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SEVEN YEARS OF CONTINUOUS DYNAMIC MONITORING OF BAIXO SABOR DAM

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Abstract

The Baixo Sabor dam is a 123 meters high concrete arch dam located in the north of Portugal. After the performance of a forced vibration test, a quite unique experimental programme was initiated in the dam during the first filling of the reservoir, with the installation of a continuous dynamic monitoring system in December 2015. The implementation of such a system aimed to study the evolution of the dam's dynamic behaviour during the first filling, as well as to monitor its condition in the long-term through the development of vibration-based damage detection supported by robust operational modal analysis.

After a description of the dam and the monitoring system, this paper presents an overview of the tools developed to perform the automated tracking of the dam's modal parameters. Finally, using the database collected during the last seven years, the long-term evolution of the dam dynamic parameters is analysed, and their seasonal fluctuations interpreted. The eventual occurrence of structural anomalies is evaluated after the minimization of the most influential operational and environmental effects on the dam, such as temperature and the reservoir water level.

Keywords: operational modal analysis; continuous dynamic monitoring; dam monitoring; minimization of operational conditions; structural health monitoring.

1 INTRODUCTION

From the point of view of renewable energies exploitation, hydroelectricity has an essential position in Europe. In Portugal, for instance, it covers about one third of the country's installed capacity to produce electricity and it plays an important role in energy storage, through complementarity with other energy sources. Moreover, having in mind the high number of dams with 30-70 years of age existing in the vicinity of populations and the important deterioration processes induced by the ageing of structural materials, dam safety control is of fundamental importance.

In this context, the development and implementation of efficient Structural Health Monitoring (SHM) systems is of utter priority in the long-term management of large civil infrastructures [1], both to prevent catastrophes and to guarantee an efficient and long due operation of these structures, through timely structural interventions

Though the monitoring of concrete dams is historically associated with the study of quasi-static quantities, such as horizontal displacements, the installation of robust vibration based SHM systems have become more common in the past decade [2-4]. The continuous dynamic monitoring of Baixo Sabor arch dam, in Portugal, which is being carried out by the Laboratory of Vibrations and Structural Monitoring (ViBest-FEUP) and by the National Laboratory for Civil Engineeing (LNEC) is a good example of the integration of such systems in the daily monitoring activities of large dams. Despite the complexity introduced by the disadvantageous signal-to-noise ratio, the influence of significant reservoir fluctuations and the disturbances induced by the operation of nearby power plants [5], it has been possible to successfully characterize the dynamic behaviour of this structure over a period of 7 years.

In this context, a brief description of Baixo Sabor dam and its dynamic monitoring system are presented in this work, followed by a summary of the tools that have been developed and implemented to assure of the monitoring of structures, as well as the results obtained since the first filling in late 2015. Operational modal analysis is used to identify the structure's dynamic properties over time and data normalization techniques are used to minimize the effects of operational and environmental conditions on modal properties. Finally, control charts are applied to the residuals obtained from the comparison between observed and predicted results, and used to detect shifts that may indicate the occurrence of novel structural behavior.

2 BAIXO SABOR DAM AND MONITORING SYSTEM

The Baixo Sabor hydroelectric development is located across the Sabor river, in the basin of the Douro river, in the northeast of Portugal. The dam is double curvature, 123 m high and 505 meters long and crest height. Its arch is composed by 32 concrete blocks, separated by vertical contraction joints, including six horizontal visit galleries. The reservoir originated by the dam (see left part of Figure 1) has a capacity of 1095 hm^3 at exploration level, which is defined for 234 m above sea level.

In order to continuously identify the dam's dynamic characteristics and their evolution over time, while considering the variation of operational and environmental conditions, a vibration-based monitoring system has been designed for the dam in 2015 considering both a numerical model and a forced vibration test developed and performed by LNEC [6]. The system was installed and testes in late 2015, being in continuous operation since December 2015. It consists of 20 uniaxial accelerometers that have been radially disposed in the dam's three upper visit galleries, three digitizers, a central computer for data storage and GPS antennas that assure the need synchronization between different measuring channels. The right part of Figure 1 shows the position of the accelerometers installed in the dam, marked with red dots over a picture of the structure. The dynamic monitoring system is configured to continuously record acceleration time series with a sampling rate of 50 Hz and a duration of 30 minutes at all instrumented points, therefore, producing 48 groups of time series every day.

