Ambient modal testing of a double-arch dam: the experimental campaign and model updating

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Abstract. A finite element model updating of a double-curvature-arch dam (La Tajera, Spain) is carried out hereof using the modal parameters obtained from an operational modal analysis. That is, the system modal dampings, natural frequencies and mode shapes have been identified using output-only identification techniques under environmental loads (wind, vehicles). A finite element model of the dam-reservoir-foundation system was initially created. Then, a testing campaneg was then carried out from the most significant test points using high-sensitivity accelerometers wirelessly synchronized. Afterwards, the model updating of the initial model was done using a Monte Carlo based approach in order to match it to the recorded dynamic behaviour. The updated model may be used within a structural health monitoring system for damage detection or, for instance, for the analysis of the seismic response of the arch dam-reservoir-foundation coupled system.

1. Introduction

The safety of concrete dams is nowadays a subject of increasing importance due to the new safety regulations and economy requirements since failure of dams may cause loss of human lives and properties downstream of the structure. The dynamic testing of dams is a very interesting non-destructive test to add to common existing monitoring systems, such as piezometric measures, pendulums, differential settlement gauges, etc. It provides valuable information about dam global structural behaviour, as well as a tool to track possible structural damage. This can be achieved updating a numerical model used within a Structural Health Monitoring system (SHM). The mechanical behaviour of the dam is highly influenced by the surrounding foundation [1–3], and the dynamic analysis of slender double-arch dams allows to obtain information of the whole structural system formed by the arch plus the foundation.

This paper describes the modal testing and the model updating of the Tajera dam. This is a double-arch concrete dam located in river basin of Tajuña River (Guadalajara, Spain). The dam is 62 m high, 220 m wide at the crest with a reservoir capacity of 64 Hm$^3$. This structure
is being intensively monitored because a crack appeared during the construction process in 1993 that required important interventions at that date.

Acceleration measurements were carried out using high-sensitivity accelerometers wirelessly synchronized which enable to undergo the Operational Modal Analysis (OMA) of the structure. In order to quantify uncertainties due to the estimation process, two OMA methods based on the Stochastic Subspace Identification (SSI) technique have been used to extract the modal parameters. The structural system formed by the dam body and the foundation has been modelled using the ANSYS® Finite Element Method (FEM) suite of software. The model updating is carried out using the experimental results.

Model updating methods are divided into direct and indirect methods. On the one hand, direct methods provide a computationally efficient approach that updates the components FEM matrix in one step [4, 5]. This methodology requires a very accurate FEM model and high quality measurements. However, the use of direct methods often make optimization of parameters unrealistic, losing thus their physical meaning [4]. On the other hand, indirect methods computes objective functions that are minimized in order to reduce the error between analytical and experimental results. The latter has been the option adopted in this work. The objective function is minimized on the material properties updating the dynamic FEM model behaviour to the measured one.

The paper continues with the description of the structure, the undergone experimental campaigns as well as the OMA results. Section 3 depicts the FEM model of the structure followed by the model calibration process carried out from the measured modal parameters. Finally, some conclusions are drawn and suggestions for future work are given.

2. Structure description and its experimental modal testing

2.1. Tajera dam. Description

The Tajera Dam is located on the Tajuña river, in the municipality of El Sotillo in the province of Guadalajara, Spain. The main function of this structure is the regulation of the river to provide the demands associated to the downstream basin. The typology of the dam is double curvature arch with 62 m high above foundation, a crest of 220 m long and a volume of 68 Hm³ reservoir. The concrete wall of the dam consists of 13 blocks, including 11 of 16.5 m long and one more at each abutment of 20 m long. The crest has a single-track road and both-side pedestrian sidewalks (see Figure 1).

In 1993, during the construction process, a crack was detected [6]. To repair the damage, the internal bottom gallery was filled with concrete and, since then, the structure has been carefully monitored. Therefore, the information available, added to the slenderness of the structure that makes it suitable for OMA, has influenced on its selection for this investigation.

2.2. Ambient modal analysis

The OMA has been carried out using 10 V/g sensitivity accelerometers (PCB 393B31 and 393B12) distributed along the crest in radial direction. The accelerometers are synchronized wirelessly using a ZigBee protocol allowing up to 100 nanoseconds of precision [7]. The synchronization process effect on the modal estimation is further studied in ref. [8].

