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Experimental methodology for measuring the structural dynamic transmission damping of a cultural heritage tower

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***Abstract* – This paper presents the dynamic experimental campaign carried out on simple model related to a stocky masonry clock tower situated in the Swabian Castle of Trani (Italy). The main objective of this paper is, after estimating the main frequencies and vibration modes of the considered structure, defining the influence on the structural damping dynamic transmission of the frequency of excitement. At this aim, firstly, an accelerations' record has been acquired simultaneously in 23 points of the tower at different levels, both due to environmental vibrations and to a series of sinusoidal forced vibrations applied at the base by using a pneumatic shaker device specify designed for the tests.**

I. INTRODUCTION

This work presents an extensive experimental analysis aimed to identify the structure modal parameters, by using the data obtained from both environmental vibrations and forced oscillations. The clock tower here analysed is located on the eastern façade of the Swabian Castle of Trani (South-East of Italy), on its main entrance. The castle 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. The castle, originally had a simple and functional quadrangular enhanced layout with four square towers of the same height. In the sixteenth century, with the advent of the first weapons, the castle was adapted to the new defensive techniques, in response to widespread demand for re-fortification of the Mediterranean coast, under threat from the Turks. These operations involved the rise of the southern front, least favorite course and overlooking towards the open country, and the construction of two bastions at opposite edges to the southwest (a spear) and northeast (square), thus ensuring a complete fire coverage around the perimeter of the fortress. Trani Swabian Castle underwent major works of transformation in 1832 when Ferdinand II Duke of Bourbon converted it in the provincial Central Prison. At present it can be visited as a historical monument and the clock tower maintains its use like a clock.

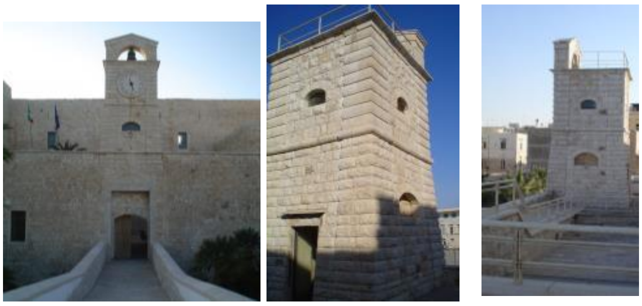
Usually, for performing a nondestructive dynamic analysis, the data are recorded by mean of a series of accelerometers installed in specific points of the structure. The recorded data will be then used for the Operational Modal Analysis (OMA) [1]–[12], which is utilized to get the real values of the modal parameters of the tower. Slender structures such as towers are particularly suitable to this type of investigation [4]–[6], because even if they are subjected to actions of low intensity, as the ones due to ambient loads, they show vibrations which can be clearly recorded by means of the usually adopted accelerometers. On the other side, in case of squat buildings - like the clock tower considered in this study – the amplitude of the vibrations induced by the environmental actions may be too much low to guarantee a good ratio between the signal and the noise, and consequently it may be necessary to use a forced excitation (examples of squat structures or forced excitation in [10]–[12]) in order to obtain enough dynamic information. To this aim an appropriately realized electro-hydraulic shaker device (vibrodine) has been used to generate forced oscillation on this kind of structures.

In this paper the equipment and the experimental setup that has been used for in-situ dynamic identification tests on the squat clock tower of Trani's Castle (in Italy) are described and an extensive analysis about the effects of the shaking device on the vibrations of the tower is presented completing the preliminary analysis shown in

[7]. The performed analysis may be considered very particular and innovative in this field of research for the use of a special equipment able to produce forced vibrations on the tower and also of an opportune post processing elaboration which may underlined the relevant characteristics of structural transmission damping.

