NOVATEUR PUBLICATIONS
INTERNATIONAL JOURNAL OF INNOVATIONS IN ENGINEERING RESEARCH AND TECHNOLOGY
[IJIERT] ISSN: 2394-3696 Website: ijiert.org
VOLUME 8, ISSUE 5, May. -2021

COMPARISON OF DYNAMIC PARAMETERS OF SCALED CONCRETE BRIDGE BY ANALYTICAL AND OPERATIONAL MODAL ANALYSIS

Furkan Günday
Ondokuz Mayis University, Faculty of Engineering,
Department of Civil Engineering, Samsun, Turkey
furkan.gunday@omu.edu.tr

Abstract

The negative effects of dynamic effects on bridges are known. Therefore, it is very important for bridges to obtain accurate and reliable dynamic parameters. Researchers have developed various methods for estimating dynamic parameters. Operational modal analysis has been developed in recent years and is used in many regions. Analytical modal analysis is a method that is still used especially in design stages. In this study, a scale model concrete bridge is used to represent randomly constructed simple concrete bridges, especially in rural areas. The aim of this study is to examine the analytical and operational modal analysis methods in the scale model concrete bridge and to examine the results. At the end of the study, dynamic parameters were obtained both analytically and experimentally. Then the obtained dynamic parameters were compared for first five modes. In addition, damping ratios of the scaled concrete bridge were obtained experimentally by operational modal analysis. The differences between analytical modal analysis and operational modal analysis frequency were found to be between 2.79% and 2.95%. In both methods, it is seen that the first five mode shapes are approximately the same. It is proposed to determine the dynamic parameters of simple concrete bridges built randomly in rural areas by operational modal analysis.

Keywords: Operational modal analysis, EFDD, Concrete bridge, Ambient vibration

Introduction

Earthquakes have been occurring in various parts of the world from past to present. Along with the earthquake, destructive effects of the earthquake are frequently encountered in these regions. Various losses of property and lives occur. Researchers working in the field of civil engineering are looking for solutions to earthquake effects. Researchers have divided the world and countries into various earthquake zones. They focused on the different effects of earthquakes on the structure in this allocated area. According to the determined earthquake effects, the researchers determined new designs and took measures against earthquakes. However, with the El Centro earthquake in Mexico, the concept of resonance emerged. Technically in resonance engineering; It is explained as amplitude going to infinity. Structures undergoing resonance make vibrations of infinite amplitude. These vibrations continue until the structure collapses. With this new terminology, earthquake engineering design rules have also changed. If the resonance situation is expressed in a more understandable language; It is the coincidence of the vibration frequency of the ground with the natural frequency of the building in the first mode. In this case, it is possible to say that the structures will receive great damage with past studies and earthquakes. The resonance effect is seen not only in buildings but also in all sub and superstructures. Transport structures are also an example. In addition, it is known that resonance can occur physically not only by earthquakes but also by environmental effects. Especially in bridges that are among transportation structures, these environmental effects are more common. Live loads are quite high due to traffic etc. on the bridges. For this reason, bridges should be examined with close lenses against resonance effect.

Experimental measurement methods are frequently used to determine the dynamic characteristics of engineering structures. These methods can be grouped into three groups as forced vibration tests, free vibration tests and environmental vibration tests. Structure in forced vibration tests; it is stimulated with the help of a vibrator. The most important disadvantage of this method is that the essential activities in the structure will be interrupted during the measurement. Environmental vibration tests are used for effects such as wind, traffic, human movement and waves. During the measurement, daily activities in the structure can continue in this way. Natural frequencies and the corresponding mode shapes and damping ratios are the dynamic characteristics of the structures. These characteristics can be determined by operational modal analysis methods. In the literature researches, many studies using the operational modal analysis methods have been reached. [1], Conducted experimental tests on the old continuous truss steel bridge. As a result of the operational modal analysis, they obtained mode shapes, frequencies of natural and forced vibrations, damping ratios, maximum amplitudes of accelerations, dynamic displacements. [2], has done the work modal testing of an isolated overpass bridge in its construction stages. [3], Conducted dynamic impact of heavy long vehicles with equally spaced axles on short-span highway bridges. [4], Conducted comparison of hybrid methods with different meta model used in bridge model-updating. [5-10], worked on operational modal analysis of bridges. The ways followed in these studies were followed. [11], modeled the long span bridge model under laboratory conditions to determine the seismic response involving the spatial variation of seismic waves in his doctoral thesis. [12], presents the operational and analytical modal analysis of a steel-girder arch bridge. [13], worked on analytical modal analysis of the bridge sample. System identification of bridges with ambient vibrations has also been benefited from [14-17].

