STRUCTURAL HEALTH MONITORING SYSTEMS AS A TOOL FOR SEISMIC PROTECTION

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ABSTRACT :
Structural Health Monitoring for civil structures is becoming increasingly popular in Europe and worldwide also because of the opportunities that it offers in the fields of construction management and maintenance. Reduction of inspection costs, research, with the possibility to better understand the behaviour of structures under dynamic loads, seismic protection, observation, in real or near real-time, of the structural response and of evolution of damage, so that it is possible to produce post-earthquake scenarios and support rescue operations, are the main advantages related to the implementation of such techniques.

Thus, Structural Health Monitoring is a very multidisciplinary field, where a number of different skills (seismology, electronic and civil engineering, computer science) and institutions can work together in order to increase performance and reliability of such systems, whose promising perspectives seem to be almost clearly stated.
Among the main issues currently on field, it is worth mentioning the development of sensors characterized by increasing performances and of wireless sensors networks, techniques for modal parameters identification and for damage detection. Sensor technology, however, develop faster than algorithms for modal identification and damage detection.

In this paper, a Structural Health Monitoring systems network designed by University of Molise and University of Naples "Federico II", and currently under implementation, is described, pointing out the solutions adopted to build a reliable SHM system. At completion, such a system will cover a wide range of structures over Molise and Neapolitan territories, taking advantage of its distributed infrastructure and of opportunities given by IT.

KEYWORDS:
Structural Health Monitoring, seismic monitoring network, automated operational modal analysis

1. INTRODUCTION

Structural health monitoring and damage identification are assuming larger and larger importance in civil engineering. Structural Health Monitoring (SHM) is defined as the use of in-situ, non-destructive sensing and analysis of structural characteristics in order to identify if a damage has occurred, define its location and estimate its severity, evaluate its consequences on the residual life of the structure (Silkorsky, 1999). Even if SHM is a relatively new paradigm in civil engineering, the assessment of the health state of a structure by tests and measurements is a common practice, so that evaluation and inspection guidelines are available since a long time (Mufti, 2001). SHM objectives are consistent with this practice but it takes advantage of the new technologies in sensing, instrumentation, communication and modeling in order to integrate them into an intelligent system.

Informations obtained from such systems could be useful for maintenance or structural safety evaluation of existing structures, rapid evaluation of conditions of damaged structures after an earthquake, estimation of residual life of structures, repair and retrofitting of structures, maintenance, management or rehabilitation of historical structures. As reported in (Aktan et al, 1999; Chang, 1999), reduction of down time and improvement in reliability enhance the productivity of the structure and the results of monitoring can be used to have a deeper insight in the structural behavior which is useful for design improvement of future structures. In order to get all these objectives, an effective Structural Health Monitoring system should be based on integration of several types of sensors in a modular architecture. Moreover, the advances in the field of Information Technology and communications assure data transmission also in critical conditions.

In this paper some aspects related to the implementation of an integrated SHM system covering several structures on a wide area is analyzed in detail, and some preliminary results will be discussed.

2. CURRENT TRENDS AND FUTURE DEVELOPMENTS IN THE SHM FIELD

A monitoring system consists of a variety of sensors to monitor the environment and the structural response to loads. A typical architecture of the monitoring systems is based on remote sensors wired directly to a centralized data acquisition system. However, the expensive nature of this architecture, due to high installation and maintenance costs associated with system wires (Lynch 2002), is causing replacement of wire-based systems with new low-cost wireless sensing units by spreading knowledge over the entire monitoring network. As a consequence, a larger effort is currently required in order to build effective data processing algorithms, in particular taking into account such a new architecture. Another relevant task is related to the strategies to be implemented to manage data and combine informations coming from a variety of sensors and, therefore, related to different physical variables.