II. GEOMETRICAL DESCRIPTION

The clock tower has an overall height equal to 7.20 m from its main door. The tower has a square plan transversal section, with the inner side of about 2.05 m, constant along the total height, while the outer side is variable along the height because of the presence of a Trani stone covering. In fact, the outer side is 4.25 m at the base and 3.55 m at the intermediate height of 4.00 m and, from this level up to the top, it keeps constant. At the intermediate height of 4.60 m there is also a toroidal stringcourse. The tower façades are characterized by openings arranged on two different levels: (i) At the lower level, there is the doorway on the west side, while on the other sides, there are archivolted windows with a width of about 1.40 m and an average height of 60 cm. (Figure 1b). (ii) At the upper level, there are archivolted windows smaller than the previous ones, with a width of 85 cm and a height of 55 cm, arranged on all sides with the exception of the east one, which is blind to host the large central clock. (Figure 1a). On the eastern facade, differently by the other ones, the masonry keeps for about 2.25 m, with a gabled portal with an arched opening in the middle where a bell is located.



(a) *(b)* *(c)*

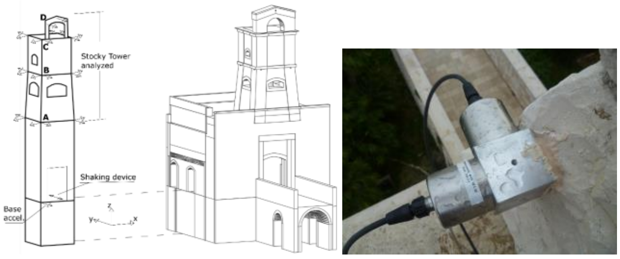
Fig. 1. Clock tower of the Swabian Castle of Trani: (a)East view; (b) West view; (c) South view.

III. THE EXPERIMENTAL TESTS

To evaluate the tower main frequencies and its experimental mode shapes, the tower has been instrumented with 23 high sensitivity seismic accelerometers ICP PCB 393B31 with a sensitivity of about 10 V/g. All the accelerometers were connected by flexible wired cables to a NI data acquisition system, the latter connected to a laptop with a specific acquisition software positioned at the base of the tower.

The accelerometers were placed on four different levels on the four lateral sides of the tower: 8 accelerometer at the four corners of the floor over the clock, 6 accelerometers at three corners at the intermediate level, 6 at the three corners at the lower level as part of the clock tower, and 1 accelerometer at the basis as a reference sensor (Figure 2a). 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 (Figure 2c). It is important to note the points A,B,C and D, aligned on the left part of the tower and placed at different levels (Fig.2a).

Two accelerometers were placed on the superior arch for monitoring the oscillation of the upper part, probably the most significant local modes for stability analysis.



(a) (b) (c)

Fig. 2. Experimental setup: (a) Positions and directions of acquisition of the 23 accelerometers; (b) 3D view of the clock tower; (c) view of two installed accelerometers.

A. Environmental tests results

Four consecutive acquisitions of environmental vibrations (called Test 1, Test 2, Test 3 and Test 4) were carried out by recordings of 15 minutes each with a sampling frequency of 1024 Hz.

The specific software ARTeMIS software [13] was used for the extraction of the modal parameters. Two different OMA methods were used for each analysis: the Enhanced Frequency Domain Decomposition (EFDD) which operates in the frequency domain, and the Stochastic Subspace Identification (SSI) using Unweighted Principal Components (UPC) which operates in the time domain. In this analysis, the SSI method has demonstrated to be able to better estimate the frequencies when it works at 1024 Hz. Figure 3 shows the SSI diagram of the first environmental test and the frequencies of the tower clearly identified.

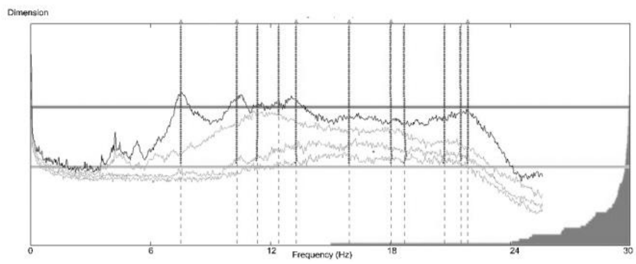


Fig. 3.SSI diagram for Test 1.