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) [18-22]. The use of ambient vibrations and experimental methods of obtaining dynamic parameters is recommended in the recommendation’s sections of many studies [23-29]. There are also studies showing the beneficial use of finite element method to determine modal parameters [30-32].

In this study, a concrete bridge example is chosen. The bridge model in the selected example is frequently used in rural areas. In addition, the fact that it is practical is another reason for this frequent occurrence. however, the designs of these types of bridges are arbitrary. For this reason, both analytical modal analysis and operational modal analysis studies were carried out in the laboratory with a sample that will represent this type of concrete bridge. The main purpose of this study is to compare the operational and analytical modal analysis results on the sample concrete bridge representation and to examine the differences that occur.

METHOD

Finite element method was used for analytical modal analysis. In the creation of the finite element model, SAP2000 package program was used. Matlab and Artemis modal pro programs were used for the operational modal analysis method. Enhanced frequency domain decomposition (EFDD) technique was used to extract modal parameters.

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 [33]

The Enhanced Frequency Domain Decomposition technique is an extension to Frequency Domain Decomposition (FDD) technique. This t technique is a simple technique that is extremely basic to use. In this technique, modes are easily picked 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 [34]. In EFDD technique, the single degree of freedom (SDOF) Power Spectral Density (PSD) function, identified about a peak of resonance, is taken back 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 [35].

In this study modal parameter identification was implemented by the Enhanced Frequency Domain Decomposition. The relationship between the input and responses in the EFDD technique can be written as, in this method, unknown input is represented with x(t) and measured output is represented with y(t)

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

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

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

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

$$G_{yy}(j\omega)=\sum_{k=1}^{n}\sum_{s=1}^{n}\left[\frac{[R_k]}{j\omega-\lambda_k}+\frac{[R_k]^{*}}{j\omega-\lambda_k^{*}}\right]$$

$$G_{xx}(j\omega)\left[\frac{[R_s]}{j\omega-\lambda_s}+\frac{[R_s]^{*}}{j\omega-\lambda_s^{*}}\right]^{\bar{H}} \qquad (3)$$

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;

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

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;

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

Where the matrix $U_i=[u_{i1},u_{i2},\dots,u_{im}]$ is a unitary matrix holding the singular vectors u_{ij} and s_{ij} 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 be obtained.

MATERIAL

If possible, the background and purpose of the study should be stated first, followed by details of the methods, materials, procedures, and equipment used. Findings, discussion and conclusions should follow in that order. Appendices may be employed where appropriate. The APA Publication Manual should be consulted for

The bridge model is an example of a concrete bridge consisting of two pillars and a deck. Bridge pillars are identical. Bridge pillars are 75 cm height, 60 cm wide and 7.5 cm thick. The span between the two pillars is 1 m. The bridge deck is 150 cm long, 75 cm wide and 7.5 cm thick. Bridge pillars are placed in the center of the deck. There are 25 cm increments in the X direction and 7.5 cm increments in the Y direction on the deck. The bridge model is made of C25 concrete with a single formwork. Connections are fully rigid. The scaled concrete bridge not is fixed to the ground. Figure 1 is given in order to better understand the dimensions of the scaled concrete bridge.

