MEMS-based system for structural health monitoring and earthquake observation in Sicily

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Abstract. The implementation of systems for Structural Health Monitoring and Earthquake Observation is increasing in the last years owing to the development of new technologies which enable low-cost and small-size devices to be installed in large-scale or high-density applications. This paper introduces the implementation of monitoring systems, either for structural health assessment and earthquake observation. The applications are based in Sicily (Italy), a region characterized by a high seismic hazard and where the buildings are often old and vulnerable. The system relies on a MEMS (Micro Electro-Mechanical Systems) sensor, a 3-axial accelerometer which has been specifically selected in order to ensure the suitability for the specific applications: accelerations from 10^0 to 10^2 Hz. We present the details of the designed monitoring station, of the network architecture, and some of the recorded data.

Keywords: Structural health monitoring, Urban seismic network, Earthquake observation, Seismic risk reduction.

1. Introduction

The implementations of systems for Structural Health Monitoring (SHM) and Earthquake Observation (EO) are highly increasing in the last years, when the limitations deriving from the traditional systems have been overcome. Such limitations basically consist in the high costs of the traditional instruments and in the difficulty to maintain, the monitoring systems in the long-term (e.g. a decade or more) after their implementation. For this reason the SHM and EO systems have been usually limited to small-scale or low-density applications with poor technical and scientific results. The advancements in term of miniaturization, sensitivity, and quality of data made possible to overcome the compromise between technical-scientific needs and the economic affordability. As a consequence, the implementation of SHM and EO increased really fast in recent time. Refer to [1, 2] for an overview of the applications in Italy.
Kinematic (acceleration, velocity, displacements), physical (temperature, humidity), or mechanical (forces, strain) parameters can be monitored by means of different types of sensors [3]. The traditional inertial sensors for the measure of kinematics parameter are based on a spring-mass mechanism and have heavy proof masses making them bulky

and difficult to transport and manage. The development Micro Electro-Mechanical Systems (MEMS) as inertial sensors (but not only) characterized by reduced size, weight, and cost played a primary role in such rising of SHM and OE systems [4]. Similarly, advancements regarded the robustness and the reliability of the systems, the capability of data transmission in terms of frequency rate and amount of information, the computational capability for data processing, and also the lowering of power consumption. In this paper we introduce the realization of the MEMS-based, real time monitoring system and its implementation for SHM and EO in Sicily (Italy).

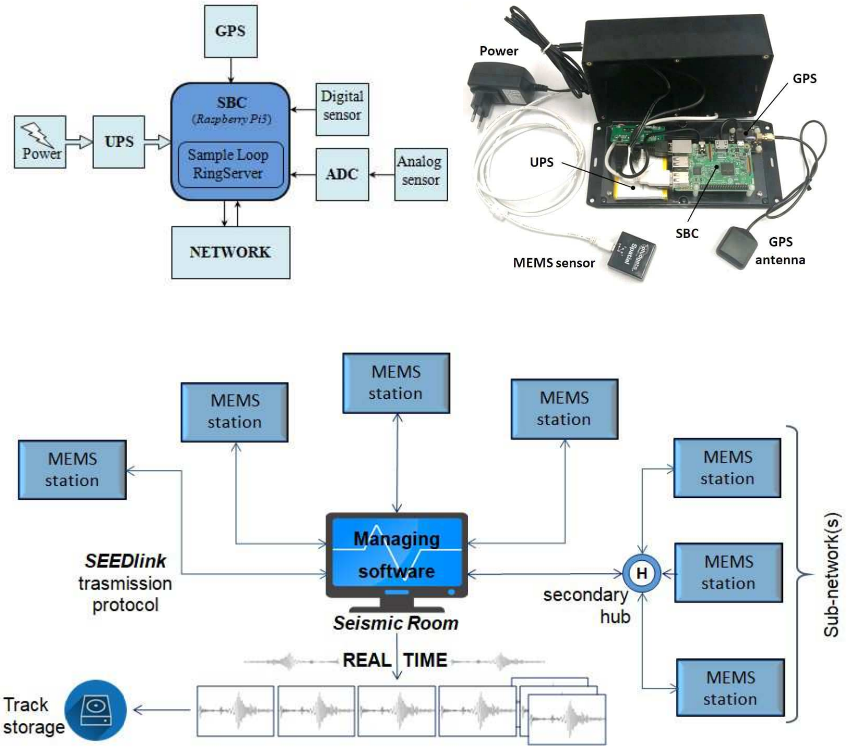

Fig. 1. Working scheme of the monitoring station (top left), the assembled station equipped with the digital MEMS accelerometer (top right), and scheme of the monitoring network (bottom). See the text for further details.

