Micro electro-mechanical devices used as vibration sensors. Measurements and comparison with traditional accelerometers.

Alessandro Sabato [a)]
Department of Mechanics, Università della Calabria
Laboratory of TCA, 87036 Rende (Cs) - Italy

The aim of the project is to verify the applicability of *MEMS* wireless accelerometers to investigate oscillatory phenomena that can jeopardize the safety of structural elements and how these devices can perform environmental monitoring campaigns of vibration measurements. This to obtain a prototype sensor which data can be compared with those measured using traditional systems to detect the accelerations (seismic piezoelectric accelerometers).
In the first part of the project, the development of a computer code, necessary for the operation of the accelerometer and to allow its data transmission was carried out. After this, a calibration curve was produced by which it is possible to associate to each voltage value read from the instrument a corresponding acceleration value in physical units (*mg* or ms^{-2}). Then laboratory tests were conducted to study the behavior of the instrumentation operating in particular situations (i.e. progressive exhaustion of the batteries and the influence that the residual value of voltage has on the initial value of "*offset*"). To conclude has been made a measurement on bridge "P. Bucci" located at the University of Calabria creating a small network of sensors placed along the bridge. The results were then compared to the same samples using traditional accelerometers.

1 INTRODUCTION

In almost all operational processes the generation of vibrations is very frequent; these are among the main causes of generating efforts, with variable intensity and direction to time and space, able to contribute to damage or even destruction of equipment, structures and artifacts. It is also important to point out that these are considered one of the contributing factors involved in the production of noise pollution. The need to evaluate the vibrations of particular structures is much felt; we can consider, for example, the utility to control the dynamic behavior of facilities or sensitive equipment (i.e. bridges, railway lines, adjacent structures in high stress areas).
The commonly used instrumentation is made by accelerometers. On the market there are many types of these transducers: piezoresistive, capacitive, LVDT, piezoelectric icp, which differed from one another in application fields and technology used. All these sensors, instead, are linked

[a)] email: sabatoale@gmail.com

by the high cost and the fact that the measuring instrument should be placed close to the system being tested, because sensors should be directly connected to the analyzer, and because the length of wiring connections is not possible to extend beyond certain limits.

In recent years the development of *MEMS* technology, which stands for *Micro Electro-Mechanical Systems*, led to the construction of the first generation of sensors even smaller and easier to handle. One of the products of this technology is represented by the *motes*. This term means, in general, each of the knots placed into a *Wireless Sensor Network* (WSN)[1] that is an electronic system that is part of a network of computer-based sensors able to communicate recorded information with each other. As shown in the Figure 1, the generic WSN is made up of many knots, the motes exactly, consisting of two modular components: a sensor board S for the acquisition of sensitive data, and a radio board M which allows the dialogue, both the different constituents of the network, as well as towards the outside represented by gateway G[2-3].

2 AIM OF THE WORK AND PRELIMINARY OPERATIONS

The idea behind this work is to estimate the real usability and reliability of sensors set up on motes, which are used as accelerometers, comparing surveyed data from MEMS sensors with those registered with traditional instrumentation and then controlling if, and in how, sensor nodes should be used to carry out the vibration analysis of environmental monitoring.

To do this some motes were used, available in Laboratory, produced by the American company Crossbow; in particular the model named MPR400 (also known as MICA2) was employed. Regarding the sensor board, for data acquisition, those of series MTS310 showed in Figure 2 were used, while, in the end, concerning the gateway the device known as MIB510 has been used, which should be connected to a computer via serial port thanks to the employment of a cable connector RS-232[4].

