Advances in Concrete Construction, *Vol. 1, No. 3 (2013) 227-237*
DOI: http://dx.doi.org/10.12989/acc2013.1.3.227

Structural identification of concrete arch dams by ambient vibration tests

Barış Sevim*[1], Ahmet Can Altunışık[2a] and Alemdar Bayraktar[2b]

[1] *Yıldız Technical University, Department of Civil Engineering, 34220, Istanbul, Turkey*
[2] *Karadeniz Technical University, Department of Civil Engineering, 61080, Trabzon, Turkey*

(Received November23, 2012, Revised February 25, 2013, Accepted April 18, 2013)

Abstract. Modal testing, widely accepted and applied method for determining the dynamic characteristics of structures for operational conditions, uses known or unknown vibrations in structures. The method's common applications includes estimation of dynamic characteristics and also damage detection and monitoring of structural performance. In this study, the structural identification of concrete arch dams is determined using ambient vibration tests which is one of the modal testing methods. For the purpose, several ambient vibration tests are conducted to an arch dam. Sensitive accelerometers were placed on the different points of the crest and a gallery of the dam, and signals are collected for the process. Enhanced Frequency Domain Decomposition technique is used for the extraction of natural frequencies, mode shapes and damping ratios. A total of eight natural frequencies are attained by experimentally for each test setup, which ranges between 0-12 Hz. The results obtained from each ambient vibration tests are presented and compared with each other in detail. There is a good agreement between the results for all measurements. However, the theoretical fundamental frequency of Berke Arch Dam is a little different from the experimental.

Keywords: arch dams; ambient vibration test; dynamic characteristics; signal processing

1. Introduction

Arch dams are one of the engineering structures which are built to get energy generally. Due to retaining large quantity water, they have strategically, logistical and economical importance. Because, in case failure of these dams a serious threat for life and property may come existence. The boundary conditions, material and geometrical properties accepted in the design can be changed by some reasons such as workers' mistakes during the construction, different load cases to be exposed to the structure in the course of time considered in the design, and reducing of strength and durability of the structure by the time. To reduce these risks, regular inspections are necessary to identify potential problems. One of the important inspections is to apply modal testing tests to existing dams to estimate their dynamic characteristics such as natural frequencies, mode shapes and damping ratios.

*Corresponding author, Associate Professor, E-mail: bsevim18@hotmail.com
[a] Associate Professor
[b] Professor

http://www.techno-press.org/?journal=acc&subpage=7 ISSN: 2287-5301(Print), 2287-531X (Online)

Modal testing, widely accepted and applied method for determining the dynamic characteristics of structures for operational conditions, uses known or unknown vibrations in structures. The method's common applications include not only estimation of dynamic characteristics but also damage detection and monitoring of structural performance. The modal testing methods are classified into two groups: Forced Vibraion Tests (FVT) and Ambient Vibration Tests (AVT) (Ewins 1995, Maia and Silva 1997).

In Forced Vibration Tests (FVT), the structure is vibrated using an input force (shaker, hammer) and output response is measured. This procedure is useless and expensive for large structures such as huge arch dams, since arch dams are not vibrated completely by an input force. In Ambient Vibration Tests (AVT), the structure is vibrated by environmental excitations (wind, earthquake, hydrodynamic effects) and only output response is measured. AVT is cheap and fast, since the equipment for excitation is unnecessary. It does not interfere with the operation of the structure. In addition, measured response is representative for the real operating conditions of the structure in AVT. Therefore, AVT become very attractive. Some of the studies published in recent years should be summarized as given: Zhang *et al.* (2013) investigated the modal parameters of the structures through ensemble empirical modal decomposition techniques. Park *et al.* (2011) studied about the output-only modal identification approach for time-unsynchronized signals from decentralized wireless sensor network for linear structural systems. Li *et al.* (2010) investigated the effect of boundary conditions on modal parameters of a special suspension bridge named as the Run Yang Suspension Bridge. Ku *et al.* (2013) studied about the output-only modal parameter identification for force-embedded acceleration data in the presence of harmonic and white noise excitations.

