Development of a real time internet based monitoring system in a nine story, shear wall building

R. Boroschek, T. Núñez, T. Yáñez
Department of Civil Engineering. University of Chile.

ABSTRACT:
The article describes the development of a Remote Structural Monitoring (RSM) system at University of Chile in Chile. Eight accelerometers have been installed on a nine story concrete building at three different heights. Additionally three humidity sensors were located beneath it's foundations to evaluate the influence of the soil humidity on the structural response. The system consists in an automatic identification algorithm and a publishing through open web resources. The article outlines the principal aspects of the system and the variation of frequency and damping ratio of the structure under different seismic and weather conditions. The system has been operating given free internet access since January 2009. Ambient and earthquake events have been recorded. Variation in frequency due to temperature and rain are in order of 2.5%. Damage due to the February 27, 2010 Chile earthquake were identify by the system.

Keywords: Remote Structural Monitoring (RSM), System identification methods, accelerometers.

1. INTRODUCTION

The instrumented building called Torre Central was constructed in 1962. It is located at the Engineering Faculty of the University of Chile. The building has office and classroom use. It has 9 stories and 2 underground levels and a total surface of 4602 m2. It has a total height of 30.2 meters and a plan area 30 x 19 meters, Fig. 1. The structural system consists on a reinforced concrete shear walls. Typical wall thickness is 35 cm. and typical slab thickness is 25 cm. The ratio between total wall area to plan area is 7.7 %.

Figure 1. General Views.

The article presents the equipment, recording process, data transmission, publication and interpretation of results of a web based remote structural health monitoring network.

2. SENSOR ARRAY

2.1. Sensor location

The system has 8 accelerometers, configured in a range +/- 0.25 [g] with two parallel acquisition systems: the first one for seismic records without amplification and with a trigger configuration; the second with amplification of 10 for ambient vibrations, Fig 2. The accelerometer location is shown in Figure 3.

Additionally, three humidity sensors have been installed in a well in the west side of the building. The humidity sensors are located at 20, 10 and 5 meters below the surface and they are connected to the accelerometers data acquisition system, Fig 4 (a) and (b).

The monitoring system also acquires information from a meteorology station maintained by the Meteorology Group of the Department of Geophysics at the University of Chile, Fig 4 (c). The station is installed on the roof of the building of the Department of Civil Engineering 40m form the Central Tower. Every 15 minutes the station collects data from temperature, precipitation and wind speed, among others.

Figure 2. Accelerometers and acquisition system.

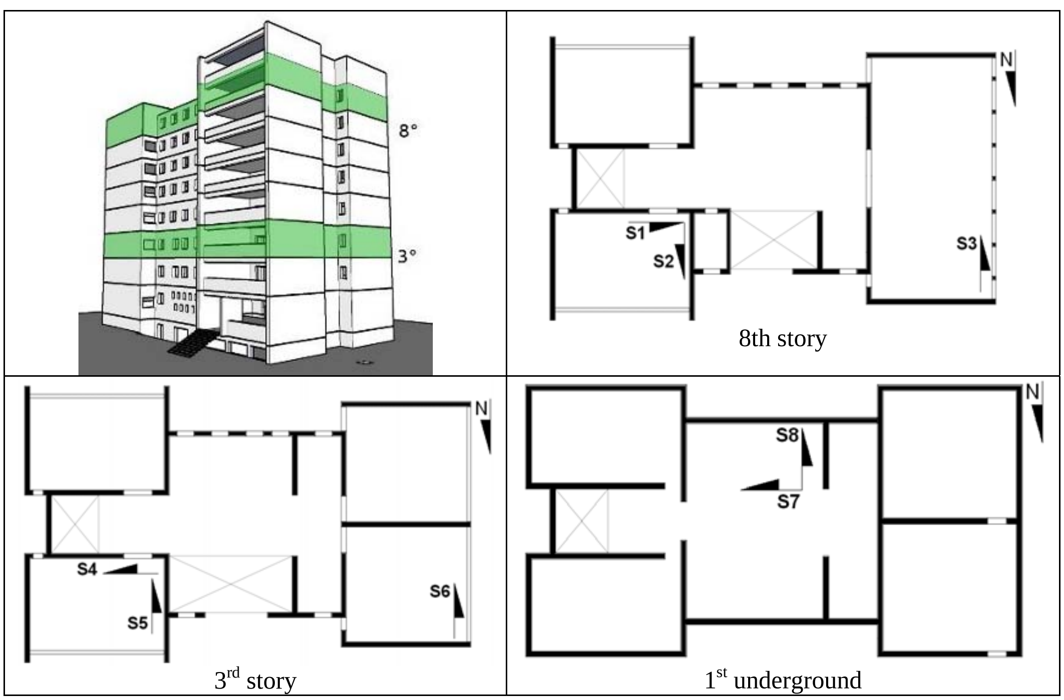


Figure 3. Accelerometer location.

