



# Chapter 9

## Ambient Vibration Tests and Modal Response Analysis of Guayaquil Metropolitan Cathedral in Guayaquil, Ecuador

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**Abstract** This paper describes a series of ambient vibration tests and modal analysis conducted on Guayaquil Metropolitan Cathedral, located in Guayaquil, Ecuador. The Guayaquil Cathedral is composed of the reinforced concrete frames and masonry infills, constructed in mid 1920s. Modal response analysis was performed to identify the dynamic properties of the structure, including predominant natural frequencies and the corresponding mode shapes to support seismic assessment and upgrading of the Cathedral. The testing program consisted of several setups on different locations of the structure including the roof of the main building, towers, and the dome. Two series of sensors were used to carry out the vibration measurements: (1) Tromino<sup>®</sup> velocity/acceleration wireless sensors; and (2) Polytec<sup>®</sup> Laser Vibrometers. The sensors were placed on predetermined locations according to the test plan; The wireless sensors were located on top of the roof, along the height of the towers, and top of the dome whereas the Laser Vibrometers were reflected to the Diaphragms to study the flexibility and also to determine the modal frequencies of the Diaphragms. The computer program ARTEMIS version 4, was used to perform the system identification of the structure. The software allows to develop a 3D model of the structure and test points; the resulting mode shapes are displayed using this geometry. Two different techniques were used for modal identification: the Enhanced Frequency Domain Decomposition (EFDD) and the Stochastic Subspace Identification (SSI). These two modal identification techniques were used to cross-validate the results. The joint analysis of the signals measured in various strategic points of the structure made it possible to identify the modal configurations and the corresponding natural frequencies. As the results of this study, the vibration modes of the main building, towers and dome in translational and torsional directions, as well as the motions of the diaphragms were discussed. Also, the natural frequencies and corresponding dynamic mode shapes were presented.

**Keywords** Ambient vibration test · Modal analysis · Cathedral · Mode shape · Frequency

### 9.1 Introduction

Ambient Vibration Tests (AVTs) are widely used for system identification and damage detection in the structures [1]. Elyamani et al. [2] and Turek et al. [3] used this technique for model updating and modal analysis of cathedral structures before, respectively. The current study focuses on a series of Ambient Vibration Test those were conducted at the Guayaquil Metropolitan Cathedral, located in Guayaquil, Ecuador in order to determine the modal frequencies and the mode shapes of the structure. The sensors were placed on predetermined locations according to the test plan; on the roof of the building, on the towers, on the dome and inside the cathedral at the level of diaphragms. A series of vibration tests were then carried out using velocity sensors and laser vibrometers on October 31st to November 3rd, 2018. The main purposes of the AVTs were to determine the fundamental frequency and corresponding mode-shape of the towers in the current condition, as well as to estimate the site period.

The Metropolitan Cathedral of Guayaquil (officially San Pedro Cathedral) is located in the Guayaquil downtown, near the Seminary Park. It was originally built by wood around 1547 next to the Municipal Palace and in the “Plaza de Armas”, (nowadays Seminary Park). The temple was destroyed by a fire in 1692 and maintained the simple colonial style for long time until the twentieth century. It was rebuilt by reinforced concrete materials between 1924 and 1937 in neo-Gothic style.

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On the facade of the original church, there was a carved wooden medallion with the image of the Apostle Santiago, patron of Guayaquil, which was removed from the old church and placed in the Office of the Mayor of Guayaquil, in the Municipal Palace of Guayaquil as decoration. The Cathedral has attached to the Archbishop's Palace of Guayaquil and the offices of the metropolitan curia, also in neo-Gothic style [4].

After the Ecuador Earthquake in 2016, the Cathedral suffered some damages in the structural and non-structural components. The Archdiocese of Guayaquil has repaired the damaged non-structural components and has carried out some studies on the structural components. This paper describes the ambient vibration tests and modal analysis that serves as the basis of the cathedral structure assessment proposal which is still under review by the Archdiocese [4].

## 9.2 Ambient Vibration Tests

AVTs were conducted at the Cathedral structure from October 31st to November 3rd, 2018 in order to determine the dynamic modal properties (modal frequencies and mode shapes) of the structure. The starting and ending time of the test setups, number of the sensors in each setup, recording time for each setup, and the average temperature at the time of the tests are presented in Table 9.1 [4].

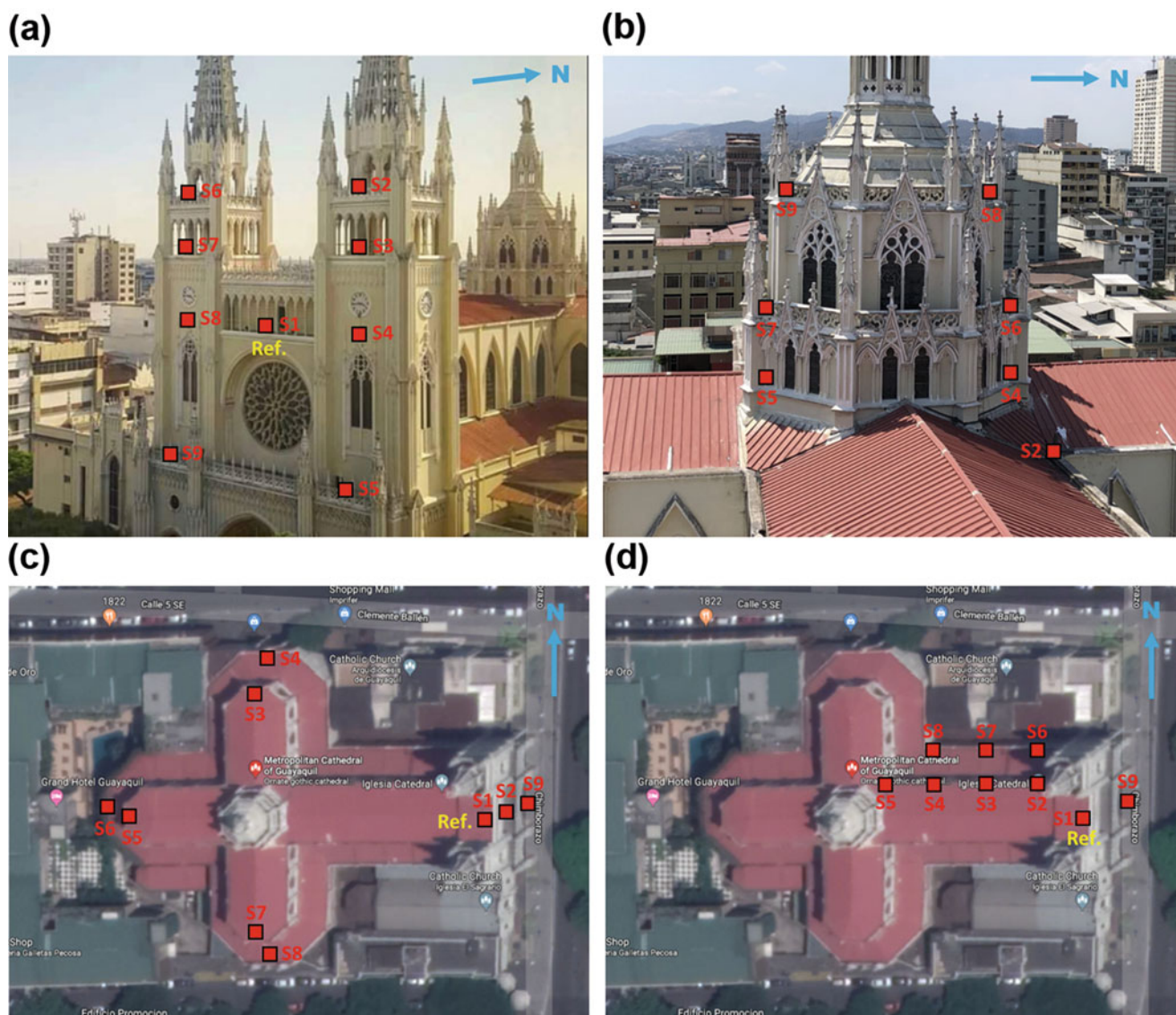
The testing program consisted of five measurement tests: Test 1 with four setups on the Towers, on the roof of the Main Building, and on the Dome using Tromino sensors; Test 2 was including five setups inside the Cathedral on the end walls in the North wing, East and West wings using Laser Vibrometers; Test 3 was including six setups inside the building on the North wall along the building using Laser Vibrometers; Test 4 was including two setups inside the building on the end walls of East and West wings using Laser Vibrometers; Test 5 including three single station Tromino sensors on ground inside and outside of the building to determine the site response. Figure 9.1 shows the layout of the measurement setups in the Test 1.

