

S.H.M. ON HISTORICAL HERITAGE: ROBUST METHODS TO FACE LARGE UNCERTAINTIES

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Abstract

Architectural heritage is a resource and a fundamental part of the cultural European background; it also causes concern, due to the huge investment needed to maintain it, or even to repair it after environmental injuries. The title recalls the subject of an Italian National project. The aim of the project is developing commercially available, user-extendable wireless and optical sensor products and technologies to mainly address the issue of the conservation of masonry architectural heritage. These technologies allow for the dense instrumentation of structures at relatively low-cost. In addition to the technological aspects of developing new kinds of sensors smaller and cheaper than the traditional ones, with particular attention to the fibre optics and MEMs, a common software and communications framework is required to allow the sensors to communicate, share information and estimate the structural state. Secondly, more traditional techniques of modal identification, probabilistic safety assessment and structural control, which already constitute a consolidated background of the proponent research group, will be available as a support tool.

Key words: *Structural Health Monitoring, Historical Masonry, Sensors, Structural Identification, Stochastic Model Updating.*

1. Introduction

Structural maintenance of historical buildings requires knowledge based strategies. To a structural engineer, knowledge means to keep under control, in real-time or nearly real-time, all the parameters governing the stability, bearing capacity and safety of the existing structure.

In many countries worldwide, especially in Italy, there is an impressive amount of historical and architectural treasures. They are in need of effective maintenance strategies that cannot be achieved without a reliable real-time or quasi-real-time knowledge of the structural behavior. Mechanical properties of ancient masonry are highly uncertain. This makes that every stage of the mechanical characterization,

from sensing system design and location to model updating, should be robust. Robustness against local property changes and spatial scattering requires distributed sensing and appropriate data mining and data fusion techniques, allowing to reduce data redundancies and to save only the useful information. This goal is among the main target of a proposal for an Italian national research project, coordinated by the Authors and involving 9 Italian Universities.

The research covers the following aspects:

- preliminary risk analysis;
- optimization of the measurement network;
- design of the signal acquisition procedure and sensors choice; dislocation of the permanent sensors in order to obtain the automatic monitoring system be sensitive to possible damage and defects;
- testing and assessment of the permanent sensor systems on few, well known, sample real structures;
- dynamic measurement acquisition and elaboration, in order to perform the identification and the symptom based diagnosis, according to the criteria stated further on;
- linear and non-linear numerical modeling, model updating and safety evaluations;
- model based formulation of retrofit solutions as a function of the experimental knowledge degree and the on line monitoring efficiency, including passive and semi-active control strategies.

The set of experimental data and the results produced, in the future shall be organized in formats and structures proper to be inserted in a common data base, according to European and international standards. In fact, one of the target points of the whole research was to produce data easily accessible and manageable.

2. Facing the problem of the large mechanical and geometrical uncertainties

Ancient masonry structures show widely uncertain mechanical properties due to the following reasons:

- not always local irregularities of geometry and internal masonry texture are visible; they can involve lack of material continuity, hidden empty volumes, walls roughly filled by debris;
- out-of plane rotation of originally vertical walls, laterally loaded by vaults, arches or roofs;
- local variability of the material strength and stiffness, due to original defects or electro-chemical degradation;
- distribution of cracks, subject to thermal path (seasonal width oscillation with basic trend to increase continuously, due to cumulated debris inside the crack,);
- effects of past, none documented, damages and repairs, architectural changes, local manipulations.

Inspections, by means of endoscopes, thermographs, radar, metal detectors; physical measures, via sonic tomography; or geometric measures, by photogrammetry, or other available technologies, can be executed once only or periodically to improve the

knowledge level and to reduce the uncertainties. False color images and spectrometry can reveal the chemical degradation.

All those observations and measures help largely to improve the knowledge level, but supply only local information, generally not automatically extendable to the whole structure. They shall be repeated wherever, in the structure, a better information is required. Usually budget limitations reduce the number of locations where such controls can be done; the result is a spot knowledge, very useful but often arbitrarily assumed as representative of the whole construction body.

Reliable evaluations of the bearing capacity and ultimate strength shall come, fundamentally, from destructive testing, but very seldom the extraction of samples is allowed in case of important architectural heritage; even in case that some extractions are allowed, they are always few, again only locally significant and statistically not relevant. Sometimes spare bricks or stones are collected from the real structure and assembled in the lab by means of a new-cast mortar. The bearing capacity of the structure is strongly dependent on the quality of mortar, so destructive testing on such reconstructed samples may prove non realistic.

Thus, so as in every case when each knowledge source is poor, it is necessary to use as many different sources as it is possible. Local inspections should be integrated with global measures using dynamic testing.

Dynamic tests supply information about the whole-body response, although local defects and irregularities can result often hidden and their influence on the whole-body response can be not so clear; anyway they can make it less arbitrary and more reliable to extend to the whole body the outcomes of the local inspections and measures.

3. “Robust” monitoring

In technical language the word “robust” applies to every algorithm, process, method or technique able to reduce the sensitivity of analysis results against input data errors or uncertainties. “Robustness” is often associated with the “Complexity” domain related to uncertain, redundant data treatment, multi-variate event interactions and non-linear problems.

Robust monitoring does not obey to stiff and always valid rules, but one can trace some general criteria to better understand and define its domain:

- stochastic approaches give more reliable answers than the deterministic ones; the concept of correlation shall replace the concept of causality;
- redundancy of data is helpful;
- In case of limited or uncertain knowledge, the search for upper and lower bound values of an analysis result can be more reasonable than the search for an exact solution;
- parallel computing processes can be more robust than sequential computing processes;
- optimization procedures are often required to make that numerical models fit well the experimental evidence.

Sensor Networks, MEMS and Data Mining

A preliminary risk analysis should always drive the measure system design. The goal is to build-up a priority list of the expected damages and structural problems. Such

kind of approach philosophy, although potentially useful for every SHM application, is not always easy to apply concretely, due to lack of systematic knowledge-bases related to observed damages in similar structural objects in the past.

The preliminary risk analysis is useful to select in rational way the kind of information needed and to design, consequently, the most effective sensors networks. If a reliable knowledge base is not available, then numerical analyses on realistic FE models can offer some help.

Anyway, due to the large uncertainty level on the consistency and behavior of ancient masonry structures, an effective structural health monitoring action requires distributed sensing capability and redundant in space and time data collections. Distributed sensing means many sensors and a huge amount of data to handle.

