STRUCTURAL MONITORING WITH GPS AND ACCELEROMETERS: THE CHIMNEY OF THE POWER PLANT IN PIACENZA, ITALY

Noemi Emanuela Cazzaniga, Livio Pinto
DIIAR – sez. Rilevamento
Politecnico di Milano
Milan, Italy
Email: noemi.cazzaniga@polimi.it, livio.pinto@polimi.it

Franco Bettinali, Antonella Frigerio
CESI Ricerca S.p.A.
Milan, Italy
Email: franco.bettinali@cesiricerca.it, antonella.frigerio@cesiricerca.it

Abstract: The construction industry is increasingly involved in the safety assessment and survey of existing structures, often following refurbishment and structural modification works. The increasing difficulty in selecting building areas and getting funding for new constructions, jointly to the not negligible costs related to the demolition of the old ones as well as to the costs for the following site clearance, has led to a greater environmental awareness and to a cultural desire to maintain ancient and historic structures. The Italian Centre for Experimental Electric Science (CESI) and Politecnico di Milano set up a monitoring system aimed at the detection of structural modification of slender structure in near real time. The system, installed on a 120 m high chimney of the Piacenza (Italy) power plant, acquires data at a frequency of 10 Hz from 3 GPS (one rover on the chimney, connected to the acquisition and processing unit by a WI-FI system, and two masters) and, at a frequency of 125 Hz, from 4 accelerometers. The paper reports on the acquisition system, explains the data analysis procedure as well as the results of the measurement campaign, three months long.

1. Introduction

Recently the interest for GPS systems, also joined to accelerometers, used in monitoring of high rise buildings (oscillations and slow movements) is growing up, [6]. Procedure generally consists in comparison of observed data to the ones foreseen by a realistic numerical model, which mechanical parameters have been identified in a preliminary activity. The Italian Centre for Experimental Electric Science (CESI) and the Politecnico di Milano (Italy) co-operated in a project focused on the structural integrity monitoring of chimneys of thermo-electrical power plants. In particular the project is aimed at identifying at any time signs of ageing, in terms of degradation of the mechanical properties of the structural materials (e.g. concrete). Slender structures as chimneys usually exhibit not negligible oscillations, due to dynamic loading induced by wind and earthquakes, and displacements due to thermal actions. In monitoring systems, the amplitude and the frequency of oscillations are continually monitored to spot anomalous behaviours, which should highlight material damages. Finite Element Method (FEM), widely used in the analysis of civil engineering structures and mechanical components, is a useful tool in the safety assessment activities and in the evaluation of the designed rehabilitation measures in case of damage. Usually the mechanical properties of structures (e.g. material properties, boundary conditions) are unknown a priori so that, at the beginning of the analysis, only guess values can be assigned to them. As it is very frequent to have shortcomings in design data, setting up of numerical models with information from a structural monitoring system is useful. In case of existing structures, non-destructive experimental methods have, obviously, to be preferred to set up reliable models. Through an updating procedure based on FE method, named structural identification, initial theoretical approximate models are corrected, step by step, to fit the observed "real" behaviour of the structure.

The same monitoring system, thus, is used also to obtain information necessary for structural identification. Such a system usually consists of accelerometers to observe the structure vibrations and the displacements can be computed only by a double integration, degrading precision of their estimation. Since in addition for tall buildings, in case of wind loads, the quasi-static component may be significant, in recent years the use of GPS for displacement measurements has been suggested. Hence, an integrated GPS/accelerometers system has been implemented in the present system so that both the dynamic and the static response can be observed. The system has been used to screen the gathered data and to identify, by means of the first modal shapes of oscillation, the mechanical models of the chimney, that are currently used to check in near real time the structural behaviour.

In this paper however, we focus on structural identification, referring to [5] for the topic of near real time monitoring stage. The paper shows the results of the structural identification analyses of the Piacenza chimney, carried out using HISTRIDE [1], a software environment which greatly extends and simplifies a non-destructive identification approach based on the dynamic response of the structure. By a continuous modification of the mechanical parameters of the FE model made by the procedure, the error between the experimental modal features and the computed ones is reduced so that, finally, the model matches the real structure. Thanks to the identified model a near real time monitoring system can operate and the trend of the structural displacement amplitude and of its frequency content can be followed.