Tromino<sup>®</sup> velocity/acceleration sensors [5] were used to carry out AVTs in Test 1 and Test 5. The collected records were time synchronized with a radio antenna and amplifier in each sensor. This allowed the synchronization of the recordings both within each measurement setup and between setups. The Tromino sensors are suitable for high-resolution ambient vibration tests as they are fully portable, wireless, compact, and light instruments. Each sensor is equipped with two sets of three orthogonal high-resolution electro-dynamics sensors (high gain and low gain velocity meter) and one set of three orthogonal digital accelerometers with a frequency range of 0.1–300 Hz. For these tests the high-gain velocity data was used for the modal identification process. The sampling frequency of the recordings at each setup in Test 1 was 128 samples per second (sps), and the total recording duration for each setup was about 30–40 minutes. This testing approach allows to capture the most important vibration modes up to a frequency of about 64 Hz. The North component of each sensor was oriented to the North direction of the site for all setups. One stationary reference sensor was used for all setups in Test 1.

Laser Vibrometer System [6] was employed for ambient vibration measurements in Test 2, Test 3 and Test 4. These tests mainly used to identify the modal properties of the diaphragms. Vibrometer System is consisting of two Laser camera units that reflect Laser beam to the targets, and two controllers that record the signals receive from the subject. Figures 9.2 and 9.3 show the Laser targets layout on North diaphragm and South diaphragm, respectively. The sampling rate for Laser Vibrometers were 240 Hz.

**Table 9.1** Test information for each setup

	Test 1	Test 2	Test 3	Test 4	Test 5
Date of the test	October 31st	November 1st	November 2nd	November 2nd	November 3rd
Time of the test	11:13 to 14:10	20:50 to 22:15	12:45 to 16:48	19:00 to 19:42	8:18
Instrument type	Tromino	Laser Vibrometer	Laser Vibrometer	Laser Vibrometer	Tromino
Number of the setups	4	5	6	2	3
Number of the sensors	9	2	2	2	1
Recording duration (min.)	30–40	9.1	9.1	9.1	20
Temperature (°C)	25	26	31	24	23



**Fig. 9.1** Location of the Tromino sensors in Test 1: (a) on the Towers (Setup 1), (b) at the Dome (Setup 4), (c) at the roof levels (Setup 2), (d) at the roof levels (Setup 3)

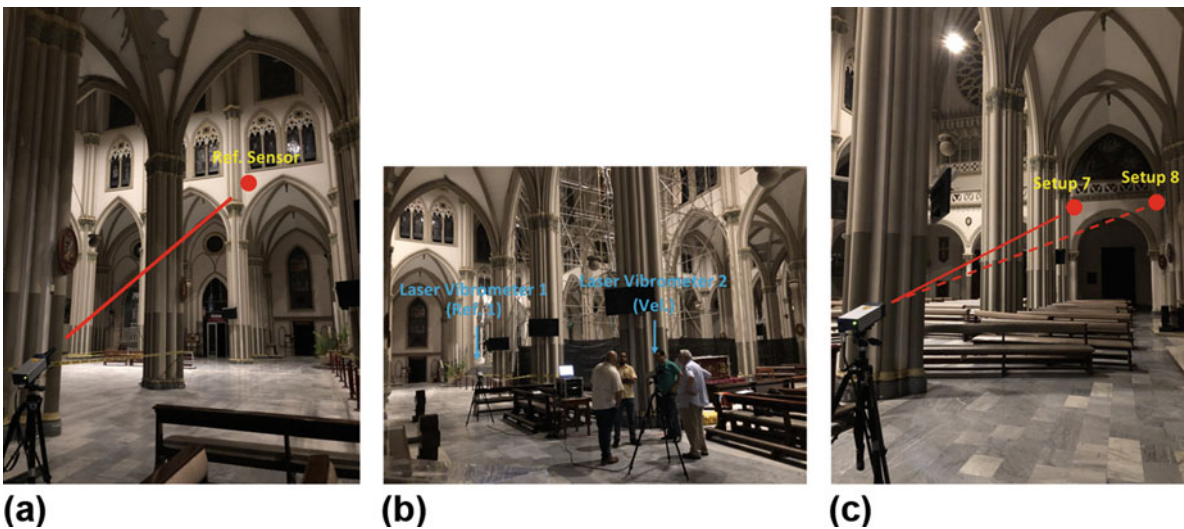
### 9.3 Methodology and Data Processing

The computer program ARTEMIS version 4 [7], was used to perform the modal identification of the structure. The software allows the user to develop a 3D model of the structure and test points; the resulting mode shapes are displayed using this geometry. Two different, complementary techniques are usually used for modal identification [8]: the Enhanced Frequency Domain Decomposition (EFDD) and the Stochastic Subspace Identification (SSI). These two modal identification techniques are used to cross-validate the results. The joint analysis of the signals measured in various strategic points of the structure makes it possible to identify the modal configurations and the corresponding natural frequencies.

The EFDD technique is an enhanced frequency domain method and the procedure consists of decomposing the system output into a set of systems of a specific degree of freedom, which are independent for each mode. The singular values are estimated from the spectral density of the specific degree of freedom system and the configuration of the modes is estimated from the singular vectors by selecting the highest peaks of the responses. The SSI technique is a time domain method which consists of adjusting a parametric model to the time series recorded by the sensors. SSI method takes a matrix of the time history data, and performs a series of geometric manipulations which results in a set of mathematical models that represent the system that produces the data; the analysis provides modes based on those models. The advantage of the SSI is more



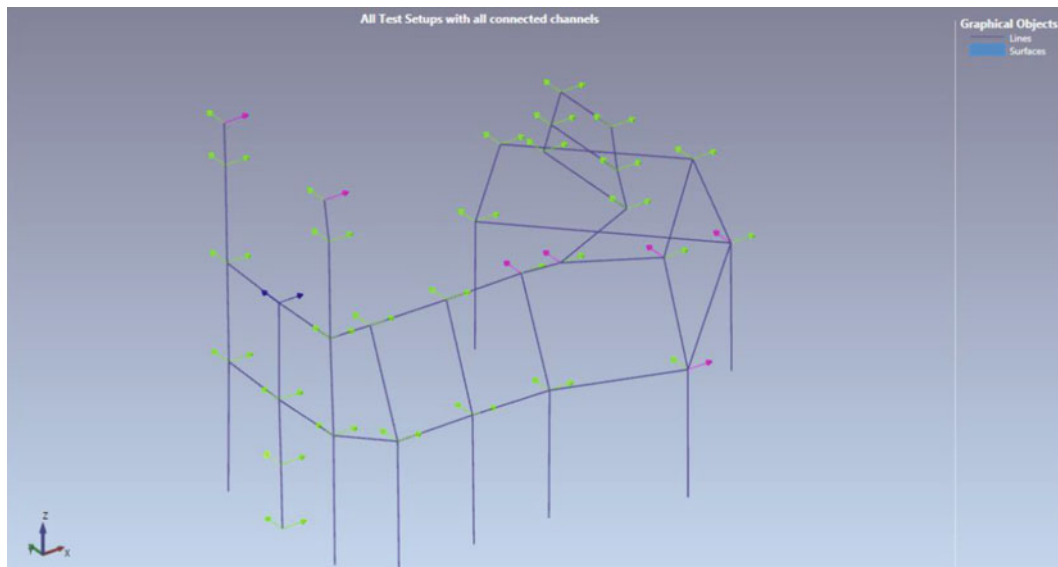
**Fig. 9.2** Location of the Laser Vibrometers' target in Test 3 at the North Diaphragm (Setups 1–6)



**Fig. 9.3** Location of the Laser Vibrometers' target in Test 4 at the South Diaphragm (Setups 7 and 8): (a) Location of reference sensor at West side; (b) Laser Cameras Station; (c) Location of Laser targets at East side

accurate modal estimations, especially in the lower frequencies when the data is properly decimated. The disadvantage is that the SSI method takes a considerable amount of time for analysis, and is not easily applied to broadband data. In contrast, the FDD method is very quick and allows for the user to pick modes anywhere in the frequency range of interest.