In the field of damage detection, a lot of algorithms has been proposed on the base of several different mechanical and physical principles. However, they can be classified into two main classes: a first group of techniques, the so-called “modal-based” algorithms, aims at tracking changes in structural response directly or indirectly related to the mechanical characteristics (such as natural frequencies, etc.) of the structure before and after damage. Conversely, the second approach is based on the post-processing of measurement data to detect anomalies from measurements (ARMAV modelling, wavelet decomposition, etc.). In both cases, the trend is in using methods able to automate the detection process by taking advantage of the recent advances in information technologies (Aktan, 2005). In this framework, identification of the modal parameters of the structures under operational conditions plays a primary role. Recently, some strategies have been set up in order to automate identification and tracking of modal parameters (Rainieri et al., 2007a; Brincker et al., 2007; Guan et al., 2005; Verboven et al., 2001) and allowing a full integration of modal identification within SHM systems.

Reliable procedures are necessary also towards data reduction and transmission, in particular after an earthquake, when a limited communication bandwidth is available: wavelet-based approaches seems to be particularly promising in this field (Li et al., 2007; Mizuno and Fujino, 2007). However, real-time interpretation of data can fail due their poor quality and, in particular, in case of sensors failure: therefore, in case of automated applications, this verification must be conducted by the data processing system itself. Recently, some interesting approaches have been proposed in this field (Kraemer and Fritzen, 2007).

The most recent and innovative applications concern of possible interaction among earthquake early warning, structural health monitoring and structural control. However, unlike traditional seismic monitoring, an event driven monitoring system is not useful: continuous condition assessment and performance-based maintenance of civil infrastructures are necessary in order to assess the short-term impact due to earthquakes and the long-term deterioration process due to physical aging and routine operation. In this framework, a monitoring system can be used for disaster and emergency management, traffic control, damage evaluation, post-earthquake scenarios definition. The use of monitoring systems on underground pipeline systems may be considered as an example of post-earthquake emergency management: damaged gas utilities, in fact, can cause secondary disasters and, as a consequence, serious losses. In this case, informations about abnormal pressure changes in gas pipelines can lead to an emergency shut-off. Similar controls can affect traffic, if informations about structural integrity of infrastructures are available. Knowledge of still operable bridges can help decision makers to arrange a route to the disaster area for rescue personnel and goods.

3. DESIGN OF AN INTEGRATED SHM SYSTEM FOR A WIDE AREA

As discussed in the previous section, a SHM system can have different purposes, related to operational and extreme event conditions: in particular, an integration with early warning systems is possible. However, SHM and EEW systems have different requirements in terms of reliability and speed of communication. Internet technologies and the recent advances in communications allow real-time monitoring of structures but the consequences of extreme events on data transmission systems have to be taken into account when early warning applications and disaster management are considered. This aspect is less critical for traditional structural monitoring where backup procedures avoid data losses through a local data storage. In order to face the occurrence of a limited bandwidth for data transmission, two strategies are usually considered: employment of redundant vectors for data transmission, reduction of the amount of data to be transmitted (Li et al., 2007). Both strategies have been used for design of an integrated SHM system at University of Molise, even if most of the attention has been focused on data processing algorithms, in order to build a reliable and fully automated monitoring system and, at the same time, to obtain a reduction of the amount of data to be transmitted.

The new monitoring system has been conceived in order to be able to monitor several different structures at the same time over a wide territory. A distributed knowledge is assured and each part of the system can work independently from the others.

In Figure 1, architecture of the monitoring system is showed. A local server will be installed near each monitored structure: it will assure a local data storage on a database. However, in order to reduce the amount of data to be sent to the master server, a certain amount of knowledge has to be spread over the monitoring network. At the moment, only damage detection procedures based on changes in modal parameters have been considered; however, since the system under development is based on LabView environment, new modal identification and damage detection procedures can be easily integrated by minor changes in the system, which will be thoroughly based on home-made software.

An automated modal parameter identification and tracking can be carried out locally using a specific software tool described in (Rainieri et al., 2007a; Rainieri et al., 2008) and shown in Figure 1e, when it is performing its tracking of natural frequencies and mode shapes of the monitored structure. In this way, some days of raw data will be stored on the local database and cyclically deleted, while just the obtained modal parameters will be sent to the master server for health assessment and visualization, but also to have a deeper knowledge of the dynamic behavior of the structures in operational conditions.

If a seismic event occurs, a link with seismic stations installed over the territory will allow identification of such events so that related data can be stored apart and never deleted. These data will be available for further more detailed analyses of the performances of the monitored structures subjected to a seismic event, allowing a deeper knowledge of the dynamic behavior of structures under strong motion excitation.

