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Vibration analysis of the civic tower in Rieti

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Abstract

In the last decades the definition of a suitable monitoring system for identifying the dynamic behavior of structures has had a central position in the civil engineering research area. The vibration analysis leads to the recognition of the reference state of structures which is essential to determine the integrity level when extreme events occur, such as earthquakes. The latest seismic events occurred in the world have shown the essential role of the new passive seismic techniques which aim to protect structures and the importance of supervising the building construction operations and the adopted improvement measures.

In this work the structural monitoring of the civic tower located in Rieti is presented. In the tower a non-conventional TMD has been installed via an inter-story isolation system at the top floor by means of High Damping Rubber Bearings (HDRB).

The general goal is to define a monitoring system suitable with this experimental case through the vibration analysis. Several aspects will be taken into account: the choice of sensors setup, the measured quantities and the extraction of structural information. Firstly this will allow to define the structure's reference state featured by frequencies, damping ratios and mode shapes. Moreover the effective design of the monitoring system would lead to the characterization of the dynamic behavior of the structure equipped with a passive vibration control system. Different tests have been carried forward: ambient vibration test (AVT), forced vibration test (FVT) with vibrodyne and seismic test (ST). The AVT and the FVT enable to define the monitoring system and check the reliability of the adopted identification tools, among which an Output Only algorithm stands out: the Observer Kalman Filter System Id. On the other hand the ST will point out some preliminary information about the dynamic behaviour of the structure equipped with a non conventional Tuned Mass Damper referring it to higher levels of vibrations.

Keywords: Vibration Analysis; Structural Health Monitoring; Observer Kalman Filter Identification algorithm; Output Only System Identification; Non Conventional Tuned Mass Damper.

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1. Introduction

Lately research on vibration analysis and monitoring of civil structures has been actively carried forward and they have shown to be the key topics fully-fledged for the identification of the structural reference state. The structural health monitoring (SHM) is the process of implementing a damage identification strategy, involving the observation of a structure over time and space in order to determine the health state of the structure [2]. Often the SHM is investigated to define the current state of buildings and it represents the first step to check any further modification to an existing

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structure. A fundamental stage in the SHM process is the interpretation of data and the extraction of information regarding a system by means of structural identification algorithm. In the last years several techniques have been developed and improved to solve such problems. One of the main issue which usually affects civil structures is the randomly nature of excitations acting on them. Because of this feature, the measurement and collection of input-data are often extremely difficult and sometimes impossible or too expensive. This obstacle has been exceeded through the introduction of the output only techniques. Among these, lately, a time domain system identification approach is catching on: the Observer/Kalman Filter Identification (OKID) algorithm which presents a relatively new Output Only (O/O) derivation [3]. This formulation comes from its original Input Output (I/O) application which was presented by the National Aeronautics and Space Administration to identify typical aerospace engineering systems [4] and that is founded on the assumption that the excitation is white and stationary and that the system is linear time invariant. Only this technique has been proven to be particularly suitable for solving civil engineering problems [5]. The OKID algorithm adopted presents four different expressions [3]; here the O/O OKID-ERA is adopted.

The topic of mitigation of vibrations is considered as well. Among the strategies to reduce vulnerability of existing buildings, the inter-story isolation [6] demonstrated its advantages. This technique involves the introduction of flexible isolators at floor levels along the height of a multi-story building. Then it is possible to disconnect one or more levels from the remaining structure and yields the possibility of realizing a non-conventional Tuned Mass Damper (TMD). The final aim is to provide supplemental damping by inducing a vibration energy transfer from the structural portion below the isolation system to the one above. The non-conventional TMD system [6] within the inter-story isolation strategy involves the conversion of masses already present on the structure into tuned masses, retaining their structural function in addition to the control function.

