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Health-monitoring and system-identification of an ancient aqueduct

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Abstract. An important historical monument of Cyprus is an aqueduct that was built in 1747 to provide water to the city of Larnaca and to its port. Because of its importance to the cultural heritage of Cyprus, the aqueduct has been selected as one of the case-study monuments in the project Wide-Range Non-Intrusive devices toward Conservation of Historical Monuments in the Mediterranean Area (WIND-CHIME). Detailed drawings of the aqueduct obtained from the Department of Antiquities of Cyprus have been used for the development of a computational model. The model was fine-tuned through the measurement of the dynamic characteristics of the aqueduct using forced and ambient vibrations. It should be noted that measurement of the dynamic characteristics of the structure were performed twice in a period of three years (June of 2004 and May of 2007). Significant differences were noted and they are attributed to soil structure interaction effects due to seasonal variations of the water-level in a nearby salt-lake. The system identification results for both cases are presented here. This monument was used to test the effectiveness of shape memory alloy (SMA) pre-stressed devices, which were developed during the course of the project, in protecting it without spoiling its monumental value.

Keywords: health monitoring; shape-memory-alloy; monuments; masonry structure seismic-protection; system-identification; model updating.

1. Introduction

The civilizations that flourished in the Mediterranean region throughout the centuries have left behind many monuments as evidence of their technological know-how and expertise. All countries that have the privilege to own such structures are interested in preserving and protecting them from natural disasters such as earthquakes.

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The conservation of ancient monuments presents many difficulties. Any intervention in their structural system should be such that it neither violates their form nor changes drastically their structural behavior and most importantly should be reversible. In addition, the materials to be used must be compatible with the ones the monument is constructed of. Traditional seismic retrofitting techniques have the disadvantage that most of them violate the above conditions. An alternative to the above is the use of innovative seismic-protection techniques, such as shape memory alloy (SMA) based devices. Such devices can be made very inconspicuous and therefore not violating the form of the monuments and at the same time can be very effective in dissipating the energy generated by earthquakes and hence protect the monuments.

Several efforts have been made towards the study of the behaviour of SMAs (Castellano 2000, Faravelli 2003, Casciati and Faravelli 2004, Evard, *et al*. 2006 Faravelli and Casciati 2002, McKelvey and Ritchie 2000, Renda, *et al*. 2000 and Torra 2001). The application of SMA and other innovative devices in protecting monuments are reported by Biritognolo, *et al*. (2000), Croci (2000), and Chrysostomou, *et al*. (2003), (2004) and (2005).

Such techniques have been evaluated within the INCO-MED project, "Wide-Range Non-Intrusive devices toward Conservation of Historical Monuments in the Mediterranean Area," WIND-CHIME. In this paper the case-study monument selected in Cyprus is presented, along with a system identification study which includes measurements and computational models. The models will be used to test the effectiveness of SMA pre-stressed devices and SMA dampers in protecting the monument from future catastrophic earthquakes. The results of the application of the SMA devices and their effects are presented by Chrysostomou, *et al*. (2008).

2 Description of the monument

A description of the Aqueduct is given by Philokypros in the Great Cyprus Encyclopedia. The aqueduct is known with the name Kamares, which means arches. It was the aqueduct of the city of Larnaca and it was built in the mid 18th century (Ottoman Empire period). This monument is located to the west of the city. It is known by the name *Aqueduct of Bekir Pasa*, from the name of the Turkish Pasa

Fig. 1 Larnaca aqueduct

who built it (Fig. 1).

Abu Bekir Pasa was a wealthy Turk who was the District ruler of Larnaca in 1746, and the same year he became the Governor of Cyprus until 1748. The construction started in 1746 and was completed in 1747. The construction cost was 50.000 grosia (6.200 pounds) and was undertaken in full by *Bekir Pasa*. It is noted by Mass Latri, that stones from the ancient city of Kition were used for the construction of this large (for that period of time and conditions prevailing in Cyprus) monument.

The aqueduct was built to provide water to the city of Larnaca and to its port, both from small springs and the river Tremithos. For a long length of its course, which is about 10.5 km, the water was transported in an open duct, but in three places where the ground was low, arches were built, on top of which runs the duct. These three parts consist of 30, 12 and 33 arches, giving a total of 75 arches. Their width and height varies.