The first part of the current work was characterized by scheduling the sensor network used in the study of the phenomenon. Considering that the management system of these devices is established by TinyOS, an operating system developed at the University of Berkeley, California; it was necessary to put together fitting routines in nesC, a sort of dialect of C++[5]. Such connection allows the channeling of data packages through a radio-communication system founded on AM/FM radio waves; in fact, beforehand, each mote is programmed in order to have an ID number, which identifies it into the network, as well as a precise transmission frequency. Furthermore each board was programmed by enabling only the use of a single sensor among all those placed on the device, to avoid useless waste of energy and to optimize the sensor functions to only physics quantity that the study is looking for. As mentioned earlier, considering that this research aims to analyze vibrations that involve mechanical systems or parts of structures, the quantity that we want to evaluate is the acceleration; in order to do this the accelerometer installed on the sensor board MTS310 is used. The accelerometer placed on the mote in question is a kind of biaxial sensor type ADXL202JE, able to measure accelerations both positive and negative up to a maximum level of ±2g. For each axis an output circuit integrated in the device converts an analogical signal into a digital one as a rectangular wave, whose duty cycle D (the relationship between the duration of the active signal and the total period of the signal) is proportional to the acceleration along each of the two axes. The deflection of the structure is measured using a variable condenser, formed by a plate attached to a vibrating mass between two immobile armatures. Acceleration will shift the internal plate putting the condenser off balance, causing the variation of its capacity and consequently a potential difference from which primarily characterized the rest condition. It is this potential difference that will produce the rectangular wave whose amplitude is proportional to acceleration, as mentioned above.

In order to set up a measurement's campaign with instrumentation scheduled previously, a set of preliminary operations was implemented to verify the functioning of the accelerometers installed on the motes. These tasks consisted of instrumentation's offset values estimation that is the value that corresponds to the absence of stress. This kind of analysis was necessary because the different models employed during the studies given were observed, in state of rest, the values of acceleration nonzero and those different from each other. In normal conditions, as it is possible to verify by using traditional accelerometers, it would be logical to expect values along the two axes X and Y close, unless the device's sensibility, is close to the value a = 0 g, if the sensor was positioned perpendicularly to the Earth's gravitational field; or equal to the value a = ±1 g whenever the sensor is set out with one of its axes oriented along the direction of the acceleration of gravity vector. Therefore, not succeeding in solving that problem by bringing modifications to both hardware and software, the accelerometer's potentiality as a static sensor for the detection of tilt angles was exploited.

The operation, conducted in the Laboratory, consisted in orienteering the board along different directions, in order to subject the axes of the sensor to a constant acceleration equal to 1 g (and of course equal to 0g in the direction perpendicular to it) and, measure the value given by the motes and then correlate it with those well-known of 0 g and ±1 g. Such procedure allowed the realization of a calibration curve, characteristic for each sensor, whose correctness is confirmed, even after by comparing the sampled data with the MEMS devices and those obtained with traditional instruments, during in-situ operational measuring.

Afterwards how and to what extent these values used as "offset" were influenced by remaining charge of the cell power has been estimated; in order to do this the sensors are arranged on a metallic support maintained at rest, and there has been measured accelerations values along the two axes were measured and the corresponding voltage values that with the passage of time decreased up to the limit for the operation of the system (about 1900 mV). As shown in the Figure 3, the representative value of the offset decreased over time and therefore with the exhaustion of battery; nevertheless that value overcomes the sensor's characteristic sensitivity only in an extremely long time, and so only for measures of duration exceeding a certain threshold must be taken into consideration, calibrating the offset value depending on the remaining charge.

3 EXPERIMENTAL EVALUATION AND FETERMINATION OF MEASUREMENT ACCURACY

To conclude, in order to verify actual utility of sensor nodes in vibration analysis field for structural health, a measurement in real operating conditions has carried out, employing the sensors installed on the motes and comparing obtained results with those obtained by using traditional devices in the same operating conditions (during that test monoaxial seismic accelerometers AP2050 by AP Tech were used).

Measurement[6] was made by a continuous recording, with a sampling time equal to 100 ms, the vibrations produced by the passage of vehicles and pedestrians over the bridge P. Bucci, located in the campus of the Università della Calabria, Cosenza, Italy and positioning both measurement devices, motes and accelerometers, on a metallic plate arranged parallel to the surface of the bridge, its support in turn lies on a metallic beam that transversally passes through the axis of the bridge. In particular the motes named as MTS310#1 and MTS310#2 were set on one of the same supports used for traditional accelerometers named as ACC#1 and ACC#2. The first one, ACC#1, was placed transversally to the bridge's axis, whereas the second one, ACC#2, was disposed with the axis along the longitudinal direction of the bridge, as shown by the pictures 4 and 5.

