EXPERIMENTAL EVALUATION OF MODAL PARAMETER VARIATIONS FOR STRUCTURAL HEALTH MONITORING

Ruben L. Boroschek[1], Patricio A. Lazcano[2] and Lenart Gonzalez[3]

[1] *Associate Professor, Dept. of Civil Engineering , University of Chile, Chile*
[2] *Engineering Student, Dept. of Civil Engineering , University of Chile, Chile*
[3] *Assistant Professor, Dept. of Civil Engineering , University of Chile, Chile*
Email: rborosch@ing.uchile.cl

ABSTRACT :

The article presents magnitudes variations of the modal parameters of a structure-soil system using modern systems identification techniques. In this building a local instrumental network has recorded more than twenty small and moderate seismic events with different usage conditions and structural and non—structural modifications since 1995; in addition, several ambient vibration records have been obtain, one of them with a duration of 7 months (continuous), to estimate modal variations due to weather, usage and seismic conditions. To evaluate these properties, parametric and non-parametric identification techniques are used. For the ambient records the methods used are spectral values and stochastic subspace identification technique. For seismic recording, parametric techniques are used such as MIMO's technique developed by S. T. Mau. With the help of these studies, ranges for predominant frequency variation are on the order of 4% for ambient vibrations and moderate earthquake events that do not produce any damage in the structure. The predominant frequency variation observed are highly dependant on ambient conditions specially rain and temperature. The results obtained are an important indicator of non damage variations of predominant frequency for Health Monitoring Studies.

KEYWORDS: Health Monitoring, Ambient Vibration, System Identification, rain, temperature

1. INTRODUCTION

The Chilean Chamber of Construction is instrumented with a permanent network of 12 accelerometers connected to a central recording system. Figure 1 presents the instrumentation layout and structure main characteristics. The structural system of the building consists in a central concrete wall and perimeter concrete columns. Wall thickness represents in average 4% of the plan area. The building present three underground levels surrounded by heavy concrete walls. The building is located on top of a gravelly soil, known as the Santiago's gravel. This deposit was formed by a sedimentary process from the Mapocho and Maipo rivers and has an average thickness of 300 m. Its mechanical properties are excellent due to its high compactness and rather good gradation. Below the second deposition corresponding to the first 4.5 to 6.5 meters, the deposit contains some plastic fines, which improves the natural cohesion of the soil.

The building instrumentation is able to record motions with amplitudes between 0.0001 up to 2 g in a bandwidth of 0.1 to 100 Hz. This network characteristic allows for the monitoring of ambient vibrations and strong seismic events. Since its installation in 1995 several earthquake records and ambient vibrations had been recorded in the building. During this time more than 30 minor and moderate events have been recorded. Table 1 show some of the events records and analyzed in this article.

