First Middle East Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures
8 – 10 February 2011, Dubai, UAE

SMAR 2011

# Experimental and numerical modal identification of L'Aquila Margherita palace

Stefano Pianta`[1], G. P. Cimellaro[1], and Alessandro De Stefano[1]

[1] Department of Structural and Geotechnical Engineering (DISTR), Politecnico di Torino, Turin, Italy

ABSTRACT: This paper focuses on the dynamic behaviour of L'Aquila City Hall (Margherita Palace) that was severed damaged during L'Aquila earthquake in April 2009, but also by the weathering and the creep phenomena during the building lifetime. Experimental and numerical investigations have been carried out on this monumental building. Firstly, detailed investigations have been devoted to the identification of the geometry of the main constructional parts as well as of the mechanical features of the constituting materials of the palace. Then, both Ambient Vibration Tests (AVT) and Numerical Modal Identification analyses by Finite Element Method (FEM) have been applied, allowing the detection of the main dynamic features. Three output-only identification methods have been compared: (i) the Frequency Domain Decomposition, (ii) the Random Decrement (RD) and the (iii) Eigensystem Realization Algorithm (ERA).

## 1 INTRODUCTION

System identification can be described as the construction of a model based on experimental measurements. In civil engineering, the "system" refers to a large scale structure such as a building and "identification" mostly involves the determination of modal parameters the natural frequencies, damping ratios, and mode shape. These experimental findings can be used to calibrate an initial analytical model of the structure or utilized in a global structural health monitoring strategy to detect the presence, location, and/or amount of deterioration within the structure. The classical identification algorithms that are input-output identification (where one applies a measurable input to a system and then collects the corresponding system response) are neither feasible nor practical for monumental structures. These consideration lead to the idea of using only output identification methods that use freely available ambient vibrations.

Very few full scale ambient vibration tests of monumental buildings damaged after earthquakes have been done, probably because of the inaccessibility right after an earthquake that severe damaged the structure and because of the difficulty of identifying its dynamic behavior after the earthquake. Therefore this paper presents the experimental identification tests that were conducted on Margherita palace right after L'Aquila earthquake in 2009. Three only output identification methods are compared. The first is a method that works in the frequency domain using the peak picking (PP) method that as the name suggests is based on the selection of the modal frequencies from the peaks of the output measurements spectra. The other two methods instead they work in the time domain. The random decrement technique (RD) converts the output signals to free decays using the RD functions. The natural excitation technique (NExT) uses the auto and cross-correlation functions of output signals that are treated as sums of decaying sinusoids and then is combined with the eigensystem realization algorithm (ERA).

## 2 OUTPUT ONLY MODAL IDENTIFICATION TECHNIQUES

### *2.1 Frequency domain decomposition technique (FDD)*

In the Frequency Domain Decomposition (FDD) method, the first step is to estimate the Power Spectral Density matrix. Thus, in the case of a lightly damped structure, the response spectral density can always be written

$$\mathbf{G}_{\mathbf{yy}}\left(j\omega\right)=\sum_{k\in Sub(\omega)}\frac{\mathbf{d_k}\ \phi_{\mathbf{k}}\ \phi_{\mathbf{k}}^{T}}{j\omega-\lambda_k}+\frac{\overline{\mathrm{d}_{\mathbf{k}}}\ \overline{\phi_{\mathbf{k}}}\ \overline{\phi_{\mathbf{k}}}^{T}}{j\omega-\overline{\lambda_k}} \tag{1}$$

The estimate of the output Power Spectral Density (PSD) $\hat{\mathbf{G}}_{\mathbf{yy}}\left(j\omega\right)$ known at discrete frequencies ω = ωi is then decomposed by taking the Singular Value Decomposition (SVD) of the matrix

$$\mathbf{G}_{\mathbf{yy}}\left(j\omega_i\right)=\mathbf{U_i}\ \mathbf{S_i}\ \mathbf{U_i}^{H} \tag{2}$$

where the matrix $\mathbf{U_i}=\left[\mathbf{u_{i1}},\mathbf{u_{i2}},\ldots,\mathbf{u_{im}}\right]$= unitary matrix of singular vectors $\mathbf{u_{ij}}$, and **S** = diagonal matrix of scalar singular value $s_{ij}$. Near a peak corresponding to the k<sup>th</sup> mode in the spectrum this mode or may be a possible close mode will be dominating. If the k<sup>th</sup> mode is dominant, there will be only one term in Equation (1). Thus, in this case, the first singular vector $u_{i1}$ is an estimate of the mode shape.

$$\phi=\mathrm{u}_{\mathbf{i1}} \tag{3}$$

and the corresponding singular value is the auto Power Spectral Density function of the corresponding single degree of freedom system, refer to Equation (1). Further detail about the description of the method can be found in Brincker et al. (2000). The Frequency Domain Decomposition (FDD) technique is exact when the input is a white noise, the structure is slightly damped and the modal forms of the coupled modes are orthogonal. If these hypotheses are not verified, the decomposition in SDOF systems is approximate, but however results are meaningfully more accurate than in the classical methods.