FVT and AVT were applied on some large dams and prototype arch dams in the literature. Zhou *et al.* (2006) investigated seismic failure of high arch dams using prototype models by vibration tests. In this study, a series of dynamic experiments for 20 models of high arch dams were recently performed on a shaking table, with the water ignored. Cantieni (2001) was assessed the structural properties of Norjö Dam by forced vibration tests. The dam has 46m height and its width is 2.5 m at the crest and 5.5 m at the bottom. In addition, the finite element model of Norjö Dam was updated using experimental results. Proulx *et al.* (2001) investigated the water level effects on the dynamic behavior of Emosson Arch Dam. The dam is located in the European Alps, and it has 180 m height. Darbre and Proulx (2002) set up an automated system with 250 m height Mauvoisin Arch Dam in Swiss Alps and the ambient vibrations were recorded twice daily for a period of 6 months. Frequency shifts were tracked throughout the testing period and the effects of the varying water level were identified. Alves and Hall (2006) determined the modal properties of Pacoima Dam located in California by vibration tests. The dam with 113 m height was constructed in 1928. Also, the finite element model of Pacoima Dam was updated according to experimental test results. Sevim *et al.* (2012) an experimental study evaluated about the crack effects on the dynamic characteristics of a prototype arch dam using ambient vibration tests. Shariatmadar and Mirhaj (2011) investigated the dam-reservoir-foundation interaction effects on the modal characteristic of concrete gravity dams.

In this study, the dynamic characteristics of thin and doubled curved Berke Arch Dam were determined by conducting several ambient vibration tests. Signals collected from the tests were processed using PULSE (2006) and dynamic characteristics were determined using OMA (2006) commercial softwares. Enhanced Frequency Domain Decomposition (EFDD) technique was used for the extraction of natural frequencies, mode shapes and damping ratios. Because of the huge body of the dam, the force vibration test is not used in the study.

2. Mathematical model

Ambient excitation does not lend itself to Frequency Response Function (FRFs) or Impulse Response Function (IRFs) calculations because the input force is not measured in an ambient vibration test. Therefore, a modal identification procedure will need to base itself on output-only data (Ren *et al.* 2004). There are several modal parameter identification techniques available such as Peak Picking (PP), Stochastic Subspace Identification (SSI), and Frequency Domain Decomposition techniques (FDD). These techniques are developed by improvements in computing capacity and signal processing procedures. In this study, Enhanced Frequency Domain Decomposition technique (EFDD) is used to extract dynamic characteristics of the arch dam.

EFDD technique is an extension to FDD technique. FDD is a basic technique that is extremely easy to use. In the technique, modes are simply picked locating the peaks in Singular Value Decomposition plots (SVD) calculated from the spectral density spectra of the responses. Animation is performed immediately. As FDD technique is based on using a single frequency line from the Fast Fourier Transform analysis (FFT), the accuracy of the estimated natural frequency depends on the FFT resolution and no modal damping is calculated. Compared to FDD, EFDD gives an improved estimate of both the natural frequencies and the mode shapes and also includes damping (Jacobsen *et al.* 2006)

technique, the relationship between the unknown input $x(t)$ and the measured responses $y(t)$ can be expressed as given in Eq. (1) (Bendat and Piersol 2004)

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

where $G_{xx}(jw)$ is the *rxy* Power Spectral Density (PSD) matrix of the input, *r* is the number of inputs, $G_{yy}(jw)$ is the *mxm* PSD matrix of the responses, *m* is the number of responses, $H(jw)$ is the *mxr* Frequency Response Function (FRF) matrix, and $*$ and superscript *T* denote complex conjugate and transpose, respectively. Solution of the Eq. (1) is given detail in the literature (Brincker *et al.* 2000).

3. Description of berke arch dam

Berke Arch Dam is the highest arch dam constructed in Turkey (GDSHW 2009). It has 201 m height, 270 m crest length, and 4.6 m crest width. In addition, it was 16th highest arch dam in World when it was built. It was built in 6 years (1995-2001) using about 700000 m^3 concrete on its body. Also, total 10 km tunnels and galleries were built before constructing the arch dam. It retains about 427E6 m^3 reservoir water, and 1700 E6kWh electrical energy is gotten in a year. It is taken place in Ceyhan River in Osmaniye where is southern of Turkey. Some photographs of Berke Arch Dam are shown in Fig. 1.