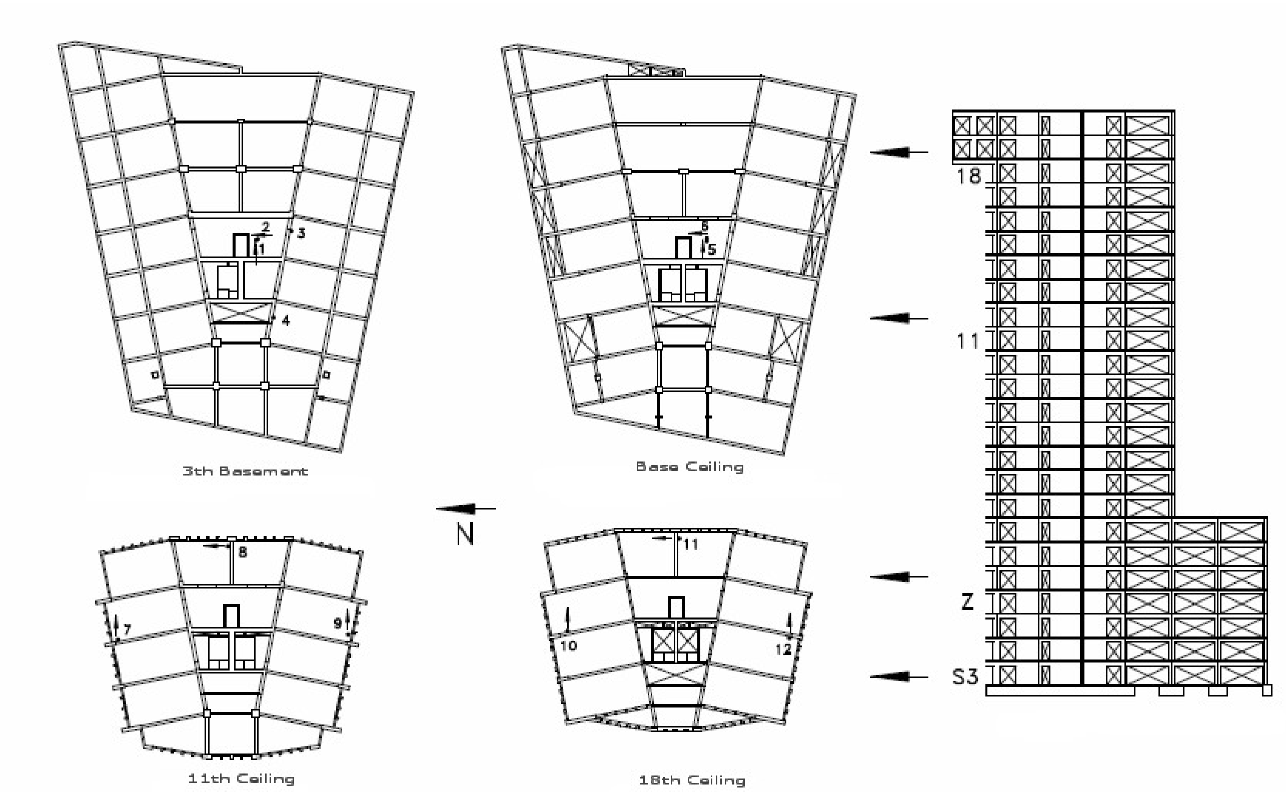

Figure 1. Sensor Location

2. MODAL PARAMETERS FROM EARTHQUAKE RECORDS

To identify the modal parameters of the structure a Multi-Input-Multi-Output (MIMO) modal minimization technique implemented by Li and Mau (1991) is used. In this case only plane model, with no torsional consideration or three dimensional behavior is considered. Records from the third basement are considered as input. Output records from all floors are considered for each direction.

Initially average modal parameters were obtained by including the total duration of the strong motion record for the analysis. Table 2 shows the variation of predominant parameters. Variations are nevertheless relative minor compare with variations in input energy. Additionally no clear tendency is observed.

Table 1. Earthquake Events

Event	Mag. Richter	Latitude	Longitude	Peak Ground Acceleration (g)	Max Structural Acceleration (g)
Jan24, 1997	5.3	33°28.1' S	70°47.1' W	0.064	0.140
April 20, 1997	5.3	33°59.7' S	70°28.0' W	0.022	0.050
Jun 19, 1997	5.1	33°09.4' S	70°18.1' W	0.013	0.040
Oct 14, 1997	6.8	30°44.5' S	71°19.7' W	0.024	0.080
Jan 12, 1998	5.9	31°18.8' S	71°25.1' W	0.009	0.046

If smaller analysis time window are used for the MIMO identification, a more clear variation from the earthquake records with amplitude of motion is observed. Figure 2 present the variations of the first four translational predominant shapes of the structure, for the five earthquake records studied. The characteristic input record is presented at the bottom of the figure. A clear tendency to reduce the modal frequency is found with increasing amplitude response. Typical variations of frequency are in the order of 4%. Additional discussion on this analysis can be found in Boroschek and Soto (2002) and Boroschek and Lazcano (2008).

