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OMA of model chimney using Bench-Scale earthquake simulator

Sertaç Tuhta*

Faculty of Engineering, Department of Civil Engineering, Ondokuz Mayis University, Atakum/Samsun, Turkey

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Abstract. This study investigated the possibility of using the recorded micro tremor data on ground level as ambient vibration input excitation data for investigation and application Operational Modal Analysis (OMA) on the bench-scale earthquake simulator (The Quanser Shake Table) for model chimney. As known OMA methods (such as EFDD, SSI and so on) are supposed to deal with the ambient responses. For this purpose, analytical and experimental modal analysis of a model chimney for dynamic characteristics was performed. 3D Finite element model of the chimney was evaluated based on the design drawing. Ambient excitation was provided by shake table from the recorded micro tremor ambient vibration data on ground level. Enhanced Frequency Domain Decomposition is used for the output only modal identification. From this study, best correlation is found between mode shapes. Natural frequencies and analytical frequencies in average (only) 1.996% are different.

Keywords: experimental modal analysis; chimney; modal parameter; EFDD; shake table

1. Introduction

In recent years, old industrial chimneys have remained as place marks that represent the industry in some of the regions in our cities. The rapid development of industrial development and the increasing need for air pollution control have made steel chimneys an important structure. These old structures cannot be recovered for reuse as they are in other industrial structures. For this reason, new uses are needed in the areas where these structures are located and evaluation is needed to protect or remove these structures. Due to large-scale industrialization, the construction of the chimney is increasing every year. In many industries, chimneys must leave hot waste gases higher. Steel chimney construction has become popular, and 25-75 m high chimneys have been widely used. Steel chimneys are ideal for works requiring short warm-up times and low thermal capacity. Also, steel chimneys are economical for height up to 45 m. For single and multi-flue steel chimneys; there are a large number of design solutions that allow for some freedom to shape the manner of their installation and use. There are freely supported structures, guyed or in a tripod, or encircled by a truss-frame. Further differences result from the manner of connecting the elements, or the applied technology of thermal protection (mineral wool, lining, etc) and the cross-sectional shape. The outside diameter of the chimney can be fixed or changed linearly. Steel thickness can be changed stepwise or linearly. Steel chimneys, like any other structures or its parts, are subjected to a variety of external and internal factors which load the structure. Steel chimneys are exposed to various loads such as their self weight, wind load, earthquake load and temperature change. Under these loads it is important to determine the current state of the structure. The literature on the dynamic analysis of chimneys is very weak, but there are many studies in the literature to determine the modal properties of masonry chimneys. Most of these studies have focused on seismic excited vibrations where some methods are applied to assess the condition of the chimneys after the earthquake. The results of modeling chimneys using linear finite element analysis under seismic and wind effects are presented in various studies. Rinki and Shashi Shekhar Singh (2016) had presented the study of structural behaviour of the flare base steel stack under equivalent static load and dynamic varying wind load. The static and dynamic wind analysis is carried out by using the Staad. The parametric study was carried out to find out static and dynamic forces, deflections for flare base steel stack. The comparison is done for three different wind speeds, constant height and shell thickness. Lapsiwala *et al.* (2014) reviewed different literature based on steel chimney analysis under wind loads and seismic forces. The most obvious and unpredictable effect is the result of the wind effect compared to the earthquake load effect. Therefore, the most critical parameters for the design and analysis of the steel chimneys are the height of the chimney, the height of the chimney top and bottom, and the chimney thickness. These parameters should be considered carefully before designing the chimneys.

Górski (2017) determined frequencies, mode shapes and structural damping ratios by using the Global Positioning System (GPS) of industrial chimneys in the wind effect. The research was carried out using the Frequency Domain Decomposition (FDD) approach. The reinforced concrete (RC) slabs affected by wind and earthquake loads were inspected using the International Standard CICIND 2001 and actual acceleration records and weak points were revealed Turkeli *et al.* (2017).