A monitoring software developed at ViBest/FEUP called DynaMo [7] is being used to process the data collected by the monitoring system. This software is responsible for backing up the original data samples, performing pre-processing procedures on the acceleration time series (such as trend elimination, filtering and re-sampling), as well as for the characterization of vibration levels and the identification of the dam modal properties through automatic operational modal analysis.

Figure 1 – Baixo Sabor arch dam: a) aerial view (on the left); b) position of accelerometers marked with red dots (on the right).

3 MODAL TRACKING

Given that only the vibration of the structure is being recorded by the monitoring system and that no excitation is purposedly imposed on it, operational modal analysis is being used to identify the modal properties of the dam. An automated procedure is considered, which takes advantage of the combination between the SSI-Cov method, as presented in [8, 9], and the algorithm for hierarchical clustering proposed in [10], to group poles with similar modal properties.

To separate physical modes from numerical ones, the modal estimates identified in each setup are compared with reference mode shapes, which were obtained from selected datasets with very clear stabilization diagrams. Each new set of modal properties is only accepted as a physical mode if the MAC (Modal Assurance Criterion) [11] between the estimated mode shape and the reference mode shape is higher than 0.55, and if the variation between their frequency values is lower than 5%.

The modal properties of the structure are strongly affected by the operational and environmental conditions of the dam surroundings. The level of water in the reservoir, for instance, has a major impact on the dam’s natural frequencies. This can be observed on the left part of Figure 2, where the estimates obtained for first mode’s natural frequency over one year of monitoring is represented (in blue) together with the variation of the level of water in the reservoir (represented in orange) for the same period. It is clear that an inverse relation exists between these two variables, that is, when the water level rises, the natural frequency decreases, and vice-versa. Moreover, temperature variations impact the dynamic behavior of the structure as well, has can be observed in the right part of Figure 2, where the evolution of the natural frequency of the seventh mode follows an oscillatory pattern characteristic of a daily thermal wave. Though to a lesser extent, the same is verified for the sixth mode.

Therefore, the procedure for modal tracking has been improved through the consideration of these effects and multiple linear regressions are used to predict the expected frequency values at each moment, continuously updating modal references and increasing the identification rates [12].

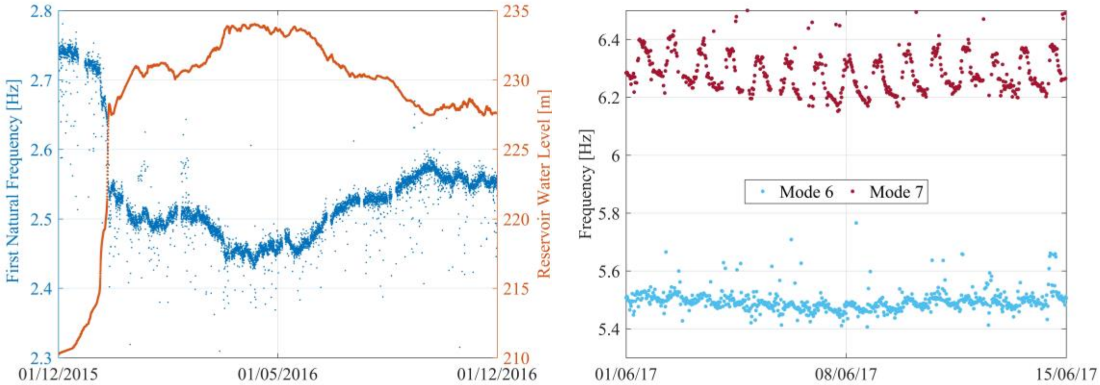

Figure 2 – Relation between natural frequency and reservoir water level (on the left); Effect of daily temperature variations on natural frequency (on the right).