Of course “many sensors” implies “low-cost sensors” and “huge amount of data” implies the necessity of techniques to select, pack, compact them and architecture of the sensor networks allowing a hierarchical behavior and a local pre-elaboration in the peripheral nodes of the network.

Recent technological progresses in micro-electro-mechanical systems (MEMS), wireless communications and digital electronics have allowed the development of a Sensor Node, that is small multifunctional low power and low costs devices, which are able to communicate between them through limited beam wireless technology. These small Sensor Nodes are composed by components able to find perceptions, elaborate data and communicate each other. Figures 1 and 2 show sensors developed at Politecnico di Torino using micro-technologies and MEMS (Chilab)

The sensor nodes inside a network cooperate reciprocally. Indeed, nodes are provided with an on-board processor; therefore, every node, instead to send "crude" data to the nodes responsible of the data gathering can just carry out simple elaborations and transmit required and already processed data [1]. A very important problem to consider while realizing a sensor network of this type is the one of the energetic consumption. Just for this reason such networks are realized with cross-layer architecture in which the sensors are distributed on routing tree, that concurs to optimize the transmission of the data between the sensors and with the node sink, allowing the maximum energetic saving.

Recently data mining techniques have been introduced the in such sensor network in order to obtain better results in the monitoring.

In particular, e.g.:

- Clustering (see more references in [2]): that is used for the partition in a jam of data;
- Fuzzy ART (Adaptive resonance theory; find wider information in [2] and [3]): this technique helps on giving architecture to the sensors in the network, when they operate within unsupervised learning with a consequent characterization of the input from sensors.
- Algorithm EM (see more references in [2] [3]): this is an optimization of the data analysis procedure data are supplied from a not perfectly working sensor network. The imperfect operation of a network is due to the energy failure in the nodes or to the malfunction of the same node.

Fibre Optic Sensors for Masonry Structures

Fiber optic sensors can be useful in several applications also in ancient masonry structures. They can replace more traditional sensors in high-rise bell-towers, where

there is a significant risk of damages caused by strong electrical fields induced by storms and lightning. Robust and temperature insensitive FO system are available on the market: they allow local or distributed sensing and can offer multiplexing capability. A special type of FO sensor, in plastic material (PFO), with very low production cost, has been designed and tested at the Politecnico di Torino to keep under control the evolution of the crack width. It is a sensor designed to measure local relative displacements through the attenuation of the monochromatic light intensity (figure 3).

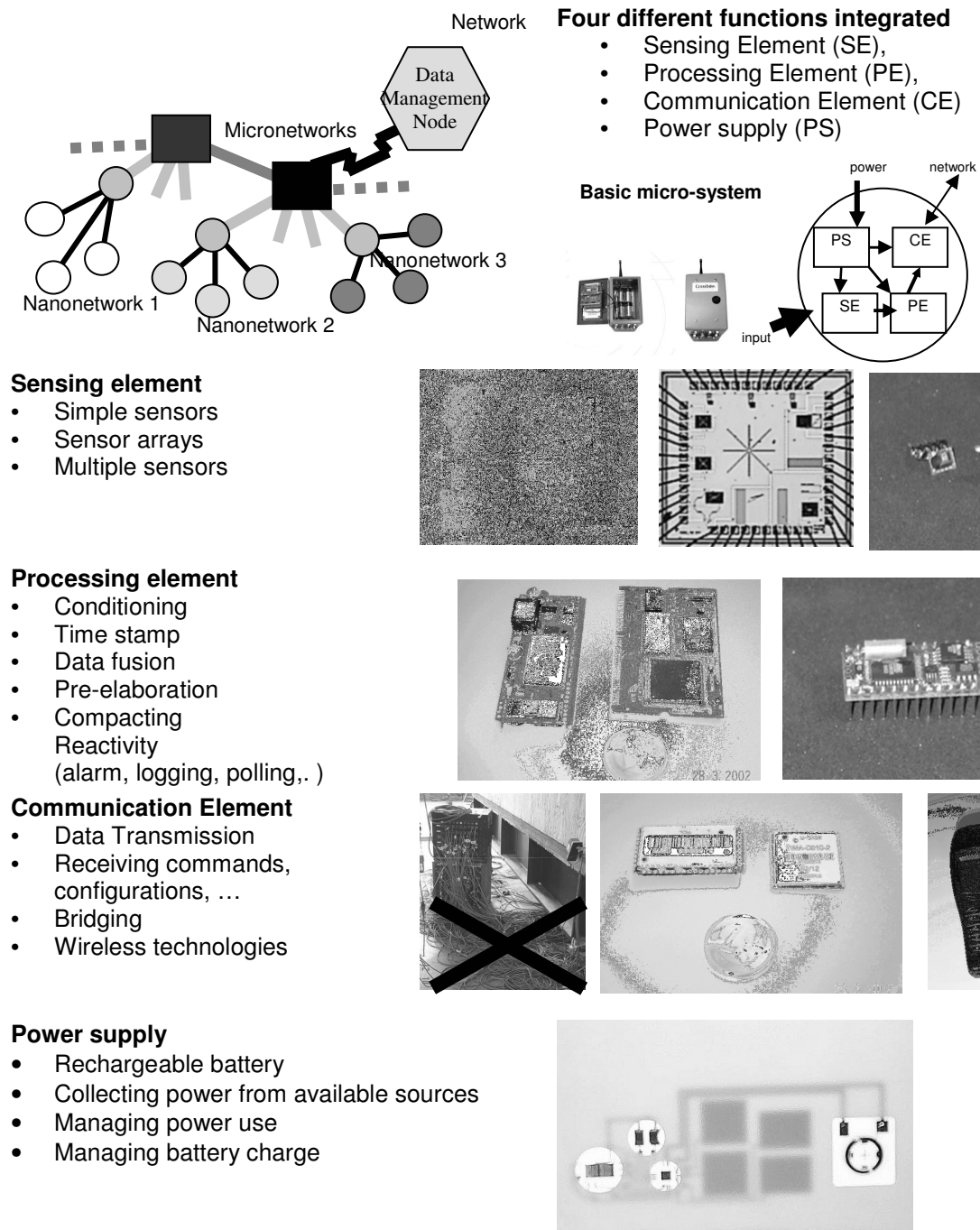


Fig. 1. Example of MEMS and its components

Ancient masonry structures show nearly always more or less important distributed or localized systems of cracks, sometimes assumed, themselves, as a damage

measure. In fact the correlation between the number and extension of cracks and the safety level, or the reduction of the residual strength, is not linear and not easy to assess. In such uncertain condition it is very important to monitor the evolution of crack width and extension. The PFO sensors have some advantageous properties: high deformability, large numerical aperture (figure 4), large section diameter.

