IDENTIFICATION OF THE MODAL PROPERTIES OF AN HISTORIC MASONRY CLOCK TOWER

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Abstract.

The aim of the paper is to describe the non-destructive tests performed on the clock tower of the Castle of Trani (Bari, Italy). The tower, built in 1848, was realized in tufa masonry (Stone of Trani); it is about 9 meters high and has a square plan with a side of about 3.9 meters; it is built on the principal enter of the Castle and supported by a barrel vault reinforced with an arch.

The non-destructive monitoring was performed by using specific accelerometers placed on the structure at different levels for measuring the acceleration in different points. The particular squat structure of the clock tower suggested the authors to make not only the traditional monitoring, with only environmental actions, but also forced tests by mean of a vibrodine ad-hoc designed and realized, for determining the building modal parameters. All the phases and the procedures of the experimental monitoring are described and the dynamic identification of the building modal parameters (the frequencies and their corresponding mode shapes) is presented discussing the results in both the operative conditions and the effects of the vibrodine excitation.
1 INTRODUCTION

The Trani castle is one of the most important among those made erect by Holy Roman Emperor Frederick II. It is placed just a short distance from the Cathedral of Trani and its location on the edge of town and the height of the towers allowed to guard the entrance of the port and the access roads to the village. Originally had a simple and functional quadrangular enhanced layout with four square towers of the same height. The clock tower of the castle (about 9 meters tall and with a square side of about 3.90 meters), in limestone, was added to the main entrance on the west side in the XIX century; it was built on the principal enter of the Castle and supported by a barrel vault reinforced with an arch.

In this work an extensive experimental analysis aimed to identify the structure modal parameters has been performed using the data obtained from environmental vibration and forced vibrations. The dynamic behavior of the historical buildings is usually analyzed in order to eventually design repair intervention solutions and retrofitting to seismic actions. Retrofitting interventions are quite common as old masonry structures, like the tower in exam, are built to resist only to vertical actions. Usually, for this kind of analysis, the data are recorded by mean of a series of accelerometers installed in specific points of the structure. The recorded data will be then used for the Operational Modal Analysis (OMA) (i.e. [1-6]), which is utilized to get the real values of the modal parameters of the tower. Slender structures such as towers are particularly suitable to this type of investigation [1-6], because if they are subjected to vibrations even of low intensity, generally produce very clear signals. On the other wise, the analyzed clock tower can be considered a squat building and for this type of structures may be necessary a forced excitation (examples of squat structures or forced excitation in [7-9]) for obtaining enough dynamic information. At this proposal an appropriately realized vibrodine has been used for forcing the structure to oscillate.

In this paper the equipment and the experimental set up that has been used for in-situ dynamic identification tests are described and an extensive analysis about the effects of the vibrodine on the vibrations of the tower is presented completing the preliminary analysis shown in [10]. The performed analysis may be considered very particular and innovative in its field for the use of a special equipment able to reproduce forced vibrations on the tower.

Using the vibration acceleration measurements, the modal parameters of the tower are identified consistently by two different output-only procedures: the first, based on the Complex Mode Identification Function, exploits a frequency representation of the response; the second, based on the Stochastic Subspace Identification Method, works in the time domain. All the experimental tests have been analyzed and the frequencies of the structure have been identified; moreover useful indication on the use of the vibrodine will complete this contribute.

2 DESCRIPTION OF THE TOWER

The clock tower analyzed in this study is about 7.0 m tall and about 4.0 x 4.0 m and it is shown in figure 1. It consists of three parts: the base, the clock and the hut where a small bell is housed. The base has a slightly trapezoidal shape and rests directly on the walls at the entrance to the Castle, immediately after the stone bridge that crosses the moat. The clock tower’s structure consists in masonry walls in Apulian tufa (with a variable thickness of about 75 cm), covered with Trani stone, of about 25 cm thick.
The clock part, of equal size of the base, is a cubic element that has, on each facade, a division in different parts. On the main facade there is the face of the clock, in perfect line with it while the other side has a lower-level openings.

On the last level, in perfect proportion with the underlying layers, there is a hut which has a small bronze bell that, at the time when the castle functioned as prison, indicated the changing of the guard. Each level is defined by a cornice; the one which separates the first from the second level is rounded and has no protrusion; the frame on which is set the hut is convex and presents a higher protrusion.

![Figure 1: The clock tower analyzed in this study, frontal and lateral view](image)

### 3 EXPERIMENTAL SETUP

The monitoring system consists of several elements properly connected: the acquisition units or piezoelectric accelerometers with a sensitivity of about 10 V/g; the data acquisition system or DAQs positioned at each of the monitored level; the laptop with an acquisition software; the cables that connect all elements to each other.