Figure 1: Dimensions of scaled concrete bridge

RESULT AND DISCUSSION

Analytical modal analysis of Scaled Concrete Bridge

A finite element model was generated in SAP2000 package program. Pillars and deck were modeled as 3D elements. Pillars and deck were modeled as 3D beam-column elements which have degrees of freedom. All supports are modeled as fully fixed. The members of concrete frame are modeled as rigidly connected together at the intersection points. In modeling of beams and columns the modulus of elasticity E=30000 MPa, Poisson ratio μ=0.2, mass per unit volume ρ=23.54 kN/m3. The 3D generated finite element model of the scaled concrete bridge is given in figure 2.

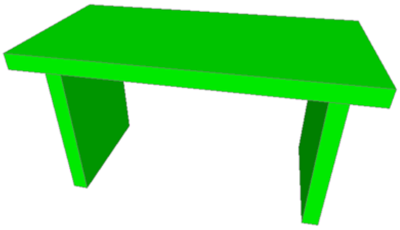

Figure 2: Finite element model of the scaled concrete bridge

İt is know that frequency and vibration modes are concerned a significant impact on the dynamic performance of buildings. A total of five frequency of the structure are attained which range between 2.15 and 13.54 Analytical modal analysis results at the finite element model are shown in Table 1.

Table 1. Analytical modal analysis results

Mode number	**1**	**2**	**3**	**4**	**5**
Frequency (Hz)	2.15	5.83	8.16	11.27	13.54

The first five vibration mode of the structure is shown in Figure 3-7.

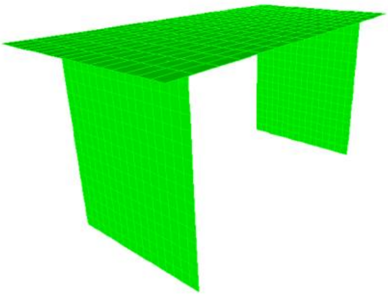

Figure 3: 1st Mode Shape (Frequency=2.15 Hz)

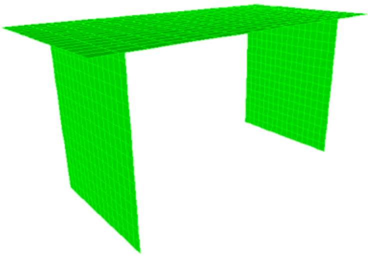

Figure 4: 2nd Mode Shape (Frequency=5.83 Hz)

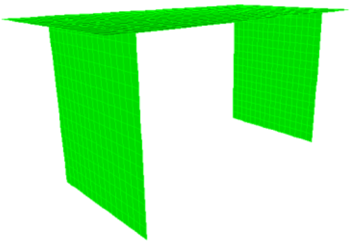

Figure 5: 3rd Mode Shape (Frequency=8.16 Hz)

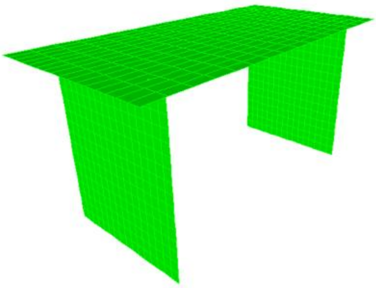

Figure 6: 4th Mode Shape (Frequency=11.27 Hz)

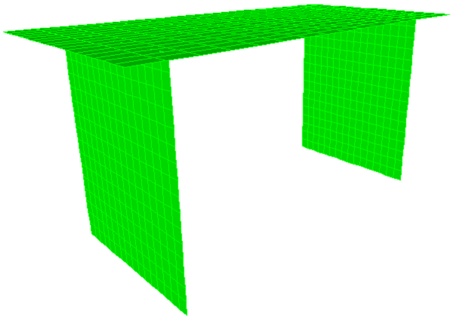

Figure 7: 5th Mode Shape (Frequency=13.54 Hz)

Operational modal analysis of Scaled Concrete Bridge

Measurements were carried out in a closed environment in the civil engineering laboratory of Ondokuz Mayis University. Ambient excitation was provided by the recorded micro tremor data on ground level. Seismometer was used for the ambient vibration measurements. Seismometer is given in figure 8.