Adoption of local processing reduces the amount of data to be transmitted and this is particularly useful in the post-earthquake phase. However, redundant vectors for data transmission will be provided: in fact, information coming from the monitored structure could be used also for disaster management (if the monitored structures are bridges, for example) and therefore a reliable data transmission system is a critical part of the system design.

The first prototype of the system is going to be installed on the School of Engineering at University of Naples (Rainieri et al., 2007b) and on a building and in a flexible retaining wall at University of Molise, about 200 km far from the first one. Both systems are provided of geotechnical sensors, on foundations in the first case and in the retaining wall and in free field in the second, in order to study the soil-structure interaction under dynamic loads for these two structural typologies. In Figure 2 a phase of installation of sensors and the head of the instrumented piles during concrete casting and before completion of the wall are shown.

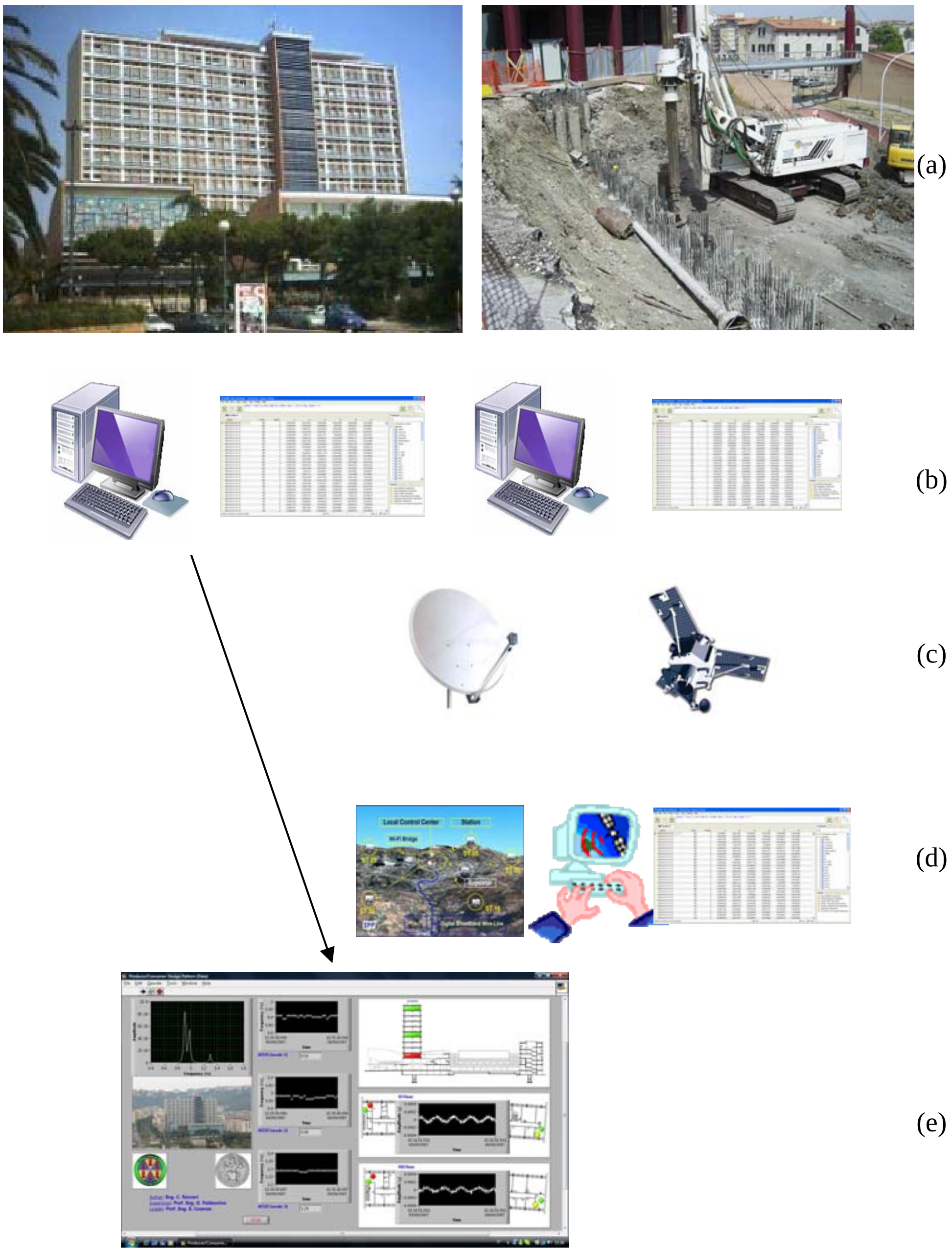

Figure 1 SHM system architecture: (a) monitored constructions, (b) local server, (c) data transmission, (d) seismic network and master server, (e) control panel

Both structures are mainly instrumented through accelerometers, even if employment of different sensors, such as strain gauges or fiber optic sensors, cannot be excluded. Specific procedures for the evaluation of the effectiveness of sensors will be implemented and integrated into the monitoring system on the local server, which will judge autonomously on data quality.