Table 2. Modal Properties identify from Earthquake Records.

Event	**24-01-1997**		**20-04-1997**		**19-06-1997**		**14-10-1997**		**12-01-1998**	
Richter Magnitude	5.3		5.3		5.1		6.8		5.9	
Predominant Frequency	Freq. Hz	β %	Freq. Hz	β %	Freq. Hz	β %	Freq. Hz	β %	Freq. Hz	β %
1	0.986	2.7	0.996	1.5	1.000	1.7	0.967	1.4	0.972	1.4
2	1.002	1.7	0.996	1.5	1.020	1.4	0.977	1.5	1.005	1.6
3	1.486	2.6	1.470	N/c	-	-	-	-	-	-
4	2.262	N/c	-	-	-	-	-	-	2.176	3.6
5	3.324	3.6	3.377	2.9	3.416	3.0	3.353	3.6	3.382	2.5
6	3.421	3.6	3.381	3.0	3.470	2.3	3.355	3.6	3.471	2.7
7	4.543	N/c	-	-	-	-	-	-	4.951	1.0
8	-	-	-	-	5.892	3.4	-	-	-	-
9	-	-	-	-	8.815	9.6	-	-	-	-
MIMO Relative Error (%)	38.0		24.0		26.3		27.1		20.4	
MIMO Absolute Error	1.75E5		2.83E4		1.59E4		2.82E5		2.20E4	

3. MODAL PARAMETERS FROM AMBIENT RECORDS

Several ambient vibration records have been obtained from the building. Some of them between earthquake events. One of the records is continuous for 7 month. These records includes the 12 channels which have been sampled at 100 Hz. Additionally weather conditions including temperature, humidity, rainfall, wind speed and wind direction have been monitor with a sampling rate of 15 minutes. Typical weather condition records are shown in Figure 3 for temperature and Figure 4 for Humidity. During the study temperature ranged from -1 to 34 °C, humidity from 10% and 100%, the maximum wind velocity was 22 m/s and the maximum rainfall during a day was 25 mm.

3.1. System Identification Technique

The Stochastic Subspace Identification Technique developed by vanOverschee, P. and B. DeMoor, (1996) is used in order to have reliable results for frequency. This technique uses a state space parametric model to identified modal parameters from output only response signals. This methods is used because allows a robust identification of linear structures that present close predominant periods, as is the case for the building studied. A description of the method can also be found in Peeters and Ventura (2003).

To validate the identification technique a computer model was developed. Random input signal was input at base level and random noise added to node responses. The identification technique was able to identify the natural frequencies with less than 0.5% of error even when the output signals where contaminated with 10% random noise.

The structure was monitored for seven month. The records were digitized and stored for post processing. In order to have a preliminary estimate of the parameters only the first 10 minutes of each recorded hour is use as reference for the predominant frequencies for the hour. This is so because the SSI method is very computer costly. Results presented in this article are base on this data. Currently a more detailed study is been performed were the hour is divided in 6 segments and the average value for the hour is used to represents the characteristic value.

3.2. Identification Results

Figure 5 presents the seven month evolution of predominant frequency for the first two modes. In general we observed a quickly variation on top of a more smooth variation. It is interesting to note that the relatively quick variations can be explained by the daily temperature variations and the amount of rainfall as presented below. When the identified frequency for each hour and for the seven month is plotted in a histogram, the identified modes present a bell shape distribution as shown in figures 6 and 7. The mean and standard deviations from the frequency distribution of natural frequency are presented in Table 3.

Table 3. Identified Frequency Mean and Standard Deviation Value.

Mode N°	Frequency [Hz]	Frequency [Hz]
1	1.0153	0.0033
2	1.0304	0.0038
3	1.5538	0.0078
4	3.4338	0.0132
5	3.4841	0.0160
6	3.8946	0.0586
7	4.5960	0.0250

Despite the fact that variations are relative small they are easily observed and correlate with environmental variables. The relative larger values of standard deviation for the 6 and 7 predominant frequency are not only related to environmental variable but rather some usage modification that affected mainly to these modes. Additionally it is important to consider that all ambient variables are acting at the same time.