Berke Arch Dam is the highest arch dam constructed in Turkey (GDSHW 2009). It has 201 m height, 270 m crest length, and 4.6 m crest width. In addition, it was 16th highest arch dam in World when it was built. It was built in 6 years (1995-2001) using about 700000 m^3 concrete on its body. Also, total 10km tunnels and galleries were built before constructing the arch dam. It retains about 427 $E6m^3$ reservoir water, and 1700E6kWh electrical energy is gotten in a year. It is taken

Fig. 1 Some photographs of berke arch dam

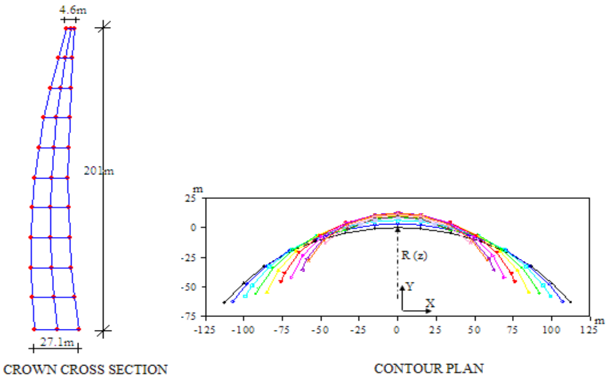

Fig. 2 Geometrical properties of berke arch dam

place in Ceyhan River in Osmaniye where is southern of Turkey. Some photographs of Berke Arch Dam are shown in Fig. 1.

Berke Dam is a thin, doubled curvature arch dam. And also, it has variable radiuses and angels. It is a symmetrical arch dam along to crown cantilever. Its crest length to height ratio is 1.34. It takes places on a Narrow-V type site. It has nine galleries on its body which are used to place measurements equipments such as strainmeters, piezometers, jointmeters, extensometers, and seismic accelerometers. Galleries are placed 20 m spaced along the cantilever. The geometrical properties of Berke Arch Dam are given in Fig. 2.

4. Ambient vibration tests

The responses of Berke Arch Dam were measured using B&K 8340 type uni-axial accelerometers which have 10 V/g sensitivity. The signals were acquired in the B&K 3560 type data acquisition system and then transferred into the PULSE Lapshop software (PULSE 2006). For parameter estimation from the ambient vibration tests, the Operational Modal Analysis (OMA 2006) software was used. Dynamic characteristics of Berke Arch Dam were determined using EFDD technique.

Berke Arch Dam is a huge engineering structure. So it is so difficult to excite it using labor

Fig. 3 Some photographs from the ambient vibration tests

force or manpower. In ambient vibration tests, the structures are excited by operation conditions such as wind, earthquake, or other effects. The sensitivity accelerometers can collect data from the structures in natural conditions. In this study, the ambient vibration tests were performed in natural conditions such as wind and water pressure effects. Also, the test time of the measurements were hold longly to take strong signals. Since input force was not measured, the using of Operational Modal Analysis to identify modal parameters was indispensable. Because of the fact that Berke Arch Dam has a huge body and long crest length, its modal responses must not measured from an ambient vibration test. So to obtain the behaviour of dam realistically, six ambient vibration tests were carried out during the period between on May 24th and May 28th, 2009. The three tests were performed in the second gallery under the crest (50 m below from the crest), and the other three tests were performed on the crest. Due to the limited availability of accelerometers and data acquisition equipment, only 13 accelerometers locations for each test setup could be monitored simultaneously. For each setup, accelerometers were placed on the normal direction of the water interacted with the dam along to crest. The primitive finite element analysis was performed to learn about the dynamic response of the dam. In the tests, frequency span was selected between 0-12.5 Hz according to initial finite element results, and tests were performed along ten minutes. During the tests, the water level was below about 10 m from the crest of the dam. Some photographs during the ambient vibration tests are shown in Fig. 3. Three tests of all ambient vibration tests are given in this study in detail.