2. System hardware components

A GPS dual-frequency geodetic Leica 1200 receivers with Leica AX1202 antennas were used. Since some degrees of redundancy are always necessary, more than two receivers have been employed. Because of its geometric and mechanical characteristics, the chimney behaves like a clamped beam, with a negligible torque component, and the motion of its top is mainly in the horizontal plane. For these reasons and in order to add some redundancy to the system, one GPS was located on the chimney, as rover station (Figure 1), and two on the ground, as master stations; the acquisition rate was set at 10 Hz.

Moreover, the chimney has been equipped with four accelerometers (CFX US4), mounted in nearly orthogonal pairs on an horizontal plane, on the chimney top and in the middle (figure 1), to record the structural acceleration components in North and East horizontal directions. Due to the coarse installation, the North-East and horizontal alignment of accelerometers axes can be affected by an error of about 10^{-2} rad. Data are collected at a frequency of 125 Hz. This signal is gathered in binary format and stored every 5' in an ASCII file.

A Wi-Fi connection with two Ethernet access points is used to transfer GPS and accelerometers raw data from the structure to the storage and processing central unit.

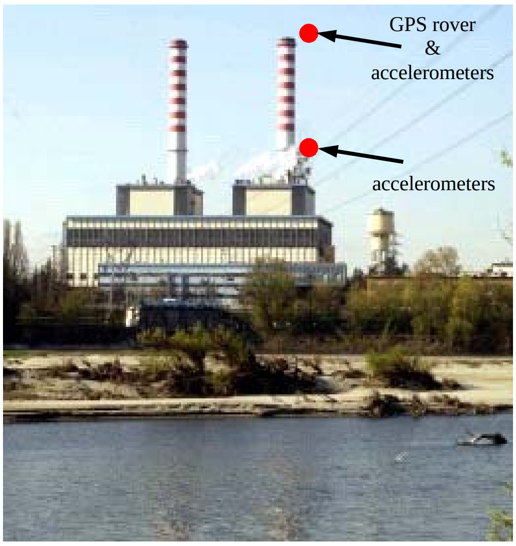

Figure 1: Chimneys view and instruments locations

3. Data acquisition and elaboration

Figure 2 shows the flow chart of the data acquisition and processing activities. As previously mentioned, data may be analysed both to perform a structural identification or to monitor the structure in time.

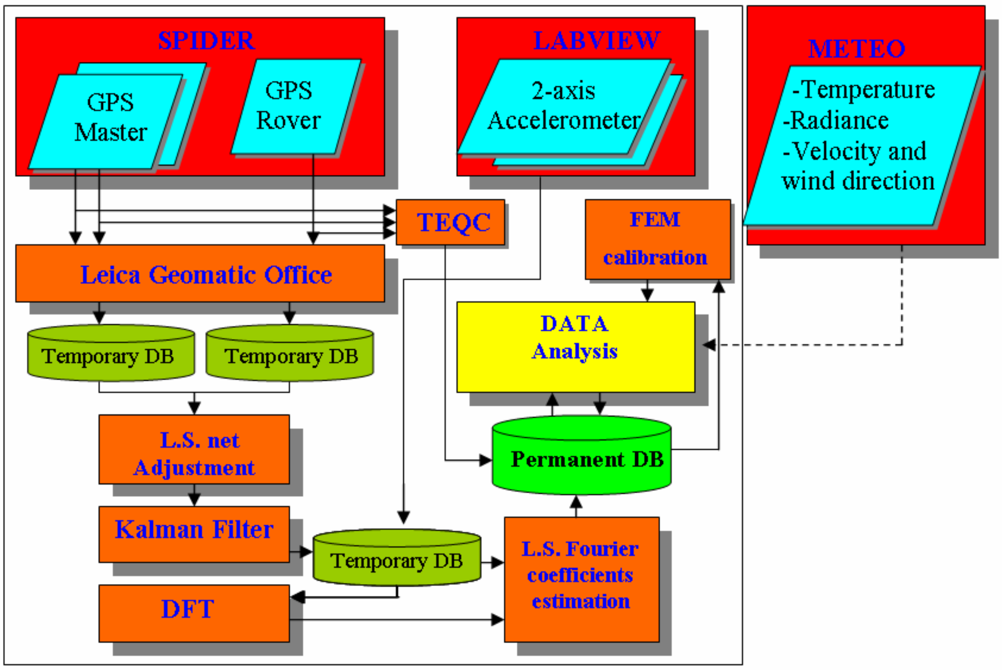

Figure 2 : Flow chart of the data acquisition and processing of the monitoring system.