Those properties make them well fit to measure even large local relative displacements. The main technology, patented by the Photon lab of the Politecnico di Torino, is based on very common and cheap components: a LED, a POF, a photo-diode and a simple integrated circuit.

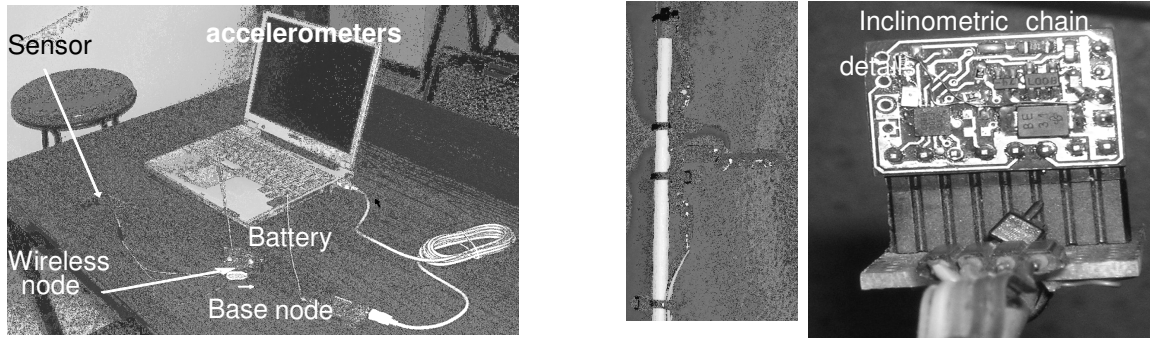


Fig. 2. Micro-sensors made and tested at Politecnico di Torino

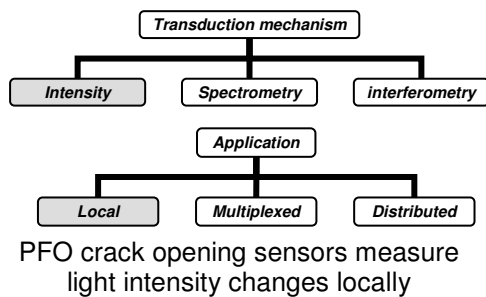


Fig. 3. Classification of properties of the FO sensors

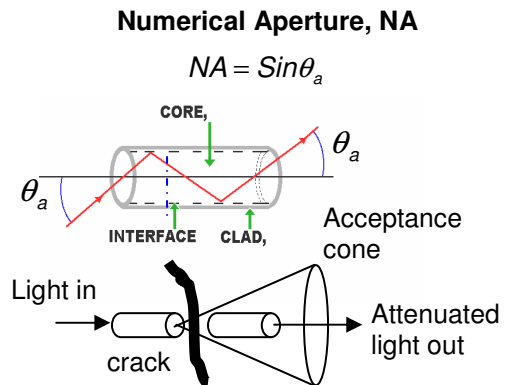


Fig. 4. PFO have a larger Numerical Aperture, NA, allowing to measure light intensity over a large gap

4. Dynamic testing on ancient masonry buildings

In the civil engineering domain, the objects of monitoring are essentially flexible structures, as modern bridges, tall buildings, frames, etc.

Ancient masonry buildings, in general, are not flexible, except towers and large domes or vaults; therefore literature shows that dynamic testing is more often applied to such types of objects. Its applicability to other types of masonry structure shall be checked case by case, but, due to the stiffness and mass distribution properties, it

happens often that more local and global modes concentrate in a narrow frequency band, making confused and hard to analyze the response. Moreover, non-linear behavior, which observable in the ancient masonry even at low strain levels, can introduce spurious spectral peaks, adding further disturbances to the analysis process.

Thus, the question about the application of these techniques to masonry structures should be considered a still unsolved issue and, more specifically, researchers should investigate whether the sensitivity of modal parameters obtained from identification is sufficient to allow the detection and identification of localized or distributed damage. One may expect that the actual existence of a fault would cause a number of symptoms that are small if considered singularly, but significant as a whole, among them: modal frequency and shape deviations, unexpected irregularity and dissymmetry in the global dynamic behavior, appearance of new vibration modes, damping growth and local dissipative behavior, non-linear effects.

A full description of the real pseudo-modal shapes and their dependency from the vibration amplitude can be a powerful diagnostic help. Unfortunately, the current available acceleration or velocity sensors are designed to give a flat response on a wide frequency band. It makes nearly impossible to detect the zero-crossing line of the modal shapes, due to low amplitudes of the modal signal about the zero crossing and the consequently too high noise-to-signal ratio. Therefore, at the Chilab of the Politecnico di Torino it is under development and validation a hierarchical sensor network, where current wide-band flat-response accelerometers are located where the modal signal is expected to be high versus noise and act as “master sensors. They detect modal frequencies and operate a remote “tuning” on a set of adaptive, low-cost, narrow band slave sensors. Slave sensors respond as low-damped SDOF oscillators, capturing the weak near-zero modal response and cutting off the wide-band noise. It is not very important to obtain a precise amplitude measure, but it is very important the phase difference between each two signals located near each-other. If the phase difference is about π it reveals that the zero-crossing line of the modal shape is passing in between.

Figure 5 shows two examples of design of the slave sensor: in figure 5a one can see a set of small, limited band, low frequency cantilevers, tunable by a second capacitive electrode on glass, with ITO (iridium-thin oxide) located under them.

The micro-cantilevers shown in figure 2b can be tuned inside a limited frequency band. An electro-static field can modify the stress distribution and the resonant frequency. A set of similar cantilevers allows enlarging the width of the frequency band.