While pictures 6 to 9 show time history recorded by the various sensors used during the test. At first sight, the graphical representation of reliefs obtained by the two different typologies of instrumentation seem very different from each other; scanning traditional instrumentation's time history (shown in picture 6 and 7), one can notice how even the smallest perturbations that run over the bridge's axis are recorded and compared with the profile of the rest of the measures. This is due to the fact that the traditional accelerometers' sensitivity, being used for seismographic reliefs, is extremely high and nearly equal to $0.01\ ms^{-2}$, that is an order of magnitude lower than that of the accelerometers installed on the motes. Examining, instead, the Fig. 8 and 9, it is simple to observe how a large portion of information is not more intelligible. In fact it will be possible to note close to zero a strip equal to $\pm\ 0.17\ ms^{-2}$ inside which it is not possible to find a match between the graphics. The amplitude of that band is exactly equal to the sensibility of the device; afterwards more energetic occurrences, represented in the pictures by peak that hacked from that strip, are clearly highlighted, even if the phenomenon's magnitude is not determined by the same accuracy obtained by the traditional instrumentation, right cause of reduced sensitivity of sensors. Ignoring that limitation relevant to the sensibility of instrumentation, how the presence of two peaks is observed, depicted more energetic transits, visualized in the time history recorded with motes and that both transits MEMS accelerometer able to highlight not only the intensity of the passage as well as the direction of the stress.

In order to explain even better what is mentioned in the previous paragraph, it seems appropriate to highlight how particular events, are recorded by the employed devices; in particular observe Fig. 10, regarding the transit of the shuttle-bus by which it is possible to compare the two signals sampled. The picture shows very clearly how the highly detailed accelerogram, reproduced in the bottom of the image, matches a rough description of the phenomenon if you are referring to the profile provided by the mote.

The signal obtained with a traditional accelerometer shows how the phenomenon develops; in fact it is possible to observe, approximately at 12.11.21 how the signal begins to be affected by the arrival of the vehicle, since it increases the amplitude of the oscillations, that reaching the maximum at 12:11:27 (equal to 0.39 ms^{-2}), and another significant value at 12:11:26 (equal to 0.35 ms^{-2}). These values are connected to the passage of the shuttle-bus's axes over the beam on which sensors are placed, in fact as soon as the transport has completely transited, the signal rapidly decreases. Observing the same picture, it is also possible to single out the transit of the shuttle-bus on the previous and on the following beams; these are represented by two peaks, having an acceleration value equal to 0.2 ms^{-2} and symmetric to the maximum value. Analyzing the first graph, instead, it is not possible to obtain all that information, indeed it is possible to estimate, in a less careful way, the value of acceleration (equal to -0.36 ms^{-2}) corresponding to the maximum amplitude, evaluation that, however, appears to be very close to the value recorded by the traditional accelerometer. Considering the minus sign, in fact, unlike the signal shown in the bottom of the chart, the one which represents the signal recorded with the mote allows the identification of the direction of stress.

4 CONCLUSION

To conclude, it is possible to affirm that the state of the art of the sensor nodes used in the field of vibration measurement, and therefore in environmental monitoring oriented for structural health, is still far away from achievement of qualitative standards that allowed the replacement of traditional measurement instrumentation with motes. That is in part imputable both to used sensors types, and to intrinsic deficits its own that stand to the base of that technology. One of the main inconveniences discovered as a result of a prolonged use of these devices is connected to the real duration of batteries in real operating conditions. What in fact was presented as one of the principal advantages of that technology, is the presence of small batteries fit for set free instrumentation from using more cumbersome supplies that would have limited the use and reduced the points of applicability, is actually far away from portraying strength. In fact, as highlighted by the second static test led, the characteristic offset value of each sensor is affected by the remaining charge held by batteries and in the long run it decreases with the unwinding of these. A possible solution to that inconvenience has been adopted in the latest generation sensors, equipped with charging systems of batteries via photovoltaic panels put on the devices' surface or through a series of piezoelectric and pyroelectric crystals which allow, when motes are hit by vibrations or heat, producing current, through the motion of excited crystals, which re-charge batteries. That ensures a constant voltage supply, or at least continuously close to the initial value, which corresponds to the offset value determined in the laboratory. At the present time, to ensure low power consumption, it is possible to predispose devices, by setting up a trigger set according to operating conditions, and sending values that exceed a predetermined threshold value, maintaining instrumentation dormant for the rest of the time.