*Corresponding author, Assistant Professor
E-mail: stuhta@omu.edu.tr

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As known forced (shaker, impact, pull back or quick release tests) and ambient vibration techniques are available for vibration testing of large structures. Force vibration methods are more complex and generally more expensive than ambient vibration tests. Ambient vibration testing (also called Operational Modal Analysis) is the most economical non-destructive testing method to acquire vibration data from large civil engineering structures for Output-Only Model Identification. General characteristics of structural response (appropriate frequency, displacement, velocity, acceleration rungs), suggested measuring quantity (such as velocity or acceleration) depends on the type of vibrations (Traffic, Acoustic, Machinery inside, Earthquakes, Wind…) are given in Vibration of Buildings (1990) can be obtained.

Response characteristics of these structures give a general idea of the preferred quantity and its rungs to be measured. A few studies the analysis of ambient vibration measurements of buildings from 1982 until 1996 are discussed in Ventura and Schuster (1996). Last ten years Output-Only Modal Identification studies of buildings are given in appropriate references structural vibration solutions. For the modal updating of the structure it is necessary to estimate sensitivity of reaction of examined system to change of parameters of a building. Kasimzade (2006) System identification is the process of developing or improving a mathematical representation of a physical system using experimental data investigated in HO and Kalman (1966), Kalman (1960), Ibrahim and Miculcik (1977), Ibrahim (1977), Bendat (1998), Ljung (1999), Juang (1994), Van Overschee and De Moor (1996), and system identification applications in civil engineering structures are presented in works Trifunac (1972), Turker (2014), Altunisik *et al.* (2010), Brincker *et al.* (2000), Roeck (2003), Peeters (2000), Cunha *et al.* (2005), Wenzel and Pichler (2005), Kasimzade and Tuhta (2007a, b), (2009, 2017). Extracting system physical parameters from identified state space representation was investigated in references. Alvin and Park (1994), Balmes (1997), Juang *et al.* (1988), Juang and Pappa (1985), Lus *et al.* (2003), Phan *et al.* (2003), Sestieri and Ibrahim (1994), Tseng *et al.* (1994). The solution of a matrix algebraic Riccati equation and orthogonality projection more intensively and inevitably used in system identification was deeply investigated in works of Aliev (1998). In engineering structures there are three types of identification: namely modal parameter identification; structural-modal parameter identification; control-model identification methods are used. In the frequency domain the identification is based on the singular value decomposition of the spectral density matrix and it is denoted Frequency Domain Decomposition (FDD) and its further development Enhanced Frequency Domain Decomposition (EFDD). In the time domain there are three different implementations of the Stochastic Subspace Identification (SSI) technique: Unweighted Principal Component (UPC); Principal component (PC); Canonical Variety Analysis (CVA) is used for the modal updating of the structure (Friswell and Mottershead 1995; Marwala 2010). It is necessary to estimate sensitivity of reaction of examined system to change of random or fuzzy parameters of a structure. Investigated measurement noise perturbation influences to the identified system modal and physical parameters. Estimated measurement noise border, for which identified system parameters are acceptable for validation of finite element model of examine system. System identification is realized by observer Kalman filter Juang *et al.* (1993) and Subspace Overschee and De Moor (1996) algorithms. In special case observer gain may coincide with the Kalman gain. Stochastic state-space model of the structure are simulated by Monte-Carlo method.

The Quanser Shake Table is a bench-scale earthquake simulator ideal for teaching structural dynamics, control topics related to earthquake, aerospace and mechanical engineering and widely used in applications. This study investigated the possibility of using the recorded micro tremor data on ground level as ambient vibration input excitation data for investigation and application Operational Modal Analysis (OMA) on the bench-scale earthquake simulator (The Quanser Shake Table) for model chimney.

For this purpose, analytical and experimental modal analysis of a model chimney for dynamic characteristics was evaluated. 3D Finite element model of the chimney was evaluated based on the design drawing. Ambient excitation was provided by shake table from the recorded micro tremor ambient vibration data on ground level. Enhanced Frequency Domain Decomposition is used for the output only modal identification.