Amplitude oscillations with their frequency content are used first in the calibration of the FE model parameters and then for the monitoring stage.

The flow consists of three steps of data processing and of a final stage of data analysis (this last stage is bypassed if the system is working in a structural calibration mode):

1. raw data acquisition from the three receivers and the four accelerometers;

2. GPS data processing to determine the rover coordinates in a N–E oriented local frame;
3. eigenfrequencies determination by frequency–domain and time–domain analysis;
4. statistical analysis to trigger (if necessary) an alarm signal.

This last monitoring stage features a short-term and a long term analysis. The former should be capable to spot sudden changes in the response to loads, the latter should highlight a (possibly slow) trend towards critical conditions, see [5] for details.

3.1. Accelerometer data analysis

Every 5 minutes, accelerometers data are downloaded from the sensors and stored in the PC hard disc. Unlike GPS data managing, no filtering of original signals is carried out to avoid phase or amplitude distortions. Raw data, channel by channel, are directly transformed by mean of a Discrete Fourier Transform, obtaining the acceleration spectrum. From that, it is possible to derive the displacement spectrum, under the hypothesis that in each direction the motion is the one of a simple harmonic oscillator without applied forces:

$$x = -\frac{\ddot{x}}{\omega^2} \tag{1}$$

where $\omega = \frac{2\pi}{T}$ with T =oscillation period.

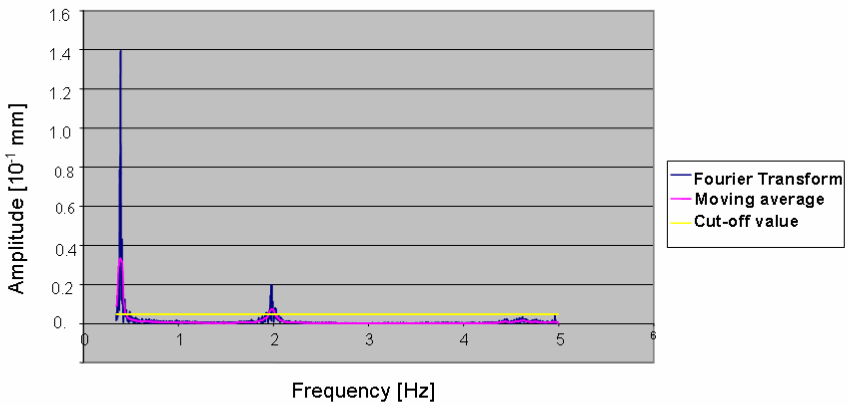

Figure 3 : Principal frequencies of chimney vibrations.

The frequency range in which the analyses are performed (0.29 - 5.0 Hz) was defined according to the fact that, following a preliminary experimental check, from 0.29 Hz noise is negligible and, by literature [2], it was possible to verify that many natural frequencies of the chimney will be less than 5.0 Hz. To identify automatically the spikes in the amplitude spectrum, a cut-off value (three times the average of amplitude) is initially defined to eliminate background noise. Then, by evaluating the signal moving average, it is possible to identify the frequency ranges in which a spike is present, which correspond to the ones having a moving average value greater than the cut-off threshold. In each interval the spike is located at the maximum amplitude value. In such a way, some pairs of values (frequency and amplitude) which represents principal modes of chimney vibrations during the 5’ period (Figure 3) can be identified. The results are stored in a permanent database.

The data collected during the characterisation stage are least squares averaged to obtain the solution with an associated variance.