The identified frequencies for the 4 tests conducted under environmental actions are summarized in Table 1. It is evident the good repeatability of the identified frequencies for all the environmental tests; moreover, similar results were obtained also adopting the EFDD technique. So, nevertheless the squat profile of the analyzed tower, the power of the recent OMA techniques and the sensitivity of the available sensors permit to identify with a good confidence the frequencies and the corresponding mode shapes. The same confidence is not possible for the evaluation of the damping ratios; for this reason the structure has been forced with a specific electro-hydraulic shaker (vibrodine) designed for exciting the structure from the basis. The mode shapes corresponding to the identified frequencies are related to bending modes (along y and x axis indicated in Figure 2, respectively) for the first two frequencies; the third frequency is related to a torsional mode, the fourth frequency to a second bending mode (y axis), the fifth frequency to a bending-torsional mode, the sixth one to a torsional mode

Table 1. Identified frequencies for the 4 environmental tests using the SSI technique.

Frequency order	Test 1	Test 2	Test 3	Test 4
1st	7.52	7.5	7.48	7.53
2nd	10.32	10.36	10.34	10.31
3rd	13.28	13.33	13.35	13.51
4th	15.93	15.98	15.79	16.09
5th	18.08	18.34	-	-
6th	21.85	21.83	21.83	22.08

B. Forced tests results

As aforementioned, other tests have been performed by installing a vibrodine exciter at the main entrance of the Tower (figure 4). The vibrodine accumulator was charged by an electric motor. This device is situated between two frames to anchor it to the base of the tower by means of four screws (figure 4 b).

(a) (b)

Fig. 4.a) transportation of the vibrodine; b) vibrodine installed at the main entrance of the clock tower.

The forces produced by the vibrodine were characterized by a chosen frequency and a fixed amplitude.

A preliminary test was carried out considering an excitation produced by a 200 kg moving mass having the same amplitude and changing the frequency from 1 Hz to 15 Hz, with a step of 2 Hz modified about every 2 minutes. Figure 5 shows the temporal acceleration values during the tests in points A, B, C and D placed at different levels as indicated in Figure 2. The final 80 seconds of acquisition have been done switching off the diesel motor, only with the pressure accumulated in the accumulator, 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.

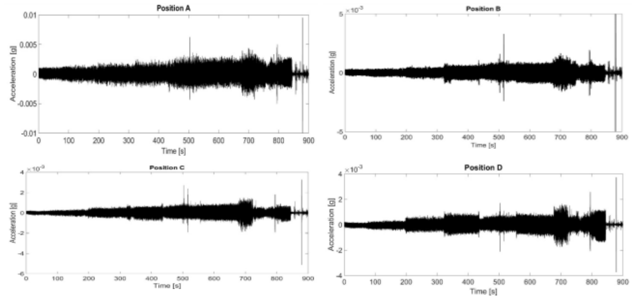


Fig. 5. Forced tests with shaker device and motor on related to the positions A,B,C and D.

From figure 5, it is evident that the shaker device amplifies the oscillations in all the positions direct contact with the tower structure. Considering the last 80 seconds of Figure 5 when the pump motor is off, the results clearly show that the dominant effect of the oscillations is due to the pump motor. This preliminary analysis convinced to use the shaker device with only the accumulator power (motor switched off), in order to excite the structure avoiding the vibrations of the motor.

The preliminary analysis was very useful for arranging further tests without doubts about the possibility of acquiring data only related to the shaker device 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 had 110 seconds of autonomy, but it decreased to about 50 seconds for 9 Hz, to about 25 seconds for 18 Hz and to only 15 seconds of autonomy for 20 Hz.

C. Filtering procedure

In order to analyse directly the effect of each forced frequency at the base with each response at each position on the tower an innovative strategy is here introduced to use the forced vibration signals in a more specific way.

The approach is based on considering a digital filtering of the acquired signals; in particular a classical windowed linear-phase FIR digital filter has been designed [14]. The filter is normalized so that the magnitude response of the filter at the centre frequency of the passband W_n = [w_1 w_2] is 0 dB. The FIR filter is a non-recursive one because the output signal is a function only of the input signal u. The response of such a filter to a generic input signal is a finite sequence of m+1 samples, where m is said the filter order. In order to generalize the response to any input signal, the system function H(z) of the FIR filter has to be evaluated. It is the Z-transform of the impulse response that is the output when the Kronecker delta function δ is given as input. The system function H(z) is calculated in (1) where a_0 and b_i (i=0,…,m) are constant coefficients, with a_0, $b_m \neq 0$.