Ambient vibration data recorded on and off the Cathedral contains both noise and the response of the structure under ambient vibrations. The noise component of the recorded data is mainly due to mechanical imperfections in the sensors, instrument noise, installation, and other aspects in the sensor such as digitalization. The noise components of the vibration data, by its nature, usually appear as a random phenomenon in the data; however, the response of the Control Tower is not random, but consistent at certain frequencies due to resonance effects of the Control Tower to environmental excitations. Removing the noise components from the data is generally achieved by using signal processing tools such as decimation,



**Fig. 9.4** 3D ARTeMIS Full Model showing the location of the measurement points of the Cathedral structure

filtering, and data averaging. In order to identify the modal properties of the Cathedral structure correctly, the Towers Structure and the Dome were analyzed separately. To study the modal properties of the structure, the Full Model, including the Main Building, Towers Structure and the Dome, was also considered, and analyzed, as illustrated in Fig. 9.4.

The data collected at all measurement locations was processed and analyzed with ARTeMIS Modal. A 3D model (for animation purposes only) of the Structure was created using the structural geometry provided by Sismica Ingenieros Consultores. The model includes the discretized locations of measurement points on the structure. The blue arrows represent the location and orientation of the reference sensor for setups 1–4, while the green and pink arrows represent the location and orientation of the roving sensors. This estimation would be correct since the readings from all of the sensors had been fully synchronized. Therefore, this method would provide a reliable estimation of a mode shape.

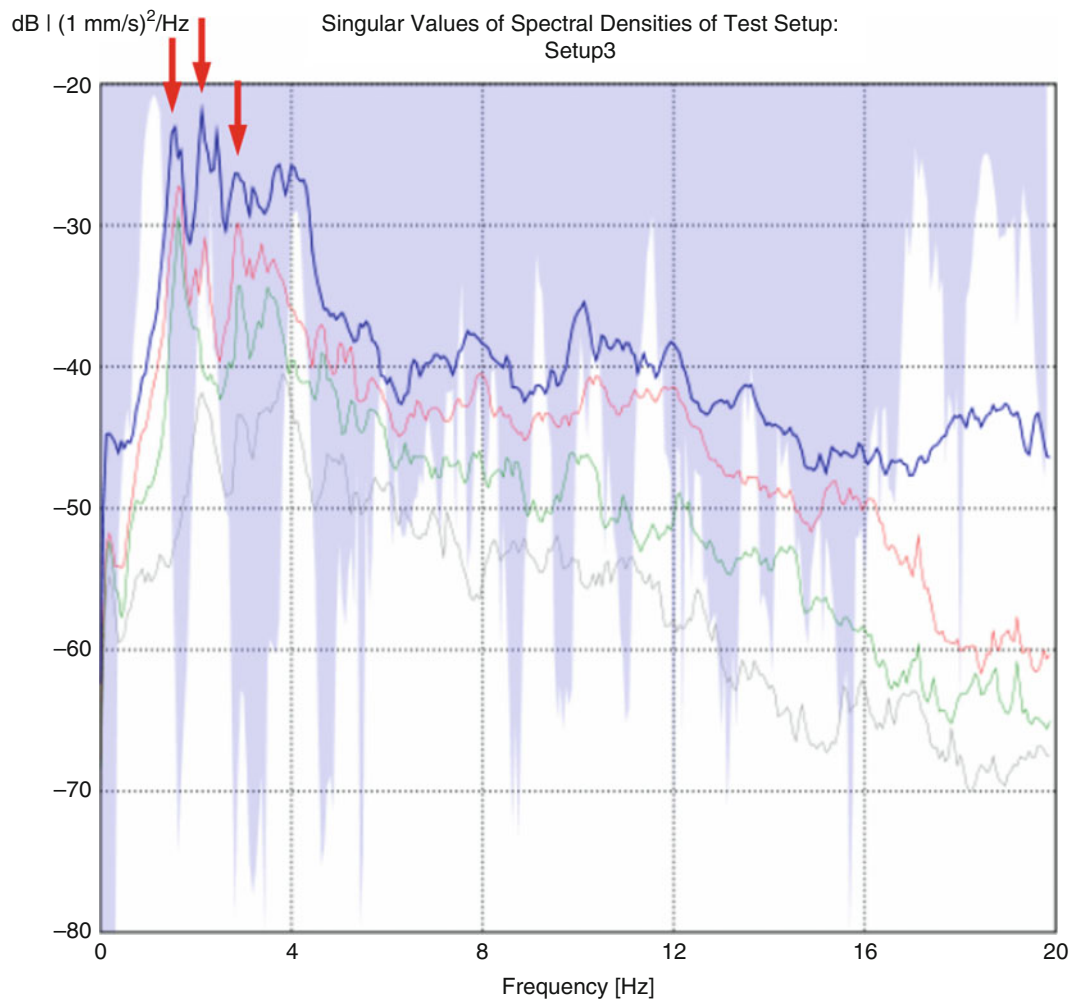
## 9.4 Test Results

The results of the Cathedral structure analysis are presented in this section for the Main Structure, Towers Structure and the Dome, separately.

### 9.4.1 Main Building

The results of the analysis using the Enhanced Frequency Domain Decomposition method (EFDD) are shown in Fig. 9.5. This figure shows a plot of the spectral density of the peak singular values of all the data from setups 3 as a function of frequency. The peak values in this plot can be associated to dominant frequencies in the datasets, and some of these correspond to modal frequencies. However, the results of the analysis of the data using the SSI method can be used to determine with greater certainty the most dominant frequencies in the dataset.

Based on this analysis, the predominant frequency (the first natural frequency) of the structure is estimated to be 1.50 Hz, and it corresponds to the fundamental mode of the Main Building in the North-South direction. The corresponding mode-shape is shown in Fig. 9.6. Table 9.2 summarizes the modal frequencies extracted from the vibration data for which the confidence on the results is high from both the EFDD and SSI-UPC methods.