3.2. GPS data analysis

The monitoring system does not require real-time capability, but a near real time solution is enough, so a post-processing cinematic solution for GPS data has been chosen. GPS data at 10 Hz rate are saved in the internal memory card of each receiver. Every 5 minutes, raw data are downloaded from the receivers and stored in the PC hard disc by the software Spider by Leica. Each file of 5' raw data from the three GPS undergoes a quality check of signal with TEQC by UNAVCO. Baselines vectors from each master station to the rover are computed at each epoch by a batch version of Leica Geomatic Office (AutoLGO). By the two computed positions of the rover and their variance-covariance matrices a program computes the l.s. average position, keeping the master coordinates fixed on a local coordinates frame; the position estimated variance is compared with the a priori variance by a χ^2 test. Afterwards, a Kalman filter and smoother are applied to remove high frequency noise. The Discrete Fast Fourier Transform (DFT) is applied to identify frequency spikes and their amplitudes and phase shifts, in a way analogous to the accelerometers case. A least squares analysis is carried out to find out the frequency confidence interval to allow testing of frequency changes in a probabilistic framework.

3.3. Rover GPS position analysis

A measurement campaign, three months long, was carried out to provide the structural identification activity with experimental validated data. From these measurements, the reference values of the displacement induced by static loads have been derived as well as the principal modes of oscillations.
By analysing the about 3000 data samples recorded during this period (figure 4), the mean position of the Rover GPS antenna on the top of the chimney is computed. This information is necessary to perform the displacements analysis. These coordinates have been determined as average of the positions weighted with their own accuracy, obtained by the elaboration of the data at every 5'.
The reference system adopted is local Cartesian, with origin in one of the two GPS master stations and North oriented. In order to compute the mean position, all the observation in X (East) and Z (Height) have been considered, while in the Y (North) co-ordinate the daytime observation, subjected to solar irradiation loads, have been eliminated. Table 1 shows the rover GPS antenna coordinates: the estimated accuracy is about 1 mm for the three coordinates.

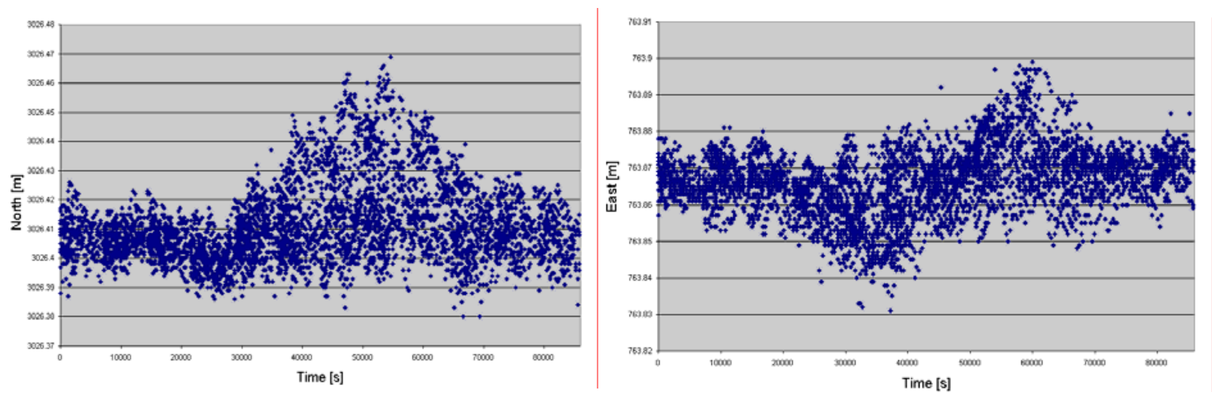

Figure 4 : Chimney daily movements in east-west direction (right) and south-north one (left).

East [m]	North [m]	Height [m]
763.865	3026.407	120.277

Table 1: Static position of the GPS rover antenna.

4. The Finite Element model of the chimney of the thermal-power plant

The chimney of Piacenza is a reinforced concrete thin shell structure of cylindrical shape and 120 m high, it has an external radius ranging from 4.24 m (bottom) to 3.52 m (top) and a thickness linearly decreasing from the base (0.48 m) to the top (0.18 m). The foundation of the chimney, a frustum of cone of 20 m diameter, rets on deep piles.