The aqueduct operated during the British occupation of the Island of Cyprus, until 1939, when the supply of water to the city of Larnaca was effected through pipes. A view of the aqueduct was printed on the back side of the Cyprus pound that circulated in 1961 and was replaced recently.

3. System identification

3.1. Measurements

It was decided to measure the dynamic properties of the last part of the aqueduct, which consists of 33 arches and is close to the City of Larnaca.

The aqueduct on its south west side is supported laterally by two buttresses, one between the 19th and 20th arch and the other between the 29th and 30th arch. Due to the massive nature of these buttresses it seemed prudent to make measurements between the buttresses since they provided firm out-of-plane support to the aqueduct. In addition, the aqueduct between the buttresses is practically straight with a length of 104 m.

In order to obtain the periods of vibration of the aqueduct so as to be able to tune the computational model, the Kinemetrics Model VSS-3000 Vibration Survey System was used, together with a triaxial EpiSensor force balance accelerometer (model FBA ES-T). The EpiSensor has user-selectable full-scale recording ranges of ± 4 g, ± 2 g, ± 1 g, $\pm 1/2$ g or $\pm 1/4$ g and a bandwidth of DC to 200 Hz. The recording range used in this work was $\pm 1/4$g and the sampling rate 1000 points per second.

The dynamic characteristics of the aqueduct were determined twice: the first in June 2004 and the second in May 2007. The need for this arose from the fact that the application of the SMA devices on the structure (May of 2007) was performed three years after the characteristics of the structure were determined, and it was therefore considered prudent to re-determine those characteristics so as to confirm the starting point. As it will be explained below, there was a considerable difference in the behaviour of the monument between those two measurements. The main contributing factor was the effect of the level of the water in the nearby salt lake. In June 2004 the lake was dry while in 2007 the water level was high and it was obvious that the foundation of the structure was under the ground water table. Both results are presented below.

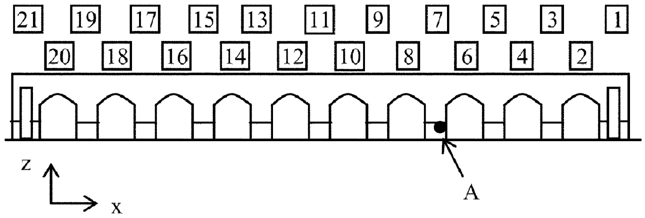


Fig. 2 Location of accelerometer and excitation

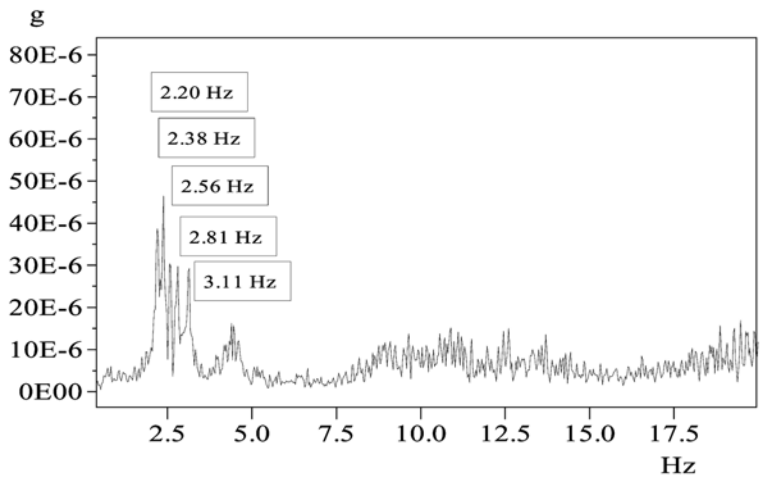


Fig. 3 FFT for position 7 (Fig. 2)

Table 1 Measured frequencies of vibration of aqueduct (June 2004)

Mode	Frequency (Hz)	Period (s)
1	2.08	0.48
2	2.20	0.45
3	2.38	0.42
4	2.56	0.39
5	2.81	0.36
6	3.11	0.32

3.1.1. Measurements in June 2004

The EpiSensor was positioned at 21 different locations on the aqueduct indicated with numbers 1 to 21 (see Fig. 2), and a rubber impact hammer was used to induce vibrations in the aqueduct in addition to ambient vibrations. One impact location was used indicated in Fig. 2 with the letter A. The x-axis, y-axis and z-axis of the EpiSensor were aligned with the longitudinal, perpendicular to its plane and vertical directions of the aqueduct, respectively.