2. Experimental Study

The civic tower located in Rieti (Fig.1) was built in 1940, following the expansion project of the City Hall constructed in the XIII century and subsequently consolidated after the earthquake occurred in 1898. The Tower has an approximately square plan of size 14.00 m x 13.70 m and an overall height of 32 m, with 7 floors above ground, plus a ground-floor level covered by a porch with vaulted ceilings and one level underground. The external structure consists of masonry walls with coating blocks of travertine. On the inside there is a reinforced concrete frame with 4 columns (Fig.2a). Recently (2014) a non-conventional TMD system was realized on the the Tower in order to reduce the seismic vulnerability. The roof slab and the columns at the last floor were demolished (Fig.2b) and a steel structure has been built up, constrained to the structure by four HDRB isolators, located where the concrete columns were standing (green circles in Fig.3a). This steel frame aims to support also the old roof which plays the role of tuned mass in the TMD system (Fig.2c). A long term monitoring system has been planned and installed on the civic tower. A multi-channel acquisition system by HBM has been adopted. It consists of a data acquisition unit MGCplus interfaced with the software Catman Professional 5.0. The acceleration time-histories are recorded using piezoelectric accelerometers by PCB Piezotronic, series 393A03, with a sensitivity of 1000 mV/g.

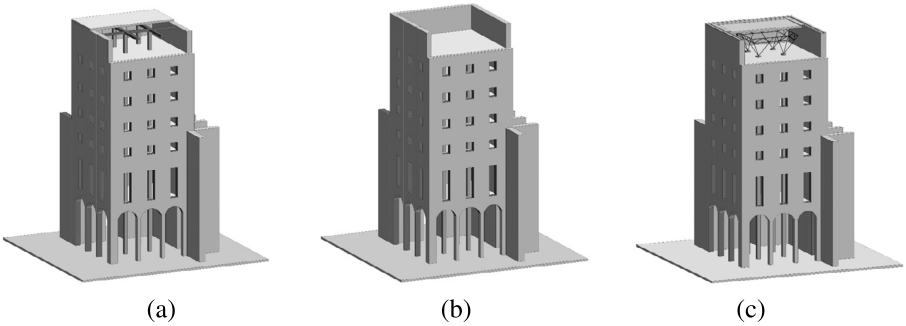
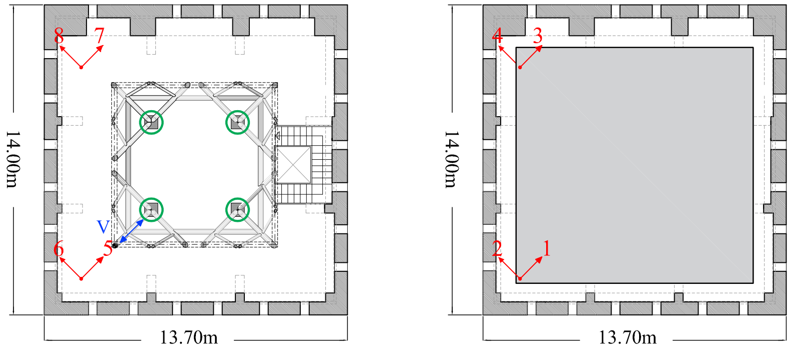

(a) (b) (c)

Fig. 1. Civic tower in Rieti: (a) Initial State, (b) Intermediate State, (c) Final State

Several campaigns have been performed: ambient vibration test (AVT), forced vibration test (FVT) with vibrodyne and seismic test (ST). The AVT and the FVT are necessary to define the dynamic reference state. Indeed, after this state definition, it is possible to check the integrity of the structure after the seismic event. Different sensors configurations have been considered. In the AVT and in the FVT 4 accelerometers (natural numbers in Fig.3a) were placed on the support floor (height=28.84m) and 4 corresponding sensors (natural numbers in Fig.3b) on the TMD level (height=32.24m) to have more reliable information to outline the reference state of the structure. The accelerometers have been rotated of 45 degrees with respect to the horizontal direction because the dominant modes are along those directions. Moreover this allowed to describe completely the kinematics of the two rigid plans (support and TMD).



(a) Support (b) TMD

Fig. 2. Sensors (natural numbers), actuator (V vibrodyne) setup and isolators location (green circles)

This setup slightly changes in the ST: two sensors have been removed (n. 4 and 8 in Fig.3) because they were needless and redundant. In the following section the vibration analysis referred to the different campaigns is reported.