In Figure 8 and 9 the first predominant frequencies are plotted in the same graph with temperature, for a 10 days period. In this figure the red line presents temperature and the blue line predominant frequency. As can be seen in this figure the temperature varies approximately 15 °C during a 24 hour period. In this case the frequency varies slightly out of phase with temperature, and for the first predominant frequency an increase of temperature generates an apparent increase in frequency. The ratio of maximum to minimum frequency for the 10 day period is 1.022, a 2.2% variation. For the third predominant frequency and inverse relation is observed. A physical explanation for this behavior is still under evaluation.

Rainfall also affects the frequency of the structure, Figures 10 and 11. For this case the red line indicates the 15 minutes rain fall (not accumulated) for a 12 day observation period. The rain lasted for two days. It can be easily seen in this figures that a few hours after the rain started a rapid increase of frequency occurred. The increase in frequency is approximately 1.5% above the previous observation period. After the end of the rain a slow reduction of frequency is observed. The original mean predominant frequency values are obtained after 6 days the rain has ended.

The other environmental variables studied wind velocity and direction and humidity do not show as a clear correlation with modification of predominant variation of building/soil system.

4. CONCLUSIONS

The variation of modal parameters of a 22 story reinforced concrete shear wall building located on gravely soil is determined using ambient vibration and earthquake records. In order to identify the predominant frequencies robust parametric identification techniques are used. These techniques were initially validated using an analytical model of the structure under controlled input and output signals, including noise.

From the analysis of medium intensity earthquakes, variations in frequency close to 4% are found, even that the building sustained no damage.

Additionally a clear effect of ambient conditions on the structure/soil system was observed. These variations were also in the order of 4% on the predominant frequency. The main environmental effects are temperature and rainfall.

Usage effects, (not consider architectural or structural modifications), do not appear to affect the predominant structural periods as concluded from the comparison of day and nigh and holiday’s results.

It is interesting to note that predominant frequency variations are shown in most of the modes but with different consequences. In some instances temperature and rainfall variations are positively correlated with frequency variations nevertheless some mode shapes show negative correlation. For the building study a clear different is observed between translational predominant modes and torsional modes.

The results obtained are an important indicator of non damage variations of predominant frequency for Health Monitoring Studies.

5. AKNOLEDGEMENTS

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.

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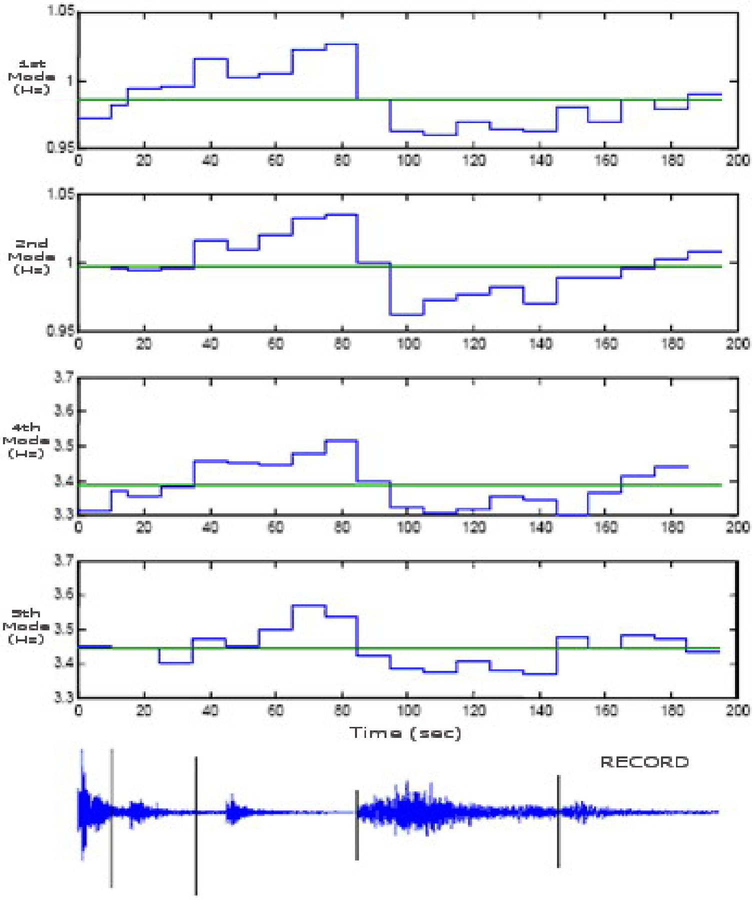

