MODAL ANALYSIS UNCERTAINTY OF A REAL-SCALE MASONRY MODEL

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Abstract

This paper presents the outcomes of an experimental campaign on a masonry triumphal arch representing a real scale model of a church element, which was built in the ELSA laboratory at the Joint Research Centre of European Commission. This study aims to evaluate the damage pattern of the structure through simplified dynamic methods producing a quick evaluation of structural safety, easy to use on real cases. As in traditional monitoring, both the instrumental precision and the measure variability due to the different testing condition (e.g. ambient conditions) must be considered. The related effects on the structural dynamic behaviour were analysed and evaluated in order to distinguish an effective change in the “structural health” (a real damage) from a modification caused by external conditions (a “false positive”).

1 Introduction

The main target of a monitoring testing campaign is, finally, to be able to judge the safety of a structure over time. Structural health monitoring are techniques that try to achieve this difficult task by the use of the modal parameters of a structure.

Once the modal parameters are identified for the so-called undamaged condition, one can use these parameters as a “fingerprint” of the “structural health”. Every modification in this fingerprint can be related to a change in the “health” of the structure (e.g. damaged condition) and, eventually, to a reduced safety level.

This assessment procedure needs to be tested as well as any kind of monitoring techniques. The tests are needed to understand the sensitivity of the modal parameters to the damage and their variability due to the different testing conditions (e.g. temperature).

Figure 1 View of the arch
This paper presents some of the results obtained during a wide testing campaign performed on a real-scale model of a masonry triumphal arch. It is a real structure: about 6 meters tall, arch radius of 3 meters and the column section of 1 m x 0.5 m. The choice of the arch typology as representative of historical structures was suggested by the fact that this structural typology is frequently present within historical church structure.

Churches (80% of the monumental heritage in Italy), even if constructed over a very long time span and with a high variety of styles and construction techniques related to different trends, are characterised by a recurrent typology where it is possible to recognize different structural elements. One of these elements, the triumphal arch, is always present as the separation element between the main church hall and the presbyteral–apse zone. In churches with only one nave (a frequent typology), it is constituted by a masonry wall with the shape similar to a hut with a wide arch opening. This element has its main seismic response principally characterised by in plane natural vibration modes in spite of its lower out of plane stiffness. The presence of the main church hall and of the presbytery and/or apse prevents in fact the activation of an out-of-plane turn over mechanism thereby restricting the vibration to the in plane one (see ref. [1]).

2 Test settings

The testing arch was constructed outside the ELSA laboratory at the JRC in order to subject it to climatic variations similar to those observed in ordinary buildings. An accelerometer setup composed of 16 accelerometer sensors was installed over the arch.

The dynamic identification was conducted mainly in plane direction, in order to analyse in detail the structural behaviour of the real triumphal arch. For the analysis of the experimental model, however, it was necessary to evaluate the out of plane dynamic response as well.

For these reasons almost all sensors have horizontal in plane measurement axes. Only one of them has vertical axis (the one in the middle of the top three). Another one has horizontal out of plane axis and was installed on the west side of the structure (the results of the out of plane testing campaign are not reported and discussed; see ref. [2]).

The tests were carried out with the instrumented hammer. The induced force was recorded in order to compare the results of the Operational Modal Analysis with classical Experimental Modal Analysis. The impact of the hammer was induced on the columns about 3.30 meters above ground level in plane direction. The sampling frequency was 200 Hz.

3 Modal analysis

From the analysis of the recorded signals the Power Spectral Density (PSD) was computed (see figure 3). The results clearly shown that, in plane, a resonance frequency at 8.65 Hz can be identified on the PSD. In the central part of the plot a double peak at nearly 28 Hz can be identified (one peak is at 27.40 Hz and the other is at 28.30 Hz).
The double peak was extensively studied and the origin of this phenomenon can be traced back to the fact that there is an out of plane natural frequency very close to the in plane second natural frequency. The first of the two peaks (27.40 Hz) was recognized as the out of plane natural frequency, while the second (28.30 Hz) was associated to the in plane natural frequency.