2. Modal parameter extractions

The (FDD) ambient modal identification is an extension of the Basic Frequency Domain (BFD) technique or called the Peak-Picking technique. This method uses the fact that modes can be estimated from the spectral densities calculated, in the case of a white noise input, and a lightly damped structure. It is a non parametric technique that determines the modal parameters directly from signal processing. The FDD technique estimates the modes using a Singular Value Decomposition (SVD) of each of the measurement data sets. This decomposition corresponds to a Single Degree of Freedom (SDOF) identification of the measured system for each singular value Brincker *et al.* (2000).

The Enhanced Frequency Domain Decomposition technique is an extension to Frequency Domain Decomposition (FDD) technique. This technique is a simple technique that is extremely basic to use. In this technique, modes are easily picked by locating the peaks in Singular Value Decomposition (SVD) plots calculated from the spectral density spectra of the responses. FDD technique is based on using a single frequency line from the Fast Fourier Transform analysis (FFT), the accuracy of the estimated natural frequency based on the FFT resolution and no modal damping is calculated. On the other hand, EFDD technique gives an advanced estimation of both the natural frequencies, the mode shapes and includes the damping ratios Jacobsen *et al.* (2006). In EFDD technique, the single degree of freedom (SDOF) Power Spectral Density (PSD) function, identified about a peak of resonance, is taken back

Table 1 Shake table specifications

Dimensions (H×L×W)	61×46×13 cm
Total mass	27.2 kg
Payload area (L×W)	46×46 cm
Maximum payload at 2.5 g	7.5 kg
Maximum travel	±7.6 cm
Operational bandwidth	10 Hz
Maximum velocity	66.5 cm/s
Maximum acceleration	2.5 g
Lead screw pitch	1.27 cm/rev
Servomotor power	400 W
Amplifier maximum continuous current	12.5 A
Motor maximum torque	7.82 N.m
Lead screw encoder resolution	8192 counts/rev
Effective stage position resolution	1.55 μm/count
Accelerometer range	±49 m/s²
Accelerometer sensitivity	1.0 g/V

to the time domain using the Inverse Discrete Fourier Transform (IDFT). The natural frequency is acquired by defining the number of zero crossing as a function of time, and the damping by the logarithmic decrement of the correspondent single degree of freedom (SDOF) normalized auto correlation function (Peeters 2000).

In this research, modal parameter identification is implemented by the Enhanced Frequency Domain Decomposition. The relationship between the input ($x(t)$) and responses ($y(t)$) in the EFDD technique can be written as

$$[G_{yy}(j\omega)]=[H(j\omega)]^*[G_{xx}(j\omega)][H(j\omega)]^T \quad (1)$$

where $G_{xx}(j\omega)$ is the rxr Power Spectral Density (PSD) matrix of the input. $G_{yy}(j\omega)$ is the mxmPower Spectral Density (PSD) matrix of the output, $H(j\omega)$ is the mxr Frequency Response Function (FRF) matrix, * and superscript T denote complex conjugate and transpose, respectively. The FRF can be reduced to a pole/residue form as follows

$$[H(\omega)]=\frac{[Y(\omega)]}{[X(\omega)]}=\sum_{k=1}^{m}\frac{[R_k]}{j\omega\text{-}\lambda_k}+\frac{[R_k]^*}{j\omega\text{-}\lambda_k^*} \quad (2)$$