Figure 8: Seismometer

Measurements were made in two setups. The purpose of making two setups is to obtain more reliable results. Three three-axis accelerometers are used in Setup 1. The accelerometer placement arrangement in Setup 1 is given in figure 9.

Figure 9: The accelerometer placement arrangement in Setup 1

Two three-axis accelerometers are used in Setup 2. The accelerometer placement arrangement in Setup 2 is given in figure 10.

Figure 10: The accelerometer placement arrangement in Setup 2

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 sensebox accelerometers (triaxial measures) and geosig seismometer, matlab data acquisition toolbox (wincon). For modal parameter estimation from the ambient vibration data, the operational modal analysis (OMA) software ARTeMIS Modal Pro is used. Singular values of spectral density matrices, attained from vibration data using PP (Peak Picking) technique are given in Figure.11.

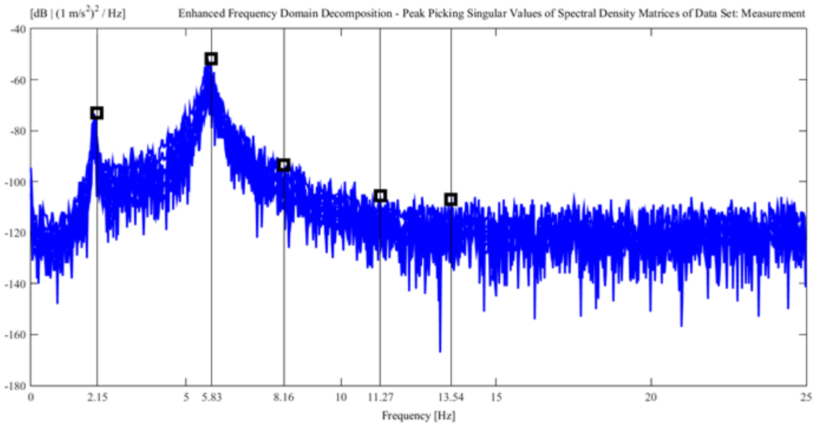

Figure 11: Singular values of spectral density matrices

Frequency and damping ratios acquired from the all-measurement setups are given in Table 2.

Table 2. Operational modal analysis results

Mode number	**1**	**2**	**3**	**4**	**5**
Frequency (Hz)	2.09	5.68	7.98	10.95	13.54
Modal damping ratio (ξ)	1.18	0.98	1.05	0.87	0.92

As a result of the analysis with the Artemis software, it is seen that the first five mode shapes are approximately the same with analytical modal analysis. It is predicted that the dimensions of the concrete bridge model cause this situation. The first five mode shapes extracted from operational modal analyses are given in Figure 12-16.

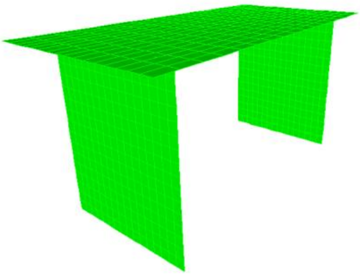

Figure: 12. 1st Mode Shape (Frequency=2.09 Hz, Damping ratio=1.18)

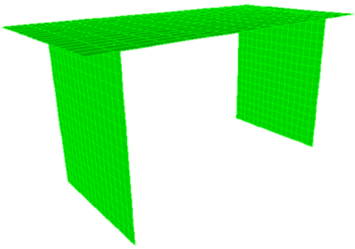

Figure: 13. 2nd Mode Shape (Frequency=5.68 Hz, Damping ratio=0.98)