**Fig. 9.5** Singular values of spectral densities of the structure in the frequency range of 0–20 Hz

### 9.4.2 Towers Structure

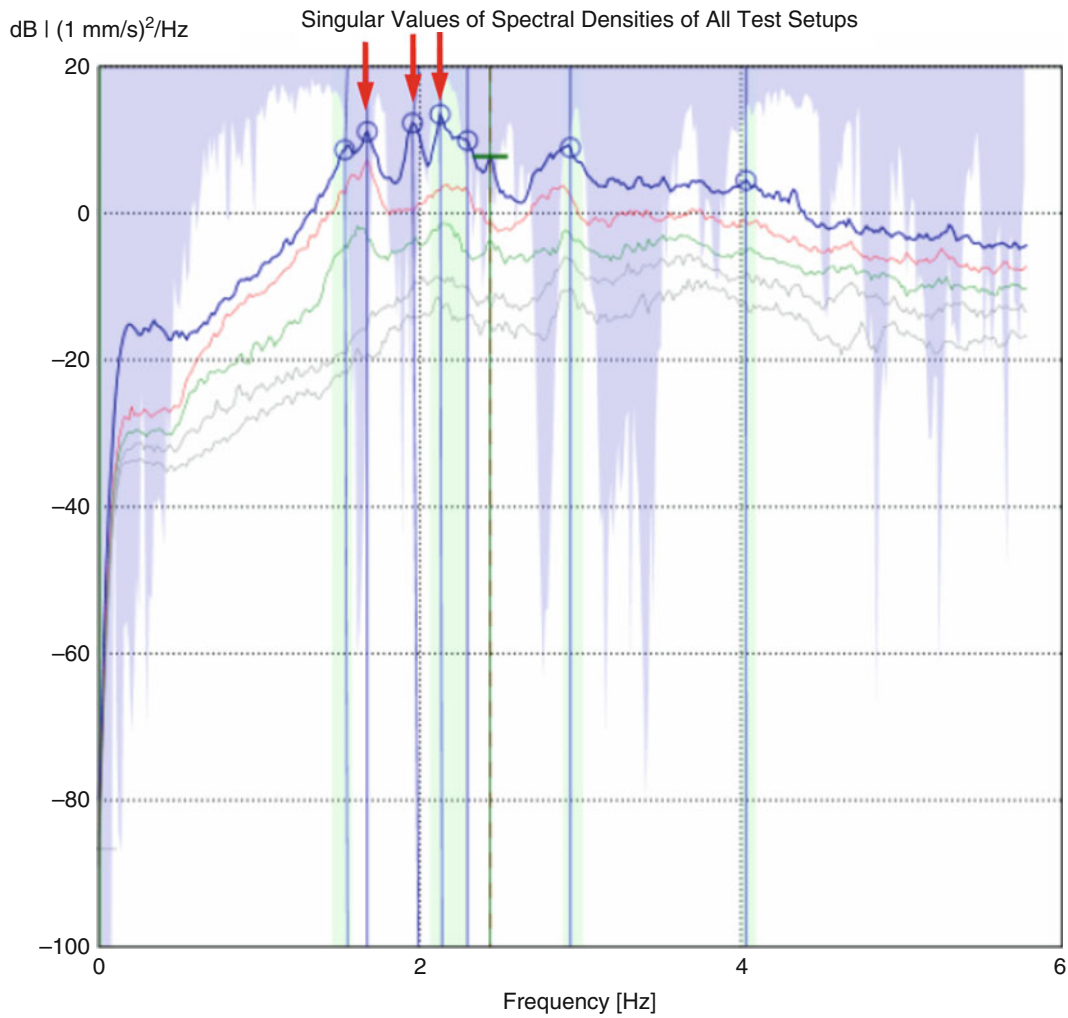
In order to identify the modal frequencies and mode shapes of the Towers Structure, the full model including the Towers Structure was used for modal analysis. Figure 9.6 shows the plot of the spectral density of the peak singular values of all the data from all setups as a function of frequency.

Figure 9.7 shows the Stabilization Diagram of all the data from setup 4. The vertical red dotted lines indicate the frequencies at which the modal frequencies are stable and can be associated to natural modes of the structure. By combining the results from both methods, it is possible to determine what peaks in Fig. 9.8 are associated to modal frequencies of the Towers [8]. The corresponding mode-shapes are shown in Fig. 9.8. Table 9.3 summarizes the modal frequencies extracted from the vibration data for which the confidence on the results is high from both the EFDD and SSI-UPC methods.

### 9.4.3 Dome Structure

In order to identify the modal frequencies and mode shapes of the Dome, the full model including the Dome Structure was used for modal analysis. Figure 9.8 shows the plot of the spectral density of the peak singular values of all the data from all setups as a function of frequency.

The corresponding mode-shapes of the Dome are shown in Fig. 9.9. Table 9.4 summarizes the modal frequencies extracted from the vibration data for which the confidence on the results is high from both the EFDD and SSI-UPC methods.



**Fig. 9.6** Singular Values of Spectral Densities of the Full Model to identify the modal properties of the Towers Structure in the frequency range of 0–6 Hz using EFDD Method

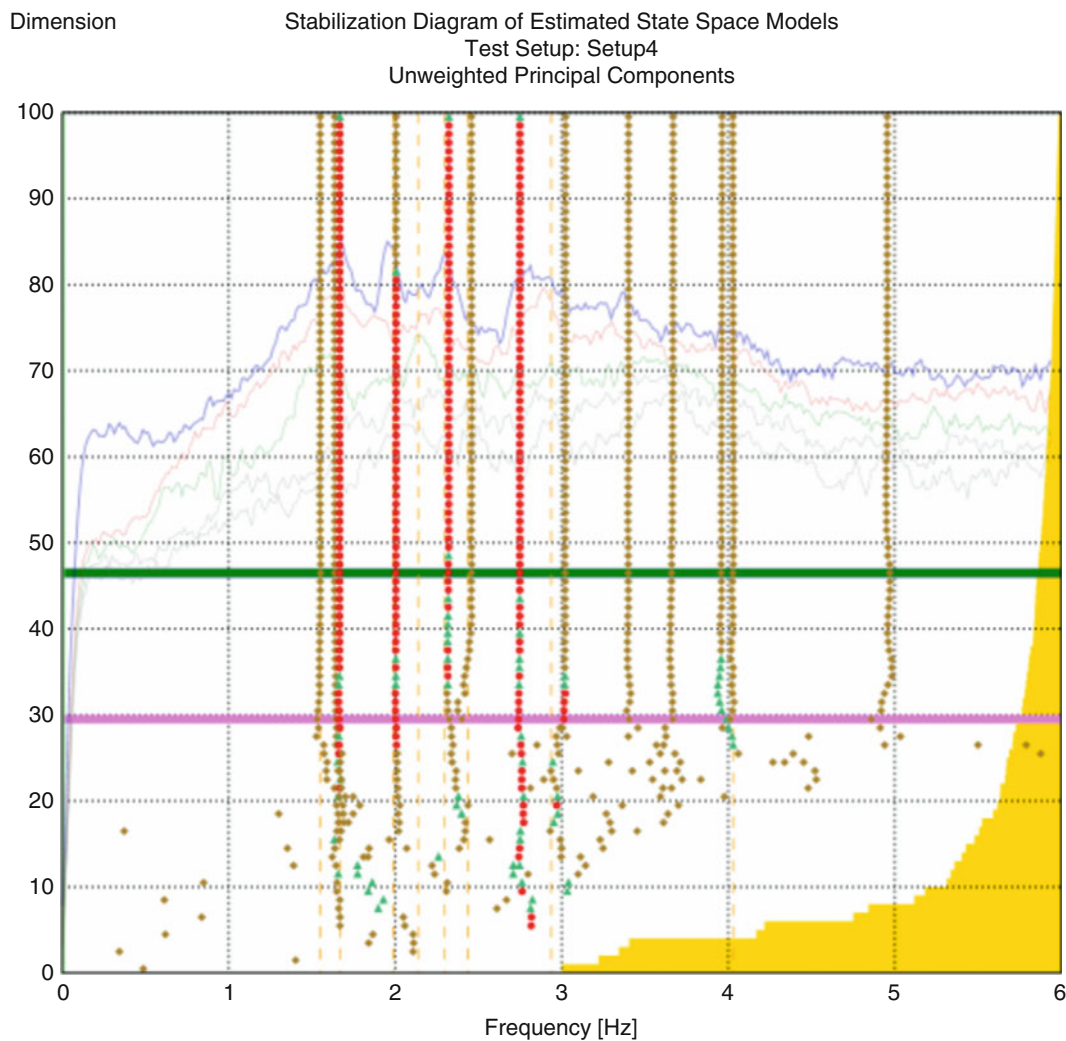
**Table 9.2** Modal frequencies of the Main Building obtained from modal analysis estimated by EFDD and SSI methods (Hz)

	EFDD method	SSI – PC method	Direction of the mode
1st mode	1.54	1.50	North-South
2nd mode	1.625	–	East-West
3rd mode	3.18–3.37	–	Torsion

#### 9.4.4 North Diaphragm in the East Wing Using Laser Vibrometers

In order to identify the modal frequencies and mode shapes of the North Diaphragm, an individual model including the North side wall (as shown in Fig. 9.2) was used for modal analysis. Figure 9.9 shows the plot of the spectral density of the peak singular values of all the data from all setups as a function of frequency. Figure 9.10 shows the Stabilization Diagram of all the data from setup 1.

The corresponding mode-shapes of the North Diaphragm are shown in Fig. 9.11. Table 9.5 summarizes the modal frequencies extracted from the vibration data for which the confidence on the results is high from both the EFDD and SSI-UPC methods.