### *2.2 Random decrement identification method (RD)*

The Random Decrement (RD) technique is a time domain method that was proposed by Cole (1968) in the late sixties within his work at NASA concerning the analysis of the dynamic response of space structures subjected to ambient loads. Neglecting all the analytical formulation that can be found in the work of Cole (1968), the concept and argument for the validity of the RD technique is easy to understand if one thinks that the response of a system to random input loads is, in each time instant *t*, composed by three parts: the response to an initial displacement; the response to an initial velocity; and the response to the random input loads between the initial state and the time instant *t*. By averaging a large number of time segments of the response with the same initial condition, the random part of the response will have a tendency to disappear from the average, and what remains is the response of the system to the initial conditions. From this simple explanation the interpretation of the RD functions as free vibration responses is immediate.

### *2.3 Eigensystem realization algorithm technique (ERA)*

The Eigensystem Realization Algorithm is a parametric method in the time domain that is used in combination with the Natural Excitation Technique (NExT). This technique was proposed in the early 1990s for modal identification from output-only measurements in the case of natural excitation. The natural excitation technique (NExT) uses the auto and cross-correlation functions of output signals that are treated as sums of decaying sinusoids. Each decaying sinusoid has a frequency and damping ratio identical to that of a structural mode. Then, the modal identification techniques that use impulse responses as input such as eigensystem realization algorithm (ERA) can be used to extract the modal parameters from these free decays.

## 3 STRUCTURAL DESCRIPTION OF THE CASE STUDY: THE MARGHERITA PALACE

An old masonry palace, the City-Hall located in L'Aquila, Italy that was mainly damaged during April 6th, 2009 earthquake, has been used as case study to compare the three identification methods. It is important to mention that additional damage in the Tower at the moment of the test might also have been caused by the weathering and the creep during the building life time. The City Hall, represented in Figure 1, is composed by a three story masonry building (Margherita Palace) and a square stone tower (Civic Tower). Margherita Palace has rectangular plan with dimensions of 56.50 × 39.90 m and has a height of 19 m. Inside there is a courtyard of analogous shape (27.40 × 12.10) m. The Tower has dimensions of 6.5 m × 7.0 m, with a height of about 43 m. In the past, the Tower was 70 m height, but in 1529 was shorted by the Spanish army because it was taller than the Spanish's fortress.

(a) (b)

Figure 1 (a) L'Aquila City Hall after April 6th 2009 earthquake; (b) collapse of the floor slab

The complex (palace + tower) has been seriously damaged during the April 6th 2009 earthquake. Some vaults and a floor slab at the second level collapsed (Figure 1b). Other signs of damage are visible on the internal and external walls with shear cracks inside the masonry. The stairs to reach the second floor are unusable, while some tiles have fallen from the roof. Shoring up interventions has been realized following the earthquake as the one shown in Figure 2. The Tower has been also damaged, because vertical cracks along the east façade at the base of the tower are observed.

## 4 INSTRUMENTATION

15 Kinemetrics SS-1 velocity sensors and two data acquisition devices Kinemetrics K-2 have been used. The Kinemetrics SS-1 is a velocity sensor for short period range, of high sensitivity and it can measure horizontal and vertical velocities by simply adjusting the spring connecting the internal mass. The Kinemetrics K2 is a self-contained, four-channel (optionally, six- or 12-channel) digital recorder with a built-in GPS timing system. The test campaign lasted three days and three configurations were tested using 15 sensors for each configuration. Every signal has been recorded for a nonstop period of about five minutes. In the first configuration (Global) the velocity sensors have been located on the second floor of the Margherita Palace uniformly as shown in Figure 2a In the second configuration (Tower) the velocity sensors have been located in the Civic Tower as shown in Figure 2b. The third configuration (Local) includes partly Margherita Palace and partly the Civic Tower. The velocity sensors disposition in the Local configuration is displayed in Figure 2c.