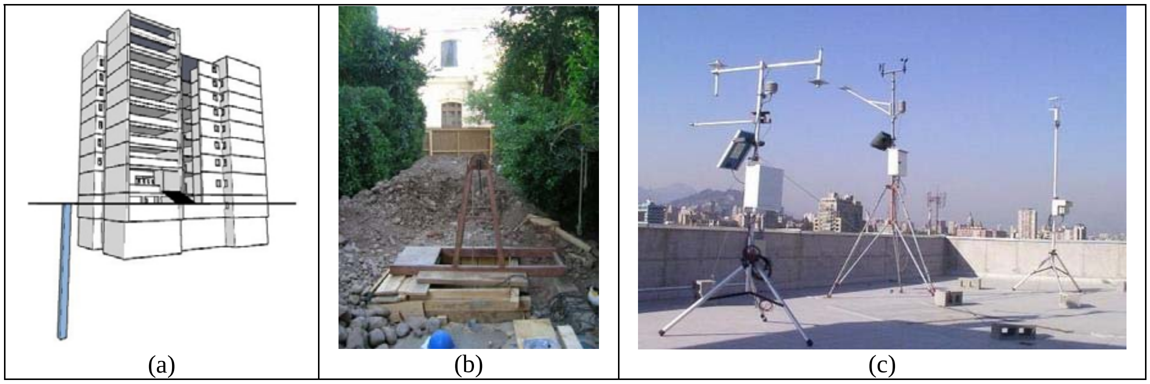


Figure 4. Sensors: (a) schematic dwell location, (b) well, humidity sensors and (c) meteorology station.

2.1. Network workflow

The structural health monitoring system stores all data in a high store capacity computer, controlled by the acquisition system. The computer and acquisition system are located in the first basement of the structure. The computer stores and post process the data using two system identification techniques to determine modal parameters: Peak Picking and Stochastic Sub-Space Identification (SSI) methods. The results are synchronized with Civil Engineering Department Server and publicated on Internet (www.ingcivil.uchile.cl/shm). The Fig. 5 shows the network and processing workflow to obtain results.

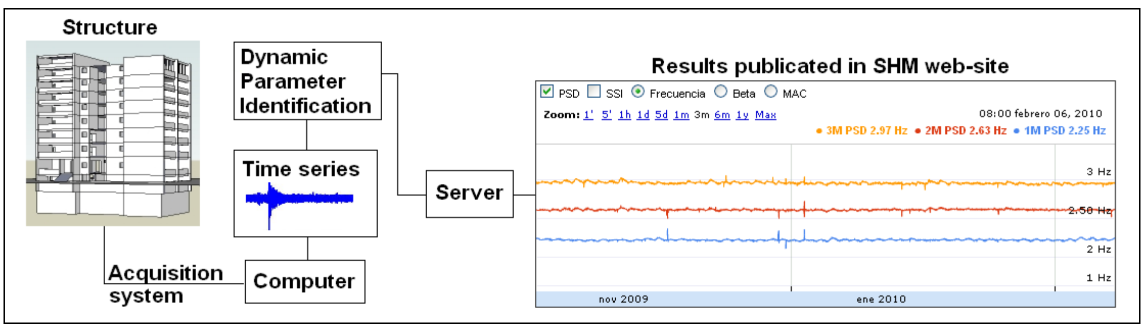


Figure 5. Structural Health Monitoring network workflow.

To obtain modal parameters from time series, the system is configured to obtain continuous records packaged on 15 minutes, 200 Hz frequency rate files. Frequency and damping ratio are updated each 15 minutes on the web site.

2. SYSTEM IDENTIFICATION TECHNIQUE

The Stochastic Subspace Identification (SSI) Technique developed by Van Overschee and De Moor is used to estimate modal frequency, damping and operational shapes. This technique uses the stochastic state space model, described by equation (1) to identified modal parameters from output only response signals.

$$\begin{aligned} \{x_{k+1}\} &= [A]\cdot\{x_k\} + \{w_k\} \\ \{y_k\} &= [C]\cdot\{x_k\} + \{v_k\} \end{aligned} \tag{1}$$

Eq. (1) constitutes the basis for time-domain modal identification through ambient vibration measurements. There are several techniques and algorithms to obtain modal parameters from stochastic subspace model, Eq. (2).