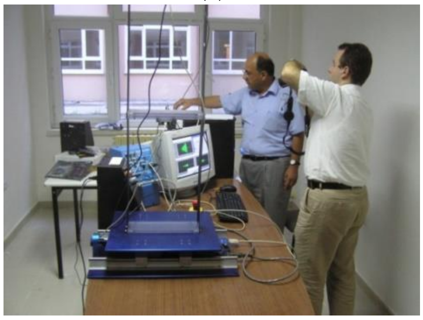
where n is the number of modes λ_k is the pole and, R_k is the residue. Then Eq. (1) becomes as

$$G_{yy}(j\omega)=\sum_{k=1}^{n}\sum_{s=1}^{n}\left[\frac{[R_k]}{j\omega\text{-}\lambda_k}+\frac{[R_k]^*}{j\omega\text{-}\lambda_k^*}\right] G_{xx}(j\omega)\left[\frac{[R_s]}{j\omega\text{-}\lambda_s}+\frac{[R_s]^*}{j\omega\text{-}\lambda_s^*}\right]^{\bar{H}} \quad (3)$$

where s the singular values, superscript is H denotes complex conjugate and transpose. Multiplying the two partial fraction factors and making use of the Heaviside partial fraction theorem, after some mathematical manipulations, the output PSD can be reduced to a pole/residue form as fallows

$$[G_{yy}(j\omega)]=\sum_{k=1}^{n}\frac{[A_k]}{j\omega\text{-}\lambda_k}+\frac{[A_k]^*}{j\omega\text{-}\lambda_k^*}+\frac{[B_k]}{\text{-}j\omega\text{-}\lambda_k}+\frac{[B_k]^*}{\text{-}j\omega\text{-}\lambda_k^*} \quad (4)$$

(a)



(b)

(c)

Fig. 1 Illustration of model chimney and shake table

where A_k is the k th residue matrix of the output PSD. In the EFDD identification, the first step is to estimate the PSD matrix. The estimation of the output PSD known at discrete frequencies is then decomposed by taking the SVD (singular value decomposition) of the matrix

$$G_{yy}(j\omega_i)=U_iS_iU_i^{\bar{H}} \quad (5)$$

where the matrix $U_i=[u_{i1},u_{i2},\ldots,u_{im}]$ is a unitary matrix holding the singular vectors u_{ij} and s_{ij}, G is a diagonal matrix holding the scalar singular values. The first singular vector u_{ij} is an estimation of the mode shape. PSD function is identified around the peak by comparing the mode shape estimation u_{ij} with the singular vectors for the frequency lines around the peak. From the piece of the SDOF density function obtained around the peak of the PSD, the natural frequency and the damping can then be obtained.

3. Description of model chimney

The Quanser shake table II is a uniaxial bench-scale shake table. This unit can be controlled by appropriate

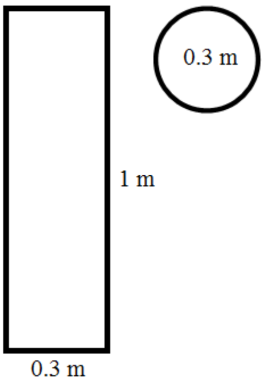


Fig. 2 Illustration of the model chimney's dimensions

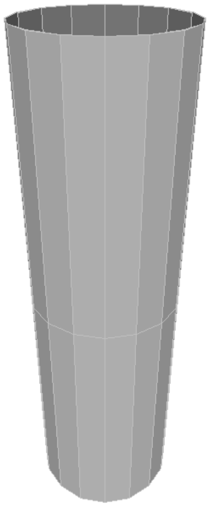


Fig. 3 Finite element model of model chimney

software illustrated in Figs. 1(a), (b), (c). It is effective for various types of experiments in civil engineering structures and models. The specifications for the Shake table are shown below Quanser (2008):

Model chimney is 1.03 m in height. Thickness of elements is 0.001588 m. The structural dimensions are shown in Fig. 2.