In the specific case, the tower has been instrumented with 23 high sensitivity seismic accelerometers ICP PCB 393B31. The accelerometers were placed on four different levels on the four lateral sides of the tower: 8 accelerometer at the four corners of the surface over the clock, 6 accelerometers at three corners at the intermediate level, 6 at the three corners at the lower level part of the clock tower, and 1 accelerometer at the basis as a reference sensor. Finally, two accelerometer were placed on the superior arch for monitoring the oscillation of the upper part, probably the most significant local modes for stability analysis. In figure 2a) a detailed description of the position of the 23 accelerometers on the tower also using a discrete model of the experimental setup. Appropriate rectangular blocks where the accelerometers were inserted with screws, were used for ensuring the orthogonality of each couple of accelerometers applied in the same point (in figure 2b).

The environmental tests (four consecutive acquisitions) were carried out on 23\textsuperscript{th} January 2014 by recordings of 15 minutes with a frequency of 1024 Hz; the data sampling frequency has been subsequently reduced for the analyzed data of the accelerometers.
The particular structure of the tower that may be considered a squat building suggested the possibility of using forced excitation for obtaining enough dynamic information.

A special equipment, an electro-hydraulic shaker (called vibrodine) has been designed and realized in order to force the structure.

The following day (24th of January 2014) the vibrodine exciter was moved with a special transport from the laboratory of the Politecnico of Bari to the tower of Trani and then, with big efforts, placed on the main entrance of the Tower (figure 3).

The forced tests were carried out on 24th January 2014 not placing the vibrodine in contact with the tower, but only placing it on the floor inside the door at the entrance of the Castle (figure 4). The vibrodine was controlled for vibrating at a defined frequency with a constant amplitude; the accumulator was charged by an electric motor.
Experimental forced tests were carried out considering a frequency oscillation of 3 Hz, 9 Hz, 16 Hz, 18 Hz and 20 Hz. The length of these tests has been influenced by the limited power of the accumulator; the tests have a length of about 1 minute, decreasing with the increasing of the frequency. Other forced tests were carried out maintaining the electric motor on for charging the accumulator and increasing the test length; but the uncontrolled effect of the motor has influenced the forcing oscillating action of the vibrodine.

4 IDENTIFICATION RESULTS

4.1 Preliminary analysis [10]

A preliminary analysis was conducted on the time histories of the accelerometers. This preliminary analysis considered the data of the accelerometers aligned in the frontal side at different levels including the superior arch and orthogonal to the main entrance and indicated as positions A, B, C and D in figure 5. The data have been under sampled to 128 Hz and also normalized eliminating the offset of each signal by subtracting the mean value of each acquisition. The preliminary analysis permitted to clearly highlight the effects of the forcing vibrodine.

Three environmental tests were analysed for testing the amplitude of the registered oscillations. The data (shown in figure 6) were normalized eliminating the offset of each signal by subtracting the mean value of each acquisition.
From the results of figure 6 two important considerations may be immediately carried out:
- the repeatability of the oscillations for the three different tests;
- the different amplitude of the oscillations for the 4 considered measure points in all the tests; the peak to peak value of the oscillations in position A is around $4 \times 10^{-4} \text{[g]}$, it decreases to $2 \times 10^{-4} \text{[g]}$ in position B, to $10^{-4} \text{[g]}$ in position C, to around $0.8 \times 10^{-4} \text{[g]}$ in position D (lower part of the turret). This consideration ensures a registered environmental oscillation of the superior part of the turret and of the arch nevertheless the very stocky profile of the building; the peak to peak values are consistent with the accelerometers sensitivities ensuring the correctness of the used experimental setup.

Figure 6: Three environmental tests results related to the positions A,B,C,D.

A test was carried out considering an excitation with the same amplitude and a changing frequency during the acquisition (the results in figure 7). The frequency was changed from 1 Hz to 15 Hz with a step of 2 Hz manually modified every about 2 minutes. The final 80 seconds of acquisition have been done switching off the motor in order to evaluate the influence of the motor to the oscillations in the considered positions; it is evident that there is a brusque diminution of the oscillations.

Figure 7: Forced tests with vibrodine and motor on related to the positions A,B,C,D.
From figure 7, it is evident that the vibrodine amplifies the oscillations in all the positions (with a factor of 5-10 times with respect to the environmental oscillations) nevertheless it is placed in the base entrance without a direct contact with the tower structure. A relevant amplitude variation according to the vibrodine frequency variations; in all the positions the signal increases in the second part when the vibrodine frequencies arrives to 9, 11, 13 and 15 Hz.