$$H(z) = Z[h(k)] = \frac{1}{a_0} Z\left[\sum_{i=0}^{m} b_i \delta(k-i)\right] = \frac{1}{a_0}\sum_{i=0}^{m} b_i z^{-i} \quad (1)$$

The aim of filtering the acquired signal was achieved by the calculation of the coefficients bi (i=0,…,m) through the fir1 function in Matlab [15]. A two element vector [w_l w_h] was passed to this function of the Signal Processing Toolbox in such a way as to specify the band of normalized frequencies for bandpass configuration. This is a Hamming-window based, linear-phase filter with normalized cut-off frequency. The lower and upper bound filters were chosen as in equation (2). Different values for the parameter ε were firstly settled for testing the filter capabilities and subsequently the value 0.05 Hz was fixed to obtain the desired bandwidth.

$$w_l = 2\left(\frac{f-\varepsilon}{f_s}\right) \quad w_h = 2\left(\frac{f+\varepsilon}{f_s}\right) \quad (2)$$

To have approximately an unvaried signal amplitude in the considered range of frequencies and a good filter performance, the high order m = 800 was fixed.

D. Application of the filtering process to the forced vibrations data

The application of digital filters to experimental accelerometers data in environmental conditions have been recently tested by the authors [16], [17]. In [16] the post-processing has permitted to synchronize different wireless accelerometers by analysing the phase of the signals; in [17] it was demonstrated that, for environmental data, a digital fir filter is not able to separate an accurate sinusoidal signal for the effect of close components. In this paper, the digital technique is applied to forced vibrations data, considering the band-pass central frequency coincident with the shaker device excitation frequency. The digital post-processing has been successfully applied to all the acquired accelerometers data. In the following the data referred to four acquisition points A,B,C,D along the y direction will be analysed.

The filtered signal and its frequency spectrum in comparison with the original signal and its spectrum are shown for the case of excitation at 9 Hz for points A, B, C, D, and, for point A, also for the case of 16 Hz and 18 Hz excitation in Figures 6-9. It is evident that the digital filter is able to eliminate the external components to the forcing frequency and that the filtered signal is almost sinusoidal with a very low fluctuation regarding its amplitude, considering a transitory time of 1 second.