In Operational Modal Analysis, one of the main important pars is to prepare a good setup. Because, if the setup is good, the results taken from the test are realistic and reliable. When preparing test setup in OMA, the behaviour of the structure should be estimated more or less. If there is any idea about the response of the structure, a simple finite element analysis are performed to take the natural frequencies and the mode shapes. In the ambient vibration test, the accelerometers must placed to anywhere to be taken motion. More specifically, the accelerometers must placed to points and the direction on the structure which have more deformation. In this study, the dam is moved along the crown cross section at crest points. The primitive finite element results are encouraged this measurement setup.

4.1 The first test

In the first test setup, the accelerometers were located from the middle of the gallery to right and left side including 135 m span. The locations of the accelerometers on the 2D view of arch dam are seen in Fig. 4.

Singular Values of Spectral Density Matrices (SVSDM) and Average of Auto Spectral Densities (AASD) of data set for the first test attained from vibration signals using EFDD technique are shown in Fig. 5. Mode shapes obtained from the first test are shown in Fig. 6. Since the accelerometers were placed on normal direction of the water interacted with the dam, only symmetrical and anti-symmetrical modes are obtained, vertical modes are not obtained. In addition, real parts of the modes shapes are obtained from accelerometers locations, the imaginary parts of the mode shapes are plotted as continuation of the real part. It means that, if accelerometers are placed from beginning of the gallery to end, mode shapes will be obtained completely mentioned in the third test.

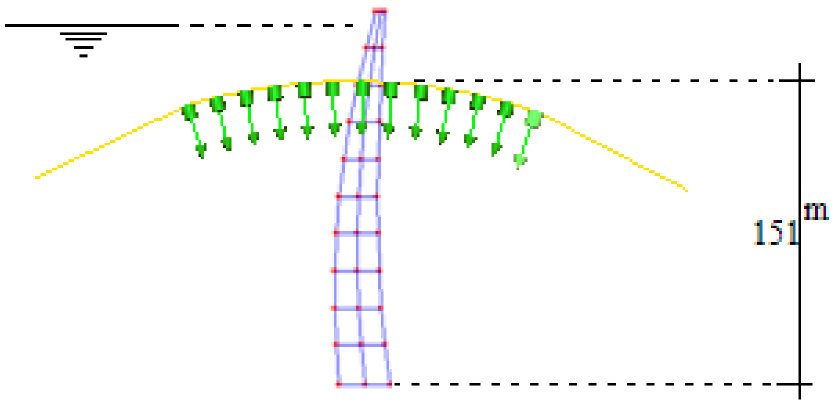

Fig. 4 The locations of the accelerometers in the first test setup

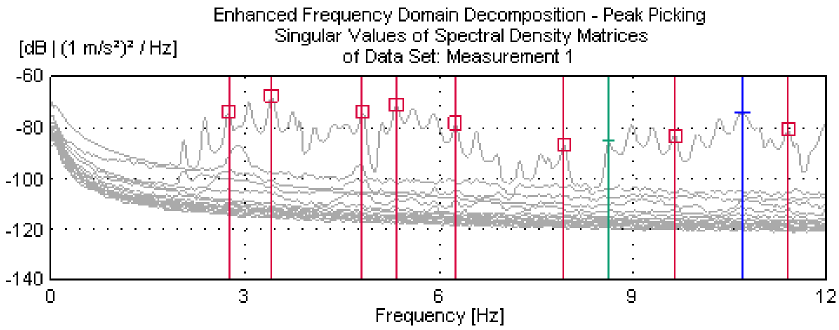

Fig. 5 SVSDM and AASD of data set for the first test

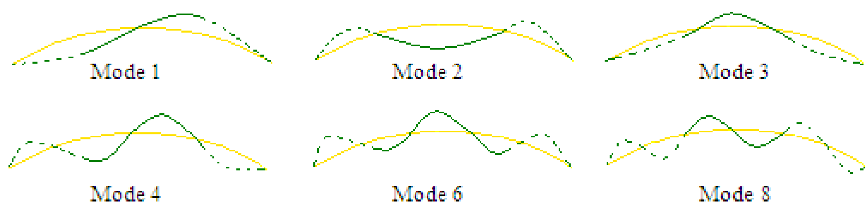

Fig. 6 Mode shapes obtained from the first test

4.2 The second test

In the second test setup, the accelerometers were located from the middle of the crest to right abutment of the dam. The locations of the accelerometers on the 2D view of arch dam are seen in Fig. 7.