The mode shapes were identified and in figure 4 the first two in plane are compared with the ones obtained from the numerical analysis.

4 Dynamic identification uncertainty

The repetition of the test in apparently the same conditions has shown that a certain amount of variation in terms of the natural frequencies of vibration was registered. This scattering in the natural frequency values must be attributed to factors that are independent of structural damage: it has to be considered as “physiological” of the structural health monitoring method [3]. In order to properly evaluate the reliability of the method, the different boundary conditions were analysed in detail. It was very important to understand the origin of the scatter and, surely more important, to quantify its entity.

Some studies [4], [5] have already shown that the variability in the natural frequency values due to changing ambient conditions can be of the same order of magnitude as structural damage modification effects. In this case the intrinsic variability disguises the damage modification on structural parameter response, making damage assessment via dynamic identification impossible. This prompted the authors to conduct a complete preliminary study to evaluate the range of structural dynamic parameters for the original structure (i.e. in its original configuration, before any induced damage).

The sources of variability recognised were:

1. the intensity of the hammer impact;
2. the impact location;
3. the ambient condition.
4.1 **Impact intensity**

The frequency variation due to the intensity of the impact was observed right from the very first tests carried out. It was observed that tests conducted very close in time during the same day (so with the same weather conditions, temperature, etc.) presented different results in terms of frequency. The first hypothesis on this scattering was correlated to the different impact intensity. To check our hypothesis some tests were conducted with the following scheme: 5 hits were given with *normal* intensity (no more than 800 N) and 5 hits with *high* intensity (no less than 1200 N). The mean PSD of the two classes of 5 hits were then computed. The results are shown in the figure 5.

![Figure 5: PSD test a117 and f117 – I and II natural frequencies](image)

It is easy to notice that there is a frequency variation between one test and the other. Especially in the second natural frequency a clear reduction in the frequency peak value due to the increasing of the hammer hit force is clearly shown. The observed change can only be given by the different intensities of the hammer impact because they were obtained hitting at the same location and under identical ambient conditions (the tests were consecutive).

In order to evaluate the influence of the hit intensity on the natural frequencies more precisely, a new test setting was defined. The pattern of these tests was: 5 consecutive hits with *normal* intensity and the other 5 with variable intensity. The very short period of test execution (15 minutes) permits one to consider the ambient conditions constant inside the same series of data.

The values of the natural frequency vs. the PSD peak amplitudes for the 10 hits are shown in figure 6. The peak value of the PSD of the acceleration signal was considered representative of the area limited by the PSD curve near the peak itself. This area is proportional to the energy related to that specific natural mode shape, so the PSD peak value became a direct measure of how much energy excited that particular resonance frequency.
It is worth noticing that the frequencies decrease when PSD amplitude increase. Taking into account all the performed series of tests, the maximum frequencies scattering range, due to the different intensities, was 0.15 Hz for the I natural frequency and 0.85 Hz for the II natural frequency. (respectively around 1.7% and 3%). A possible reason of this variation could be connected to the non-linear stiffness of the structure.

4.2 Impact location

The impact point location is another important parameter to be taken into account because it can considerably influence the dynamic response of the structure (especially in the case of local mode shape, see [3]). In order to evaluate the variability range connected with impact location, some dedicated tests were performed on the arch hitting the structure at different locations, exciting the structure differently but taking care to control a constant intensity hit (at a nominal value of 800 N). The hit series was obtained hitting the two columns at different locations with heights varying from the ground level to 3.30 m.

The scattering obtained, as in the previously described case with different hitting forces, cannot be due to different ambient conditions because, also in this case, the time span of one hitting series is lower than fifteen minutes. Analysing each acceleration time history, the following graphs can be obtained (see figure 7).