The measurements were analyzed using the software DaisyLab 5.6. A Fast Fourier Transform (FFT) was used with a low pass Butterworth filter of 25 Hz and a Hanning data window. The results have shown that at least the first six frequencies recorded were in the y-direction. This is further verified from the results obtained by the computational model described later in this paper. Figs. 3 and 4 show

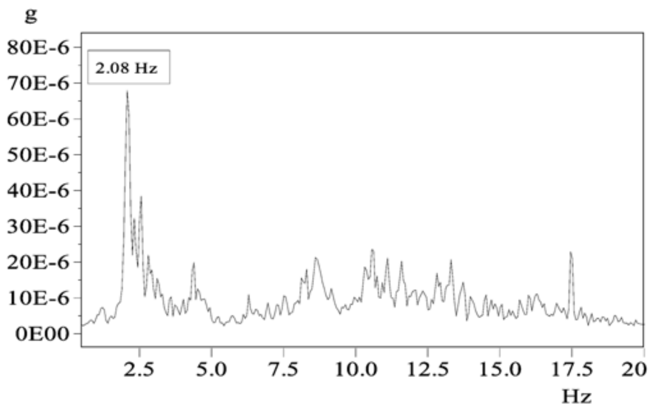


Fig. 4 FFT for position 19 (Fig. 2)

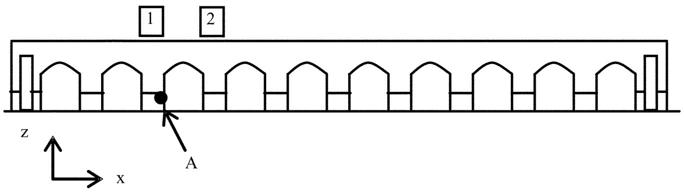


Fig. 5 Location of accelerometers and excitation (May 2007)

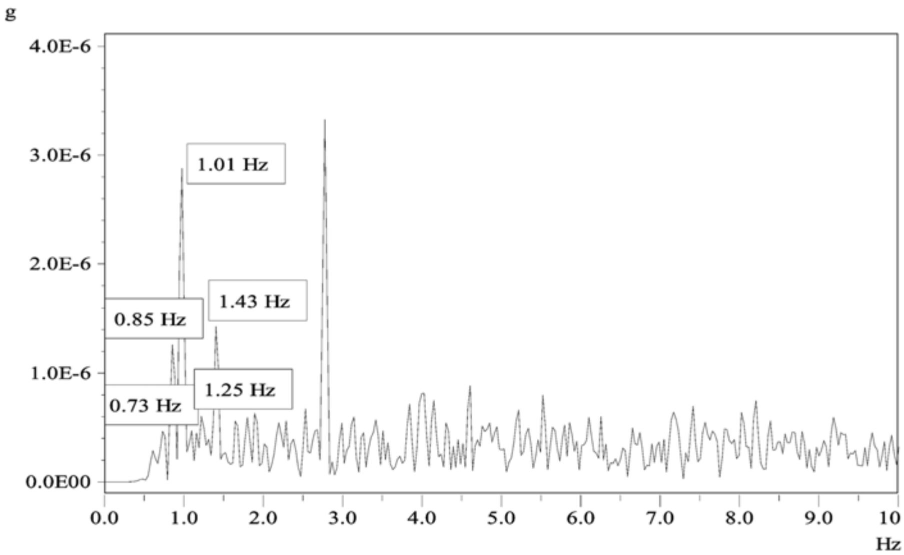


Fig. 6 FFT for position 1 (Fig. 5)

the FFT for positions 7 and 19, respectively.