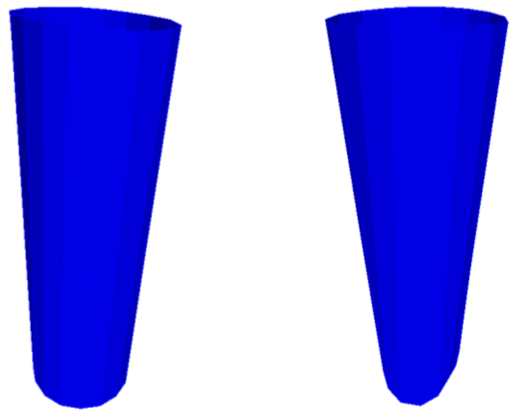
4. Analytical modal analysis of model chimney

A finite element model was generated in SAP2000 (1997). Chimney was modeled as 3D shell element (in Fig. 3 shown by the grey color). The selected structure is modeled as a space frame structure with 3D elements. Chimney was modeled as 3D shell element which has six degrees of freedom per node. At the base of the structure in the model, the ends of every element were fixed against translation and rotation for the 6 degree of freedom (DOF). Then, the FEM model of the structure was produced in SAP2000. The following assumptions were taken into account. Model chimney structure is modeled using an equivalent thickness and shell elements with isotropic property. All supports are modeled as fully fixed. The member of shell is modeled as rigidly connected together at the intersection points. In modeling of shell the modulus of elasticity E=2.000E11 N/m^2, Poisson ratio μ=0.3, mass per unit volume ρ=78500 N/m^3

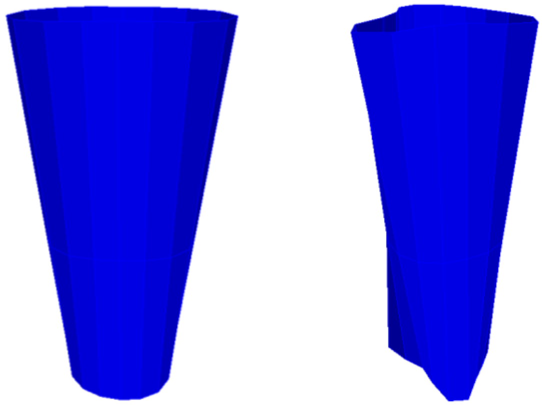
Natural frequencies and vibration modes are concerned a significant impact on the dynamic properties of structures. A total of five natural frequencies of the structure are attained which range between 2 and 9 Hz (Table 2). The first five vibration mode of the structure is shown in Fig. 4.

Table 2 Analytical modal analysis result at the first at the Finite Element (FE) model

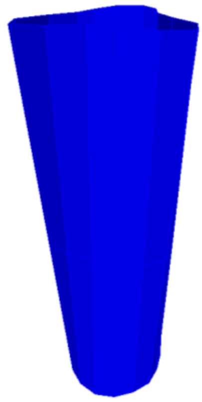
Mode number	1	2	3	4	5
Frequency (Hz)	8.228	8.423	8.667	8.813	9.009



1st Mode Shape (f=8.228 Hz) 2nd Mode Shape (f=8.423 Hz)

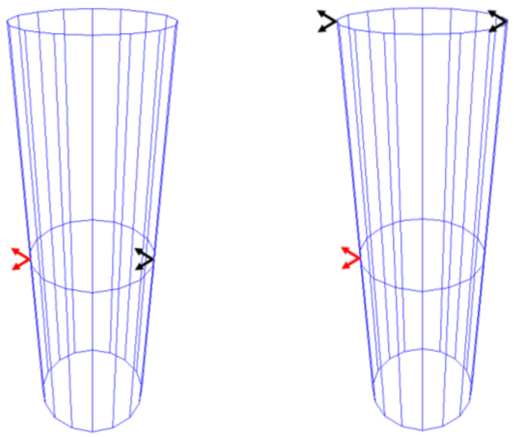


3rd Mode Shape (f=8.667 Hz) 4th Mode Shape (f=8.813 Hz)



5th Mode Shape (f=9.009 Hz)