The operation of the power plant is another external factor affecting the modal identification process and introducing bias in the analysis. While using operational modal analysis in general, and the SSI-Cov method, it is assumed that the excitation on the structure is a white noise. Good results can still be achieved even if the excitation noise is not completely white, but problems arise when well-defined frequencies are significantly present in the excitation. This is the case with the power production turbines operating in the power plant nearby the dam, which rotate at 214 rpm (~3.57 Hz).

The turbine rotation frequency is close to the frequency of the dam's third vibration mode, leading to several misidentifications by the automated procedure when the power plant is operating. This can be observed in the left part of Figure 3, where an unusual number of identifications around 3.57 Hz is found in the histogram of the third mode's identified frequencies. To solve this problem, a procedure using the uncertainties associated with the modal properties estimated by the SSI-Cov was proposed, considering that the turbine rotation frequency is very well-defined and, therefore, presents low uncertainty [13]. In this sense, the frequency estimates identified for the third mode that present frequency standard deviations lower than 0.005 Hz were represented in yellow in the right part of Figure 3. The vast majority of yellow points correspond to frequencies very close to 3.57 Hz, therefore associated with the turbine rotation frequency.

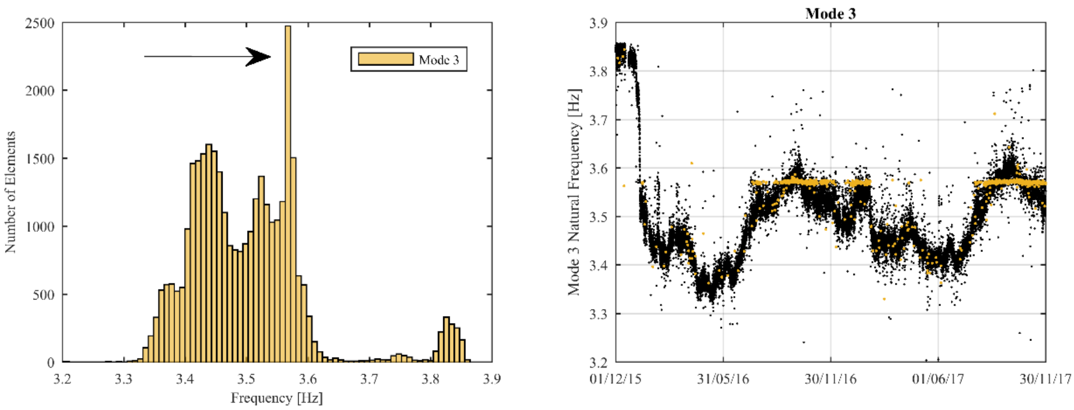

Figure 3 – Histogram of frequencies identified for the third mode (on the left); Evolution of the third mode natural frequency with estimates associated with the turbine operation highlighted in yellow (on the right).

The set of tools presented was used to identify the first 10 vibration modes of the structure for more than 7 seven years, between 01/12/2015 and 31/12/2022. In this sense, the evolution of the natural frequencies of the dam is presented in Figure 4, where each point represents 1 hour of data and each mode is represented by a different color. Visually inspecting Figure 4 it is verified that natural frequencies are significantly affected by external factors, and that higher scatter occurs for higher order modes. This is corroborated by Table 1, where mean values and standard deviations are presented for each mode's frequency. The standard deviation varies from 0.048 Hz for the first mode, to 0.228 Hz in the case of the tenth mode.

It should be noted that blank spaces correspond to periods when the monitoring system was either malfunctioning or under maintenance procedures. Excluding a period in 2020 when Portugal was under general lockdown due to the COVID-19 pandemic and access to the system was severely restricted, the system has been behaving as expected for the past seven years.