From the results it is clear that the first six dominant frequencies arranged in increasing order of magnitude are: 2.08 Hz, 2.20 Hz, 2.38 Hz, 2.56 Hz, 2.81 Hz, and 3.11 Hz (see Table 1). The corresponding periods in decreasing order of magnitude are: 0.48 s, 0.45 s, 0.42 s, 0.39 s, 0.36 s, and 0.32 s. It should be noted that, as expected, these values appear consistently irrespective of the location of the

Table 2 Measured frequencies of vibration of aqueduct (May 2007)

Mode	Frequency (Hz)	Period (s)
1	0.73	1.37
2	0.85	1.18
3	1.01	0.99
4	1.25	0.80
5	1.43	0.70

instrument, except for the frequency 2.08 Hz, which starts appearing after location 14 (see Fig. 2). The reason for this is closely related to the first mode shape obtained by the computational model that will be presented in the next section.

3.1.2. Measurements in May 2007

Two EpiSensors were positioned at 2 different locations on the aqueduct indicated with numbers 1 and 2 (see Fig. 5), and a rubber impact hammer was used to induce vibrations in the aqueduct in addition to ambient vibrations. One impact location was used indicated in Fig. 5 with the letter A. The x-axis, y-axis and z-axis of the EpiSensors were aligned with the longitudinal, perpendicular to its plane and vertical directions of the aqueduct, respectively.

The measurements were analyzed using the software DaisyLab 9.0. A Fast Fourier Transform (FFT) was used with a low pass Butterworth filter of 10 Hz, a high pass Butterworth filter of 0.6 Hz and a Hanning data window. Fig. 6 shows the FFT for position 1.

From the results it is clear that the first five dominant frequencies arranged in increasing order of magnitude are: 0.73 Hz, 0.85 Hz, 1.01 Hz, 1.25 Hz, and 1.43 Hz (see Table 2). The corresponding periods in decreasing order of magnitude are: 1.37 s, 1.18 s, 0.99 s, 0.80 s and 0.70 s. It should be noted that, as expected, these values appear consistently both in location 1 and location 2.

By comparing the values of Tables 1 and 2 we can see that there is a considerable shift of the measured frequencies of the aqueduct from 2.08 Hz in 2004 to 0.73 Hz in 2007. This shows a softening of the structure since the fundamental period of vibration shifts from 0.48 s to 1.37 s. Since the properties of the structure have not been changed, then a possible explanation is the soil-structure interaction.

Since the aqueduct is located at the shore of a salt lake, the level of the water of the salt lake affects the condition of the foundation of the aqueduct. In 2004 the measurements were performed in the end of June when the salt lake was dry. In 2007 the salt lake was full due to some out-of season rainfall giving rise to a high ground-water table. Therefore, in the latter test the foundation of the aqueduct was under the ground water table. This was confirmed by digging close to the foundation and finding out that the ground water table was a few centimeters below the ground level.

3.2. Computational model

Following the measurements on the aqueduct and the establishment of the first few periods of the structure, for both cases, computational models were developed so as to model the measured behavior of the aqueduct as closely as possible. The program SAP2000, (2007) was used with shell elements. First, the results of the initial test were used and by considering the foundation as fixed, the modulus of elasticity was varied until agreement between the measured and the

Fig. 7 Pier of the aqueduct

calculated frequencies was reached. Considering this as the initial condition, springs were added at the foundation to simulate the soil-structure interaction. The stiffness of the out-of plane springs were varied until agreement of the results was reached. The details of these two model updates are described below.

3.2.1. Computational model for June 2004

The aqueduct is made of calcareous sand-stone (based on information obtained from the Geological Survey Department of Cyprus, such stones have unit weight of the order of 21.6 kN/m^3) build in isodomic construction (see Fig. 7). The modeling of such a construction presents many problems especially in establishing the modulus of elasticity of the matrix. The methodology used in this research was to vary the modulus of elasticity of the shell elements representing the wall until the periods calculated by the eigenvalue analysis matched, as closely as possible, the measured ones.

The span of the arches varies from 5.05 m to 6.60m while the height of the bottom of the channel varies from 6.75 m (position 1 in Fig. 2) to 9.4 m (position 21 in Fig. 2). The thickness of the aqueduct is on the average 1.85 m for the lower part of the aqueduct (varying in height from 1.95 m to 4.10 m) and 0.85 m for the top part of the aqueduct. The total thickness of the two sides of the channel and its depth is on the average 0.50 m.