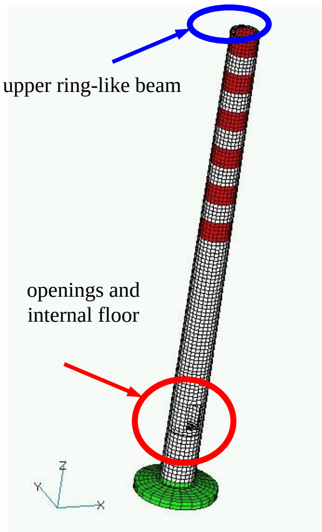

Figure 5 : Chimneys Finite Element model

In the numerical model (mesh) of the chimney (25959 nodes and 4004 three-dimensional parabolic finite elements) have been considered the main openings in the lower part (used to allow the smoke flow), the upper ring-like beam and the internal floor at 12.78 m elevation (Figure 5). Due to the high rigidity of the piles system, no portion of the ground foundation has been modelled.

4.1. Material parameters

Given the lack of data, initial guess values, typical of similar structures, were assigned to the concrete material parameters (see table 2).

Young modulus [MPa]	Density [kg/m^3]	Poisson coefficient
20000	2500	0.20

Table 2: Concrete material parameters

Afterward, by means of a structural identification analysis, based on modal data, these initial parameters have been automatically modified (§5.1) by a fitting process (experimental modal features versus numerical) and more realistic parameters computed.

5. The numerical analyses

In order to identify the concrete material parameters, a structural identification analysis, based on modal data, was carried out. Then more realistic structural analyses of the chimney, subjected to thermal (solar irradiation) and wind loads, have been performed.

5.1. Structural identification analysis

In HISTRIDE structural identification process, numerical modal data (frequencies and modal shapes) are tuned with the experimental ones. The preliminary modal analysis, obtained with the guess material parameters values, has been performed. The experimental frequencies, on the top of the chimney, obtained by the three month long measurements of the accelerometers, are shown in table 3, while in figures 6 there are some modal shapes.

Number – Direction	Frequency [Hz]	Number - Direction	Frequency [Hz]
1° - West/East	0.393±0.003	3° - North/South	1.938±0.012
2° - North/South	0.408±0.004	4° - West/East	1.979±0.012

Table 3: Experimental frequencies

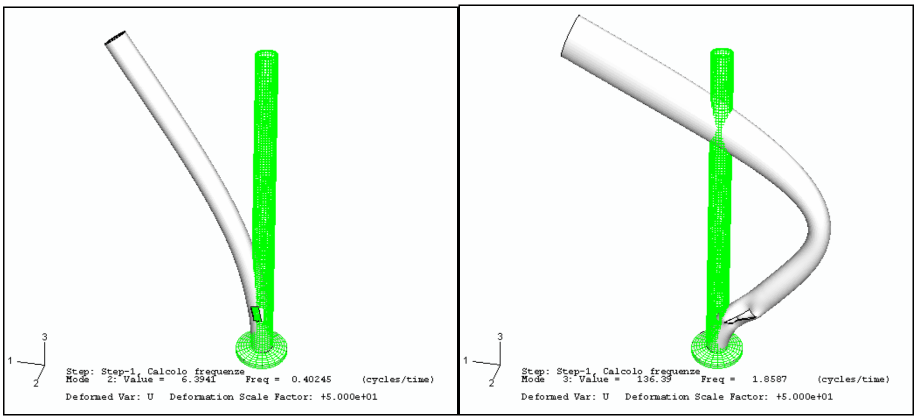

Figure 6 : Second and third modal shapes, computed by the numerical model

Several identification processes were carried out, by assigning different guess values to the material parameters of the four groups in which the chimney was subdivided (Figure 7). The analyses were based mainly on the second and third experimental frequencies which shown a better definition, despite the very limited number of recording positions. In Figure 7 the results in terms of identified material parameters are shown. The average Young modulus of the whole structure is about 21000 Mpa, quite close to the guess one.