Another inconvenience highlighted by tests conducted is portrayed by not highly sensitivity of accelerometers installed on the sensor boards, a characteristic that causes the loss of events with intensity less than a certain threshold. Considering, however, the purpose for which instrumentation needs to be used, that problem is not a limit to the use of sensor nodes, as stresses which should represent a grave danger for structural health are bigger than current threshold value. Obviously, achievement of greater sensitivity allowed sensor nodes use to affect vibration analysis about structures, warranting the possibility to investigate not only high intensity phenomena. The results obtained with the last tests are, nevertheless, encouraging and give hope for a quick solution to the problem. At the current state of the art, a characteristic that renders these devices very interesting is their inexpensiveness compared to other systems and their capability to send data package via radio, avoiding the use of cables and other transmission systems.

Considering that these instrumentations still do not allow quantitative analysis, but only qualitative ones, at the current state of the art, the sensor installed on motes can provide valuable guidance on the emergence of vibrant phenomena and we can safely say that they can find application as an alert system if there are any events of intensity. Of course, therefore, it is important to be able to individualize the system to increase the sensitivity of the sensors: the result of carrying out quantitative analysis of the phenomena in a simple and economical way could be achieved.

This work, therefore, intends to be a stimulus and a starting point for initiating new research through which we can develop and increase the use of these sensors in the vast field of environmental monitoring.

Future goals of such research will consist in the analysis of devices characteristic hardware and software, to improve, with dynamic tests using vibrating bars, instrumentation's sensitivity.

5 ACKNOWLEDGEMENTS

This research has been made possible thanks to Regione Calabria, within a PhD project, founded by a FSE – Fondo Sociale Europeo – scholarship.

6 REFERENCES

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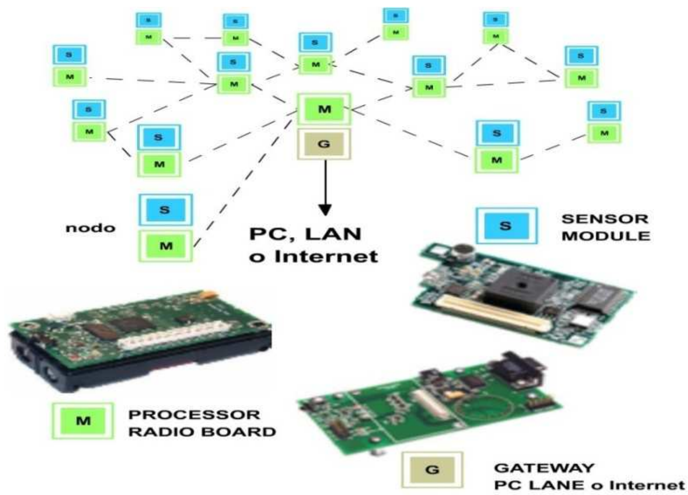