A first trial analysis of the model using a modulus of elasticity of 2 kN/mm^2, resulted in a fundamental period of vibration of 0.39 s. The relationship between the original fundamental period of vibration, $T_{original}$ and modulus of elasticity, $E_{original}$, and the targeted ones ($T_{targeted}$ and $E_{targeted}$) is given by Eq. (1).

$$\frac{T_{original}}{T_{targeted}} = \sqrt{\frac{E_{targeted}}{E_{original}}} \tag{1}$$

Substituting in Eq. (1) the original values given above and the targeted period of vibration of 0.48s obtained from the signal processing, the modulus of elasticity was then calculated as 1.35 kN/mm^2.

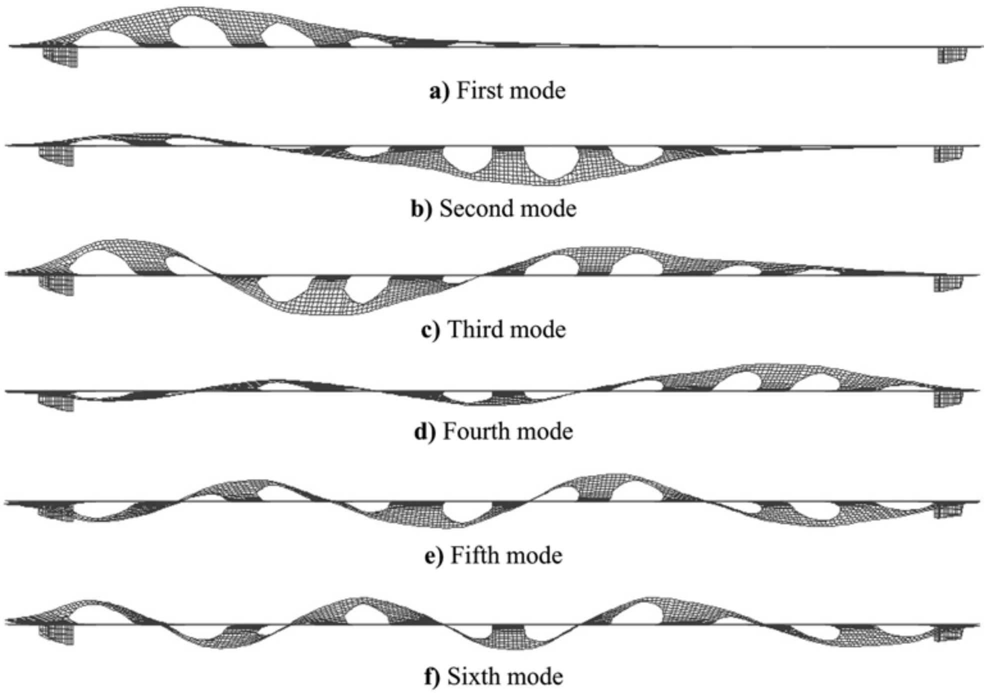


Fig. 8 Perspective plan view of the first six modes of vibration (Model for June 2004)