An experimental campaign was carried out on 9 July 2015 without presence of precipitation and with 49.74% of water volume capacity (950.369 m.s.n.m. and 29.625 Hm³). The maximum, minimum and average temperatures recorded on the day were 18.5, 11.6 and 14.4 °C, respectively.
At the measurement time, the temperature was 18.1 °C. After several trial tests, it was decided to place only accelerometers along the crest of the dam. During this campaign two measurements of 30-min. recording were carried out. Figure 2 shows the 20 test points used for both tests. All these points were distributed along the crest of the dam, at locations where the highest modal displacements occur. In addition, the lack of intermediate galleries makes the placing of sensors at different heights a complex task so that this possibility was dismissed.

For the first test, it was decided to record the data with the bottom outlet open initially and after 15-min. recording was cut-off. It was observed that under the bottom outlet working, high-frequency noise was added to the measures. Figure 3 shows channel 5 time history in which the closing of the bottom outlet is clearly appreciated. Additionally, it was observed that accelerometers located near the abutments showed less-noisy signals than those located closed to the center. This fault might be due to: a) the operation of the bottom outlet introduces high-frequency noise, and b) the higher wind at the center of the dam, as compared to the area near the abutments.
The sampling frequency of the acquisition system is 1302.083 Hz. The raw data are filtered using a Butterworth low-pass filter of order 5 with a cut-off frequency at 17.5 Hz. Besides, the raw data are decimated with a decimation factor of 36 providing a final sampling frequency of 36.17 Hz; therefore, the Nyquist frequency becomes 18.08 Hz. Figure 4 shows the spectrogram of channel 1 using the short Fast Fourier Transform. Interestingly, the natural frequencies are observed during the whole test for this near-to-abutment point.

Two different OMA techniques based on the SSI [9] and programmed in MATLAB® are used for test. The techniques used are: covariance-driven SSI (SSI-cov) and data-driven SSI (SSI-data). The same criteria to define a pole of the stabilization diagram as stable are used for the two identification techniques. These criteria have to fulfill three requirements against estimates of the previous state-space order: (i) the frequency must match within 1% (relative), (ii) the damping ratio must match within 5% (absolute), and (iii) the mode shapes must match within 95%, using the Modal Assurance Criteria (MAC) for comparing. Additionally, modes with identified damping ratios higher than 5% are also rejected.
Figure 5. Selected poles with two different methods. (--) SSI-cov and (○) SSI-data.

Figure 6. First two modal shape estimates along the dam crest for the second test using SSI-data technique. (- - -) represents the undeformed dam crest and (○) indicates the modal displacement at the test points.

The SSI-cov, programmed in MATLAB®, has the advantage of its conceptual simplicity and the ability to compute the Probability Density Function of the identified system parameters. It selects the average values of the modal parameters for each column (of stable aligned poles) with a minimum number of stable poles [10]. The SSI-data has been applied using MACEC (Commercial Toolbox of MATLAB® for modal analysis [11]), and it has the advantage of an optimal statistical performance when the weighting matrices are properly chosen. A statistical analysis of the stable poles is used to select final results [12]. Figure 5 illustrates the final selected poles for the two techniques and the averaged normalized power spectral density both the second test. From the above mentioned characteristics, the recommendations given in [13] and the author’s experience, the use of several methods simultaneously is a good way to improve the results as well as to quantify the estimation uncertainties. Finally, Table 1 shows the estimated natural frequencies for both test and for both techniques. Frequencies with the same color belong to the same vibration mode. Figure 6 shows an example of identified modal shapes corresponding to the lowest two modes obtained with SSI-data in the second test.
Table 1. Frequencies of the selected modes ($f_{OMA}$).

3. Finite Element Model Updating

3.1. Finite Element Model description

This work makes use of a previous model statically calibrated with different measurements related to the static behaviour of the dam. This first calibration makes that the starting model is already a fairly well adjusted model. The model is a 3D FEM model with 2247 8-nodes solid elements, 3608 nodes and 5 different types of materials: one for the concrete vault of the dam and 4 for the foundations, which further enhances the model. Figure 7 and Table 2 shows the location and the material properties used in the FEM model. The boundary conditions in the foundation were considered at a distance where the tension influence added from these restrictions on the vault can be neglected.