The mathematical background for many of such methods is similar, differing only in implementation aspects. The algorithms identify the state–space matrices ($[A],[C]$) based on the measurements by using robust numerical techniques, such as *QR* factorization, singular value decomposition (SVD), and least squares.

Once the mathematical description of the structure is found, modal parameters such as frequency, ω_i, damping ratio, ξ_i, and operational mode shapes, $[\phi]$ are determined from:

$$\lambda_i = \frac{\ln(\mu_i)}{\Delta t} \qquad \omega_i = |\lambda_i| = \sqrt{\lambda_i \cdot \lambda_i^*} \qquad \xi_i = \frac{real(\lambda_i)}{|\lambda_i|} \qquad [\phi] = [C]\cdot[\Psi] \tag{2}$$

To validate results the Power Spectrum Density (PSD) method complemented with window correction method to obtain damping ratios is used.

2. RESULTS OF REMOTE-CONTINUOUS MONITORING

2.1. Ambient vibration, initial modal parameters.

Several ambient vibration tests were performed to obtain the modal parameters of the building. These parameters are used as reference (signature) to identify and qualify the variations on the structure modal characteristics.

The first four frequencies, corresponding damping ratios and modal shapes are shown in Table 1 and 2. Acceptable correlations are obtained between the PSD and SSI methods, except for the damping ratio. As known, damping ratio is strongly dependent with vibration amplitude and observation window type and length.

Table 1. Frequency values obtained by PSD and SSI methods using remote SHM network.

Mode	PSD f [Hz]	SSI f [Hz]	Difference (%)
1	2.23	2.23	0.00
2	2.63	2.64	0.38
3	2.99	2.99	0.00
4	6.33	6.32	0.16

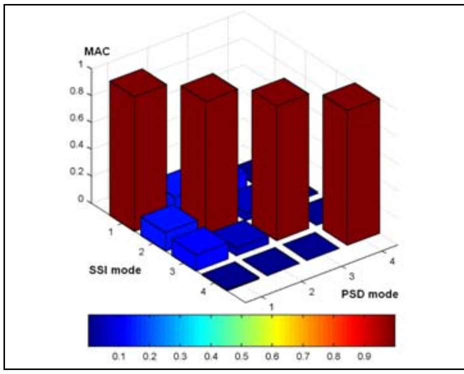
Table 2. Damping Ratio values obtained by PSD and SSI methods using remote SHM network.

Mode	PSD ξ [%]	SSI ξ [%]	Difference (% of ξ SSI)	ξ [%] range
1	1.1	0.7	57.1	[0.7 – 1.1]
2	1.3	0.8	62.5	[0.8 – 1.3]
3	1.1	0.8	37.5	[0.8 – 1.1]
4	1.2	1.3	7.7	[1.2 – 1.3]

Modal shapes are also identified with both methods, showing an acceptable correlation using the Modal Assurance Criteria (MAC) values, defined as:

$$MAC\left(\{\Psi_i\},\{\Psi_j\}\right)=\frac{\left|\{\Psi_i\}^T\cdot\{\Psi_j\}\right|^2}{\left(\{\Psi_i\}^T\cdot\{\Psi_i\}\right)\cdot\left(\{\Psi_j\}^T\cdot\{\Psi_j\}\right)} \tag{3}$$

Where $\{\Psi_i\}$ and $\{\Psi_j\}$ are the compared modal shapes. Fig 6 shows the matrix and values of MAC parameter between PSD and SSI modal.



Mode	1	2	3	4
1	1.00	0.14	0.12	0.01
2	0.14	1.00	0.06	0.00
3	0.12	0.06	1.00	0.00
4	0.01	0.00	0.00	1.00

Figure 6. MAC parameter between PSD and SSI modal shapes.

2.1. SHM web page display. Correlation with soil and ambient parameters.

At present one of the challenge of SHM remote monitoring is to reduce processing time of different algorithms to report modal parameters on the Web. Research is focusing on how to organize and upload real-time results of modal parameter. The web-site designed for this investigation is in beta-version, doing continuous improving to the system. For the moment results are stored and published each 15 minutes on the Web and it can be access from any computer. The web-site main page shows three graphics: the first are the modal parameters showing the frequency and damping variations. The second shows soil humidity and the third shows ambient parameters, Fig. 7.