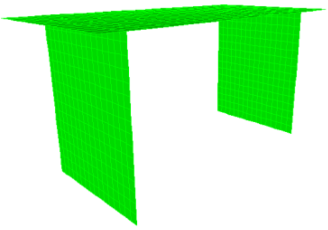

Figure: 14. 3rd Mode Shape (Frequency=7.98 Hz, Damping ratio=1.05)

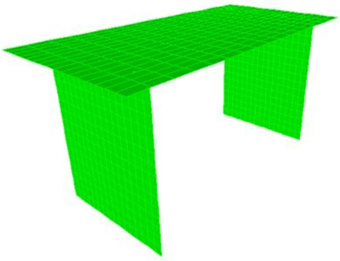

Figure: 15. 4th Mode Shape (Frequency=10.95 Hz, Damping ratio=0.87)

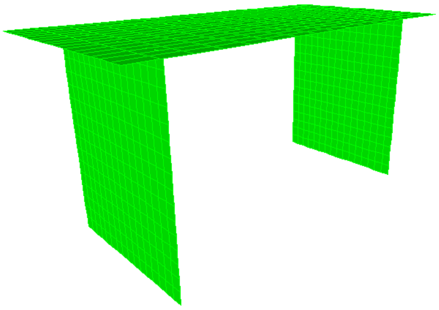

Figure: 16. 5th Mode Shape (Frequency=13.14 Hz, Damping ratio=0.92)

COMPARISON OF RESULTS

Table 3 is made in order to compare the results of analytical modal analysis and operational modal analysis.

Table 3. Comparison of analytical and operational modal analysis results

Mode number	**1**	**2**	**3**	**4**	**5**
Analytical Frequency (Hz)	2.15	5.83	8.16	11.27	13.54
Operational Frequency (Hz)	2.09	5.68	7.98	10.95	13.14
Difference (Hz)	0.06	0.15	0.18	0.32	0.40
Difference (%)	2.79	2.57	2.21	2.84	2.95

CONCLUSIONS

In this paper, analytical and operational modal analysis of scaled concrete bridge was presented. The frequencies and mode shapes of the first five modes of the scaled concrete bridge were obtained analytically and experimentally. In addition, damping ratios of the scaled concrete bridge were obtained experimentally by operational modal analysis.

When comparing the analytical and experimental results for mod shapes, it is clearly seen that there is very best agreement between mode shapes. It is seen that the first five mode shapes are approximately the same. Analytical modal analysis and operational modal analysis frequency differences are between %2.79 - %2.95. Analytical modal analysis and operational modal analysis frequency difference for 1st mode is 0.06s and %2.79. It is understood that there are theorical assumptions in the analytical modal analysis method in the formation of this difference.

It has been clearly demonstrated that the damping ratios vary in each free vibration mode but in analytical modal analysis, it is known that the damping ratio is accepted as constant and this value is 2 percent for concrete. As a result of the operational modal analysis, the damping ratio in the 1st free vibration mode was obtained as 1.18 percent. Operational modal analysis was found to be more reliable in obtaining damping ratios. It is known that the obtained parameters are more reliable than theoretical methods in terms of representing the real values. Therefore, the obtained modal parameters better represent the scaled concrete bridge.

The dynamic parameters of concrete bridges built randomly in rural areas can be determined easily by operational modal analysis.

REFERENCES

1) Kilikevičius, A., & Bacinskas, D., & Jurevičius, M., & Kilikevičienė, K., & Fursenko, A., & Jakaitis, J., & Toločka, E. (2018). Field testing and dynamic analysis of old continuous truss steel bridge. The Baltic Journal of Road and Bridge Engineering, 13(1), 54-66.
2) Aras, F. (2018). Modal testing of an isolated overpass bridge in its construction stages. The Baltic Journal of Road and Bridge Engineering, 13(1), 67-76.

