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.

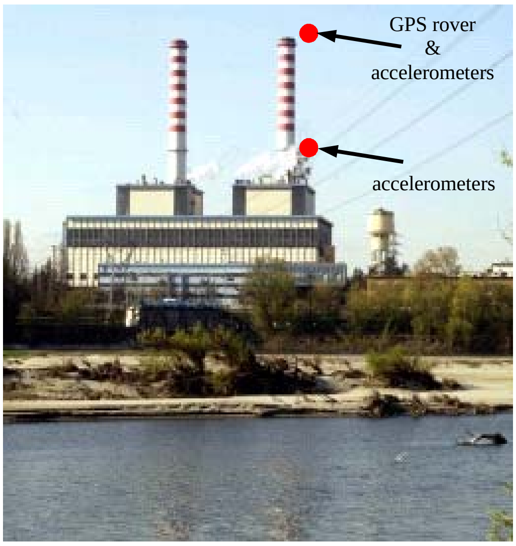

Figure 1: Chimneys view and instruments locations

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.

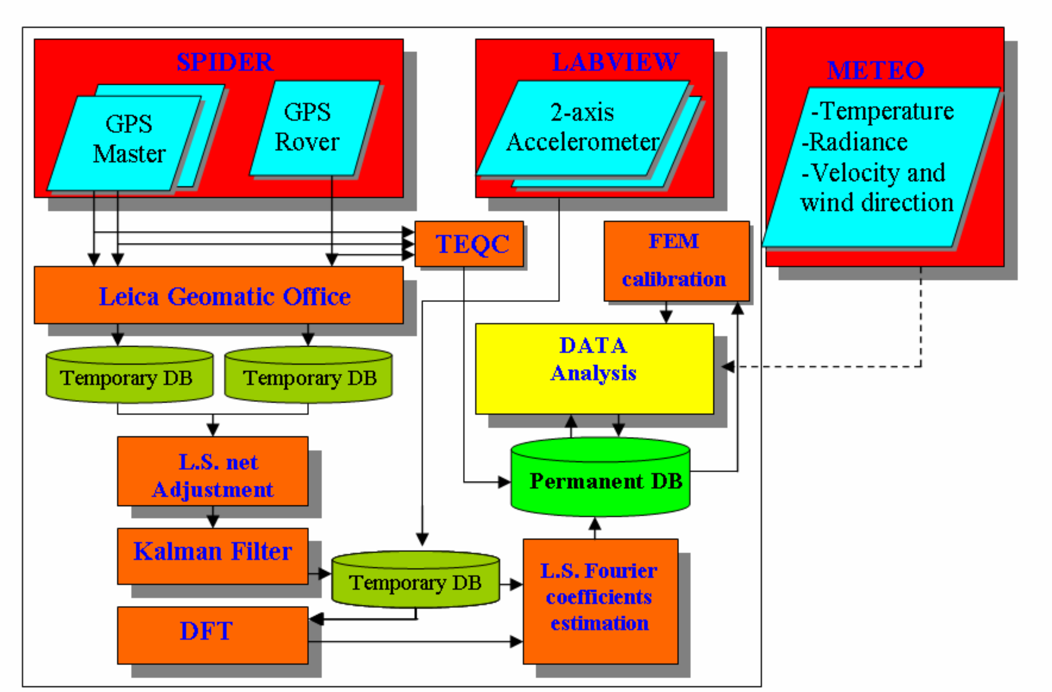

Figure 2 : Flow chart of the data acquisition and processing of the monitoring system.

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.

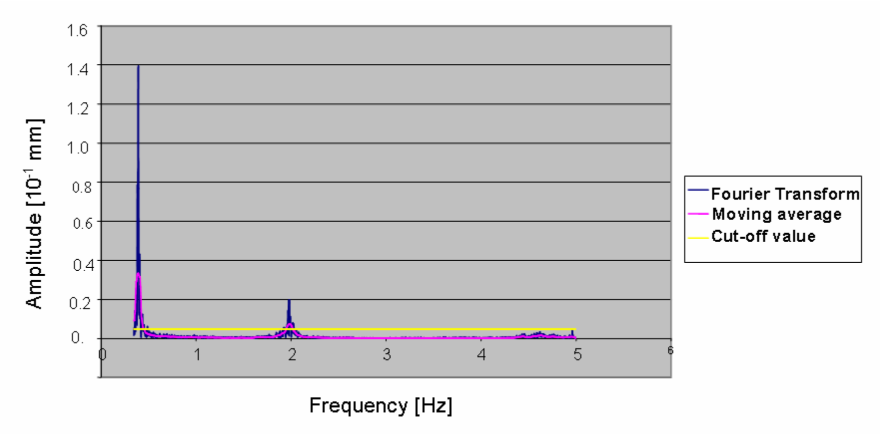

Figure 3 : Principal frequencies of chimney vibrations.

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.