The designed system will be an interesting application of integration between structural health monitoring and seismic early warning: in fact, both approaches of early warning, the regional one and the site-specific one (Wald et al., 1999; Wieland et al., 2000), could be extensively tested. In fact, the SHM system in Naples, taking advantage of the link to the seismic network issued in the framework of the AMRA center (Weber et al., 2006), can be used as a benchmark for regional seismic early warning, since the fault is located about 100 km far from the structure. The SHM system of University of Molise, instead, operates on a small scale regional area, so that site specific early warning systems seem to be reliable.

Figure 2 Installation of sensors (left) and the instrumented piles during preparation and concrete casting (right)

4. PRELIMINARY RESULTS OF AUTOMATED MONITORING

Integration among all these different (structural, geotechnical, seismological) systems is mainly achieved by a number of MySQL database for data storage and remote query. The LabView software for automated extraction of modal parameters (Rainieri et al., 2007a; Rainieri et al., 2008) is able to access over the Internet to the remote database and can continuously download datasets for processing. In Figure 3 monitoring results in terms of natural frequencies for the first three modes of the School of Engineering Main Building at University of Naples are reported. They are referred to more than two days of continuous monitoring. As shown in Table 4.1, these results (obtained by considering a frequency resolution of 0.01 Hz) are in perfect agreement with those ones obtained by a classical output-only test carried out by the Frequency Domain Decomposition technique (Brincker et al., 2000); moreover, the system is able to track changes in modal parameters due to environmental factors (i.e. temperature) and, eventually, damage.

Table 4.1 Statistics on values of natural frequencies (Automated FDD) in comparison with single test results

Mode number	**Mode** [Hz]	**Mean** [Hz]	**Standard deviation**	**Single test (FDD)** [Hz]
1	0.91	0.91	0.0063	0.92
2	0.98	0.99	0.0062	0.98
3	1.29	1.29	0.0054	1.29