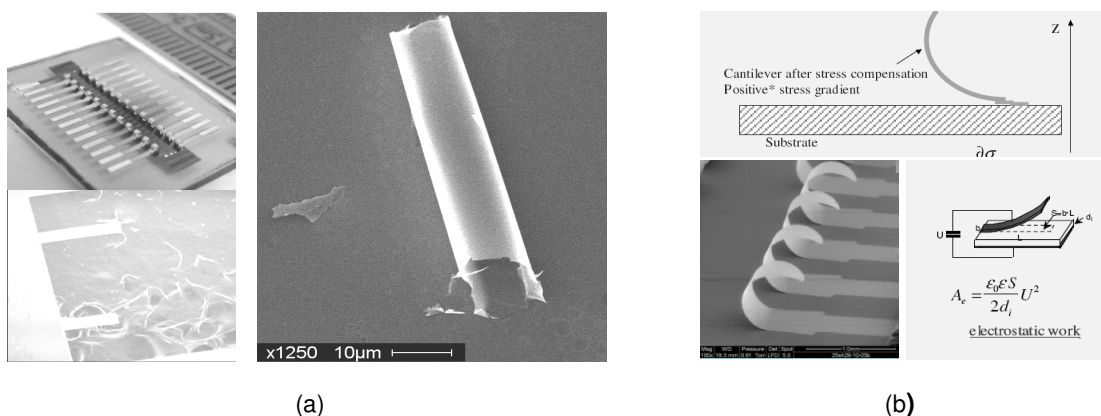


Fig. 5. tuned adaptive slave modal sensors

Dynamic testing can be used not only, and not mainly, to obtain a modal characterization, but also to check and evaluate the statistical parameters of the recorded response signals, supplying quantitative information.

Every irregular or unexpected property of the dynamic response can reveal a “symptom” of structural disease. The presence of several small symptoms might make a direct and deterministic interpretation difficult: “pattern recognition” and neural techniques may reveal to be very effective. Alternative methods are those founded on updating numerical models: model correction is based the results of a previous structural identification (model updating techniques).

Methods in Structural Identification

Many effective techniques are now available for structural identification. Time domain methods, in particular, allow high spectral resolution and the modal identification and mechanical characterization of complex structures. In the sector of civil engineering, of special interest are the methods which do not require a prior knowledge of the dynamic input and are able to take advantage of the natural excitation to which a structure is subjected, so as to enable the behavior of the structure to be monitored in operating conditions. The most successful unknown input techniques are based on the assumption of stationarity of the response; it should be noted, however, that the use of auto-regressive methods, or Random Decrement based methods, were first developed, and found widespread application, in the mechanical and aerospace sectors, where such an assumption is often reasonable.

In civil engineering domain, the excitation, e.g. the action of the wind on a tower, or the dynamic force transmitted by a vehicle to a viaduct, is generally non stationary, whilst the most important characteristic seems to be the gradualness in the application of energy, resulting in the response being interpreted as a sum of modulated harmonics concentrated at the modal frequencies. These considerations prompted some proposals for recent more adaptive and robust identification methods, to handle these types of non-stationary excitation, which are based on special amplitude and phase estimators defined in the time-frequency domain. The advantage of these methods is that identification is based solely on the properties of the modal signals that are dealt with as modulated harmonics. Deviations in modal parameters may reflect changes in local mechanical properties.

All direct structural identification techniques retain the problem of incompleteness. They can be used to build-up functional black-box models for modal parameter estimation. It is generally more meaningful to associate these techniques with F.E. models in automatic model updating procedures.

Time domain techniques have been used successfully [4,5], and they seem gaining more and more success, thanks to the great spectral resolution offered by these methods in the analysis of complex systems, and thanks to their modal uncoupling capability. Frequency domain techniques, though affected by the disturbance due to the needing of a edge-smoothing time window on digital samples, are again made interesting by the powerful cleaning effect of SVD tool [6]. It should be added that many stationary techniques are used nowadays also in the presence of a low degree of stationarity, and can supply an acceptable level of accuracy in the estimate of modal shapes and frequencies, especially when using special windowing techniques. These methods can also provide statistical confidence factors.

The common limitation of time and frequency approaches lies in the fact that they have both been conceived for the analysis of response signals that do not deviate much from stationarity and in actual fact they are widely used for the analysis of

signals whose main characteristic is far from being stationary (bridges excited by vehicle traffic, towers exposed to wind gusts, etc.).

Damping, primarily, affects the modulation of modal signals, but it has no significant effects on frequency, or on the instantaneous phase and amplitude relationships between channels. It. The quality of the estimate of damping achieved by output-only methods, used most widely, is not very high, mostly when these methods are applied to real structures. It has been ascertained that when Random Decrement techniques are used, slight non-stationarity can cause slow changes in the amplitudes of correlation function, similar to the effect of higher damping. On the other hand, ARMAV algorithms may prove effective in damping estimation when they are applied in short time windows, but this is accomplished only if the sampling ratio is well chosen and the signal-noise ratio is good enough.

In numerical test simulations errors are seen to occur, of ca 20% in stationary conditions (or even bigger errors on the least excited modes), whilst in non-stationary conditions, in some instances, the errors can be as high as 100%. Errors decrease largely if the recorded signals are very long, say some tenths of minutes. In real world this results are not extendable, mainly because real damping is not generally viscous and linear and it grows-up with signal amplitude. Short time-windows can cause larger processing errors, but potentially allow estimating the correlation between damping values and signal amplitudes.

Time-frequency Domain Identification

In structural response signals, the main characteristic appears to be the slow variation in modal energy; the response might be viewed as a time-varying combination of modulated harmonic functions. Furthermore, in non-stationary conditions, classical Fourier analysis should be replaced by the more general time-frequency analysis. Currently the algorithms used for time-frequency identification belong to three main branches: Short-time Fourier Transforms (or Gabor transforms), Wavelets and wavelet filter banks, Cohen-class bi-linear transforms. Although Wavelet transforms captured the attention of the largest part of researchers worldwide, the Author focuses his attention to the bi-linear transforms, due to their powerful intuitive properties and their high resolution both in time and frequency, independent from the frequency range (figure 6).

A method has been recently proposed that works out instantaneous quantities (Time-Frequency Instantaneous Estimators, or TFIE, [7, 8, 9]), such as the phase difference and the amplitude ratio between channels, as a function of frequency. In linear systems, modal components are recognized since they show estimator values that are characterized by stability over time. The estimators are defined on the basis of the time-frequency analysis of vibration response signals, so these techniques might be placed into a new class of time-frequency domain methods.

This method supplies a better reliability and accuracy in damping estimate; it may be accomplished by defining an instantaneous estimator of damping, which calls for proper time-frequency transforms, also in order to preserve the original instantaneous characteristics of the signal.

Based on the foregoing considerations, the proposed method includes the following stages:

- 1) Modal frequency and shape identification, based on the respective time-frequency estimators.

- 2) Time-frequency transformation of the response signals and regularisation, in order to obtain diagrams showing the instantaneous estimate of damping.
- 3) The final value of the damping is obtained by averaging over time the instantaneous damping diagrams. Results coming from different channels should be averaged, or combined by resorting to multi-criteria techniques.

