Displacement Based Approach for a Robust Operational Modal Analysis

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ABSTRACT

Robust estimation of the dynamic modal parameters of structures during shaking table experiments is done by means of efficient time domain data-driven Crystal Clear Stochastic Subspace Identification (CC-SSI) of vibration data recorded by a new, innovative, high resolution 3-D optical movement detection and analysis tool tracking the dynamic displacement of several selected points of the structures during the dynamic tests of natural (earthquake) and artificial (mechanical) induced vibrations. The measure of the displacements is a crucial task for the numerical and experimental studies in structural dynamics, especially within the displacement based approach in seismic design and calculations. The innovative monitoring technique measures 3 axial absolute displacements with easy and fast test set-up, high accuracy and the possibility to link the 3D-motion time histories of the tracked markers with CAD drawings of the structure and validate the FE models in real time experimental data assimilation.

1 Introduction

Estimation of the dynamic modal parameters of structures is the prior activity to be performed, in laboratory or in situ, to validate the empirical or numerical models for verification of the capacity to withdraw the dynamic forces induced by mechanical vibrations or earthquakes. For laboratory experiments, powerful test facilities are needed to apply the required amount of input energy on large scale models of civil, industrial and cultural heritage structures. In this paper is discussed the use of an efficient time domain data-driven Crystal Clear Stochastic Subspace Identification (CC-SSI) during the shaking table experiments of two structures: the 1/6 scaled mock-up of a structural macro element of a church and a model representative of a 5 storey steel frame building. For the results reported herein the 6 Degree of Freedom (6DOF) 4x4 m shaking table at the ENEA C.R. Casaccia, Italy has been used. The identification of the structural parameters has been processed by the software ARTeMIS Extractor Pro.

Beside the traditional sensors (accelerometers, LVDT, strain gauges) used during the shaking table tests, the displacement data have been acquired by a new, high resolution 3-D optical movement detection and analysis tool. Its purpose is to track the absolute coordinates of several selected points of the structures during the shaking table tests This system uses twelve Infrared Cameras to measure accurate 3-D positions of hundred of markers placed on the structure during the seismic tests [2]. The innovative monitoring technique allows measuring 3 axial absolute displacements x(t), y(t), z(t) with easy and fast test set-up, high accuracy and the possibility to link the 3D-motion time histories of the tracked markers with CAD drawings of the structure and validate the FE models in real time experimental data assimilation [3]. The new monitoring system has been tested during several shaking table experiments for the estimation of the modal parameters of structures and components prior the seismic qualification for mechanical, transportation and nuclear industry.

The possibility to synchronize visible and infrared cameras allows the remote participation and control of the shaking table tests in a networking configuration of distributed experiments [4]. The conceptual structure of this networking configuration within the virtual framework DySCo (structural Dynamic, numerical Simulation, qualification tests and vibration Control) is shown in the fig.1.1.

As the experimentation goes on, remote users have the possibility to interact step by step with the operator. The connection to DySCo is provided by the ENEA grid of numerical computation, the results are shared in real time via Internet among the partners of the experiment.

The fig. 1.1 displays the images shared during the seismic tests of the drum of the vaults of the San Nicolò l’Arena of Catania (Italy). It is a critical macro structure of the church which needed a preventive anti seismic intervention of restoration. The assimilation of the marker’s displacements in the FEM allowed the validation of the numerical model of the drum-vault system for successive analyses. Images and data were shared in real time by the ENEA GRID with the partners of the experiment, see the fig 1.1 and fig.1.2 for the shared experiment tool.