Fig. 1 - Topology of a generic Wireless Sensor Network WSN

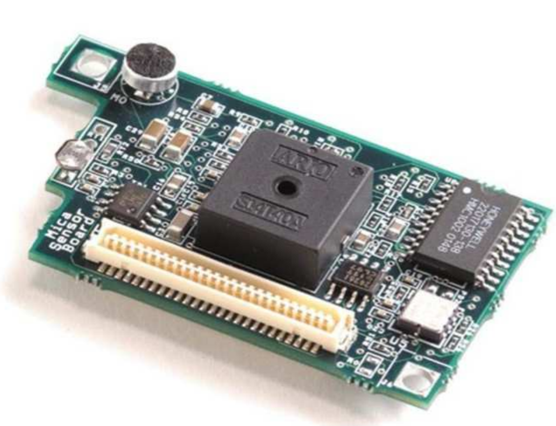

Fig. 2 - Sensor board MTS310 used for acceleration measurements

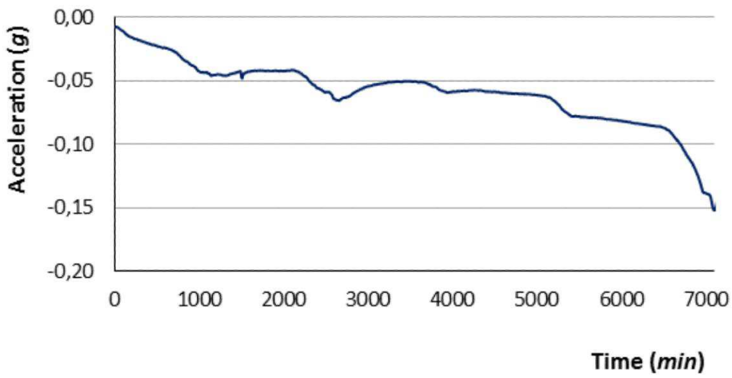

Fig.3 – Variation in offset value due to variation of supplied voltage

Fig.4 – Arrangement of sensors on the bridge axis

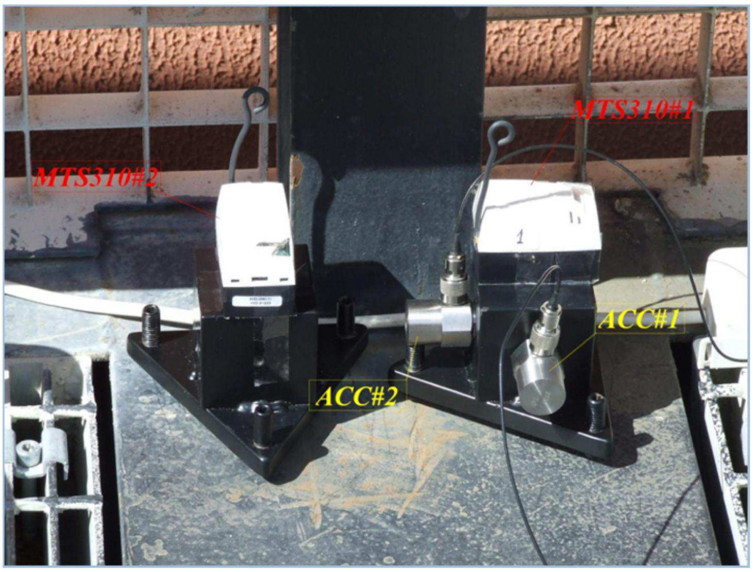

Fig.5 – Detail of the sensors layout on the bridge axis