In a few applications the results of the previous procedure were compared with those achieved, on the same signals, by stationary type time-domain identification methods, such as: Direct System Parameter Identification (DSPI), Eigensystem Realisation Algorithm (ERA), Polyreference Time Domain (PRTD) [4, 9, 10, and 12]. The latter two were applied on the response signals' Random Decrement function.

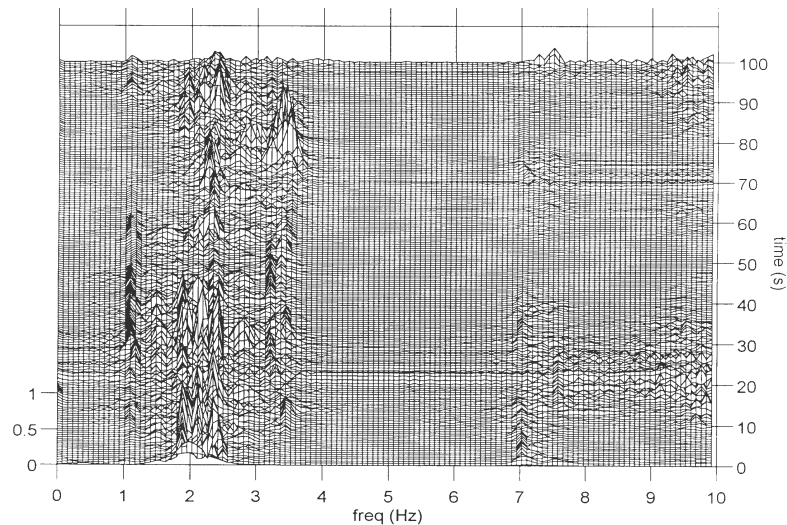


Fig. 6. Bi-linear Cohen-class auto spectrum D_{si} of an accelerogram recorded from a real structural vibration test; different modulated-harmonic components reach the maximum energy level in different time intervals.

Let us assume that the structure, subjected to unknown excitation, is instrumented with simultaneous acquisition channels according to some of the N degrees of freedom. In the time-frequency representation of the response signals, the energy appears to be concentrated around the modal frequencies and modulated according to the evolution of the time-frequency transform of the modulating waveform. In other words, though the input is randomly varying without any stationary character, the modal response remains nearly stable on the modal frequency for a time interval that is long, at least, as the free decay after an impulse.

Due to the fact that in the (t,f) plane at each modal frequency the shape of the modulating waveform is similar for all N records, it can be demonstrated that the amplitude ratio and phase difference between two measured signals $s_i(t)$ and $s_j(t)$ can be determined directly from their bilinear time-frequency auto and cross representations

$$D_{s_i}(t, f), D_{s_j}(t, f), D_{s_i s_j}(t, f)$$

in the following manner [8]:

$$AR(t, f) = \sqrt{\frac{D_{s_i}(t, f)}{D_{s_j}(t, f)}} \quad \text{or} \quad AR(t, f) = \frac{D_{s_i s_k}(t, f)}{D_{s_j s_k}(t, f)} \quad (1)$$

where s_k is a third arbitrary, purely sinusoidal signal.

$$PH(t, f) = \text{phase}\{D_{s_i, s_j}(t, f)\} = \frac{\text{Im}\{D_{s_i, s_j}(t, f)\}}{\text{Re}\{D_{s_i, s_j}(t, f)\}} \quad (2)$$

$AR(t, f)$ represents the time-frequency estimator for the amplitude ratio, and $PH(t, f)$ the time-frequency estimator for the phase difference.

In frequency intervals where a single modal component is predominant, the estimators tend to become steady in time. As this property increases progressively up to a peak at the modal frequencies, the latter can be identified by searching the minima of the estimators' standard deviation as a function of frequency. The strategy of the method consists in the following procedure: the scattering of the phase difference along the time axis between two contemporarily recorded signals is checked step by step for increasing values of frequency. The RMS value of that difference is around $\pi/2$, except for the modal frequencies, revealed by a sharp downward peak, corresponding to a RMS phase difference value converging to zero. At a given identified modal frequency, the AR estimators supply amplitude relationships between channels as a function of time, and, by averaging, an estimate of the modal shapes.

In structural dynamics, usually we expect that the release of dynamic energy from a system will be gradual enough to give rise to a response characterized by a number of modulated waveforms. Under these conditions, the identification of modal frequencies and shapes reduces to separating modal components and does not call for strict model assumptions (in the described method only the stability over time of modal shapes was introduced). At first sight, the extension of the results discussed above to the evaluation of damping may appear direct. Actually, in this case new problems arise:

- Damping affects the modulation of the signal rather than its instantaneous frequency;
- In practical applications damping evaluation is critical, and any available data about the system's behavior should not be neglected by the identification procedure.

Based on the foregoing considerations, a time-frequency damping identification approach may include the following stages [8,10]:

- Modal frequency and shape identification, based on the respective time-frequency estimators;
- Time-frequency transformation of the response signals and regularisation.

The latter point is achieved by imposing, at any time t , the linear model formulation in the frequency domain, or, in other words, by searching the Frequency Response Functions (FRF) that best fit the instantaneous response spectra.

The final value of the damping is obtained by averaging over time the instantaneous damping diagrams. Results coming from different channels may be averaged over a given time window, or combined by resorting to multi-criteria techniques.

It has been observed that estimation accuracy depends on the relative energetic importance of the modes. In other words, the instantaneous estimator is more

accurate in the temporal segments where the mode to be identified is predominant and is not affected by the residuals of the other modes. The definition of an instantaneous damping makes it possible to work out temporal weighted averages or to select temporal segments to improve the estimation of weaker modes. A possible solution can be the introduction of functions allowing for the relative energetic importance of the k-th mode as a function of time. [10].

5. Case studies: applications to monumental buildings

Applications have been done to some outstanding historical constructions, as the dome of the S. Gaudenzio Basilica in Novara (Piedmont, Italy, figure 7); the bell towers of the S. Lorenzo Cathedral, Alba (Piedmont, Italy, figure 8) and of the Renaissance church “SS. Annunziata” in Roccaverano (Piedmont, Italy, figure 9); the the medieval “Torre di Matilde” in S.Miniato, near Pisa (Tuscany, Italy, figure 10) . Due to the lack of space, the attentino is focused only on the two sast cases.