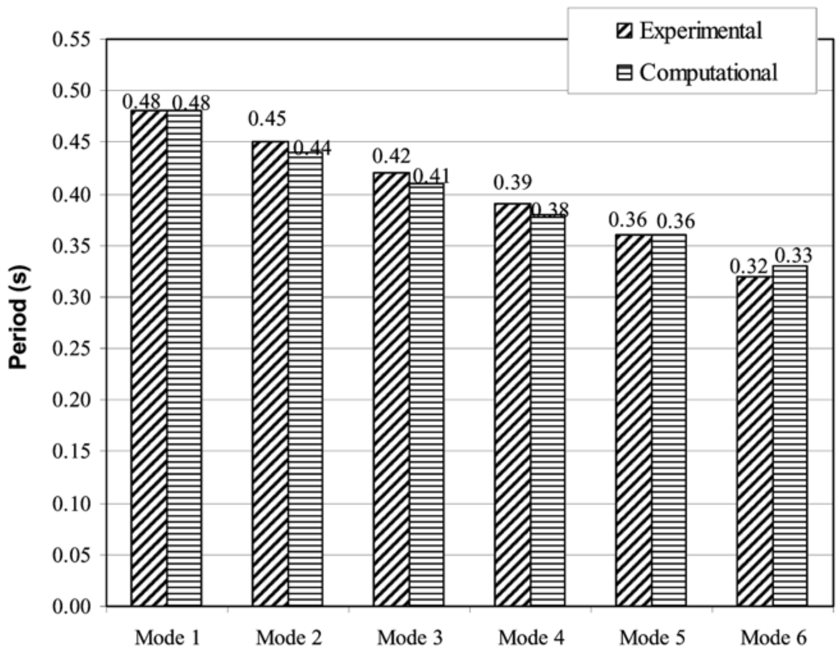
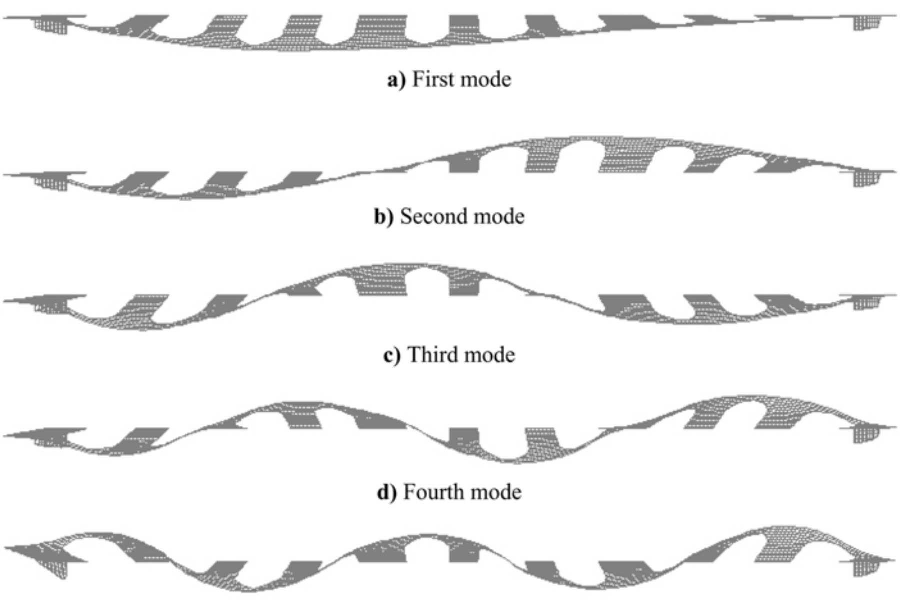


Fig. 9 Comparison between measured and calculated periods of vibration (June 2004)



a) First mode

b) Second mode

c) Third mode

d) Fourth mode

e) Fifth mode

Fig. 10 Perspective plan view of the first six modes of vibration (Model for May 2007)

The eigenvalue analysis of the model with the new modulus of elasticity resulted in the mode shapes shown in Fig. 8 and the following periods of vibration: 0.48 s, 0.44 s, 0.41 s, 0.38 s, 0.36 s and 0.33 s. The comparison of the measured and computed periods of vibration for the first six modes is shown in Fig. 9. It should be noted that there is a very close agreement between the calculated and the measured periods of vibration. All of these modes have mass participation factor in the y-direction. The analysis has shown that the first mode in the x-direction appears in the 17th mode while in the z-direction no mode appears in the first forty modes of vibration.

The fact that the first period of vibration (Fig. 4) started appearing in the recorded signals after point 14 is confirmed by the computational model in which the first mode of vibration consists, primarily, of movement of the arches in that region (Fig. 8a).

Another important observation is that points 1 and 21, at which the buttresses are located, behave as fixed points due to the high lateral stiffness provided by the buttresses (Fig. 8). This supports the decision of analyzing only this part of the aqueduct ignoring the rest of the structure.

3.2.2. Computational model for May 2007

The model developed in the previous section was used as the starting point for the updating of the finite element model to match the results of the signal processing of May 2007. The supports were replaced by springs so as to be able to vary their stiffness in order to simulate soil-structure interaction. No attempt was made to obtain the properties of the soil and use soil-structure interaction models to simulate the behaviour. Rather, a trial and error approach was used.