3) Mohammed, O., & Gonzalez, A., & Cantero, D. (2018). Dynamic impact of heavy long vehicle with equally spaced axles on short-span highway bridges. The Baltic Journal of Road and Bridge Engineering. 13(1), 1-13.
4) Xia, Z., & Li, A., & Li, J., & Duan, M. (2017). Comparison of Hybrid Methods with Different Meta Model Used in Bridge Model-Updating. The Baltic Journal of Road and Bridge Engineering, 12(3), 193-202.
5) Kasimzade, A.A., Tuhta, S., Günday, F. & Aydın, H. (2021). Obtaining Dynamic Parameters by Using Ambient Vibration Recordings on Model of The Steel Arch Bridge. Periodica Polytechnica Civil Engineering. 65, 2 (Jan. 2021), 608-618.
6) Tuhta, S., Günday, F., & Aydin, H. (2020). Update of Structural Parameters on the Bench-Scale Aluminum Bridge Model Using Ambient Vibration. International Journal of Latest Technology in Engineering, Management Applied Science, 9(4), 10–18.
7) Tuhta, S., Aydin, H., & Günday, F. (2020). Updating for Structural Parameter Identification of the Model Steel Bridge Using OMA. International Journal of Latest Technology in Engineering, Management Applied Science, 9(3), 59–68.
8) Tuhta, S., & Günday, F. (2019). Application of Oma on The Bench-scale Aluminum Bridge Using Micro Tremor Data. İnternational Journal of Advance Research and Innovative İdeas in Education, 5(5), 912–923.
9) Kasimzade, A., Tuhta, S., Günday, F., & Aydin, H. (2019). Investigation of Modal Parameters on Steel Model Bridge Using EFDD Method. Presented at the 2nd International Conference on Tecnology and Science, Burdur, Turkey.
10) Kasimzade, A., Tuhta, S., Aydin, H., & Günday, F. (2019). Determination of Modal Parameters on Steel Model Bridge Using Operational Modal Analysis. Presented at the 8th International Steel Structures Symposium, Konya, Turkey.
11) Yang, C. (2007). Seismic analysis of long span bridges including the effects of spatial variation of seismic waves on bridges. PhD Thesis, Hong Kong University of Science and Technology.
12) Ren, Wei-Xin & Tong, Zhao & Harik, Issam E. (2004). Experimental and Analytical Modal Analysis of Steel Arch Bridge. Journal of Structural Engineering, 130(7), 1022-1031.
13) Tuhta, S., Günday, F., Aydin, H., & Alalou, M. (2020). Modal Analysis of Model Steel Bridge by Finite Element Method. Presented at the 2nd International Eurasian Conference on Science, Engineering and Technology, Gaziantep, Turkey.
14) Tuhta, S., Günday, F., & Aydin, H. (2019). Numerical Algorithms for System Identification of Benchmark Steel Bridge. Presented at the iSTE-CE’xx2019- International Conference on Innovation, Sustainability, Technology and Education in Civil Engineering, Hatay, Turkey
15) Tuhta, S., Günday, F., & Aydin, H. (2020). System Identification of Model Steel Bridge with Fuzzy Logic. International Journal of Research and Innovation in Applied Science, 5(1), 50–54.
16) Tuhta, S., & Günday, F. (2020). Study for Artificial Neural Network of AluminumBenchmark Bridge. International Journal of Research and Innovation in Applied Science, 5(2), 90–95.
17) Tuhta, S., Günday, F., & Aydin, H. (2020). System Identification of Model Steel Bridge with Genetic Algorithms. International Journal of Research and Innovation in Applied Science, 5(1), 55–59.
18) Kasimzade, A.A., & Tuhta, S. (2007). Particularities of monitoring, identification, model updating hierarchy in experimental vibration analysis of structures, EVACES'07: Experimental Vibration Analysis for Civil Engineering Structures, Porto, Portugal, Oct. 24-26.
19) Kasimzade, A.A., & Tuhta, S. (2009). Optimal estimation the building system characteristics for modal identification, IOMAC 2009: 3rd International Operational Modal Analysis Conference, Portonovo, Italy, May, 4-6.
20) Kasımzade, A., & Tuhta, S. (2012). Stochastic Parametric System Identification Approach for Validation of Finite Element Models. Industrial Applications, TWMS Journal of Pure and Applied Mathematics, 3(1), 41-61.
21) Kasımzade, A.A., & Tuhta, S. (2017). Application of OMA on the Bench-Scale Earthquake Simulator Using Micro Tremor Data, Structural Engineering and Mechanics, 61(2), 267-274.
22) Tuhta.S. (2019). OMA of model chimney using Bench Scale earthquake simulator. Earthquakes and Structures, 16(3), 321–327.