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Figure 2. Variation on modal frequency during earthquakes. Moving window analysis.

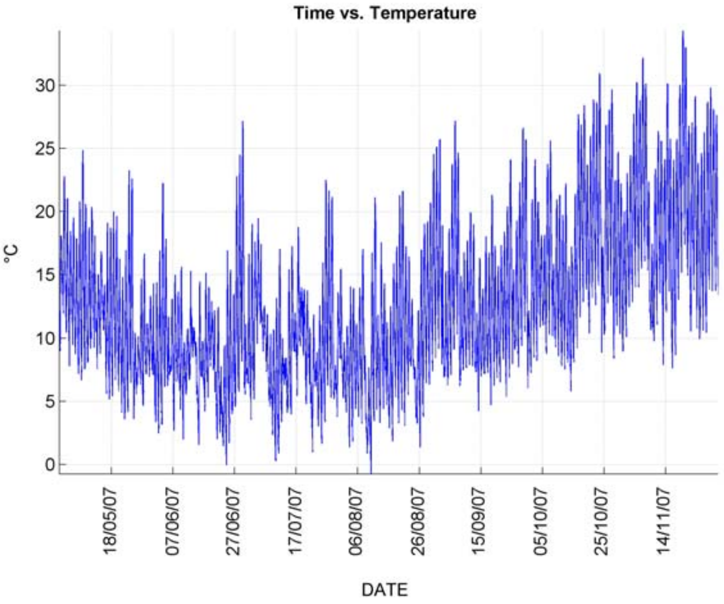

Figure 3. Temperature Variation May-November

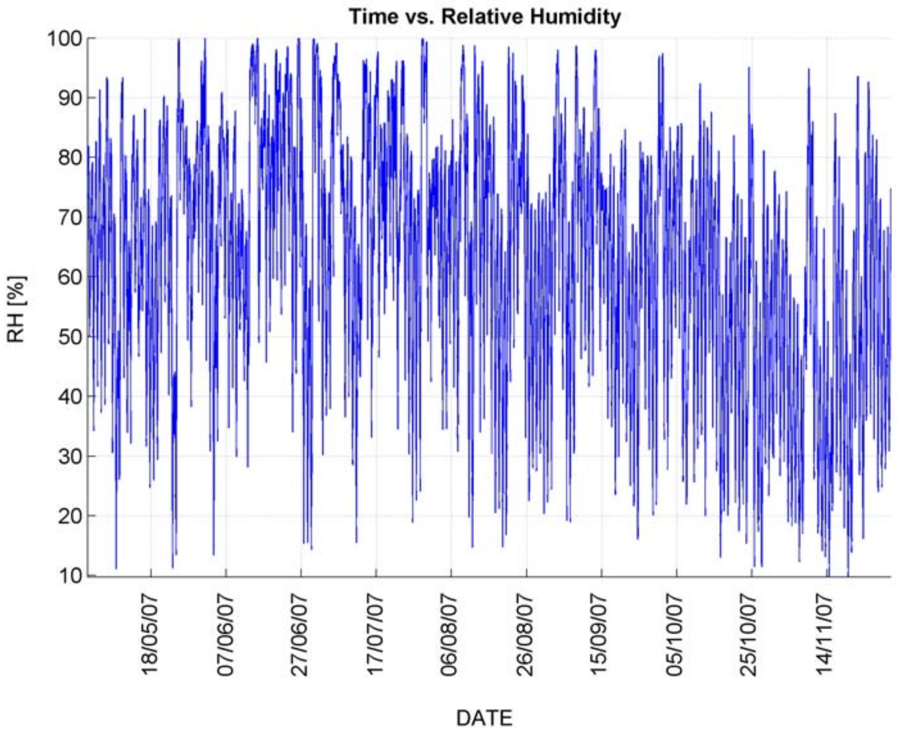

Figure 4. Humidity Variation May-November