This behaviour is completely similar to that previously stated for the variation due to the different impact force hits. Also in this case, if the PSD peak increases, the corresponding resonance frequency decreases. To hit the structure at different locations, if ambient conditions are not changed and if the hit is given with roughly the same force, necessarily, different oscillation
amplitudes are registered, inducing the same non-linear responses observed in the previously described case.

Taking into account all the performed series of tests, the maximum range of the frequencies scatter, due to the different locations, was 0.25 Hz for the I natural frequency and 0.60 Hz for the II natural frequency. (respectively around 2.9% and 2.1%).

4.3 Ambient condition

The influence of the natural frequency variation with respect to the ambient conditions was analysed after the evaluation of the variability range due to the hit location and intensity. The study of this parameter was conducted considering only the data obtained hitting the arch always on the same position and with normal hit intensity. In this way we tried to minimise the influence of the previously described source of variation.

The values of the first and the second natural frequencies vs. the temperature are shown in figure 8. It is possible to identify a general trend of the natural frequencies with the temperature increases, but a solid correlation is not so clear.

![Figure 8 Temperature vs. natural frequencies](image)

The maximum difference between the obtained natural frequency is 0.60 Hz and 1.80 Hz for the I and the II natural frequency respectively (6.9% and 6.3%). In order to explain this high variability, a specific testing campaign was performed.

During an entire day 6 tests were performed. The ambient temperatures were recorded and the natural frequencies are obtained from only hits characterised by normal impact intensity.

Normalising these three series of data registered (the two frequencies and the temperature) with respect to the maximum value recorded for each of them during the day, the graph shown in figure 9 was plotted. As already stated, it can be noticed that the natural frequencies initially grow during the day until a maximum value, then decrease at the sunset. In this variation they follow the natural progress of the temperature.

![Figure 9 PSD of the undamaged condition](image)

The maximum values of the temperature and of the frequencies, however, do not take place at the same time. This behaviour is probably related to the fact that more sophisticated correlation exist between these two variables, for example the real temperature of the structure and its distribution.
on the arch should also be taken into consideration instead of only correlating it to the ambient temperature.

From the analysis of any single hit it is possible to study the influence of the ambient condition together with the influence of the hit intensity. The graphs in figure 10 report the distribution of the natural frequency. Each colour corresponds to a set of impacts and its trend line.

![Figure 10 PSD peak value vs. natural frequencies (different impact intensity and ambient temperature)](image)

It’s worth noticing that the ambient temperature doesn’t affect significantly the behaviour of PSD peak value – natural frequency. In fact the trend lines are all similar and follow the behaviour of the “mean” value stated in figure 9.

5 Conclusion

The natural frequencies recorded during all the tests can be summarised in the graphs of figure 11. The variability due to the different impact forces is shown for each test reporting the maximum and the minimum frequency value obtained by the analysis of that test. Inside this value range the typical value (i.e. the value obtained calculating the mean of the tests performed with *normal* force) is marked.

These values obtained for each test are then placed side by side on the same graph in order to evaluate the variability due also to the ambient condition and the impact position. The results are reported in the graphs of figure 11 for the first and the second natural frequency respectively.

![Figure 11 First and second natural frequency range](image)

The scattering of the measured natural frequencies obtained during the testing campaign can be considerably reduced eliminating those causes of variation that can be easily controlled during the tests. Thus considering only the tests obtained with *normal* impacts, the graphs in figure 12 can be obtained.
The results show that the natural frequencies of the triumphal arch are highly dependent on the boundary conditions and on the way the tests are performed. This aspect may be negligible for a common dynamical identification, but it is critical for structural health monitoring based on natural frequency shift. It is important to know whether the observed variation in these parameters can be attributed to an evolving damage or simply to a changing testing condition.

The preliminary testing campaign on the identification of uncertainties, described in this paper, was fundamental for the success of the following campaign on the damage detection (see ref. [6] e [7]).

6 References