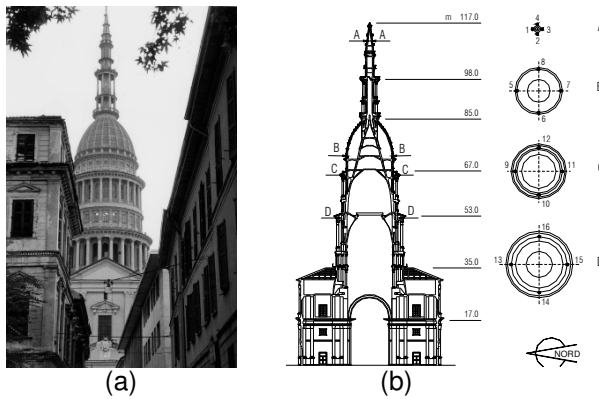


Fig. 7. S.Gaudenzio dome, Novara



Fig. 8. Cathedral and bell tower, Alba



Fig. 9. SS. Annunziata church, Roccaverano

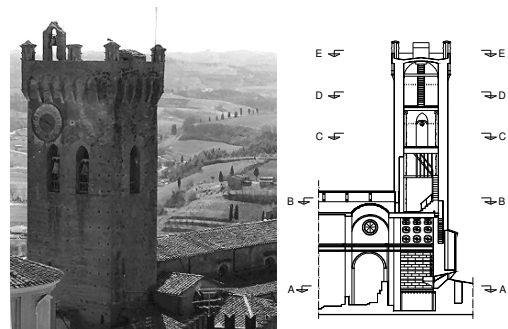


Fig. 10. Torre di Matilde, S. Miniato (Pisa)

SS. Annunziata Bell Tower, Roccaverano

A vibration test campaign was carried out on the XVI century bell-tower rising in Roccaverano (Asti-Italy), belonging to the SS. Annunziata church (Figure 9). In the past the church was exposed to an earthquake which caused serious damages both on the facade and on the bells-tower and subsequently some interventions of restoration were made. The tower has been subjected to an extensive experimental investigation both under ambient vibrations and actions induced by the bells.

Vibration measurements were performed on the bell tower only, by placing the accelerometers on the landings, arranged in the horizontal direction. Each set-up is made up of the signals relating to four acquisition channels, of which two were fixed as reference channels and two were moved to the levels of the different landings.

The measurements were made separately in the E-W and N-S directions, but one of the tests was conducted with two accelerometers arranged in the orthogonal direction, according to the two main axes of the bell tower, in a central position.

Different types of excitation were used, and namely, the one generated by bell tolling in two different directions, the one produced by pulses applied to the bells and finally the one arising from environmental noise.

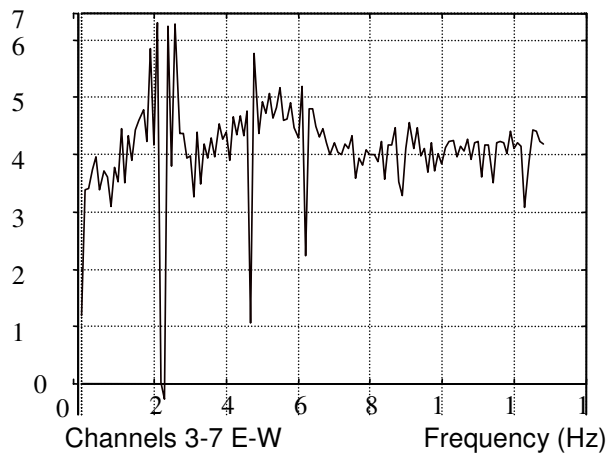


Fig. 11. SS. Annunziata bell-tower: standard deviation of sample phase difference estimator as a function of frequency.

Let us now examine the results obtained with the TFIE method. Figure 11 shows a sample phase difference estimator; this kind of diagrams displays very clear minimum points and it also identify frequencies which did not appear at all in the PSD's. The results are listed in Table 1. The diagram in figure 11 shows the robustness of the estimator, given that the modal frequencies are so clearly extracted from an ambient vibration test. After the experimental check a retrofit was done.

The repair consisted of mortar injections and prestressed cables at each landing level. The results of new test campaign on SS. Annunziata tower, after a repair intervention, are summarized and compared with the original ones (Tables 2). One may notice the splitting effect on the two fundamental frequencies, already reported on repaired structures and due probably to non-linearity.

Mode	Identified frequencies (Hz)
1	1.66
2	2.26
3	4.67
4	6.18
5	6.40
6	8.90

Table 1. SS. Annunziata bell tower: first six modal frequencies as identified through TFIE method

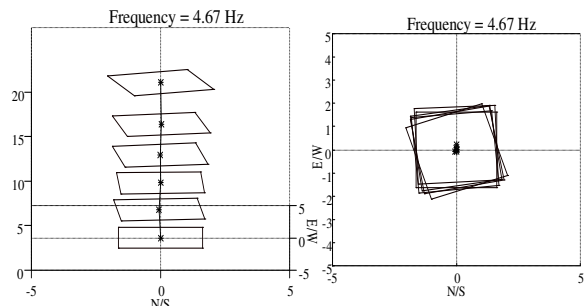


Fig 12. SS. Annunziata bell tower: a sample modal shape identified in the range 1-5 Hz (1st torsional).

There is a 20-30% increase in the flexural frequencies (Young modulus) and a slight decrease in the torsional one (shear modulus). Thus, we can draw the following conclusions:

- a slight increase in G , probably a fictitious effect of the mass increase, show that the tower's shear behaviour has not significantly changed;
- a considerable increase in the Young modulus and bending stiffness demonstrates the efficacy of the intervention.

Table 2. SS. Annunziata: identified and updated model frequencies, before and after the repair.

Mode	Measured frequencies before repair (Hz)	Measured frequencies after repair (Hz)
1	1.66	1.97 ÷ 2.12
2	2.26	2.34 ÷ 2.54
3	4.67	4.30
4	6.18	
5	6.40	
6	8.90	

Application to the Matilde's Tower in San Miniato

The Torre di Matilde (Figure 10), erected in San Miniato (Pisa) in the 12th century, is a rare surviving example of the military architecture of the time: its construction dates back to when the Emperor Henry IV (1184-1194) visited the city. The structure, including the bell tower, was badly damaged by the bombings of 1944. The tower, rising ca 35 m above the cathedral floor, is parallelepiped shaped, with crown and end shrines added in the 13th century. Inside the tower, three wooden storeys prove too weak to ensure a valid connection between the four walls. At the top of the tower, a small masonry vault closes the structure by linking together the side walls. The cracking pattern of the building displays major lesions at the corners, extending over virtually the entire height [4,12].