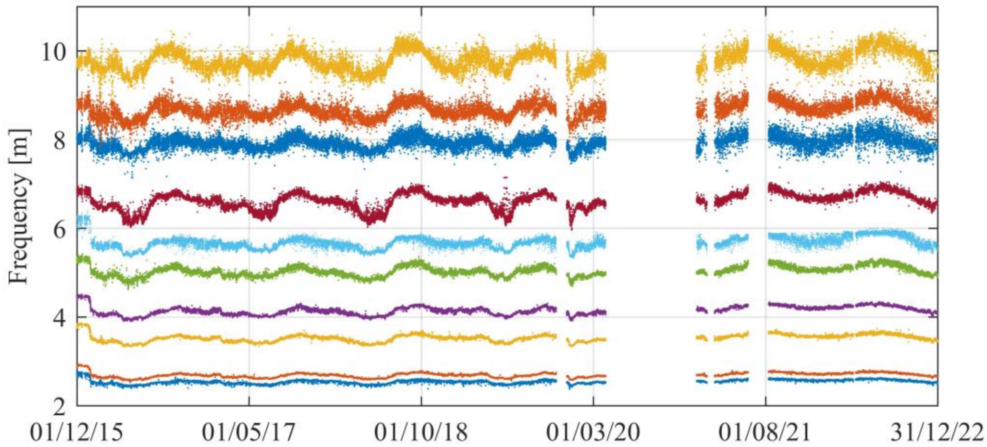

Figure 4 – Natural frequencies of the first 10 vibration modes between 01/12/2015 and 31/12/2022.

Mode	1	2	3	4	5	6	7	8	9	10
f_{mean} [Hz]	2.54	2.69	3.52	4.15	5.03	5.67	6.62	7.92	8.67	9.80
f_{std} [Hz]	0.048	0.054	0.083	0.095	0.113	0.140	0.189	0.148	0.174	0.228

Table 1: Statistical characterization of the natural frequencies estimates from 01/12/2015 to 31/12/2022

4 DATA NORMALIZATION AND NOVEL BEHAVIOUR

The occurrence of novel structural behavior in a structure, which may be due to damage, can be detected through variations in their natural frequencies. However, the effects of small damages on frequencies can be significantly lower than those resulting from the variation of environmental and operational conditions. Therefore, it is necessary to minimize data variability due to external factors, such as reservoir water level and temperature.

For this, the Minimum Mean Square Error (MMSE) estimator [14] has been used to predict the evolution of each mode's natural frequency, based on the observed frequencies of the remaining modes. The model was trained using data obtained between 01/12/2015 and 01/12/2017. Finally, the residuals that result from the difference between the observed and the predicted data, are characterized by significantly lower standard deviations and distributions close to the normal distribution.

The distributions of the natural frequencies of the first two vibration modes (in blue and orange) and those of the corresponding residuals (in black) are represented in Figure 5, as examples, showing the success of this approach in minimizing the effects of external conditions. It should be noted that the mean frequency of each mode was added to the corresponding set of residuals, for representation purposes.

The reduction in data variability achieved is ascertained in Table 2, where the standard deviations of the identified natural frequencies are compared to those of the residuals obtained after the data normalization procedure. In most cases, reductions of over 50% are achieved.