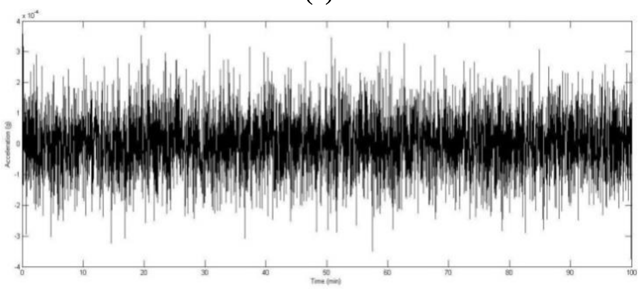
Fig. 4 Analytically identified mode shapes of model chimney



(a) First setup (b) Second setup

Fig. 5 Accelerometers location of experimental model in the 3D view

(a)



(b)

Fig. 6 (a) Ambient vibrations recorded by the accelerometer, (b) Ambient excitation data from the recorded micro tremor data on ground level used in the shake table

5. Experimental modal analysis of model chimney

Ambient excitation was provided by the recorded micro tremor data on ground level. Three accelerometers (with both *x* and *y* directional measures) were used for the ambient vibration measurements, one of which were allocated as reference sensor always located in the first floor (they are shown by the red line in Fig. 5(a), (b)). Two accelerometers were used as roving sensors (they are shown by the black line in Fig. 5(a), (b)). The response was measured in two data sets (Fig. 5(a), (b)). For two data sets were used 3 and 5 degree of freedom records respectively (Fig. 5(a), (b)). Every data set (Fig. 5(a), (b)) was measured 100 min. The selected measurement points and directions are shown in Fig. 5 (a), (b).

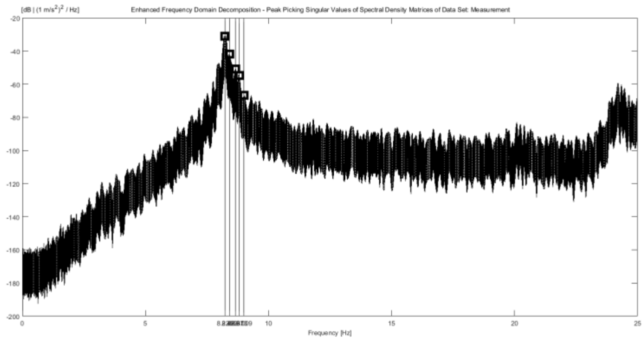


Fig. 7 Singular values of spectral density matrices

Table 3 Experimental modal analysis result at the model chimney

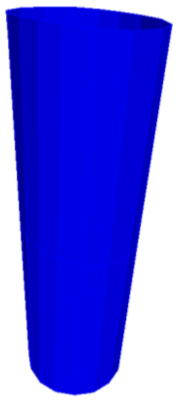
Mode number	1	2	3	4	5
Frequency (Hz)	8.060	8.254	8.495	8.640	8.830
Modal damping ratio (ξ) (%)	0.730	0.614	0.400	0.261	0.333

The data acquisition computer was dedicated to acquiring the ambient vibration records. In between measurements, the data files from the previous setup were transferred to the data analysis computer using a software package. This arrangement allowed data to be collected on the computer while the second, and faster, computer could be used to process the data in site. This approach maintained a good quality control that allowed preliminary analyses of the collected data. If the data showed unexpected signal drifts or unwanted noise or for some unknown reasons, was corrupted, the data set was discarded and the measurements were repeated.

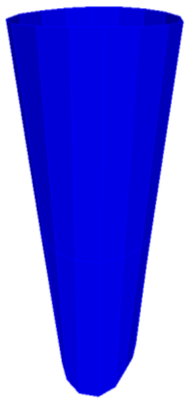
Before the measurements could begin, the cable used to connect the sensors to the data acquisition, equipment had to be laid out. Following each measurement, the roving sensors were systematically located from floor to floor until the test was completed. The equipment used for the measurement includes three quanser accelerometers (with both *x* and *y* directional measures) and geosig uni-axial accelerometer, matlab data acquisition toolbox (wincon). For modal parameter estimation from the ambient vibration data, the operational modal analysis (OMA) software ARTeMIS Extractor (1999) is used.