An extensive measuring campaign was performed on the tower, within the framework of an inter-university national scientific program (PRIN). The results discussed in what follows refer in particular to dynamic response signals to environmental conditions acquired by means of 23 accelerometers of which 10 were positioned on the parapet of the roofing (level E), 10 at the next to the last level (level D) and the remaining 3 at the level underneath (level C). Measuring directions were parallel to the main axes of the cross section of the building.

Different recorded segments were analyzed, most of them obtained at a sampling rate of 1.6 kHz. A preliminary qualitative analysis with Welch window energy spectra and representations in the joint time-frequency domain revealed important shares of spectral energy localized around three prevalent frequencies: 2.70Hz, 3.40Hz and 6.40Hz. The analysis of a certain number of signals also revealed the presence of less pronounced peaks around the frequencies of 2.95Hz, 4.70Hz and 6.05Hz.

A structural identification was performed by using two time domain methods, ERA and PRTD, whose extension to environmental type signals required the prior extraction of the Random Decrement functions. Then time-frequency identification was added through the TFIE method.

This study was limited to the analysis of vibration modes with frequencies lower than 10Hz; in this range, all methods identified a considerable number of modes, which invariably included modes associated with the frequencies already observed in the preliminary analysis. Table 7 lists the modal frequency values corresponding to the

three principal modes obtained with the three methods by averaging the results over the various recorded segments analyzed.

Table 7. Modal frequencies identified with the various methods

ERA	PRTD	TFIE
2.6880 Hz	2.7036 Hz	2.7344 Hz
3.4109 Hz	3.4086 Hz	3.3913 Hz
6.3274 Hz	6.3538 Hz	6.3232 Hz

Figures 13 shows two sample diagrams of phase difference estimators (TFIE method), calculated on pairs of signals measured according to each of the two main directions. The concomitance of the main frequencies along the two orthogonal axes demonstrates that all the modes are affected by appreciable oblique and torsional components, an effect determined by the markedly asymmetrical configuration of the plan.

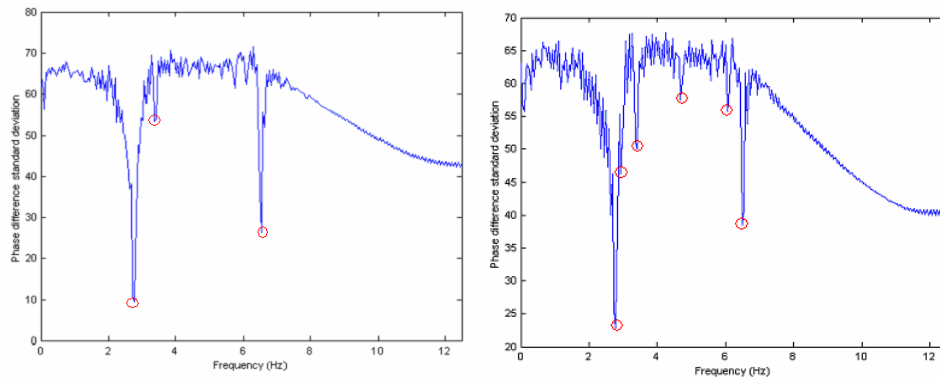


Fig. 13. Phase difference estimators – Sensors arranged along the Y and X axes respectively

The damping values obtained from the analyses in the time domain were seen to be affected by considerable scatter and, as already observed in earlier studies on “output only” methods, should be considered with some caution. Accordingly, these results have been omitted waiting for a more accurate, and more painstaking, evaluation by means of instantaneous damping estimators [10].

As for mode shapes, it was decided to represent them on a preliminary basis with vectors having their origins coinciding with the positions of the sensors and intensity and direction defined by the modules and phases of the eigenvectors, respectively (Figure 15). This made it possible to check the directions, which, in some segments, sometimes turned out to be reversed due to phase evaluation problems. This type of difficulty is very frequent in the identification of masonry buildings, on account of the non-linear behavior of the materials, as well as structural complexity. To obviate phase problems, especially between channels acting in orthogonal directions, in addition to spatial analyses, separate analyses were performed in the two orthogonal directions.

The first vibrating mode is flexural in the lower stiffness plane. Once this mode has been identified, from the analysis of its associated eigenvector (Figures 15) it can be seen that the top storey of the tower does not only translate but it also has a pronounced rotational component; this rotational behavior of the top floor was also brought out by the analysis performed in the orthogonal direction. By averaging the different results a modal shape of a basic translational type in the lower stiffness plane was obtained.

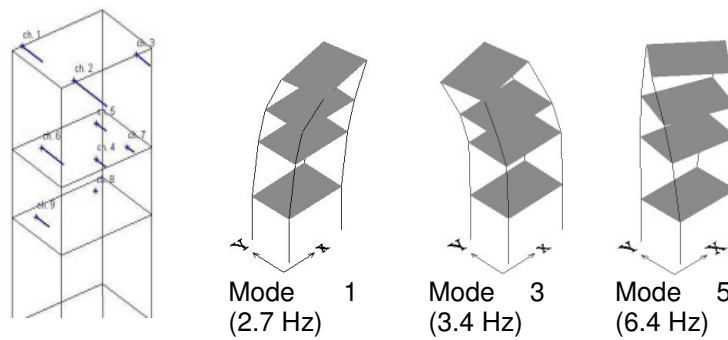


Fig. 15. The three modes identified reliably

“Output only” techniques prove effective in identifying complex masonry structures: reliability is achieved by comparing the results obtained from several identification sessions based on different methods. Forced excitation can be justified in the presence of significant non-linearity or as a further identification step in the case of particular structures.

Masonry buildings require special care in test planning, which should be accomplished with the support of an accurate mathematical model; an iterative model updating and dynamic identification procedure would improve the accuracy of the results.

Damping estimation in masonry structures is a critical issue. Hopefully the use of instantaneous damping estimators will enhance the reliability of this methodology and make it suitable for use in structural diagnosis.

6. Looking for Simplicity and Robustness in Model Updating

Model updating techniques require, generally, the knowledge of the stiffness and mass matrices of the FE model. The approach used for this case-study allowed skipping that requirement.