**Fig. 9.7** Stabilization Diagram of Estimated State Space Models of the Full Model. This plot is for the Unweighted Principal Components (UPC) Test Setup 4 in the frequency range of 0–6 Hz

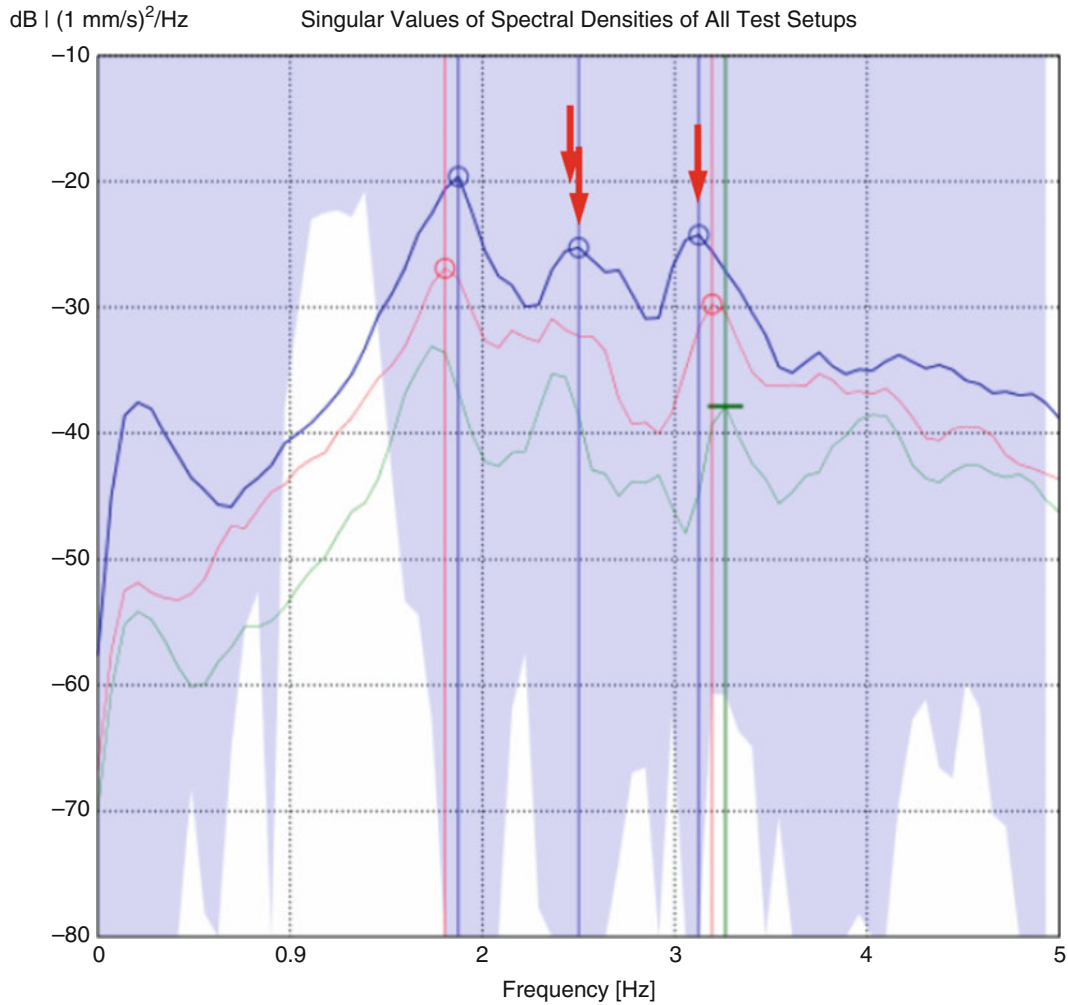
#### 9.4.5 South Diaphragm of the East Wing

In order to study the behavior of the South Diaphragm, an individual model including the East side Wall and West side Wall (as shown in Figs. 9.3) was used for modal analysis. Figures 9.12 and 9.13 show the plot of the spectral density of the peak singular values of all the data from Setup 7 and Setup 8, respectively as a function of frequency.

Also, the Fast Fourier Transform functions of data from Reference Sensor and other Sensor in Setup 7 are shown in Figs. 9.14 and 9.15, respectively. The modal frequencies obtained from Setups 7 and 8 confirm the test results of the other tests and provide higher level of confidence for the modal properties; Main Building frequency in East-West direction ( $f_2 = 1.64$  Hz); Tower Structure ( $f_1 = 1.82$  Hz,  $f_2 = 2.125$  Hz); and Dome ( $f_1 = 2.81$  Hz,  $f_2 = 2.875$  Hz,  $f_3 = 3.62$  Hz).

The measurements in Setups 7 and 8 show that the vibration of West side and East side of the South Diaphragm is not in the same order. The displacement of the West side was measured 3.5 times larger than the East side of the diaphragm. This observation confirms that the diaphragms in the Church are flexible and there is a potential risk of failure in diaphragm corners.





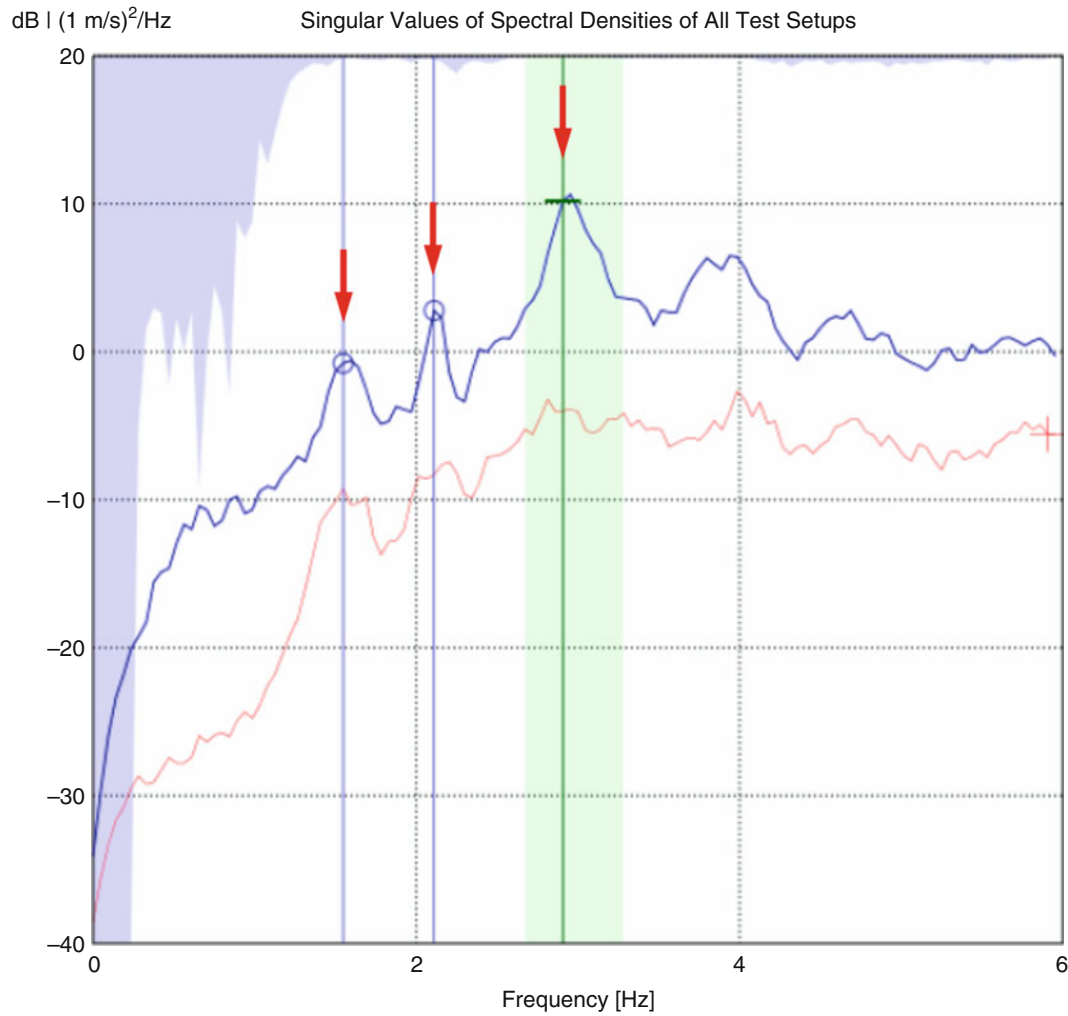
**Fig. 9.8** Singular Values of Spectral Densities of the Full Model to verify the modal properties of the Dome in the frequency range of 0–5 Hz using EFDD Method