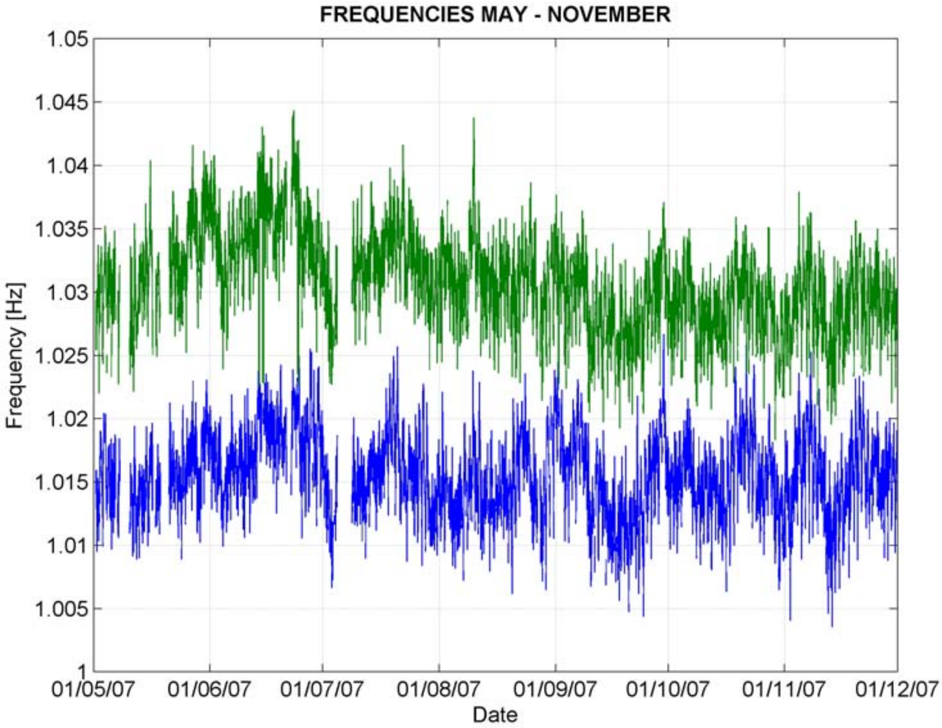

Figure 5. First and Second Mode Variation May-November

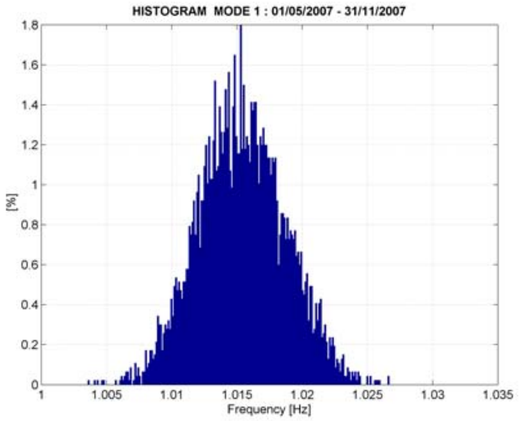

Figure 6. First Mode Histogram

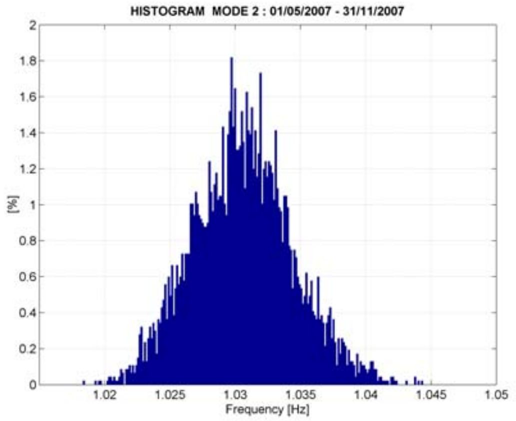

Figure 7. Second Mode Histogram

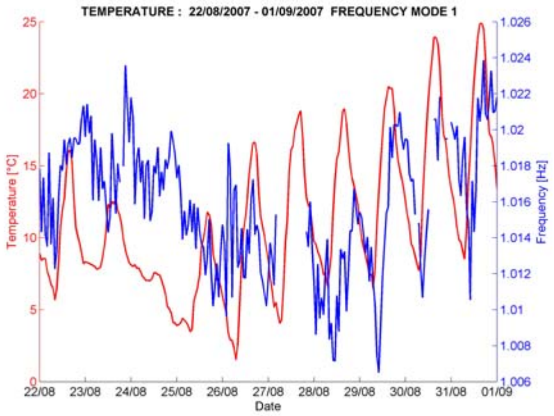

Figure 8. First Mode Parameter Variations with Temperature.