The numerical modal analysis allows a number of vibration modes limited by the number of degrees of freedom available. However, only a reduced set of the first modes is usually considered. In this case, the first ten modes have been extracted and consistent mass matrix has been used, given the natural frequencies shown in the Table 3. The Block Lanczos method has been used to solve the eigenvalue problem. Figure 8 shows the first vibration mode, from top and isometric view, and Figure 9 shows the top view of the first four vibration modes. Finally, Table 4 shows both, experimental and numerical estimations of natural frequencies, together with initial relative errors, for the first four estimations. The sum of the errors is also included for comparison. The experimental estimation obtained from the second test with SSI-data has been adopted as the experimental solution, $f_{OMA}$, since the higher number of estimations similar to the numerical ones were obtained (see Tables 1 and 3).

| Material number | Element   | $E$ (N/m$^2$) | $\rho$ (kg/m$^2$) | $\nu$ |
|-----------------|-----------|---------------|-------------------|-------|
| 1               | Foundation 1 | $1.37 \cdot 10^{10}$ | $2.40 \cdot 10^3$ | 0.22  |
| 2               | Foundation 2 | $6.86 \cdot 10^{10}$ | $2.40 \cdot 10^3$ | 0.25  |
| 3               | Foundation 3 | $9.81 \cdot 10^{10}$ | $2.40 \cdot 10^3$ | 0.23  |
| 4               | Foundation 4 | $4.90 \cdot 10^{10}$ | $2.40 \cdot 10^3$ | 0.35  |
| 5               | Dam       | $3.43 \cdot 10^{10}$ | $2.40 \cdot 10^3$ | 0.22  |

Table 2. Summary of FEM materials. $E$: Young’s Modulus, $\rho$: density and $\nu$: Poisson’s ratio.
**Figure 7.** FEM of the dam. Numbers indicate the material types.

| Mode | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    |
|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| $f_{FEM}$ (Hz) | 4.9220 | 6.1435 | 7.2747 | 8.2567 | 10.511 | 11.285 | 11.639 | 12.209 | 12.760 | 13.244 |

**Table 3.** Frequencies of the FEM.

**Figure 8.** Modal shape of the first vibration mode at $f = 4.9220$ Hz of the Tajera Dam.
Table 4. Summary of frequencies before updating with \( \varepsilon = \frac{|f_{\text{OMA}} - f_{\text{FEM}}|}{f_{\text{OMA}}} \)



| Mode | \( f_{\text{OMA}} \) (Hz) | \( f_{\text{FEM}} \) (Hz) | \( \varepsilon \) (%) |
|------|-----------------|-----------------|-------------|
| 1    | 5.3114          | 4.9220          | 7.33        |
| 2    | 6.2727          | 6.1435          | 2.06        |
| 3    | 7.6435          | 7.2748          | 4.82        |
| 4    | 9.3148          | 8.2567          | 11.36       |

25.57

3.2. Model updating

As a first approach to the model updating, the following objective function has been adopted:

\[
J = \sum_{i=1}^{N} \mu_i \left| \frac{f_{i,\text{OMA}} - f_{i,\text{FEM}}}{f_{i,\text{OMA}}} \right|. \tag{1}
\]

The first four modes are considering, \( N = 4 \), and using Table 4, the initial value of \( J = 6.2229 \% \) is obtained. Parameters \( \mu_i \) weight the importance of each mode. Thus, the following weights have been adopted \( \mu_1 = 0.2039, \mu_2 = 0.1635, \mu_3 = 0.1376 \) and \( \mu_4 = 0.1262 \).
The weight associated to each mode is numerically selected with ANSYS®, according to the modal mass mobilized for each frequency (modal participation factor).