**Table 9.3** Modal frequencies of the Towers Structures obtained from modal analysis estimated by EFDD and SSI methods (Hz)

	EFDD method	SSI – PC method	Direction of the mode
1st mode	1.50	1.610	North-South
2nd mode	1.938	1.990	East-West
3rd mode	2.125	2.138	Torsion

### 9.4.6 Site Response Analysis

The single instrument recording technique was used for site period estimation via horizontal-to-vertical (H/V) spectral ratio analysis [9]. A three-component ambient vibration recording was performed using three sensors that were placed on the ground inside the cathedral and also on the site nearby the Cathedral (at the Parque Seminario). The orientation of the sensors was consistent and was parallel to North direction. The GEOPSY software was used for modal analysis in frequency domain [10]. The observed response of the peak frequency suggests consistent ground conditions around the Cathedral. The peak frequency at the site ranges between 0.72 and 0.92 Hz (The average is 0.92 Hz (T = 1.087 Sec.)).



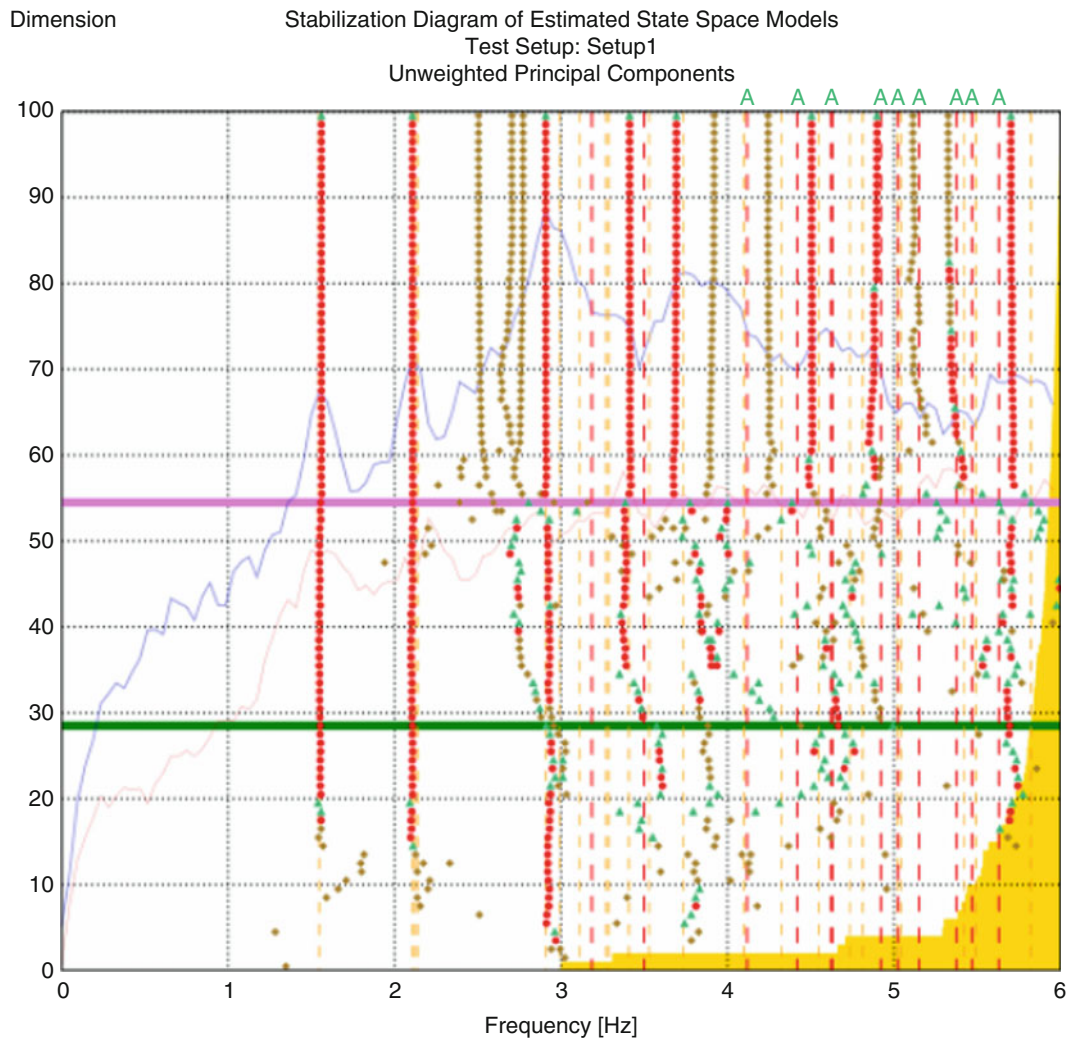
**Fig. 9.9** Singular Values of Spectral Densities of data setups 1–6 of Test 3 to identify the modal properties of the in-plane motion of the North diaphragm in the frequency range of 0–6 Hz using FDD Method

**Table 9.4** Modal frequencies of the Dome from modal analysis estimated by EFDD and SSI methods (Hz)

	EFDD method	SSI – PC method	Direction of the mode
1st mode	2.813	–	North-South
2nd mode	2.875	2.938	East-West
3rd mode	3.688	–	Torsion

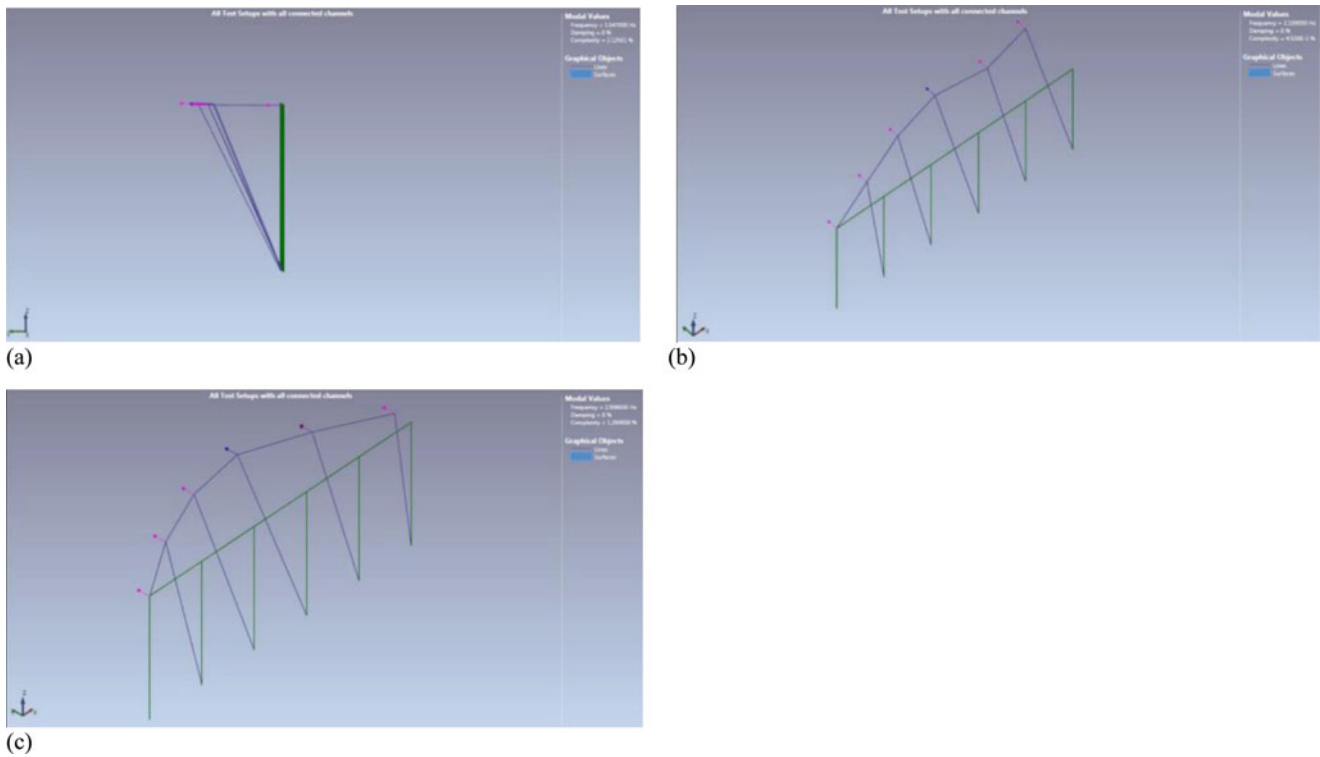
## 9.5 Conclusion

A series of Ambient Vibration Tests was conducted on the Guayaquil Metropolitan Cathedral from October 31st to November 3rd, 2018. The testing program consisted of five Tests using wireless digital seismometers and Laser Vibrometers placed on the roof of the Main Building, on the Towers structure, the Dome and reflected to the Diaphragms. Vibration of the structure was recorded for approximately 30–40 minutes in each setup for seismometers and 9 minutes for Laser Vibrometers. To identify the modal properties of the structure, the Towers, the Dome and the Diaphragms were analyzed separately. The