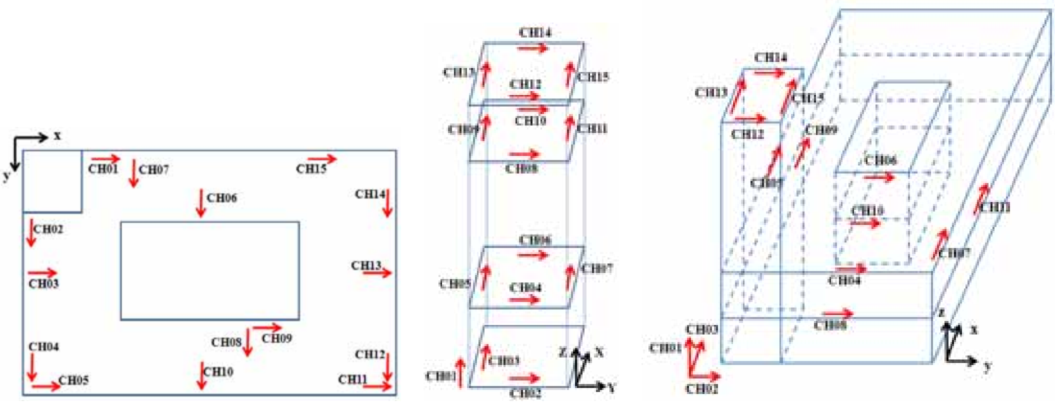


Figure 2 Location of the velocity sensors (a) at the second floor (global configuration); (b) in the tower (tower configuration); (c) in the first and second floor of the palace and in the tower (local configuration)

Multiple tests were repeated for the same configuration, because the recorded signals were disturbed by the external noise of man working on props interventions of adjacent buildings and by the moving of heavy trucks on the road adjacent to Margherita Palace. The cleaner signals were obtained in the late afternoon when props intervention on adjacent buildings terminated.

## 5 RESULTS OF THE MODAL IDENTIFICATION

In the tower configuration first the SVD of the PSD matrixes has been applied. Peaks from the plot of the singular value spectrum have been selected and the respective modal frequencies and eigenvectors are identified. Only the values of the first mode have been shown in Table 1. Due to the geometric symmetric shape of the tower that is squared with rod ties symmetrically located in the North-West/South-East direction, the mode shapes in the two principal directions have about the same frequencies and the same modal shapes. The frequencies obtained with the three identification techniques are very similar with a first bending mode that has a period of 0.68 second in both directions. The deformed shape is shown in Figure 3a. Besides the damping ratio varies from 1.54% along the y direction to 2.65% along the x direction. The MAC coefficient is quite high indicating that the results are reliable. The recorded signals of the Tower configuration are reliable considering the simple geometry, and this allowed identifying also the higher modes. In fact, the second bending mode (Figure 3b) has a period of about 0.31

sec in the x direction and 0.30 sec in the y direction. In the y direction a damping ratio of about 17.59% is obtained that is too high for a masonry tower and in fact the MAC coefficient is very low. This could be caused by numerical problems (Table 2). The third mode (the torsional one) has a period of 0.24 sec and its deformed shape is represented in Figure 3c, while the fourth mode is displayed in Figure 3d. Further information can be found in Cimellaro et al. (2010).

Table 1 Frequencies and modal shapes of the 1st mode of the Civic Tower

| Tower configuration - 1st mode | | | | | | | |
|---|---|---|---|---|---|---|---|
| x direction | | | | y direction | | | |
| Technique | FDD | RD | ERA | Technique | FDD | RD | ERA |
| Frequency [Hz] | 1.48 | 1.46 | 1.46 | Frequency [Hz] | 1.48 | 1.46 | 1.45 |
| Period | 0.68 | 0.68 | 0.68 | Period | 0.68 | 0.68 | 0.69 |
| Damping [%] | n.d. | n.d. | 2.65 | Damping [%] | n.d. | n.d. | 1.54 |
| MAC | n.d. | n.d. | 98.7 | MAC | n.d. | n.d. | 96.9 |

Table 2 Frequencies and modal shapes of the 2nd mode of the Civic Tower

The data acquired with the sensors organized in the Global configuration have been also elaborated using the three techniques to get the PSD matrixes. These matrixes have subsequently been decomposed with the SVD. The modal properties of the Tower have been found also in the global configuration, therefore these information has been removed from Tables related to the City Hall where are shown only the modal parameters of the City Hall.