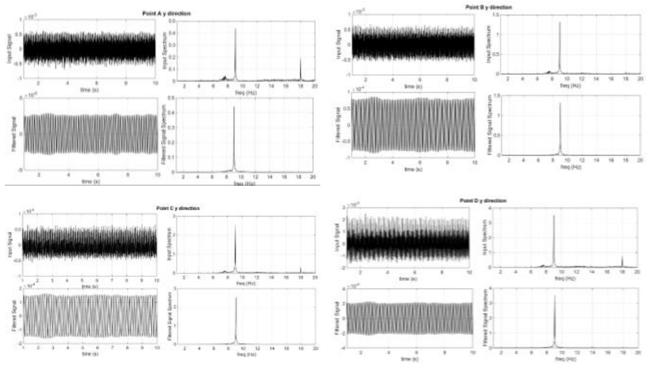


Fig. 6. Filtering effect for points A,B,C and D, excitation at 9 Hz

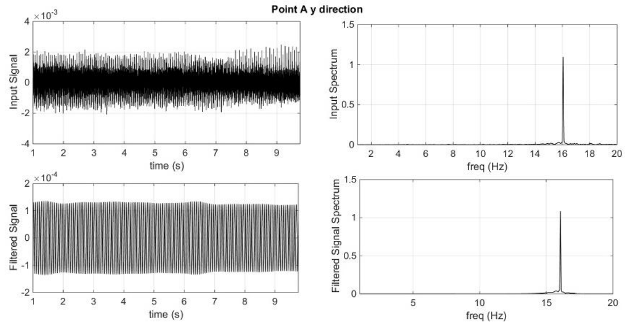


Fig. 7. Filtering effect for point A, excitation at 16 Hz

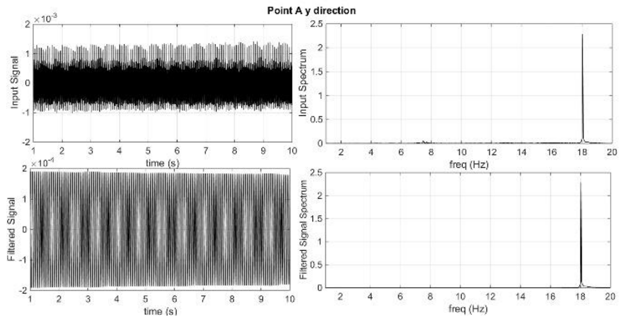


Fig. 8. Filtering effect for point A, excitation at 18 Hz

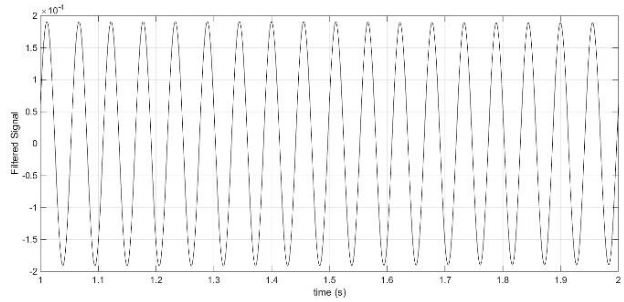


Fig. 9. Zoom of the filtering effect for point A, excitation at 18 Hz

For all the considered filtered sinusoidal signals it is possible to calculate the Amplitude automatically as the average value of half of the peak to peak value all over the full acquisition period, and also an initial Phase angle may be calculated for estimating the delay respect to the initial evaluation time (1 second) of the first maximum. In order to compare the effect of the digital filter with the environmental situation, in Figure 10 also the case of environmental excitation is shown with reference to the same point A (y direction) and considering the same digital filter cantered at the first estimated frequency (7.5 Hz). This demonstrates the importance of the shaker device effect that allows to analyse the data as really forced vibration data, using parameters such as the Amplitude and the Phase Angle also for testing the dynamic behaviour of the structure.

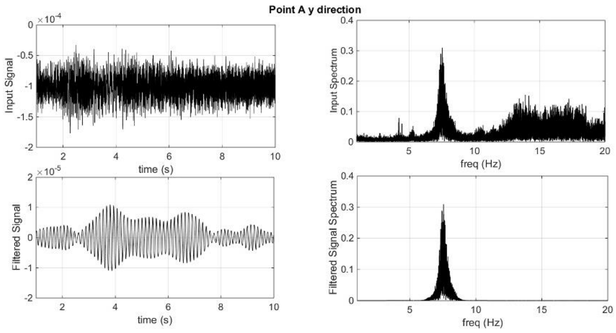


Fig. 10. Filtering effect for point A, environmental conditions.

E. Procedure for structural damping evaluation

The parameters obtained by means of the described filtering procedure may be used for evaluating the structural damping because they give a perfect idea of the transmitted vibrations for the different excitation frequencies. The parameters may be used for validating opportune models. In Table 2, for example, the Amplitude of transmitted vibrations, normalized with respect to the point A, for the different excitation frequency are obtained with the proposed methodology.

Table 2. Normalized Amplitude calculated at the different positions.

Excitation frequency	Point A	Point B	Point C	Point D
9 Hz	1	3	5.72	7.98
16 Hz	1	0.35	0.94	3.62
18 Hz	1	0.47	1.69	4.17
20 Hz	1	1.78	6.58	12.3

It is evident, from Table 2, the different dynamic behavior of the structure by varying the excitation frequency. This behavior may be used for identifying optimal damping values in order to guarantee simulated amplifications in according with the experimental ones.

IV. CONCLUSIONS

The paper discusses the dynamic experimental tests performed on the clock tower of the Swabian Castle of Trani (Italy) and the subsequent dynamic identification.

In detail, the tests have been conducted acquiring the vibrations induced by environmental actions and also by installing an electro-hydraulic shaker device.

The analysis of the environmental vibrations performed in the framework of the OMA has allowed the identification of the natural frequencies with a good accuracy, as demonstrated by repetitiveness of the obtained values.

Moreover, the forced vibrations have been analysed by means of a properly chosen post processing procedure in order to highlight the relevant characteristics of structural transmission damping.

V. ACKNOWLEDGMENT

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