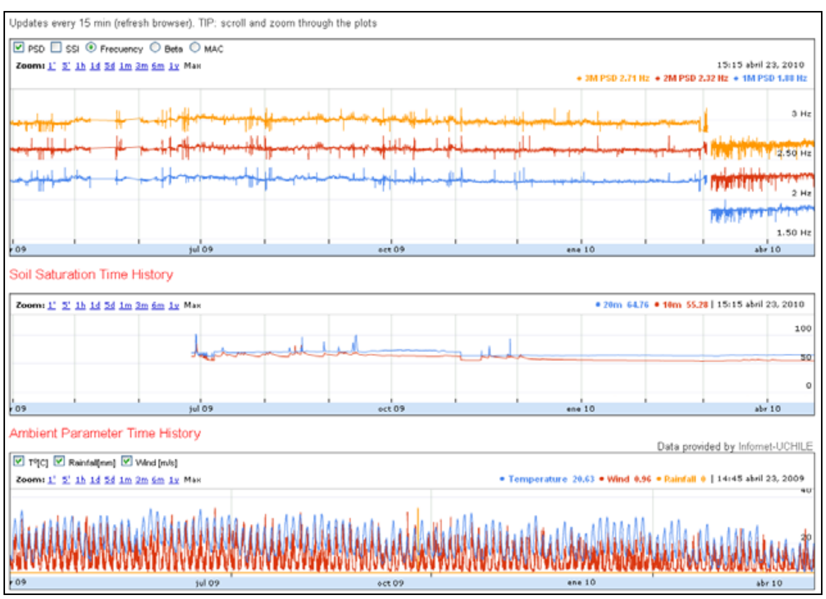


Figure 7. SHM web-page. www.ingcivil.uchile.cl/shm. Beta-version.

Important results could be obtained from large amount of data. One of the objectives of this type of monitoring is to correlate ambient variables (temperature, rainfall, wind speed) with variations on modal properties associated to the structure. Current investigation is focusing also to determinate relationship between variables, to uncouple the effects on modal frequencies and damping ratios. As an example, Fig. 8 shows the effects on the first modal frequency (a) and damping ratio (b) due to temperature variations.

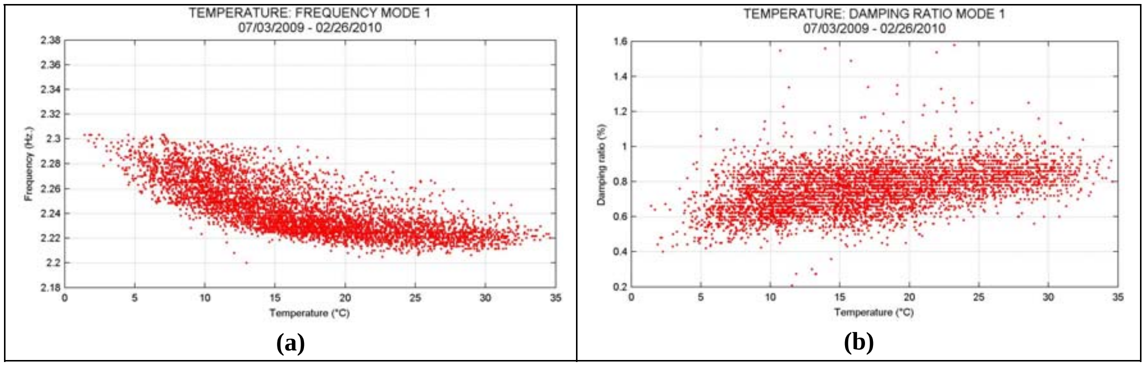


Figure 8. (a) Temperature effects on frequency variations, mode 1. (b) Temperature effects on damping ratio, mode 1. Samples were taken between July 3, 2009 and February 26, 2010.

This kind of analysis is useful to recognize non-linear behavior due to ambient parameters, or to conclude that some variables have no influence on dynamic parameters.

3. VARIATIOS ON MODAL PARAMETERS DUE CENTRAL-SOUTH CHILE MW = 8.8 EARTHQUAKE

The Central-South Chile Mw = 8.8 earthquake recorded on February 27th 2010, provided additional and important information for this research. The results of remote-continuous health monitoring of Torre Central during the earthquake detected the change of modal parameters and correlated with damage on structural elements of the building. From Fig. 9 is possible to observe an abrupt drop for the frequencies during the earthquake. SHM website reports a decrease of 16.58% (21.08% 1^{st} frequency, 16.86% 2^{nd} frequency and 11.82% 3^{rd} frequency) in average for the first 3 frequencies, during the earthquake. Later analysis, using ambient vibration, showed a small increase of these frequencies, respect to the ones obtained during earthquake, but they did not recovered to values before the earthquake. Table 3.1 shows a difference of 12% in average for the frequencies.