Singular Values of Spectral Density Matrices (SVSDM) and Average of Auto Spectral Densities (AASD) of data set for the second test attained from vibration signals using EFDD technique are shown in Fig. 8. Mode shapes obtained from the second test are shown in Fig. 9. Since the accelerometers were placed on normal direction of the water interacted with the dam, only symmetrical and anti-symmetrical modes are obtained, vertical modes are not obtained.

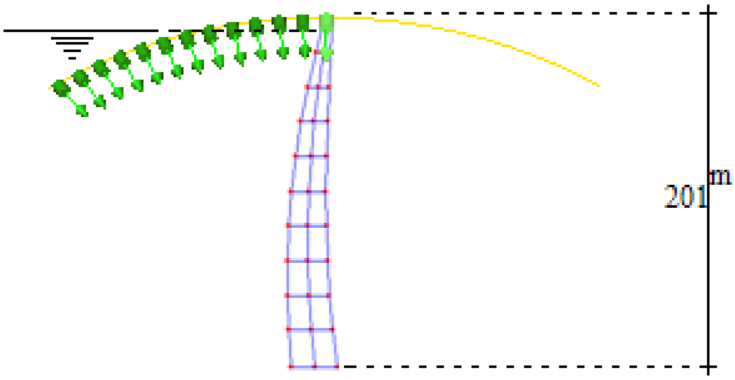

Fig 7 The locations of the accelerometers in the second test setup

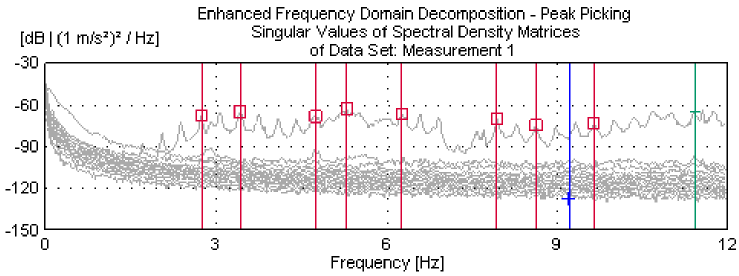

Fig 8 SVSDM and AASD of data set for the second test

Fig 9 Mode shapes obtained from the second test

4.3 The third test

In the third test setup, the accelerometers were located from beginning of the crest to end along the 270 m. The locations of the accelerometers on the 2D view of arch dam are seen in Fig. 10. Since the intended space of measurement is long, tests were performed in two steps. In the first step, 12 accelerometers placed at left abutment of the dam; and in the second step, 12 accelerometers placed at right abutment of the dam. Ten minutes records were taken for each step. The signals obtained from first and second step incorporated using a reference uni-axial accelerometer.

Singular Values of Spectral Density Matrices (SVSDM) and Average of Auto Spectral Densities (AASD) of data set for the third test attained from vibration signals using EFDD technique are shown in Fig. 11. Mode shapes obtained from the third test are shown in Fig. 12. Since the accelerometers were placed on normal direction of the water interacted with the dam, only symmetrical and anti-symmetrical modes are obtained, vertical modes are not obtained.