| Tower configuration - 2nd mode | | | | | | | |
|---|---|---|---|---|---|---|---|
| x direction | | | | y direction | | | |
| Technique | FDD | RD | ERA | Technique | FDD | RD | ERA |
| Frequency [Hz] | 3.20 | 3.22 | 3.21 | Frequency [Hz] | 3.24 | 3.47 | 3.38 |
| Period | 0.31 | 0.31 | 0.31 | Period | 0.31 | 0.29 | 0.30 |
| Damping [%] | n.d. | n.d. | 1.56 | Damping [%] | n.d. | n.d. | 17.59 |
| MAC | n.d. | n.d. | 96.6 | MAC | n.d. | n.d. | 52.4 |

Margherita palace has been severe damaged and the structure itself is very complex, therefore the main natural modes were more difficult to identify with respect to the Civic Tower.

Table 3 Frequencies and modal shapes of the 1st mode of the City Hall (y direction)

| Global configuration - 2nd mode | | | | | | | |
|---|---|---|---|---|---|---|---|
| x direction | | | | y direction | | | |
| Technique | FDD | RD | ERA | Technique | FDD | RD | ERA |
| Frequency [Hz] | 2.23 | 2.20 | 2.24 | Frequency [Hz] | 2.23 | 2.20 | 2.21 |
| Period | 0.45 | 0.45 | 0.45 | Period | 0.45 | 0.45 | 0.45 |
| Damping [%] | n.d. | n.d. | 0.21 | Damping [%] | n.d. | n.d. | 1.18 |
| MAC | n.d. | n.d. | 76.7 | MAC | n.d. | n.d. | 87 |

However, removing the signals obtained by sensors located in damage zones where local damage was observed, it was possible to identify the frequencies of the first bending modes in the x and y directions. The first modes of the Margherita palace are about 0.45 secs in the x and y direction respectively. It is important to mention that the building is longer in the x than in the y direction, therefore the stiffness in the x direction should be higher, while the period should be shorter. This implies that the results in the x direction might be not correct due to the fact that the MAC coefficient in the x direction is lower, therefore only the data related to the y direction are shown in Table 3.