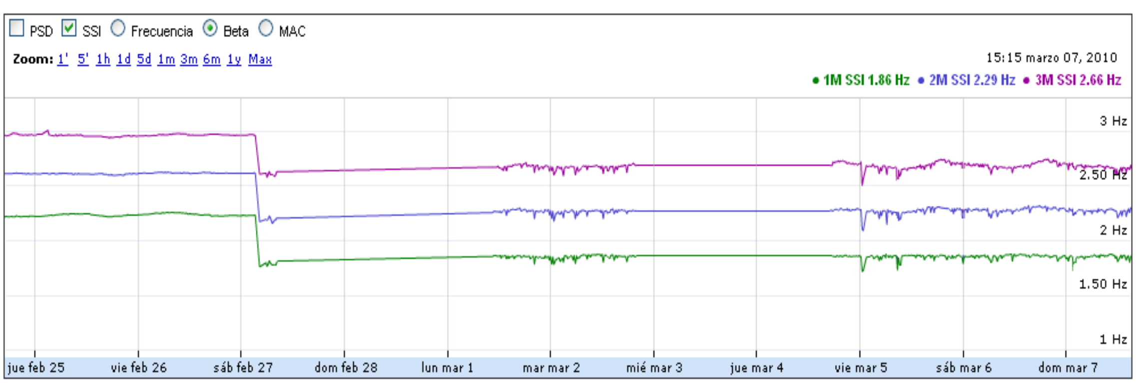


Figure 9. Frequency variation due to Cauquenes Earthquake. Frequencies published on www.ingcivil.uchile.cl/~shm.

Table 3.1. Frequency comparison between before and after earthquake using ambient vibration tests.

Before Earthquake Frequency [Hz]	After Earthquake Frequency [Hz]	Difference [%]
2.22	1.89	15.09
2.63	2.27	13.64
2.94	2.70	8.11
	Average	**12.28**

The SHM system showed an increased of the critical damping ratio during the earthquake, reaching values around 8%. However, post-earthquake, ambient vibration test showed similar values to those obtained before the earthquake, which correlates acceptably with the level of damage observed in the building, Table 3.2.

Table 3.2. Damping ratio comparison between before and after earthquake using ambient vibration tests. SSI method.

Before Earthquake Damping Rati0 [%]	After Earthquake Damping Rati0 [%]	Difference [%]
0.7	0.7	0.0
0.8	0.7	12.5
0.8	0.8	0.0
	Average	**4.2**

3. CONCLUSIONS

Structural health monitoring has many applications that allow better understand the behavior of structures. The combination between technologies and structural diagnosis allow smart structures "report" its state continuously and in real time, according to current information needs. Remote-continuous structural health monitoring system was shown as an important tool of structural diagnosis. The fifth largest earthquake of the world showed the effectiveness of the system.

AKCNOWLEDGEMENT

The Civil Engineering Department of the University of Chile and the Chilean Council for Research and Technology, CONICYT Fondecyt Project # 1070319 supported this research paper. Part of this research was part of the Engineer Thesis of Tomas Yañez of the University of Chile.

REFERENCES

Brinker, R., Anderson, P. (2006). Understanding Stochastic Subspace Identification. *IMAC-XXIV: A Conference & Exposition on Structural Dynamics*.

Clinton, Bradfor, Heaton and Favela. (2006). The Observed Wander of the Natural Frequencies in a Structure. *Bulletin of the Seismological Society of America*, **Vol. 96**, February 2006.

Han, L., Newhook, J., Mufti A. (2005). Some practical issues in remote structural health monitoring. *Nondestructive Evaluation and Health Monitoring of Aerospace Materials, Composites, and Civil Infrastructure. IV Proceedings* of the SPIE, **Vol. 5767**, pp. 187-194 2005.

Ni, Y., Xia, Y., Liao W., Ko, J. M. (2009). Technology innovation in developing the structural health monitoring system for Guangzhou New TV Tower. Structural Control and Health Monitoring. **N° 16**: pp. 73-98. 2009.

Nunez T. (2009). Variation due to changes in mass and stiffness of dynamic properties of a structure in construction process. *M.Sc. Earthquake Engineering Thesis. University of Chile.*

Van Overschee P., De Moor B. (1996) "Subspace Identification for Linear Systems: Theory-Implementation-Applications". Kluwer Academic Publishers, Dordrecht, The Netherlands.

Yáñez T., 2009. Implementation of continuous monitoring network, dynamic parameters identification system of a shear-wall building. *Civil Engineering Thesis. University of Chile.*