Considering the last 80 seconds of figure 7 when the pump motor is off, the results show clearly that the dominant effect of the oscillation is due to the pump motor. This preliminary analysis convinced to use the vibrodine with only the accumulator power (motor switched off), in order to excite the structure avoiding the vibrations of the motor.

The preliminary analysis has been very useful for arranging further tests without doubts about the possibility of acquiring data only related to the vibrodine forcing action and not influenced by the pump motor effects.

Short tests were carried out using only the accumulator energy as forcing action. But the accumulator autonomy was very short and also depending by the frequency; for a frequency of 3 Hz the accumulator has 110 seconds of autonomy, but it decreases to about 50 seconds for 9 Hz, to about 25 seconds for 18 Hz and to only 15 seconds of autonomy for 20 Hz.

In figure 8 the plots of the tests in positions A, B, C and D; it is evident that the amplitude varies at changing the frequency of the vibrodine; in all the positions the maximum amplitude is achieved with a frequency of 18-20 Hz, letting us consider that this value could be considered close to a frequency of the building. The results here obtained are interesting because they demonstrate the applicability of the vibrodina for forcing the structure also if applied not directly in contact with the turret.

Figure 8: Forced tests with vibrodine and motor on related to the positions A, B, C, D.

4.2 Extraction of the modal parameters: environmental tests

A specific software (ARTeMIS) [11] was used for the extraction of the modal parameters.

Two different OMA methods were used for each analysis: the Enhanced Frequency Domain Decomposition (EFDD) in the frequency domain and the Stochastic Subspace Identification (SSI) using Unweighted Principal Components (UPC) in the time. In Figure 9 the plot of the two methods applied to two environmental acquisitions and in Table 1 a summarize of the identification results for all the environmental tests.
The identification results for the environmental tests are very satisfying; the first six frequencies may be estimated with a good repeatability for the two techniques (especially for SSI method) and for all the experimental tests.

### 4.3 Extraction of the modal parameters: forced tests

The same identification methods have also been applied for the forced tests acting only for the effect of the accumulator: some plots of the most accurate technique (the SSI technique) for the forced tests are shown in figure 10.
From the identification results plotted in figure 10, it is evident that the effect of the vibrodina forcing is that of creating a number of additional frequencies almost uniformly spaced in the frequency domain. The estimated frequencies appear interrupting the regularity of the frequency added by the vibrodina. It is evident, for example, that the first frequency (around 7.5 Hz), breaks the uniform distribution of the frequencies of the test in figure 10 d) that has a regular step of about 4 Hz. The same behavior for all the tests analyzed, with a uniform distribution of the frequencies that has a step that increases increasing the vibrodina excitation frequency and that is interrupted by the presence of the building frequencies. The repetition step of the forced frequencies seems to be around 0.8 Hz for the test with forcing frequency of 3 Hz, 1 Hz for the test with forcing frequency of 9 Hz, 2 Hz for the test with forcing frequency of 18 Hz and, finally, 4 Hz for the test with forcing frequency of 20 Hz. This very interesting aspect will be further investigated in the future. Anyway, there is to consider that the forced tests have a limited duration due to the limited power of the accumulator and so, the identification techniques may be subjected to errors.

4.4 Extraction of the mode shapes

The good results of the identification applying both the techniques of all the environmental tests, confirmed by the presence of the same frequencies also in the forced tests, has permitted to complete the OMA considering the corresponding mode shapes. In figure 11 a plot of the mode shapes referred to the environmental test 1. It may be clearly noted that the first and second frequencies are identified as the first couple of flexional modes directed respectively on the y and x axis. The third mode is the second flexional mode directed on the x, the fourth is a mixed mode (flexional and torsional), the fifth frequency is a pure torsional mode and the sixth is a local mode referred to the superior arch.

The extraction of the mode shapes is very important for permitting the validation of a model of the clock.

5 CONCLUSIONS

The analysis of the clock tower of Trani has been performed by using the environmental acquisition nevertheless the very squat profile; the modal identification was carried out with two different statistical approaches in different domains.
The designed and realized vibrodine has been applied to the floor of the building increasing the amplitude of the oscillations; its effect on the frequency identification is related to the presence of new and ripetute values, related to the vibrodine oscillation period.

The experimental results will permit to tune a Finite Element model of the structure, in phase of completion; the tuning phase should give us important information about the material data values constituting a reference for the evaluation of the state of the building and for the planning of eventual renovations works.

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