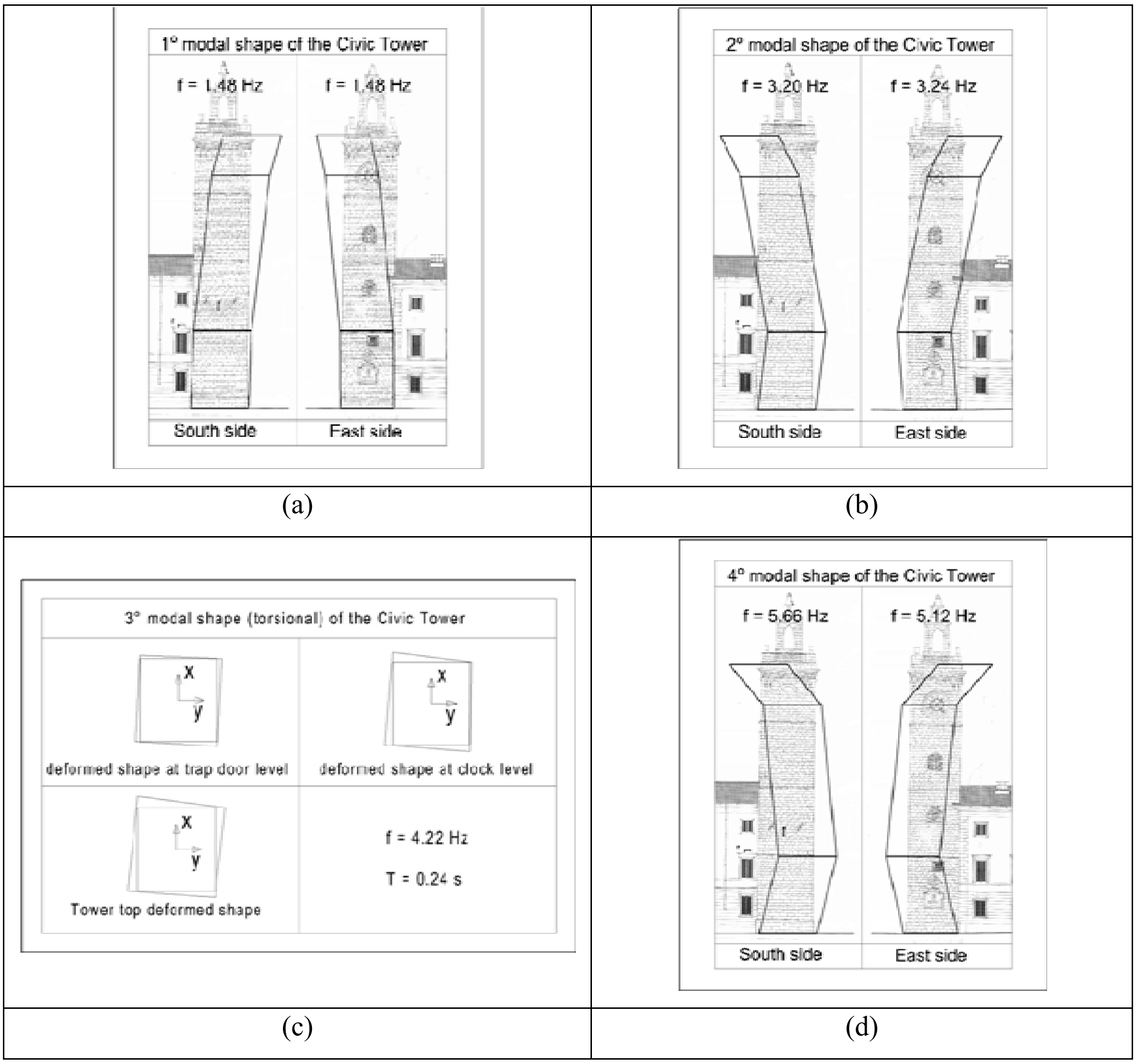


Figure 3 Modal shapes of the Civic Tower

In synthesis the first modes of the City Hall are characterized by a period of 0.30 secs in the x direction and 0.45 secs in the y direction. Therefore while for the Civic Tower the first mode in the two directions had about the same frequency, for the case of the Margherita palace, they have slightly different frequencies. This is due to the fact that the Tower has symmetric dimensions in both directions, while Margherita Palace has greater dimension in the x direction, which indicates a greater stiffness and accordingly a greater frequency in that direction. Further comments cannot be added due to the severe damage condition of the palace.

## 6 COMPARISON WITH THE FINITE ELEMENT MODEL

The building has been modeled in SAP2000, a finite elements software for the structural analysis. The global finite element model, shown in Figure 4 includes the City Hall and the Civic Tower together and it is using a linear material model.

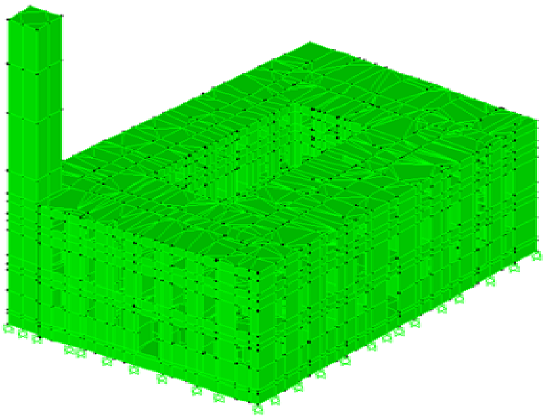

Figure 4 Finite element model of L'Aquila City Hall

The reason of this choice is due to the high computational time of the global finite element model that has been used to compare the results obtained with another model that is base isolated, for which the palace is suppose to remain in the linear range. The building masonry walls of the palace and the squared stone walls of the tower were modeled with thick Shell elements. These elements take in account the effects of the shear deformation using Mindlin–Reissner theory. In the model were also included the partition walls. The columns of the main courtyard that sustain the arcades are made of square stone are modeled with "frame elements". The floor slabs are modeled with "thick Shell elements" and not knowing their material properties they have been modeled as "equivalent reinforced concrete shells". The wooden roof instead has been modeled as uniformly distributed load on the floor slab of the second level.

Table 4 Comparison between operational modal identification data and Finite Element Model

| Modal identification technique | | | Finite Element Model (FEM) | | | | |
|---|---|---|---|---|---|---|---|
| Mode | T | F | T | f | Participation factor | | Modal shape |
| [-] | [s] | [s-1] | [s] | [s-1] | x direction | y direction | [-] |
| 1st | 0.67 | 1.49 | 0.70 | 1.42 | 0.51% | 7.04% | 1st mode of the Tower (y direction) |
| 2nd | 0.67 | 1.49 | 0.67 | 1.49 | 5.81% | 0.66% | 1st mode of the Tower (x direction) |
| 3rd | 0.45 | 2.20 | 0.36 | 2.80 | 1.09% | 32.58% | 1st mode of the City Hall (y direction) |
| 4th | [-] | [-] | 0.32 | 3.17 | 0.82% | 0.03% | local mode of the FEM |
| 5th | 0.30 | 3.33 | 0.31 | 3.22 | 34.44% | 1.13% | 1st mode of the City Hall (x direction) |