2. The monitoring system

The monitoring system consists of a single-board computer which manages the acquisition and the transmission of data through a dedicated code (Fig. 1). The main sensor is a 3-axial MEMS capacitive accelerometer with digital output. This sensor is suitable for dynamic accelerations in the range of ±2 g, it is characterized by a measure resolution of 76.3 µg, and white noise of 280 µg. Several studies indicate the suitability of such devices for earthquake and structural monitoring systems [5-10] when they are characterized by flat noise response to acceleration and resolution (smallest detectable acceleration) in the order of 10^{-2} – 10^{-3} m/s^{-2} [4].

A devoted software for the acquisition automatically runs cyclically, sampling the data at frequency of 200 Hz. Three waveform files, one for each component, are written in miniSEED format which is a standardized protocol for the exchange of earthquake data used by seismologists worldwide. The data transmission exploits a ring-server conceived by the Incorporated Research Institutions for Seismology (IRIS) which runs continuously and cyclically. The synchronization of the signals between the various stations is fundamental and is ensured by a GPS or, alternatively by a NTP server (Network Time Protocol). Finally, the monitoring station carries a 5,200 mAh power bank (UPS) to stabilize the energy flux and to provide power supply in case of temporary black-out.

Every monitoring stations is linked to a main hub by means of internet connection to form a monitoring network. The network topology chosen for the SHM and OE applications is a star network where each host is connected to a central hub with a point-to-point connection (Figure 1, bottom). This topology has been chosen because it complies with the main needs of our system: flexibility and reliability. From the hub can depart *n* linear connections, therefore further devices (i.e. monitoring stations) can be added or removed without disturbing the network. Moreover, two or more end-points can be merged in a sub-network and, similarly, two or more networks can be merged into a unique network simply connecting their hubs. Every node (i.e. monitoring station) can be accessed remotely to fix possible malfunctions or to update the software. The set-up and the arrangement of the monitoring stations at the sites, and within the edifices, have been accurately planned.

All the details about the device, the hardware and software components, and about the code and the can be retrieved in the technical report by [11].

3. Case studies

The MEMS-based systems have been implemented in Sicily (Italy), a region where the seismic hazard is high (Fig. 2). In such context, the vulnerable historic buildings often represent the most exposed place to seismic risk. Some prototypal urban seismic networks implemented in relevant public buildings are being installed in municipalities of Acireale, Catania, Messina, Noto, Ragusa, Santa Ninfa, and Siracusa (Fig. 2), located in the areas struck by strong earthquakes (M>6) several times during history (1169, 1542, 1693, 1818, 1908, 1968).

The monitored building are the strategic (for its function or value) ones in the selected municipalities. SHM is a fundamental tool to integrate and support conservation strategies of infrastructures and to preserve their strategic function (i.e. security, management, organization) and the architectural heritage. SHM should be considered necessary, at least for public edifices with strategic function, since stress factors acting on all the structures (either natural or anthropogenic) lower their resistance properties and may induce potential risks in the long-tem.

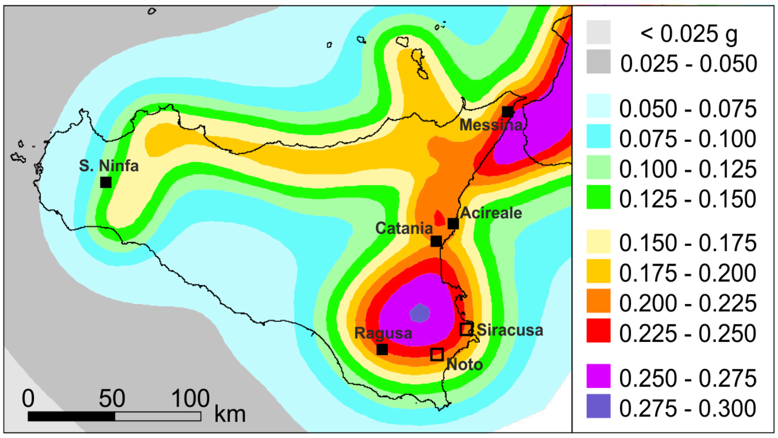

Fig. 2. **S**eismic hazard map of the Sicily region from http://zonesismiche.mi.ingv.it/. Colours indicate the peak ground acceleration with probability of exceeding equal to 10% in 50 years. The black full squares indicate the installed monitoring networks, the empty squares the planned ones.