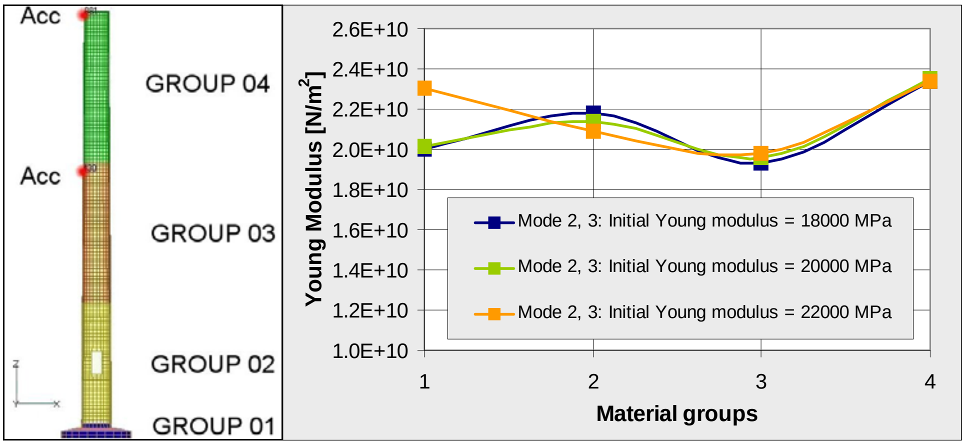

Figure 7: Finite element groups and relevant identified material parameters

5.2. Thermal analysis

The temperature distribution on the chimney surface induced by the solar irradiation brings displacements that, at the top of the chimney, are depicted in figure 4. The figure shows the horizontal positions achieved daily every 5’, for a period of about three months. The displacements in relation with the mean position have a periodic behaviour, both in North-South direction and in East-West one. There is a remarkable correlation between the positioning data obtained with GPS and those of the solar radiance provided by the meteorological station located near the chimney. Figure 8 shows, for the Giulian day 299, the patterns of solar radiance and displacements in North-South direction (normalized to zero average and standard deviation equal to one).

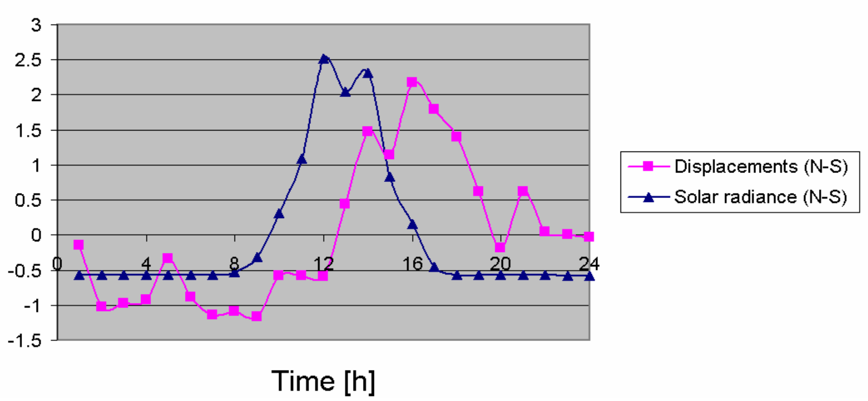

Figure 8: Displacements and solar radiance on East-West direction.

Considering stress analysis, the temperature distribution on the chimney surface induced by the solar irradiation has been computed in accordance with the current Italian technical prescriptions, [2]. The numerical analysis shows horizontal displacements in agreement with the thermal load. In particular, since the south side of the chimney is directly irradiated, the higher temperature induces a horizontal displacement towards the north direction, increasing moving away from the bounded foundation (Figure 9). Being the thermal load a constraint, the tensional pattern is almost negligible all over the chimney.

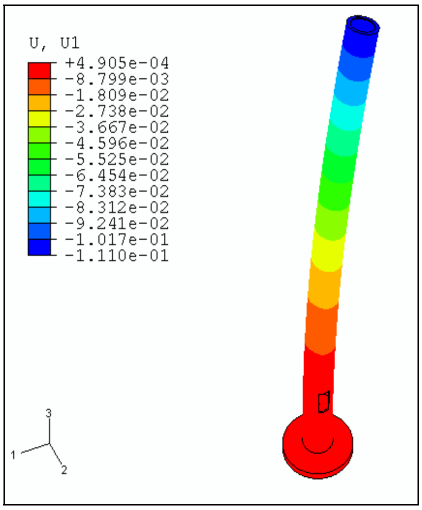

Figure 9: Horizontal displacements of the chimney [m] due to the thermal load

5.3. Wind analysis

The prevalent wind direction, provided by the meteorological station located near the chimney, is the north one. The reference wind velocity (15m/sec) and the distributed wind pressures along the chimney are supplied by the French legislation in force.