At first very stiff springs were used that gave the same results as the ones obtained in the previous section with fixed supports. The stiffness for the linear springs was set to 1×10^5 kN/m while the one for angular ones to 1×10^8 kNm/degree.

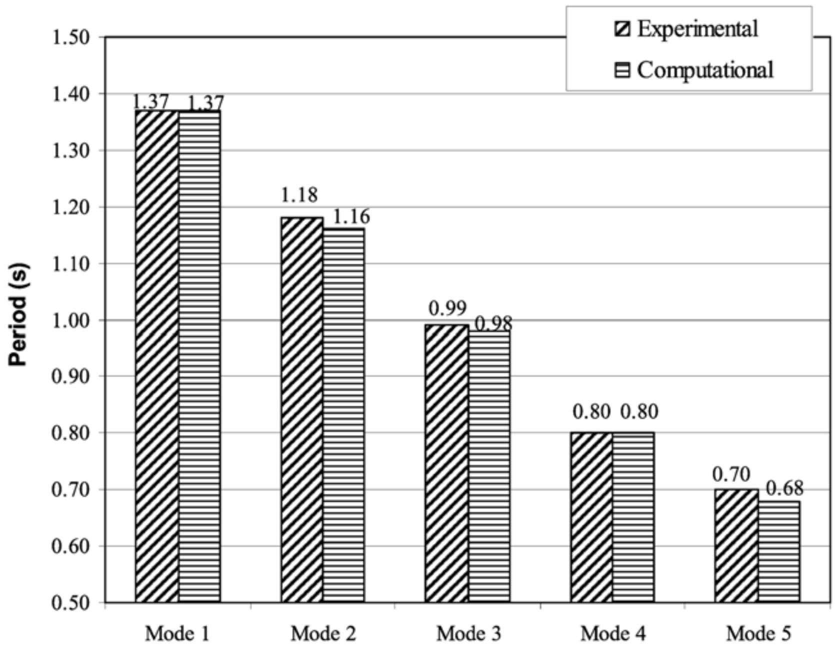


Fig. 11 Comparison between measured and calculated periods of vibration (May 2007)

Then, the angular spring that corresponded to out of plane rotation was changed until matching was obtained between the fundamental period of vibration obtained from the measurements and the eigenvalue analysis of the model. To avoid repetitive calculations three trials were made, with spring constants 2000, 5000 and 10000 kNm/degree which gave periods of vibration 2.21s, 1.56s and 1.19s, respectively. Then a regression equation (Eq. 2) was obtained using the above results.

$$T = 41.278 \times K^{-0.3847} \tag{2}$$

Substituting in Eq. (2) the targeted period of 1.37 (Table 2), the resulting spring constant is $K = 7000$ kNm/degree.

The eigenvalue analysis of the model with the above spring constant resulted in the mode shapes shown in Fig. 10 and the following periods of vibration: 1.37 s, 1.16 s, 0.98 s, 0.80 s and 0.68 s. The comparison of the measured and computed periods of vibration for the first five modes is shown in Fig. 11. It should be noted that there is a very close agreement between the calculated and the measured periods of vibration.

4. Conclusions

In this paper the methodology used to obtain the periods of vibration of an aqueduct was presented along with the computational models for the monument. Considerable differences were noted between the measurements of 2004 and those of 2007, which are attributed to the modification of the soil conditions due to the level of the water in the nearby salt lake. It is therefore important, before performing a system identification and planning the retrofitting of a monument, to consider all possible parameters that may affect its behaviour, including seasonal effects. This seasonal change in the behaviour should lead to the design of adaptive retrofitting schemes that will be able to accommodate the considerable change in the dynamic characteristics of the structure. In both cases the measured frequencies of vibration are very closely matched by the ones obtained from the eigenvalue analysis of the computational models. This model can therefore form the basis for the analytical studies of the effects of shape memory alloy (SMA) pre-stressed devices on the behaviour of the monument. The results of the effects of the SMA devices on the monument are presented by Chrysostomou, *et al.* (2008).

Acknowledgments

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