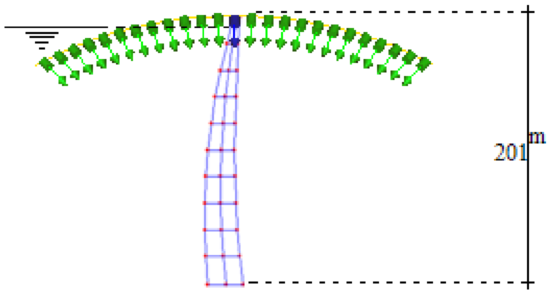

Fig. 10 Mode shapes obtained from the second test

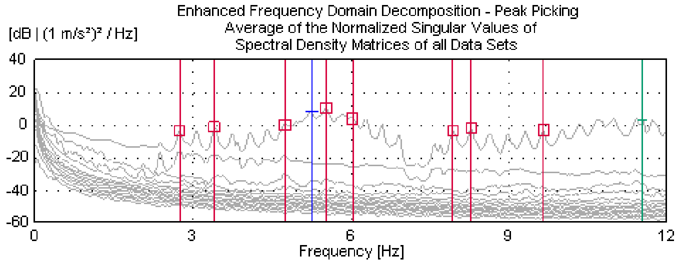

Fig. 11 SVSDM and AASD of data set for the third test

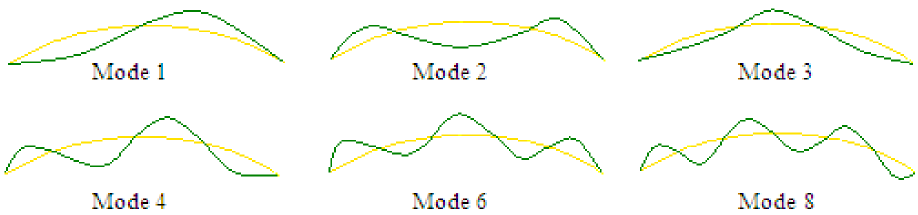

Fig. 12 Mode shapes obtained from the third test

4.4 Comparison of dynamic characteristics

Natural frequencies of Berke Arch Dam obtained from each test are compared in Table 1. As it can be seen from Table 1, the first eight natural frequencies are near to each other. In addition, the theoretical fundamental frequency of arch dams for full reservoir is presented in Eq. (2) by Priscu *et al.* (1985)

$$f = \frac{1}{0.1 + 0.2\left(\frac{H}{100}\right)} \tag{2}$$

where, f is the natural fundamental frequency, and H (in metres) is dam height.

According to Eq. (2), the theoretical fundamental frequency of Berke Arch Dam with full reservoir is 1.99 Hz. The natural fundamental frequency of Berke Arch Dam from ambient vibration tests is 2.75 Hz. The theoretical fundamental frequency is different from the experimental frequency. But the empirical formulation is only based on the height of the dam. However, the theoretical results also give an idea about the behaviour of the dam.

Damping ratios obtained from each test are compared in Table 2. Damping ratios have not a good harmony with each other. Average damping ratio is obtained as 0.6%.

Table 1 Natural frequencies of berke arch dam

Frequencies (Hz)	Test 1	Test 2	Test 3
1	2.75	2.74	2.75
2	3.41	3.42	3.41
3	4.81	4.75	4.75
4	5.34	5.30	5.53
5	6.25	6.27	6.03
6	7.94	7.94	7.94
7	8.63	8.63	8.28
8	9.64	9.64	9.66

Table 2 Damping ratios of berke arch dam

Damping Ratios	Test 1	Test 2	Test 3
1	1.23	0.67	1.03
2	0.42	0.40	0.54
3	0.67	0.93	0.75
4	0.61	0.30	0.63-
5	0.53	0.22	0.76
6	0.48	0.43	0.44
7	0.30	0.68	0.15
8	0.75	0.87	0.62

5. Conclusions

In this paper, the dynamic characteristics of Berke Arch Dam located in southern of Turkey were determined by conducting several ambient vibration tests under natural excitations such as wind and water effects. Comparing the result of the study, the following observations can be made:

The first 8-10 modes are obtained between 0-12 Hz from primitive finite element analysis, which is used to learn about the dynamic response of the dam more or less.

A total of eight natural frequencies are attained by experimentally for Test 1, Test 2 and Test 3 setups, which ranges between 0-12 Hz.

The theoretical fundamental frequency of Berke Arch Dam is different from the experimental.

The modes can be classified into symmetrical and anti-symmetrical. Since the accelerometers are not located into vertical direction, vertical modes are not attained from the tests.

Natural frequencies and mode shapes obtained from each test are almost close to each other.

Average damping ratio of the dam is obtained as 0.6%.

Ambient vibration test is used in the study. But, both of ambient and forced vibration tests should be used frequently to identify the structural behaviour of engineering structures such as large arch dams.

Acknowledgements

This research was supported by the TUBITAK and Karadeniz Technical University under Research Grant No. 106M038, 2006.112.001.1, respectively. The authors thank to Bülent SELEK, and İsmail KAYA who are the engineers in the 6th General Directorate of State Hydraulic Works, and Nevzat ERDEM, M. Sadi ANKIN and Electricity Generation Corporation Company workers for their helps.