The aim of the model updating processes is the correction of the modal, or pseudo-modal”, parameters passing through the adjustment of the originally assumed mechanical and/or geometrical constitutive properties of the structural FE model.

In the case of stochastic local variability of the constitutive properties, the modal parameters too become a set of stochastic variables.

Constitutive properties (input) and modal parameters (output) are correlated. A covariance matrix describes these correlations. Each term of the covariance matrix can be replaced by a correlation coefficient, playing as a weighting factor, showing how much the variation of each single constitutive property can influence the variation of a modal parameter. See e.g. figure 16, showing an application to the “Torre di Matilde” case study. The model of the tower is divided into eighteen macro-elements, each-one associated with a young modulus ruling the local average deformability.

The modal parameters are 22 amplitudes of the modal shapes times and frequency associated with the first three modes (sixty nine parameters all). The 2D diagram of figure 16 describes the correlation level between the two sets. A more rough but simple way to weight the input data consists in replacing the correlation coefficients with the amplitude of the theoretical modal shapes.

The weighting factors act as selective sensitivity operators; at the first step the changes in modal parameters are made to depend only from constitutive properties with which they have the highest correlation. The dimension of the problem is now strongly reduced and the numerical noise introduced by taking into account the contribution of non influent data is cut-off. Between variations in constitutive properties and changes in modal parameters there is a strong causal link, although significant information sources can have been neglected. The search for the optimal adjustment of the constitutive properties is performed through a self learning automatic procedure, specifically through a neural network, a three-layer perceptron, feed-forward with back propagation algorithm for error correction [11]. The experimental modal parameters fill the input layer; the updated properties are the outcome from the output layer.

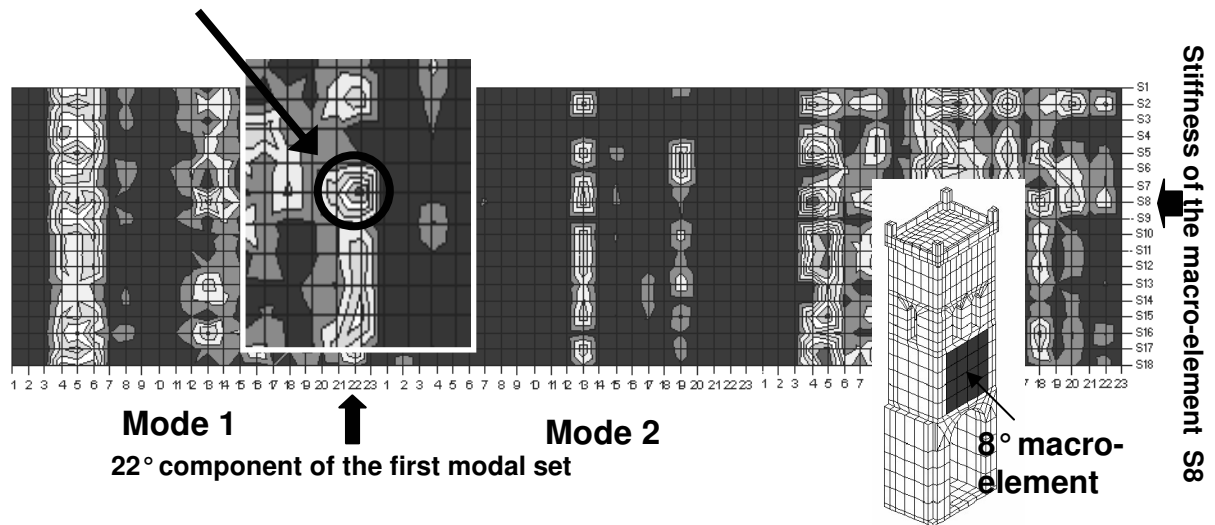


Fig. 16. Correlation between constitutive properties (macro-element stiffness) and modal parameters

Neural networks need training, based on simulated experiments. The training actions proceed through a large number of iterations.

The neural approach is a parallel computing process, intrinsically robust if the network is well designed. Once fixed the constitutive parameters more correlated, further elaborations are done to assess the more weakly weighted data. Then other similar tours allow refining the whole assessment through an iterative procedure, until the requested error limit is reached, or it is sure that it is impossible to reach it.

7. References

- [1] www.xbow.com
- [2] 2005 SIAM international, Conference on Data Mining , Sutton Place Hotel Newport Beach CA april 21-23 2005
- [3] Olaf Wolkenhaue, Data Engineering: Fuzzy Mathematics in Systems Theory and Data Analysis, 2001, John Wiley & Sons.
- [4] Asmussen, J.C, Ibrahim, S.R., Brincker, R. (1996). "Random Decrement and Regression Analysis of Traffic Responses of Bridges." Proc. 14th International Modal Analysis Conference, Society of Experimental Mechanics, Bethel, CT, USA, 453-458.
- [5] J.N. Juang, Applied system identification, 2001, Prentice Hall
- [6] Brincker R., Zhang L., Andersen P. (2000) Modal Identification of Output-Only Systems using Frequency Domain Decomposition, Proc. European COST F3 Conf. On System Identification & Structural Health Monitoring, Madrid.
- [7] P. Bonato, R. Ceravolo, A. De Stefano, F. Molinari, "Application of the Time-Frequency Estimators Method to the Identification of Masonry Buildings", Mechanical Systems and Signal Processing, N.14, 91-109, 2000.
- [8] P. Bonato, R. Ceravolo, A. De Stefano, F. Molinari "Use of cross Time-Frequency Estimators for the Structural Identification in Non-Stationary Conditions and under Unknown Excitation", J. Sound Vib., Vol. 237, No. 5, pp. 775-791, 2000.
- [9] A. De Stefano, R. Ceravolo, and P. Zanon, "Seismic Assessment of Bell Towers through Modal Testing", Proc. IMAC-XX Conference, Society for Experimental Mechanics (SEM), February 4-7, 2002, Los Angeles, California, CD-ROM, 2002.
- [10] R. Ceravolo, "Instantaneous Estimators of Structural Damping", Compte-rendu final de l'étude: Auscultation de structures par vibrations, Ecole Nationale des Ponts et Chaussées, Laboratoire Analyse Matériaux et Identification, Paris, juin-octobre 2001.
- [11] L. Sampietro, " Model Updating stocastico con uso di Reti Neurali" (in Italian), Laurea Thesis, Politecnico di Torino, July 2005.
- [12] R. Ceravolo et Al, "Bell-towers monitoring through ambient vibration measurements", 3ECSC, July 2004, Vienna, Austria