So, the FEM model was calibrated based on the experimental results using the Monte Carlo method [14], which is based on distributing randomly independent variables into prescribed ranges [15]. The material properties $E_j$ and $\rho_j$ shown in Table 2 have been considered as independent variables. The updating process is illustrated in Figure 10 in which the flowchart indicates that two packages of software have been used. That is, 10000 combinations of independent variables are generated in MATLAB® and the modal analysis is carried out in ANSYS®. Finally, the updated material properties are derived from the minimization of functional (1):

$$\min_{E_j, \rho_j} J(E_j, \rho_j, \nu_i) \quad \text{with} \quad j = 1, \cdots, 5,$$

in which the ten considered independent variables are within a ±50 % range of the initial values. Table 5 shows the summary of frequencies and errors after updating de FEM model of the Tajera Dam (as compared to Table 4). After this process, the value of the objective function becomes $J = 2.8479\%$. The relative error reduces more than 50% with respect to the initial model. Table 6 shows a comparison between material properties values (before and after updating and the difference). The parameters have been changed up to ±35%. As it was expected, due to the weighting adopted in functional (1), the smallest error is obtained for the first mode. Figure 11 shows the frequency estimations for all the tests. Note that there is overlapping between estimations. The final numerical solution adopted are enclosed in a red cycle. Figure 12 depicts the influence of vault material properties on the first natural frequency estimation.

4. Conclusions and ongoing works

The FEM model updating of a double-arch dam has been presented in this work. A quite simple model, using solid elastic elements, has been shown to represent quite well the dynamic...
Table 5. Summary of frequencies after updating.

| Mode | $f_{OMA}$ (Hz) | $f_{FEM}$ (Hz) | $\epsilon$ (%) |
|------|----------------|----------------|----------------|
| 1    | 5.3114         | 5.2973         | 0.27           |
| 2    | 6.2727         | 6.6052         | 5.30           |
| 3    | 7.6435         | 7.8061         | 2.13           |
| 4    | 9.3148         | 8.8842         | 4.62           |

Table 6. Comparison between material properties values (before and after updating and difference).

| Element  | Parameter | Initial value | Updating value | Difference (%) |
|----------|-----------|---------------|----------------|----------------|
| Foundation 1 | $E$ (N/m$^2$) | $1.37 \times 10^{10}$ | $1.67 \times 10^{10}$ | 21.78          |
|          | $\rho$ (kg/m$^3$) | $2.40 \times 10^3$ | $2.95 \times 10^3$ | 22.64          |
| Foundation 2 | $E$ (N/m$^2$) | $6.86 \times 10^{10}$ | $5.43 \times 10^{10}$ | $-34.08$      |
|          | $\rho$ (kg/m$^3$) | $2.40 \times 10^3$ | $2.15 \times 10^3$ | $-10.47$      |
| Foundation 3 | $E$ (N/m$^2$) | $9.81 \times 10^{10}$ | $1.30 \times 10^{11}$ | 33.02          |
|          | $\rho$ (kg/m$^3$) | $2.40 \times 10^3$ | $2.29 \times 10^3$ | $-4.74$       |
| Foundation 4 | $E$ (N/m$^2$) | $4.90 \times 10^{10}$ | $5.47 \times 10^{10}$ | 11.62          |
|          | $\rho$ (kg/m$^3$) | $2.40 \times 10^3$ | $2.10 \times 10^3$ | $-12.57$      |
| Dam      | $E$ (N/m$^2$) | $3.43 \times 10^{10}$ | $4.01 \times 10^{10}$ | 16.97          |
|          | $\rho$ (kg/m$^3$) | $2.40 \times 10^3$ | $2.41 \times 10^3$ | 0.42           |

Figure 11. Frequency estimations for the first four mode and for all the simulations. The red cycle indicates the solution adopted.
Figure 12. Vault material properties against the first frequency estimation. The red cycle indicates the adopted solutions.

behaviour of this structure. This model has been calibrated from the OMA using a fairly simple optimization approach based on Monte Carlo method. It has been demonstrated that our wireless synchronized acquisition system can be used from this kind of structure.

A second campaign was also carried with different ambient conditions and water volume stored. This campaign was on 26/09/2015, without presence of precipitation and with a volume stored of 35.15% (946.729 m.s.n.m. and 20.935 Hm$^3$). The maximum, minimum and average temperatures recorded were 10.5, 6.7 and 7.8 °C, respectively. The results obtained using the same signal processing and OMA parameters are shown in Table 7. It can be observed that under less water stored and smaller temperature, the natural frequencies are reduced appreciably. Therefore, further measurements must be made to study the impact of environmental agents on the modal parameters.