**Fig. 9.10** Stabilization Diagram of Estimated State Space Models of Test 3. This plot is for the Unweighted Principal Components (UPC) in Test Setup 1 in the frequency range of 0–6 Hz

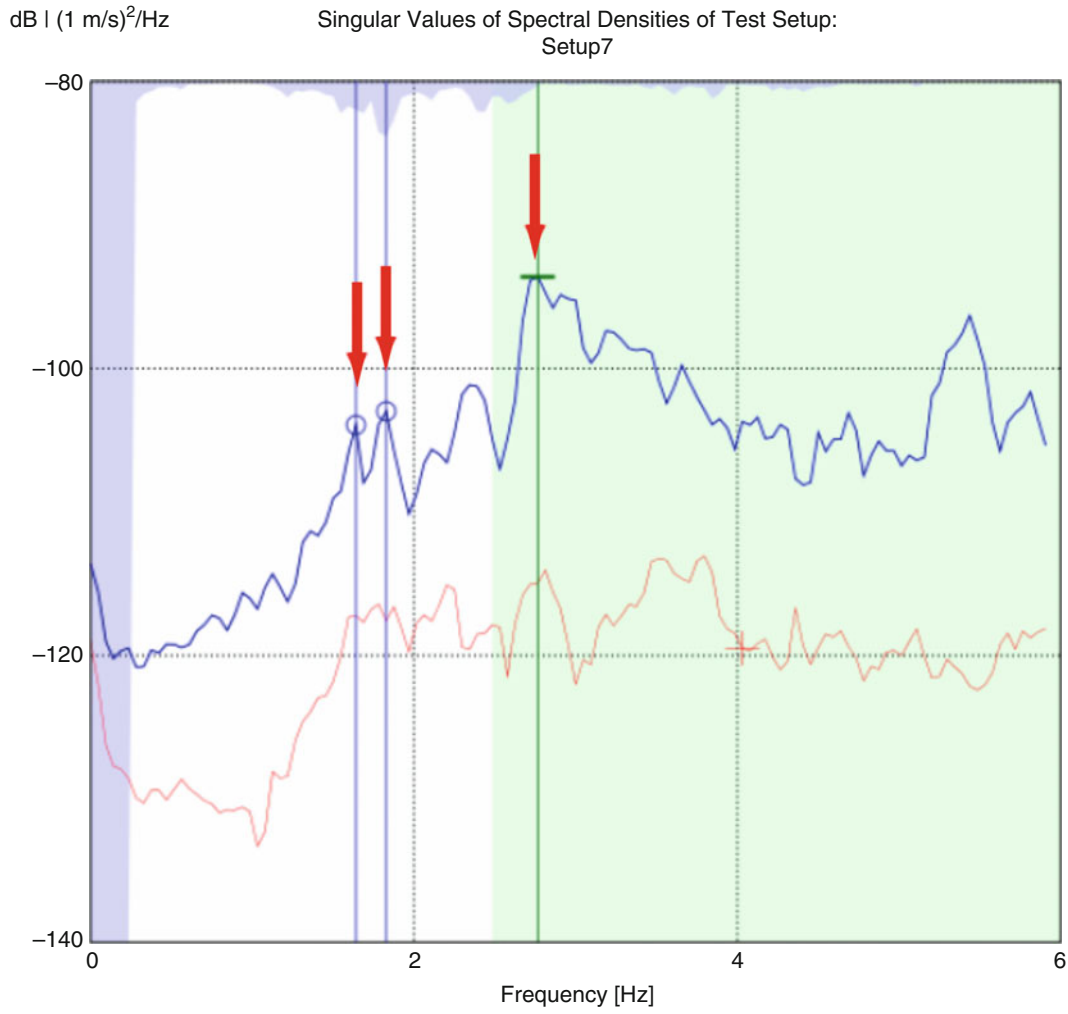
results from modal analysis indicated that the frequencies of the Main Building are 1.54 Hz and 1.64 Hz in North-South and East-West direction, respectively. The fundamental frequency of the Towers Structure in the North-South direction was identified as 1.50–1.61 Hz. The modal frequencies corresponding to the second and third modes of vibration are 1.938 Hz in East-West direction and 2.125 Hz in Torsional direction, respectively. The frequencies of the Dome were also identified as 2.813 Hz, 2.875 Hz, and 3.688 Hz for the first mode (North-South), second mode (East-West), and the third mode (Torsion), respectively. The analysis of data extracted from Laser Vibrometers on North Diaphragm indicates that the diaphragm is flexible and the frequency of in-plane bending mode is 2.95 Hz in North-South direction. The identified frequencies and periods of the Main Building, Towers Structure, and the Dome of the Cathedral are summarized in Table 9.6. The main direction of the associated mode shapes is also included in the table. The main direction of the associated mode shapes are also included in the table. By analyzing the site response, the average peak frequency of the H/V curves at the site was determined as 0.92 Hz.



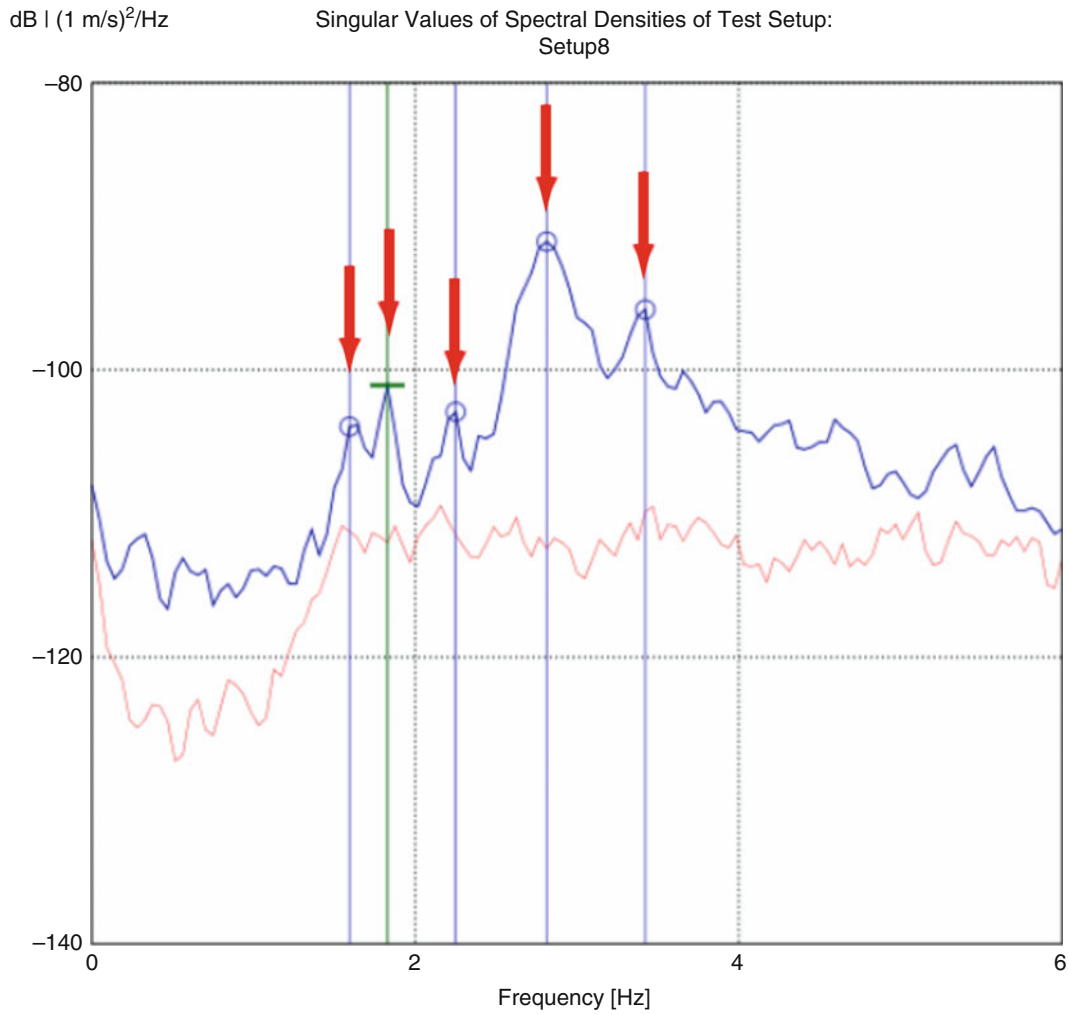
**Fig. 9.11** Mode shapes of the North Diaphragm in East wing: (a) Confirmation of the 1st mode of the building in Translational (North-South) direction-Elevation view ( $F = 1.55$  Hz); (b) 2nd mode of the building in Torsional motion of the East wing-Perspective view ( $F = 2.11$  Hz); (c) In-plane mode of the diaphragm at Elevation 15.7 m – Perspective view ( $f = 2.95$  Hz)

