In particular, the clamp is modelled as follows: the spring *a* works against the piston *b*. The mass *c* represents the total moving mass of the clamp; the corresponding block includes friction and end stops. The block *g* imposes a constant temperature and a user defined pressure law upstream the pipe *e* and the included pneumatic resistance *f*.

The contact between the clamp and the MEMS is modelled by the block *d*, which includes the internal rigidity and damping of the MEMS and its support as a whole.

The numeric parameters of each block have been obtained through specific tests on the real components.

By comparing the results from the model and those from experimental tests, the model itself can be validated. In particular, the model has been set up to duplicate the conditions of the experimental tests shown in Fig. 17. The comparison in the case of no pneumatic throat is shown in Fig. 20, while Fig. 21 shows a zoom-in of the force peak in the case of the pneumatic throat with a diameter of 0.8 mm. Note the X axis scale in the latter figure: it represents a time frame of about 4 ms.

The model presents a very good validity against experimental data, even in different set up conditions. In particular, the impact peaks from the model are nearly the same as the real ones, and also the pulsation frequencies correspond. The tiny differences between the curve pairs

depend on the very small time scale of the physical phenomenon and on the uncertainty in the determination of a few parameters such as friction, stiction and internal damping. Therefore, the model can be used to test virtually the possible changes in the system configuration, with an excellent degree of confidence. Altering the parameters of the model, for instance the spring rigidity, the turret piping volume or the pneumatic resistance, the performance of the system can be adapted to different needs, such as higher clamping speed or lower impact or static force, performing virtual tests with good reliability until the desired conditions are found.

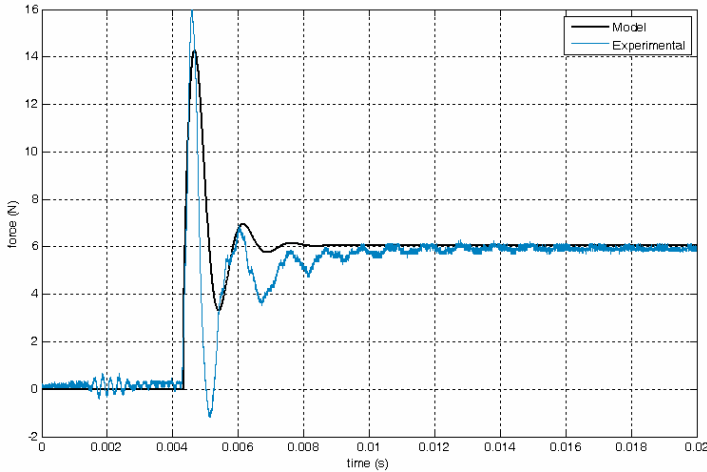


Fig. 20. Comparison between model and experimental data in the case of no pneumatic throat

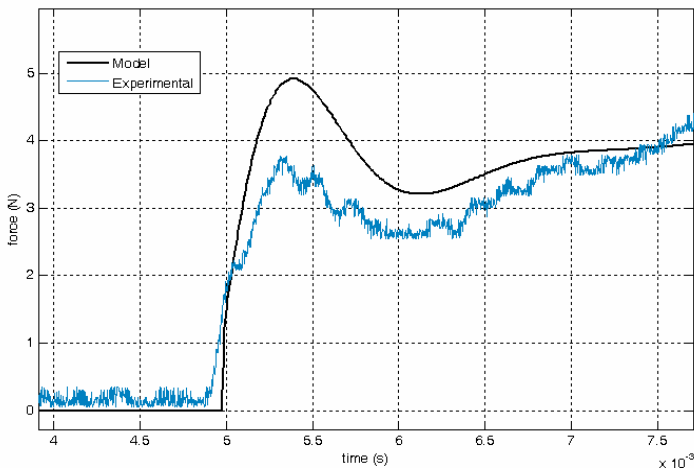


Fig. 21. Comparison between model and experimental data in the case of a 0.8 mm pneumatic throat.

As an example, the model can simulate the behaviour of the system when different pneumatic throats are used. This result is shown in Fig. 22, where the corresponding diameters of the throat inserted along the pneumatic line are: A=0.5 mm, B=0.8 mm, C=1.1 mm, D=1.4 mm, E=2.5 mm.

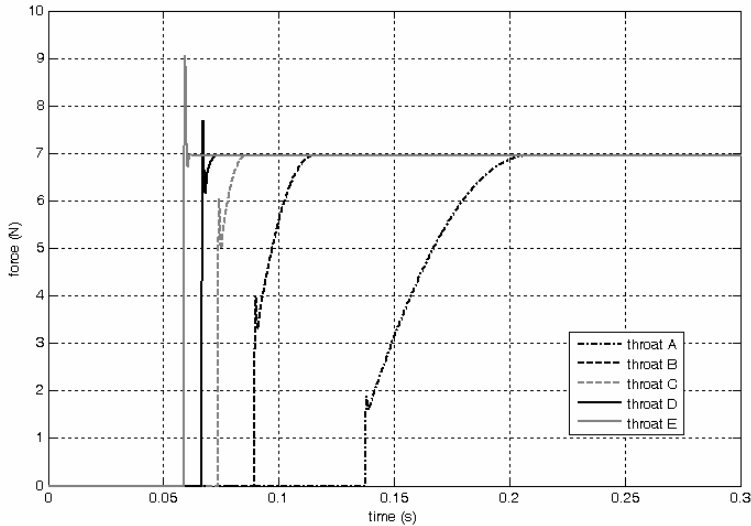


Fig. 22. Simulation of the clamp behaviour with different pneumatic throats

6. Conclusion

During the last few years, MEMSs have become more and more diffused in a large variety of applications requiring a high level of reliability. At the same time they have become more and more complicated, being able to allow different operations.

Since the reliability of MEMSs must be tested for every single component by special automatic test equipments, we decided to study the functioning of a specific MEMS Test Cell (MTC), in order to verify the existence of potentially critical situations for the tested components.

In particular we have focused on three cycle phases in which some kinds of MEMS, e.g. gyroscopes and low-g accelerometers, may suffer damage because of shocks that the component can undergo during the test cycle, namely acceleration peaks and impulsive contact forces.

To allow the producer to limit and control these shocks during the test cycle it is necessary to evaluate each phase and to design adequate tools. For this reason we have performed experimental tests on critical phases highlighting the parameters that may cause shock on MEMS.

As concerns acceleration peaks, they may occur mainly during manipulation operated by pneumatic drives, which present difficulties in motion control. Usually a direct measurement of the acceleration values is possible and that allows to individuate proper remedies, which consist mainly in paying particular attention in design and selection of the various components of the pneumatic circuit.

On the other hand, impulsive contact forces take place in pick and clamping phases. A direct measurement was carried out in the pick phase, thus obtaining definite indication about possible occurrence of critical values. On the contrary, contact forces could not be measured in real conditions during the clamping phase, since the experimental apparatus influenced the measure itself. So it was necessary to realise a numerical model of the clamping system, validated by comparison with experimental measures in altered condition. In this way the model represents a possible useful tool capable of simulating the MEMS real behaviour in the Test Cell, allowing a correct analysis of actual condition and the design of future test equipments.

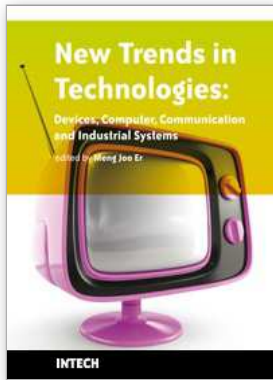
7. Acknowledgement

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