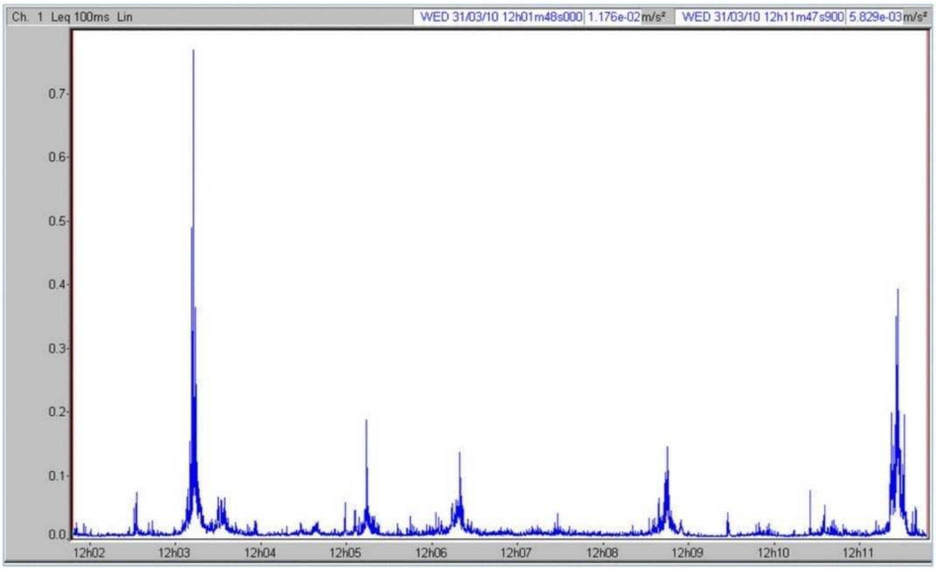

Fig.6 – Time history recorded by traditional accelerometer Acc#1 (transversal bridge axis)

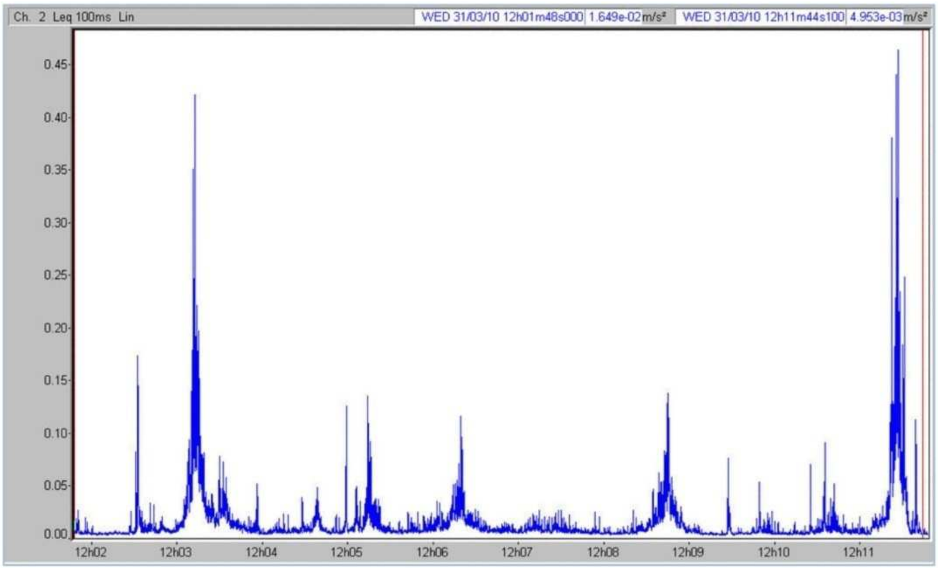

Fig.7 – Time history recorded by traditional accelerometer Acc#2 (longitudinal bridge axis)

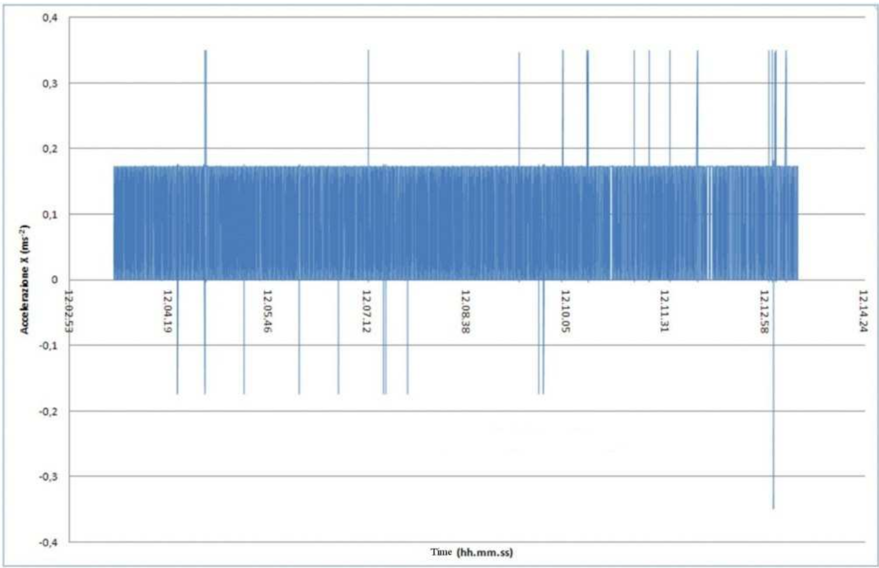

Fig.8 – Time history recorded by mote MTS310#1 along the X axis (transversal bridge axis)