2.1. Vibration Analysis

Ambient Vibration Test

The ambient vibration test consists in 300 s recording with sampling frequency equal to 100 Hz. The structural response measurements have been processed at first looking at the Fourier Transform (FT), and then applying the OKID O/O algorithm. This technique was combined with the Stabilization Diagram (SD), a system order identification tool. The purpose is to find the structural modes and extract the modal parameters of the system: frequencies, damping ratios and mode shapes. The SD gives the stability of the identified modes. The SD limits are: 1% on frequencies, 5% on damping ratios and 0.95 for MAC index [7]. The lower order limit is set at 10 in Fig.4a and at 20 in Fig.4b.
From the FT in Fig.4 six frequencies clearly emerge (green circles): 3.03, 3.42, 3.55, 4.57, 4.95, 5.65. The SD combined with OKID O/O (Fig.4) gives the effective identification of four of these frequencies and the corresponding damping ratios: 3.03 (0.9%); 4.56 (1.4%); 4.95 (2.2%); 5.62 (1.6%). These four frequencies (blue lines) present a distinct stability, confirmed by the clustered damping ratios. However, the algorithm shows uncertainty in the identification of very close modes, as it happens for the two frequencies localized around 3.5 Hz. In this preliminary analysis, not being able to distinguish them, the algorithm provides a middle frequency (dashed blue line) at 3.48 Hz with 2.0% of damping ratio. Subsequently the same recording has been processed with an established system identification technique, the Subspace Stochastic System Identification in its output only formulation (DD-SSI). This algorithm leads to almost coincident results (Table1), validating the OKID O/O identification.

Besides frequencies and damping ratios, OKID O/O provides the complex eigenvectors. They have been plotted in the complex plane, and they resulted to be strongly aligned along the origin. Accordingly, the imaginary part of the eigenvectors was minimized and the real mode shapes were plotted Fig.5. It can be noticed that for low levels of vibration, such as the ambient ones, the TMD and the support move in phase. The modes results mainly translational and rotational, in line with the analysis of the instantaneous rotation centers.

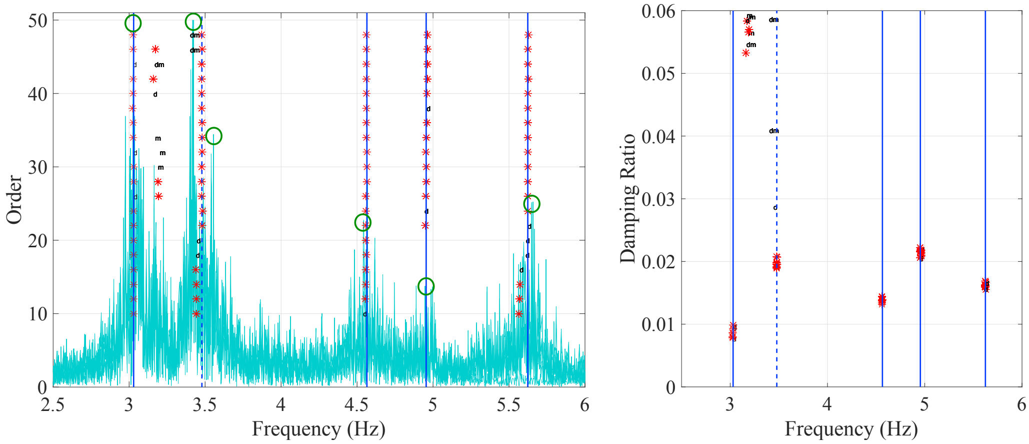
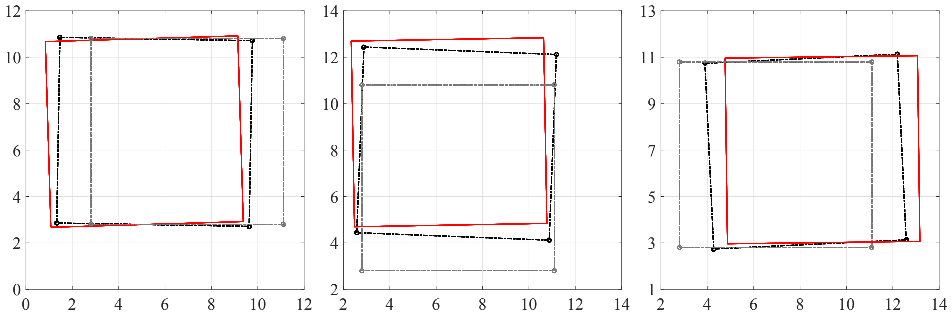
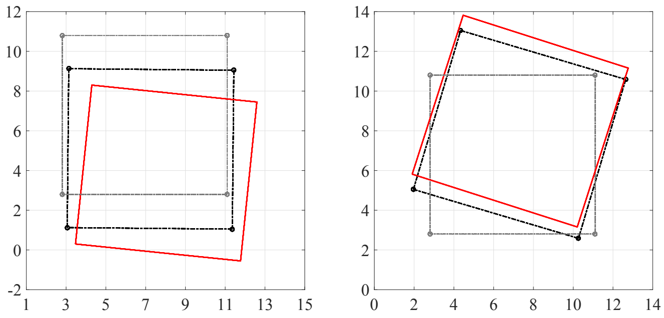