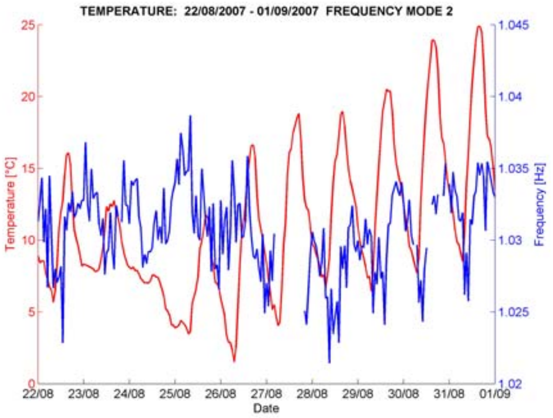

Figure 9. Second Mode Parameter Variations with Temperature.

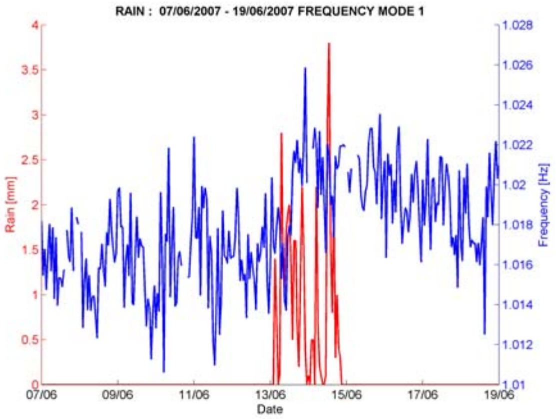

Figure 10. First Mode Parameter Variations with Rain.

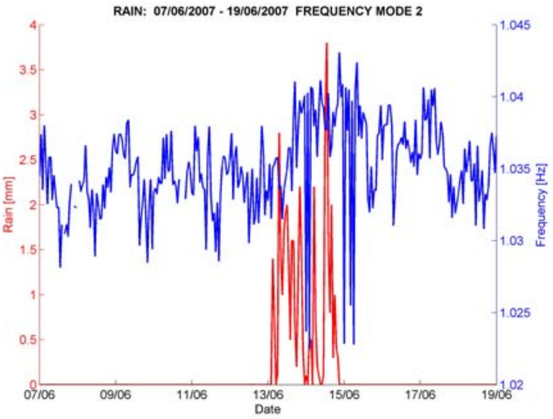

Figure 11. Second Mode Parameter Variations with Rain.