**Table 9.5** Modal frequencies of the North Diaphragm of the East wing estimated by FDD and SSI methods (Hz)

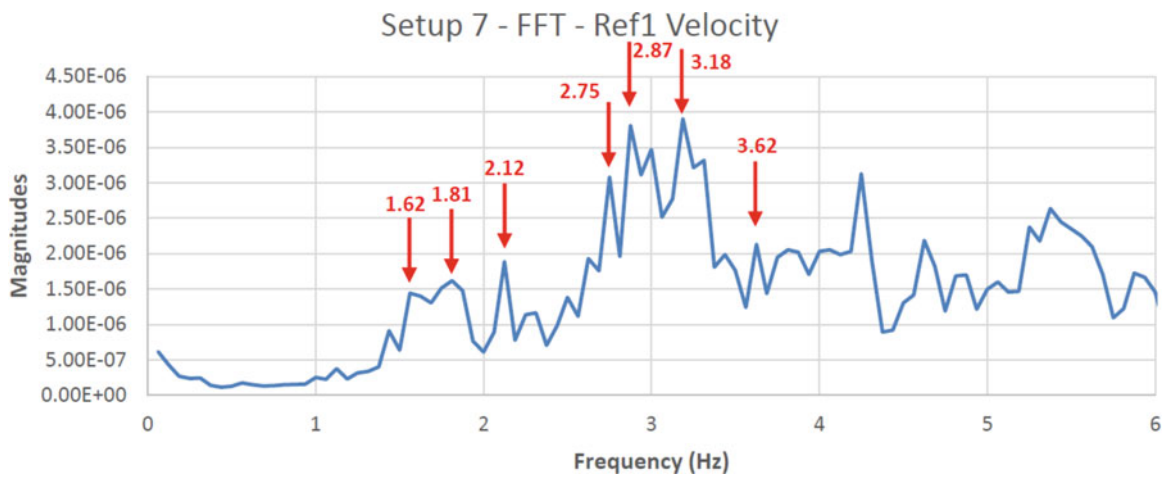
	FDD method	SSI – UPC method	Direction of the mode
1st mode	1.54	1.56	Translational (North-South) of the whole building (Confirmation of the Test 1 results)
2nd mode	2.11	2.11	Torsional of the East wing of the building
3rd mode	2.95	2.91	Out-of-Plane motion of North wall (In-plane motion of the diaphragm at elevation 15.7 m)



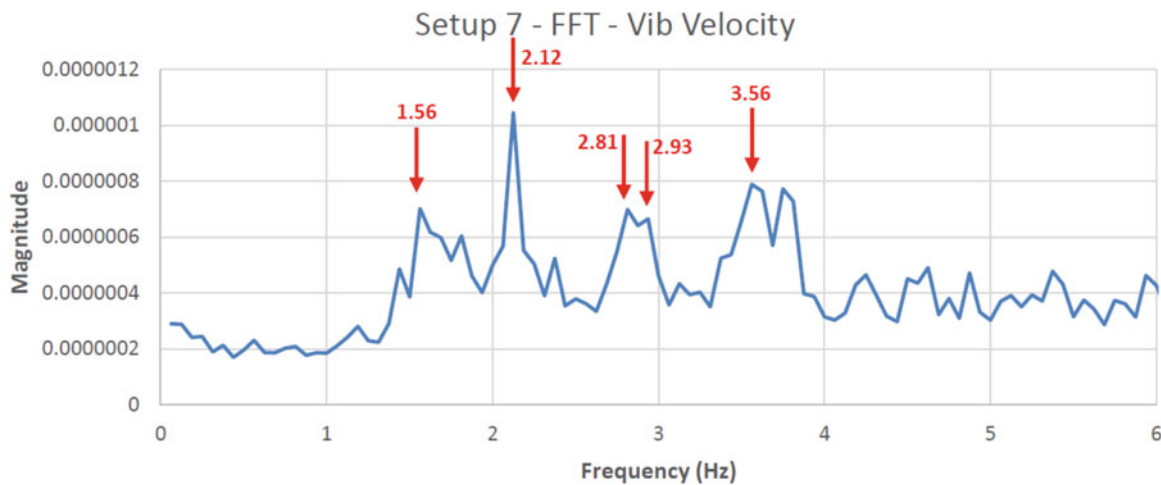
**Fig. 9.12** Singular Values of Spectral Densities of Setup 7 of Test 4 to identify the modal properties of the South diaphragm in the frequency range of 0–6 Hz using FDD Method ( $f_1 = 1.64 \text{ Hz}$   $f_2 = 1.828 \text{ Hz}$   $f_3 = 2.766 \text{ Hz}$ )



**Fig. 9.13** Singular Values of Spectral Densities of Setup 8 of Test 4 to identify the modal properties of the South diaphragm in the frequency range of 0–6 Hz using FDD Method ( $f_1 = 1.594$  Hz  $f_2 = 1.828$  Hz  $f_3 = 2.25$  Hz  $f_4 = 2.812$  Hz  $f_5 = 3.422$  Hz)



**Fig. 9.14** Fast Fourier Transform of Ref. [1] sensor of Setup 7 in Test 4



**Fig. 9.15** Fast Fourier Transform of Vel. 1 sensor of Setup 7 in Test 4

**Table 9.6** Summary of modal periods obtained from the ambient vibration tests

	Church component	Mode No.	Frequency (Hz)	Period (Sec.)	Mode & direction
Global vibration modes	Whole structure	1st mode	1.54	0.649	Translational (North-South)
		2nd mode	1.64	0.610	Translational (East-West)
		3rd mode	3.18–3.37	0.314–0.297	Torsion
Local vibration modes	Towers Structure	1st mode	1.50–1.61	0.666–0.621	Translational (North-South)
		2nd mode	1.938	0.516	Translational (East-West)
		3rd mode	2.125	0.471	Torsional
	Dome Structure	1st mode	2.813	0.355	Translational (North-South)
		2nd mode	2.875	0.348	Translational (East-West)
		3rd mode	3.688	0.271	Torsional
	North diaphragm (at elevation 15.7)	1st mode	2.95	0.33	Out-of-plane (In-plane diaphragm) Single curvature bending mode in (North-South)
	Site		0.92	1.087	Average of peak frequencies of H/V curves

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