Fig. 3. Stabilization Diagram, AVT, November 2015



(a) Mode 1 (b) Mode2 (c) Mode3



(a) Mode 4 (b) Mode 5

Fig. 4. Real Mode Shapes: support in black; TMD in red, reference configuration in grey.

Forced Vibration Test

In the forced vibration test a vibrodyne (blue V in Fig.3a), series VTE 40k by Valtronic Europe, has been used with sampling frequency equal to 200 Hz. The vibrodyne configuration adopted consists in 2 eccentric masses with a static momentum of 0.896 kgm and a maximum force approximately of than 32 kN at 30 Hz.

In the forced vibration test two kind of trials have been carried out: a sine sweep in which the force frequency linearly grows and decreases within the range 2-7 Hz in 140 s; a forced input test in which the force frequency is maintained fixed for a number of cycles until the stationary signal is reached. In Fig.6 there are the Frequency Response Functions (FRFs); the acceleration values (red circles) in the stationary phase for each frequency and the identified frequencies of the AVT (blue lines).

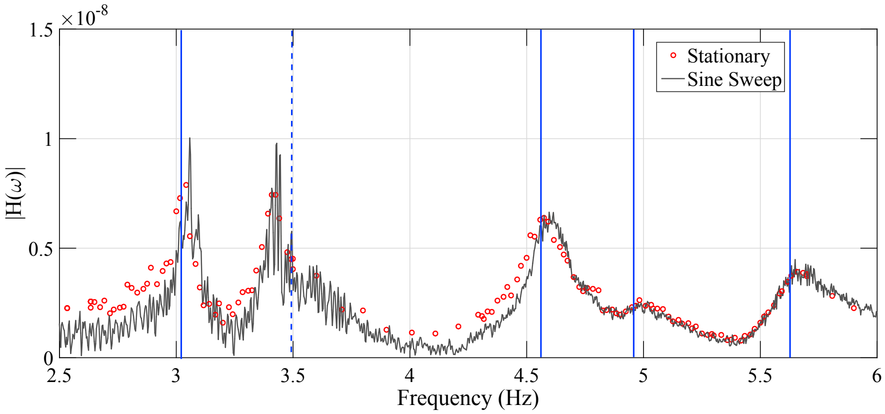


Fig. 5. FVT, November 2015, Sensor 7

The values associated with the sine excitation are higher than the ones coming from the sine sweep. This is more evident for lower frequencies, while they are substantially coincident for higher frequencies. This could be due to the high velocity of the sine sweep test and then the structure did not have enough time to reach the stationary response in the lower frequency range where the number of cycles is not adequate. Comparing the AVT results and the ones derived from the FVT, it is evident the accordance between the structural frequencies. Five frequencies are identified distincly (Table1), while around 3.5 Hz, there could probably be another structural frequency that is difficult to identify. This shows that it would be appropriate to repeat the forced input tests inspecting more thoroughly that frequency range.