Considering the scheme of a generic multi-storey building in reinforced concrete, the literature suggests to install sensors at every level and in correspondence with changes of stiffness for buildings with irregular scheme [12]. The sensors at the base of the building would also provide an almost unaltered record of the input motion which can be used as ground motion reference . For the masonry buildings, the scheme of a regular multi-storey one [13] can be directly reused taking account the numerous irregularities that often occurs in the historic edifices (Fig. 3). Therefore, it is necessary to consider the type and quality of connection between the walls, before to proper positioning the measuring points. All the sensors were levelled on the horizontal plane and the horizontal components accurately oriented along the N-S and E-W directions in order to have a unique reference systems for the signals at every station (Fig. 3).

Fig. 3. Operation of installation and configuration of a monitoring station at the ground floor of the 18th century "Elefanti Palace" located in the main square of Catania (Sicily Italy). Schemes for the sensors' distribution into edifices: a) minimum necessary requirements for a regular multi-storey building, and b) ideal extensive installations for irregular masonry buildings.

4. Results

The MEMS-based monitoring system enables the real-time structural health monitoring of the key infrastructures playing the major role during a crisis. The monitoring represents also the base for the fast damage assessment of the urban area in case of damaging events. The stress factors acting on the structures can be due to natural or anthropogenic factors: seismic events, atmospheric agents (wind, thermal cycles), vibration due traffic flow, applied loads, lowering of the resistance properties (corrosion, alteration, etc.) which effects can be assessed by means the appropriate monitoring (c.f. [3] for a complete review).

The SHM allow also to compile a register of historical data, and to create files for post-processing. Moreover, in case of strong earthquake, the monitoring stations allow to study the site response due to local geological conditions and also to assess the structural health and the characteristic features of the buildings. In fact, the analysis of the recorded signals enables to characterize the input signal (e.g. the earthquake) and the output signals (i.e. the edifice shaking) allowing, in a successive phase, to describe the relationship between the shaking level at the site and the variation of the equivalent structural modal parameters, while keeping into account the effects of soil–structure interaction.

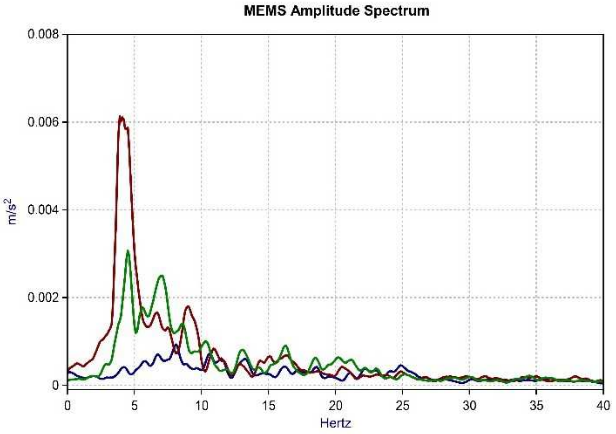

Fig. 4. Amplitude spectra of the seismic signals (unfiltered accelerations) recorded in a monitored building in Santa. Ninfa after the M_L 3.1 earthquake occurred on October 10th, 2018. (modified from [11]). Blu line: Up-Down component; red line: North-South component; green: Est-West component.

As example, we show the amplitude spectra recorded by the MEMS-based monitoring station installed in the second floor of a reinforced concrete building (the Town Hall of Santa Ninfa municipality) after a moderate earthquake (M_L 3.1) at about 5 km distance (Fig. 4). The spectra of the horizontal components (red and green lines) show a main peak at about 4 Hz which is ascribable to the resonance of the building under the seismic shaking [11].

5. Conclusive remarks

Such designed monitoring systems with real-time transmission and small-scale design (buildingor urban) represent powerful tools for several tasks in the post-earthquake scenario which can be summarized with a continuous chain of actions, before, during, and after the arrive of the seismic waves at the nodes of the network. These tasks include the rapid assessment of earthquake damage through the automatic production of intensity maps (shakemaps), the procedures for search and rescue, the seismic microzonation. However, the most relevant future development in the near future would the realization of an on-site early warning, systems [14].

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