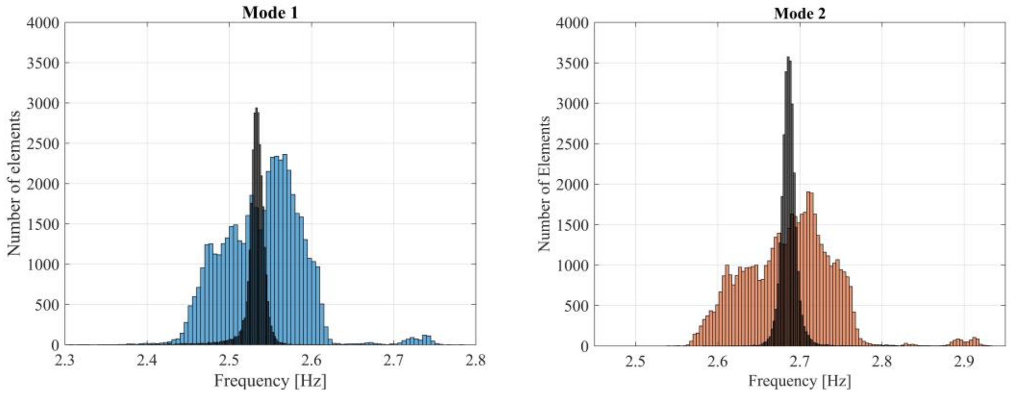

Figure 5 – Histograms of natural frequencies (in blue and orange) and residuals (in black), for the first two vibration modes.

Mode	1	2	3	4	5	6	7	8	9	10
f_{std} [Hz]	0.048	0.054	0.083	0.095	0.113	0.140	0.189	0.148	0.174	0.228
r_{std} [Hz]	0.016	0.010	0.016	0.018	0.040	0.074	0.086	0.126	0.129	0.151

Table 2: Comparison between the standard deviation of the identified natural frequencies (f_{std}) and those of the residuals (r_{std}) achieved after data normalization.

Control charts are especially adequate to detect changes in processes characterised by several variables, such as the natural frequencies of the different tracked vibration modes, being commonly used in the detection of novel structural behavior.

In this context, the residuals obtained after the application of the MMSE procedure, were used to build a control chart resorting to the statistical test T^2, which is presented in Figure 6. Data from 01/12/2015 to 30/11/2017 was used as reference period, whereas observations from 01/12/2017 to 31/12/2022 were considered for the validation period, each point corresponding to 2 days of data. The training period was also used to determine the upper control limit (UCL), which was set as the [0 ; 3σ] interval, where σ represents the standard deviation of the process.

It was verified that 3.2 % points were above the UCL during the training period, while only 2.8 % of the points were above the UCL during the validation period, indicating that the process is in control and, therefore, that the structure is not showing novel structural behavior.

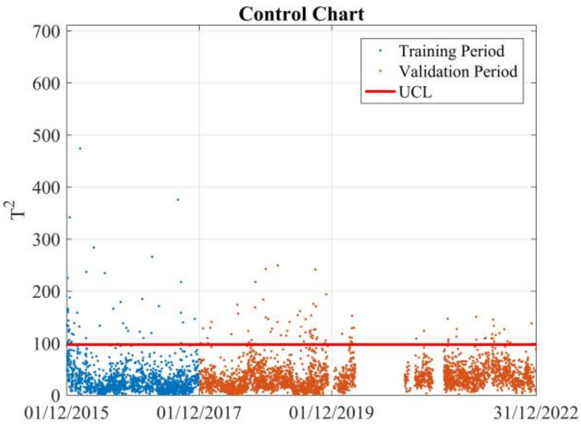

Figure 6 – Natural frequencies of the first 10 vibration modes between 01/12/2015 and 31/12/2022.

5 CONCLUSIONS

The dynamic monitoring system of Baixo Sabor arch dam has been installed in 2015 and it has been operating continuously ever since, showing efficiency and robustness. Additionally, the characterization of the dynamic behavior of the structure for a period of over 7 years, constitutes quite an unusual database that now allows the study of the long-term health of the structure based on modal properties.

To achieve an efficient automated procedure for the performance of operational modal analysis in the dam, state of the art methods were used and complemented with processing tools developed specifically for this application, that can now be generalized for similar structures. It was verified that natural frequencies present high variability, mostly due to the effects of operational and environmental conditions. The analysis of such effects revealed an inverse relation between frequencies and the level of water in the reservoir, and that the effect of daily temperature variations should not be despised.

It was possible to significantly minimize the effects of external factors on natural frequencies through data normalization techniques, considering only two years of monitoring data for the training period, which resulted in (close to) normally distributed residuals. Finally, the residuals obtained in the previous step allowed to build a control chart, using the same training period. It was verified that the process is in control, suggesting that the structure is not presenting novel behavior.

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