23) Tuhta, S., Abrar, O., & Günday, F. (2019). Experimental Study on Behavior of Bench-Scale Steel Structure Retrofitted with CFRP Composites under Ambient Vibration. European Journal of Engineering Research and Science, 4(5), 109–114.
24) Tuhta, S., Günday, F., & Abrar, O. (2019). Experimental Study on Effect of Seismic Damper to Reduce the Dynamic Response of Bench-Scale Steel Structure Model. İnternational Journal of Advance Research and Innovative İdeas in Education, 5(5), 901–911.
25) Tuhta, S., Günday, F., & Alalou, M. (2019). Determination of System Parameters on Model Lighting Pole Using ANN by Ambient Vibration. International Journal of Research and Scientific Innovation, 6(11), 191–195.
26) Tuhta, S., & Günday, F. (2019). MIMO System Identification of Industrial Building Using N4SID With Ambient Vibration. International Journal of Innovatıons in Engineering Research and Technology, 6(8), 1–6.
27) Kasimzade, A., Tuhta, S., Günday, F., & Aydin, H. (2019). Investigation of Modal Parameters on Steel Structure Using FDD from Ambient Vibration. Presented at the 8th International Steel Structures Symposium, Konya, Turkey.
28) Tuhta, S. (2018). OMA of GFRP Retrofitted Model Concrete Structure Using Ambient Vibration. International Journal of Trend in Scientific Research and Development, 3(1).
29) Kasimzade, A., & Tuhta, S. (2017). OMA of model steel structure retrofitted with CFRP using earthquake simulator. Earthquakes and Structures, 12(6), 689–697.
30) Tuhta, S., & Günday, F. (2020). Analytical Modal Analysis of RC Building Retrofitted with CFRP using Finite Element Method. International Journal of Latest Technology in Engineering, Management Applied Science, 9(2), 78–82.
31) Tuhta, S., Günday, F., & Alihassan, A. (2020). The Effect of CFRP Reinforced Concrete Chimney on Modal Parameters Using Finite Element Method. International Journal of Innovations in Engineering Research and Technology, 7(2), 1–6.
32) Ziada, M., Tuhta, S., Gençbay, E. H., Günday, F., & Tammam, Y. (2019). Analysis of Tunnel Form Building Retrofitted with CFRP using Finite Element Method. International Journal of Trend in Scientific Research and Development, 3(2), 822–826.
33) Brincker, R., Zhang, L. & Andersen, P. (2000), Modal identification from ambient responses using frequency domain decomposition, Proceedings of the 18th International Modal Analysis Conference (IMAC), San Antonio, Texas, USA, February.
34) Jacobsen, N. J., Andersen, P., & Brincker, R. (2006), Using enhanced frequency domain decomposition as a robust technique to harmonic excitation in operational modal analysis, International Conference on Noise and Vibration Engineering (ISMA), Leuven, Belgium, September.
35) Peeters, B. (2000), System identification and damage detection in civil engineering, Ph.D. Dissertation, Katholieke Universiteit Leuven, Leuven, Belgium.
36) American National Standards Institute. (1990). ANSI S2.47: Vibration of building: Guidelines for the measurement of vibrations and evaluation of their effects on buildings.