Future work will explore other techniques to update the FEM model. Besides, a continuous monitoring together with automated modal identification is being planned to be installed in order to analyse dependencies between modal properties and water volume stored and environmental agents. The author’s experience on a footbridge [16] will be employed for this task.

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| Mode | 3\textsuperscript{rd} test |
|------|-------------------|
|      | SSI-cov (Hz) | SSI-data (Hz) |
| 1    | 5.1598        | 5.1647        |
| 2    | 5.9002        | 7.1592        |
| 3    | 7.1551        | 8.7833        |
| 4    | 8.8124        | 8.8743        |
| 5    | 8.9573        | 14.4433       |
| 6    | 11.1068       | 15.1067       |
| 7    | 12.5673       |               |
| 8    | 13.2872       |               |
| 9    | 14.4391       |               |
| 10   | 15.1293       |               |
| 11   | 15.7180       |               |
| 12   | 16.1362       |               |

Table 7. Frequencies of the selected modes.

References

[1] Paulo Mendes and Sérgio Oliveira. Influence of the Intake Tower Dynamic Behaviour on Modal Identification of Cabril Dam. In *IOMAC - 3rd International Operational Modal Analysis Conference*, Lisboa, 2009.

[2] S Oliveira and M Espada. Long-term dynamic monitoring of arch dams. The case of Cabril dam, Portugal. In *15th World Conference On Earthquake Engineering*, Lisbon, 2012.

[3] Sérgio Oliveira, Anca Maria Toader, and Paulo Vieira. Damage identification in a concrete dam by fitting measured modal parameters. *Nonlinear Analysis: Real World Applications*, 13(6):2888–2899, 2012.

[4] Y. B. Yang and Y. J. Chen. A new direct method for updating structural models based on measured modal data. *Engineering Structures*, 31(1):32–42, 2009.

[5] A. Berman and E. J. Nagy. Improvement of a Large Analytical Model Using Test Data. *AIAA Journal*, 21(8):1168–1173, 1983.

[6] Nuevas tecnologías en la reparación de presas. la tajera. v0. Technical report, Hidráulica, Construcción y Conservación (HCC), 2002.

[7] Álvaro Araujo, Jaime García-Palacios, Javier Blesa, Francisco Tirado, Elena Romero, Avelino Samartín, and Octavio Nieto-Taladriz. Wireless measurement system for structural health monitoring with high time-synchronization accuracy. *IEEE Transactions on Instrumentation and Measurement*, 61(3):801–810, 2012.

[8] Jaime García-Palacios, Francisco Tirado-Andrés, José M. Soria, Iván M. Díaz, and Álvaro Araujo. Effects of time synchronization on operational modal analysis. In *6th International Operational Modal Analysis Conference, IOMAC’15*, May 2015.

[9] P. Van Overschee and B. De Moor. *Subspace Identification for Linear Systems*. Boston: Kluwer Academic, 1996.

[10] Bart Peeters and Guido De Roeck. Reference-Based Stochastic Subspace Identification for Output-Only Modal Analysis. *Mechanical Systems and Signal Processing*, 13(6):855–878, November 1999.

[11] E. Reyners, M. Schevenels, and G. De Roeck. MACEC: a Matlab Toolbox for Experimental and Operational Modal Analysis. Technical report, University of Leuven (KUL), Belgium, 2008.

[12] Edwin Reyners, Jeroen Houbrechts, and Guido De Roeck. Fully automated (operational) modal analysis. *Mechanical Systems and Signal Processing*, 29:228–250, May 2012.

[13] Helmut Wenzel and Dieter Pichler. *Ambient vibration monitoring*. John Wiley & Sons, 2005.

[14] George Fishman. *Monte Carlo: concepts, algorithms, and applications*. Springer-Verlag, New York, 1996.

[15] Roger Eckhardt. Stan Ulam, John von Neumann, and the Monte Carlo Method. *Los Alamos Science*, pages 131–141, 1987.

[16] José M Soria, Iván M Díaz, Jaime H García-palacios, and Norberto Ibán. Vibration Monitoring of a Steel-Plated Stress-Ribbon Footbridge: Uncertainties in the Modal Estimation. *Journal of Bridge Engineering*, 2016.