The simple peak-picking method (PPM) finds the eigenfrequencies as the peaks of nonparametric spectrum estimates. This frequency selection procedure becomes a subjective task in case of noisy test data, weakly excited modes and relatively close eigenfrequencies. Also for damping ratio estimation the related half-power bandwidth method is not reliable at all. Frequency domain algorithms have been the most popular, mainly due to their convenience and operating speed.

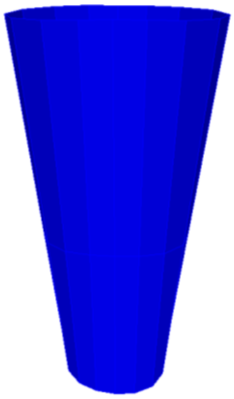
Singular values of spectral density matrices, attained from vibration data using PP (Peak Picking) technique are shown in Fig. 7. Natural frequencies acquired from the all measurement setup are given in Table 3. The first five mode shapes extracted from experimental modal analyses are given in Fig. 8. When all measurements are examined, it can be seen that best accordance is found between experimental and analytical mode shapes. When the



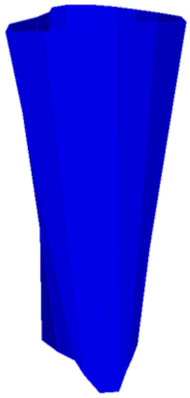
1st Mode Shape
(f=8.060 Hz, ξ=0.730)



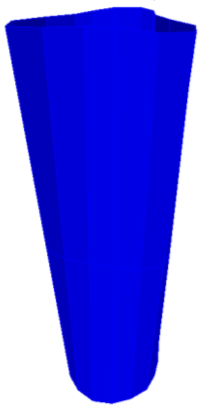
2nd Mode Shape
(f=8.254 Hz, ξ=0.614)



3rd Mode Shape
(f=8.495 Hz, ξ=0.400)



4th Mode Shape
(f=8.640 Hz, ξ=0.261)



5th Mode Shape (f=8.830 Hz, ξ=0.333)

Fig. 8 Experimentally identified mode shapes of model chimney

analytically and experimentally identified modal parameters are compared with each other, it can be seen that there is a best agreement between the mode shapes in experimental and analytical modal analyses (Table 4).

6. Conclusions

In this paper, analytical and experimental modal analysis of a model chimney was presented. Comparing the result of study, the following results can be made:

From the finite element model of model chimney a total

Table 4 Comparison of analytical and experimental modal analysis results

Mode number	1	2	3	4	5
Analytical frequency (Hz)	8.228	8.423	8.667	8.813	9.009
Experimental frequency (Hz)	8.060	8.254	8.495	8.640	8.830
Difference (%)	2.041	2.006	1.984	1.963	1.986

of 5 natural frequencies were attained analytically, which range between 8 and 10 Hz. 3D finite element model of model chimney is produced with SAP2000 software and dynamic characteristics are determined analytically. The ambient vibration tests are conducted under provided by shake table from ambient vibration data on ground level. Modal parameter identification was implemented by the Enhanced Frequency Domain Decomposition (EFDD) technique. Comparing the result of analytical and experimental modal analysis, the following observations can be made:

From the finite element model of the model chimney, the first five mode shapes are attained analytically that range between 8 and 10 Hz.

• From the ambient vibration test, the first five natural frequencies are attained experimentally, which range between 8 and 9 Hz.

• When comparing the analytical and experimental results, it is clearly seen that there is best agreement between mode shapes.

• Analytical and experimental modal frequencies differentiate from each other approximately between 1.963%-2.041%.

• Presented investigation results are shown and confirm of possibility using the recorded micro tremor data on ground level as ambient vibration input excitation data for investigation and application Operational Modal Analysis (OMA) on the bench-scale earthquake simulator (The Quanser Shake Table) for model chimney and shed light on the development of related research.

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