Initially the materials used in the model have been characterized with the mechanical properties defined by the Italian building standard (D.M. 14/01/2008). Then the model has been updated by changing the material properties (elastic modulus) in order to obtain the real natural frequencies. In detail the elastic modulus of the materials considered are: (i) 1500 N/mm$^2$ for the building masonry; (ii) 6300 N/mm$^2$ for the squared stone of the tower; (iii) 4200 N/mm$^2$ for the squared stone of the columns of the arcades. The elastic modulus has been reduced of about 25%, to obtain the same frequencies of the modal identification techniques. In Table 4 are shown the natural periods obtained from the output-only modal identification techniques compared with those obtained from the modal analysis of the updated numerical model. The error on the frequencies of the tower is only 4% due to its simple cantilever behavior, while the frequency error in the palace reaches 20% on the first mode. These discrepancies between the linear finite element model and the frequencies obtained by the modal identification techniques are justified by the extreme damage condition of the palace that behaved highly nonlinearly during the earthquake, therefore its dynamic behavior is very difficult to predict with a linear model.

## 7 CONCLUDING REMARKS

In this paper have been illustrated three modal identification techniques that can be used to find the vibration periods of large monumental structure using ambient noise. In some cases, but with less accuracy some of these methods can also be used to obtain some estimates of the modal shapes and the damping ratios. The three output-only methods compared are: (i) the Frequency Domain Decomposition , (ii) the Random Decrement (RD) and the (iii) Eigensystem Realization Algorithm (ERA). They have tested on a monumental masonry building and they have shown similar performance. Then modal parameters identified have been used to update a finite element model (FEM) that has been used to predict the dynamic behavior of Margherita palace. The finite element model will be used to compare different restoration strategies.

## 8 ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Community's Seventh Framework Programme (Marie Curie International Reintegration Actions - FP7/2007-2013 under the Grant Agreement n° PIRG06-GA-2009-256316 of the project ICRED - Integrated European Disaster Community Resilience.

## 9 REFERENCES

Abdel-Ghaffar, AM, and Scanlan, RH, 1985. "Ambient Vibration Studies of Golden Gate Bridge: II. Pier-Tower Structure." *Journal of Engineering Mechanics*, 111(4), 483-499.

Brincker, R, and Rodrigues, J. 2005. "Application of the Random Decrement Technique in Operational Modal Analysis." Proceedings of the 1st International Operational Modal Analysis Conference (IOMAC), Copenhagen, Denmark.

Brincker, R, Zhang, L, and Andersen, P. 2000. "Modal Identification from Ambient Responses using Frequency Domain Decomposition." International Modal Analysis Conference (IMAC), San Antonio, Texas.

Cimellaro, G. P., Pianta`, S., and De_Stefano, A. (2010). "Output-only modal identification of L'Aquila City-Hall and old Civic Tower." *Journal of Structural Engineering, ASCE*, in review.

Cole, HA, 1968. "On-the-line Analysis of Random Vibrations." *AIAA Paper*, 68-288.

Giraldo DF., Song, W., Dyke, S. J., and Caicedo, J. M. 2009. "Modal Identification Through Ambient Vibration: Comparative Study." *Journal of Engineering Mechanics*, 135(8), 759-770.

Gul, M, and Catbas, FN. 2008. "Ambient Vibration Data Analysis for Structural Identification and Global Condition Assestement." *Journal of Engineering Mechanics*, 134(8), 650-662.

He, X, Moaveni, B, Conte, JP., and Elgamal, A. 2006. "Comparative study of system identification techniques applied to new carquinez bridge." Third International Conference on Bridge Maintenance, Safety and Management (IABMAS 2006), Porto, Portugal.

James, G. H., Carne, T. G., and Mayes, R. L. 1996. "Modal parameter extraction from large operationg structures using ambient excitation." Proc. 14th Int. Modal Analysis Conf., Dearborn, Michigan, USA.

Juang, JN., Cooper, JE., and Wright, JR. 1988. "An eigensystem realization algorithm using data correlations (ERA/DC) for modal parameter identification." *Control Theory and Advanced Technology*, 4(1), 5-14.