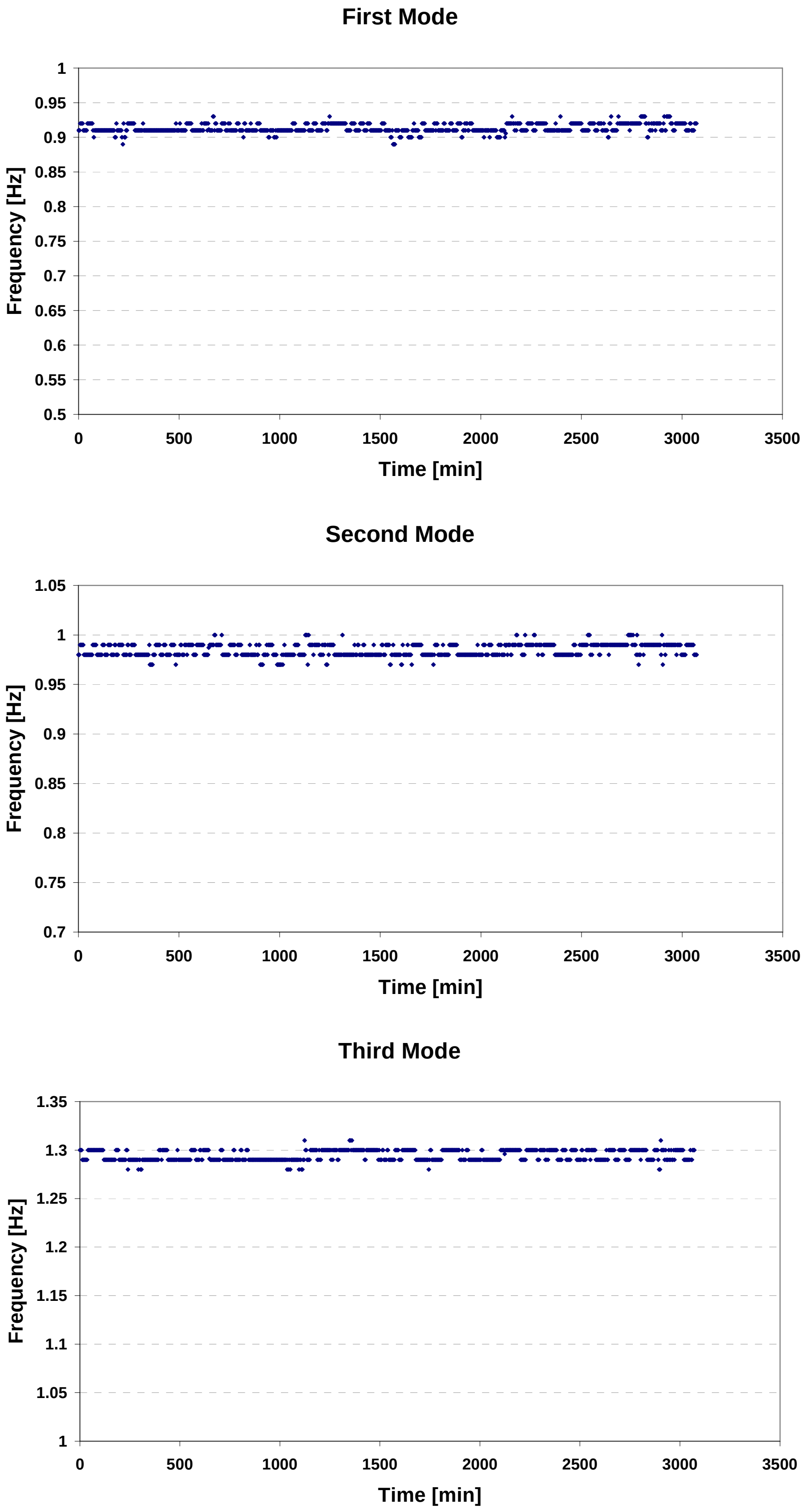

Figure 3 Automated identification results of natural frequencies for the first three modes of the School of

Engineering Main Building at University of Naples

4. CONCLUSIONS

Health monitoring of structures is becoming more and more important: its ultimate target is the ability to monitor the structure throughout its working life in order to reduce maintenance requirements and subsequent downtime. Currently, visual inspection is the standard method used for health assessment of structures, along with non-destructive evaluation techniques. However, most of these techniques require a lot of manual work and a significant downtime. Thus, currently an increasing interest in SHM is rising, because it can provide cost savings by reducing the number of manual inspections (Achenbach, 2007). MEMS and wireless sensing are becoming desirable features in SHM systems and there has been a large development of new sensors during the last years. However, optimized and autonomous SHM systems are still not so spread.

In this paper, after a review of some sample cases worldwide, some aspects related to the implementation of an integrated SHM system covering several structures on a wide territory has been analyzed. An effective Structural Health Monitoring system has been designed based on integration of several sensors and hardware components in a modular architecture. Even if the advances in the field of Information Technology and communications assure data transmission also in critical conditions, it is worth noting that availability of procedures able to reduce the transmission data volumes is a key aspect for reliability and sustainability of infrastructure, in particular when several constructions are monitored at the same time by a single master node. The distributed structure of the system, based on local and master nodes, and the availability of automated modal parameters identification and tracking procedures, will ensure a significant reduction of the volume of data to be transmitted, so increasing the performance and the reliability of the system. It will be based on integration of several procedures in a home-made software developed in LabView environment and will be an interest benchmark also for early warning applications.

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