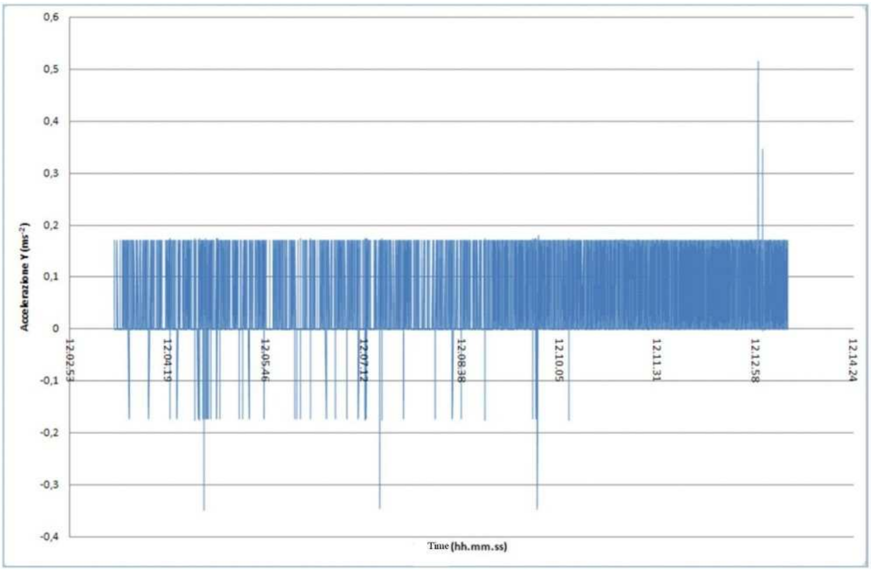

Fig. 9 – Time history recorded by mote MTS310#2 along the Y axis (longitudinal bridge axis)

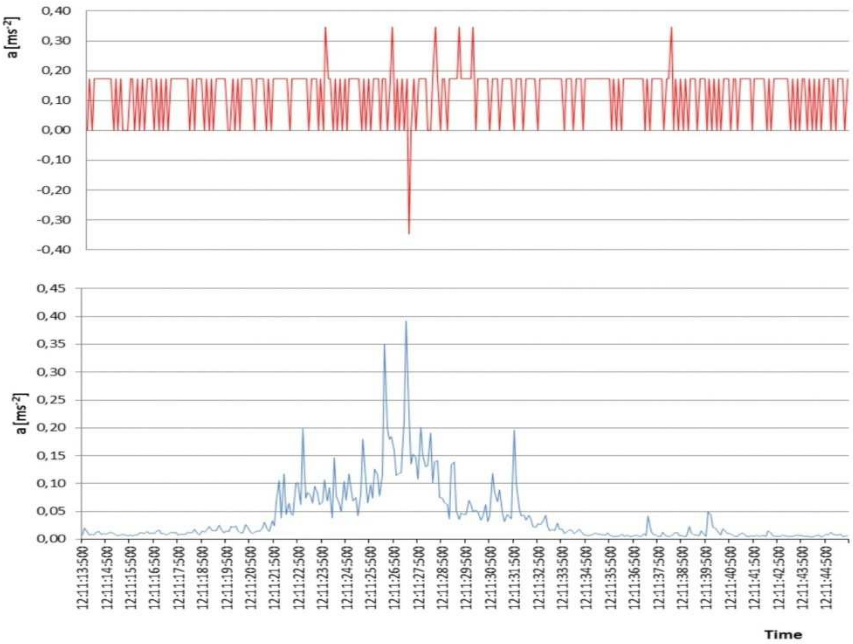

Fig.10 - Comparing the time histories measured with the mote MTS310# and the accelerometer Acc#1 during the shuttle-bus transit