References

Alves, S.W. and Hall, J.F. (2006), "Generation of spatially nonuniform ground motion for nonlinear analysis of a concrete arch dam", *Earthq. Eng. Struct. D.*, **35**, 1339-1357.

Bendat, J.S. and Piersol, A.G. (2004), *Random Data, Analysis and Measurement Procedure*s, John Wiley and Sons, USA.

Brincker, R., Zhang, L. and Andersen, P. (2000), "Modal identification from ambient responses using frequency domain decomposition", *18th International Modal Analysis Conference*, San Antonio, USA, **4062**(2), 625-630.

Cantieni, R. (2001), "Assessing a dam's structural properties using forced vibration testing", *Proceedings of IABSE: International Conference on Safety, Risk and Reliability-Trends in Engineering*, Malta, 1001-1006.

Darbre, G.R. and Proulx, J. (2002), "Continuous ambient-vibration monitoring of the arch dam of Mauvoisin", *Earthq. Eng. Struct. D.*, **31**(2), 475-480.

Ewins, D.J. (1995), "Modal Testing: Theory and Practice", Wiley, New York, USA.

GDSHW (2009), General Directorate of State Hydraulic Works, Ankara, Turkey.

Jacobsen, N.J., Andersen, P. and Brincker, R. (2006), "Using enhanced frequency domain decomposition as a robust technique to harmonic excitation in Operational Modal Analysis", *Proceedings of ISMA2006: International Conference on Noise & Vibration Engineering*, Leuven, Belgium.

Li, Z., Li, A. and Zhang, J. (2010), “Effect of boundary conditions on modal parameters of the Run Yang Suspension Bridge”, *Smart Struct. Syst.*, **6**(8), 905-920.
Ku, C.J., Tamura, Y., Yoshida, A., Miyake, K. and Chou, L.S. (2013) “Output-only modal parameter identification for force-embedded acceleration data in the presence of harmonic and white noise excitations”, *Wind Struct.*, **16**(2), 157-178.
Maia, N. and Silva, J. (1997), *Theoretical and Experimental Modal Analysis*, Research Studies Press, Taunton.
OMA, (2006), “Operational Modal Analysis, Release 4.0”, Structural Vibration Solution A/S, Denmark.
Park, J.H, Kim, J.T. and Yi, J.H. (2011), “Output-only modal identification approach for time-unsynchronized signals from decentralized wireless sensor network for linear structural systems”, *Smart Struct. Syst.*, **7**(1), 59-82.
Priscu, R., Popovici, A., Stematiu, D. and Stere, C. (1985), *Earthquake Engineering for Large Dams*, John and Wiley Sons, Romania.
Proulx, J., Paultre, P., Rheault, J. and Robert, Y. (2001), “An experimental investigation of water level effects on the dynamic behavior of a large arch dam”, *Earthq. Eng. Sturct. M.*, **30**, 1147-1166.
PULSE, (2006), “Labshop, Version 11.2.2”, Brüel & Kjaer Sound and Vibration Measurement A/S.
Ren, W.X., Zhao, T. and Harik, I.E. (2004), “Experimental and analytical modal analysis of steel arch bridge”, *J. Struct. Eng. ASCE*, **130**, 1022-1031.
Sevim B., Altunisik, A.C. and Bayraktar, A. (2012) “Experimental evaluation of crack effects on the dynamic characteristics of a prototype arch dam using ambient vibration tests”, *Comput. Concr.*, **10**(3), 277-294.
Shariatmadar, H. and Mirhaj, A. (2011), “Dam-reservoir-foundation interaction effects on the modal characteristic of concrete gravity dams”, *Struct. Eng. Mech.*, **38**(1), 65-79.
Zhang, J., Yan, R.Q. and Yang, C.Q. (2013), “Structural modal identification through ensemble empirical modal decompositionz”, *Smart Struct. Syst.*, **11**(1), 123-134.
Zhou, J., Lin, G., Zhu, T., Jeffersonm, A.D. and Williams, F.W. (2000), “Experimental investigations into seismic failure of high arch dams”,*J. Struct. Eng*., **126**(8), 926-935.