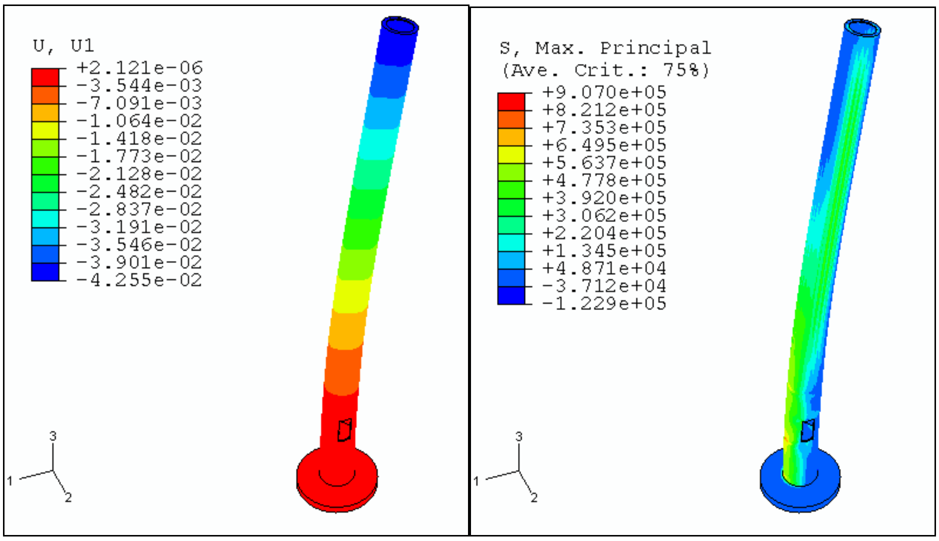

Figure 10: Horizontal displacements of the chimney [m] and principal max stresses due to wind

The numerical analysis shows that the horizontal displacements are lower compared to those due to the thermal load; while the principal tensile stresses are greater, but anyway modest.

6. Conclusions

This paper reports on the monitoring system configuration consisting of GPS receivers and accelerometers installed on a chimney of the power plant of Piacenza (Italy) and the results achieved. The structural identification analysis, carried out by taking into account the observed natural frequencies and the relevant modal shapes provided by the monitoring

system, has been obtained by processing the accelerometers recorded data. The results are moderately satisfying, although the modal shapes are roughly described (only two measure points). The GPS system was not able to provide good frequency data because, when subjected to environmental loads, the chimney displacements were very often quite low and less than the real time GPS accuracy (1 cm).
Anyway the system has shown good characteristics and it should be tested on different structures, which exhibit displacements greater then about 10 cm.

7. Acknowledgements

This work has been financed by the Research Fund for Italian Electrical System established with Ministry of Industry Decree DM 26/1/2000. Part of the project has been also financed in the framework of the National Research Program COFIN 2004 by the Ministry of the University and Scientific Research of Italy. We are grateful for the support of CESI in particular of geom. Paolo Abruzzi. Thanks also go to the Leica Geosystems staff for technical advice and support.

References:

[1] Bolognini, L., Frigerio, A.: Histride: an integrated software environment for dynamic structural identification, STREMAH, Bologna, Italy, 2001.
[2] UNI ENV 1991-2-5: Eurocodice 1: Basis of design and actions on structures. Part 2-5: Actions on structures - Thermal actions, 2001.
[3] SNBATI: Règles de conception et de réalisation des réfrigérants atmosphériques en béton arme, 1996.
[4] Bettinali, F., Frigerio, A.: Identificazione strutturale e analisi del comportamento di una struttura monitorata con un sistema ibrido (GPS e accelerometri), Prot. CESI A5056002, Milan, Italy, 2005.
[5] Cazzaniga N.E., Pinto L., Forlani G., Abruzzi P.: Monitoring oscillations of slender structures with GPS and accelerometers. In proceeding of “FIG Working Week 2005”: New Measurement Technology and Its Application to Archaeological and Engineering Surveys, Cairo, Egypt, 2005.
[6] Ogaja C., Rizos C., Wang J., Brownjohn J.: GPS and Building Monitoring Case Study: Republic Plaza Building, Singapore, 2002.