Table 1. Frequencies (f) and Damping Ratios (ξ), November 2015

Test	f_1 *(Hz)*	ξ_1 *(%)*	f_2 *(Hz)*	ξ_2 *(%)*	f_3 *(Hz)*	ξ_3 *(%)*	f_4 *(Hz)*	ξ_4 *(%)*	f_5 *(Hz)*	ξ_5 *(%)*	f_6 *(Hz)*	ξ_6 *(%)*
FT	3.03	-	3.42	-	3.55	-	4.57	-	4.95	-	5.65	-
OKID	3.03	0.9					4.56	1.4	4.95	2.2	5.62	1.6
SSI	3.03	0.9					4.56	1.6	4.95	2.0	5.64	1.5
FVT	3.06	-	3.43	-	3.57	-	4.60	-	4.99	-	5.65	-

Seismic Test

Afterwards the seismic recordings have been analyzed. For sake of brevity only the preliminary analysis concerning the earthquake of the 26 October 2016 (Magnitude 5.4) will be reported. Because of the non-stationary nature of the input and the slight nonlinearity of the structure, the OKID O/O algorithm gave rough information about modal parameters. The frequencies, as it was expected, reduce in comparison to those identified under environmental vibrations. The first structural frequency shift from 3.03 Hz to 2.8 Hz with a reduction of 7.6%
To better understand the dynamic behavior of the TMD together with the structure, the accelerations have been integrated to get the corresponding absolute displacement. The TMD and Support displacements (Fig.7) point out that in the first instants of the earthquake they move in phase; while in the core of the seismic recording they move out of the phase.

3. Conclusions

The analysis carried forward in this work, which is not exhaustive on the matter, about vibration analysis of the civic tower in Rieti has given a series of observations from different perspectives about the definition of a monitoring structural system and the techniques which can be applied to define the reference state of a structure equipped with a

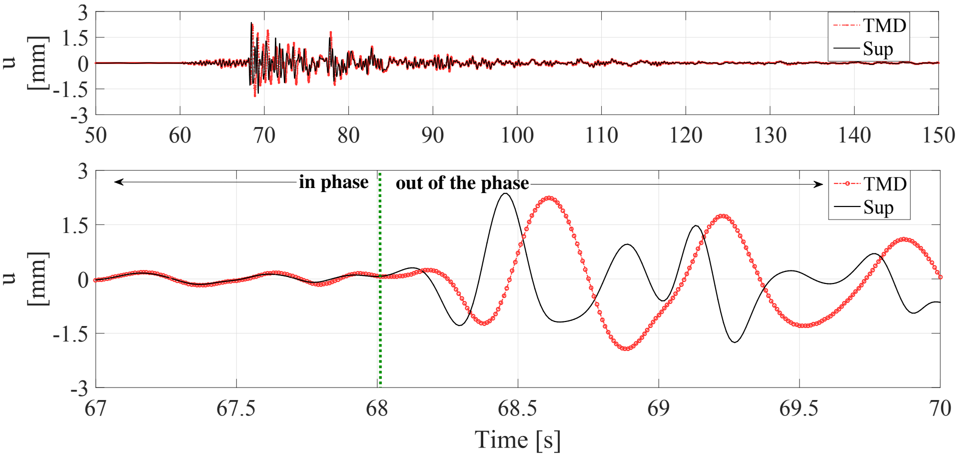


Fig. 6. Absolute Displacements Sensors 2-6, Earthquake 26 October 2016 (Mw 5.4): (a) Complete time history, (b) Zoomed time history

non conventional TMD. The reference sensors setup has been defined through the vibration analysis of the AVT and FVT. This setup allows to effectively describe the reference state of the structure. The installation of the TMD turns the structure into a slight nonlinear system. Even if the linear system assumption of the OKID O/O technique is not observed, the algorithm leads to a reliable identification of the modal parameters (frequencies, damping ratios and mode shapes), which characterize the structural reference dynamic behavior. However it showed also its weakness in the identification of very close modes which represent a very well known tricky point in the system identification research area. The FVT strengthens the possibility of the presence of two structural frequencies around 3.5 Hz and pointed out the necessity of further FVT to explore that frequency range. The OKID O/O proved to have some problems in these first seismic tests because of the extreme stretching of the assumptions on which it is founded. It seems to be less reliable in this peculiar case in which the excitation presents a non-stationary nature and the system is slightly nonlinear. However a simple displacement analysis pointed out how the TMD system correctly moves out of the phase with respect to the support when the induced vibrations are significant.

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