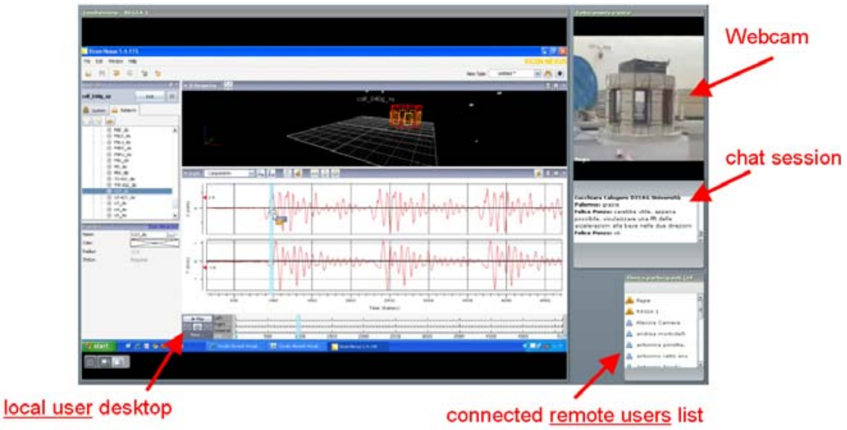
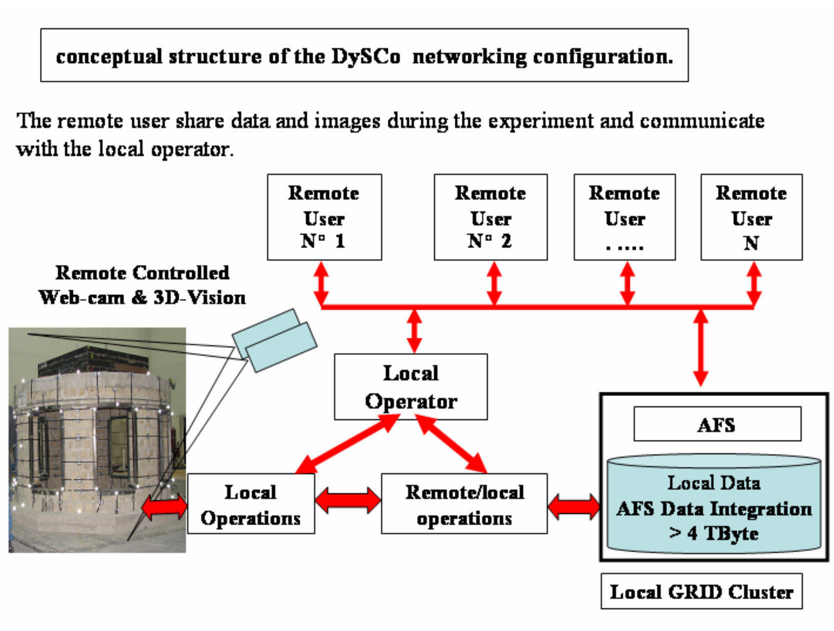


Fig. 1.1 Images shared during the seismic tests of the drum-vault model of the San Nicolò l'Arena Church, Catania (Italy).


conceptual structure of the DySCo networking configuration.

The remote user share data and images during the experiment and communicate with the local operator.

Fig. 1.2 The possibility to synchronize visible and infrared cameras allows the remote participation to the shaking table tests in a networking configuration of distributed experiments.

2 Estimation of the dynamic modal parameters of a masonry structural macro element

Structural rehabilitation of historical monumental buildings is very difficult and mainly involves two kinds of problems: the former is related to the knowledge of the mechanical characteristics and of the state of damage; the latter involves the artistic values and is related to its architectural interests and the value of the contents in the building.

The masonry structure analyzed herein is the slender drum with large windows sustaining the dome of the S. Nicolò l'Arena church, Catania, Italy [1].The drum was heavy damaged and an experimental test campaign was carried out in order to design the optimal conservative restoration. A reduced 1:6 scale model of the drum-dome system was built to be subjected to dynamic tests and different kinds of reversible devices for the improvement of the structural behavior were experienced. The model with reinforcement frames in the fig. 2.1-a was positioned on the shaking table and monitored with markers at the node of the FEM model as represented in the fig. 2.1-b and submitted to a three times repeated seismic input corresponding to an event recorded in the Colfiorito area (italy) during the 1997 Umbria-Marche earthquake.

The test was concluded when cracks appeared in the pier sears. The cracks was horizontal and translated towards the middle of the piers.

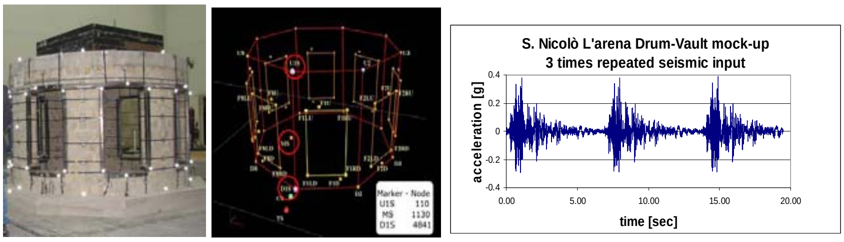


Fig. 2.1-a) Drum-vault reduced scale structural macro element; Fig. 2.1-b) Wire frame reconstruction of the 3D_vision motion detection; Fig. 2.1- c) The seismic input for the shaking table experiments was the 3 times repeated accelerograms recorded at Colfiorito, italy during the 1997 Umbria Marche earthquake.

The seismic input at the base of the shaking table was the 3 times repeated accelerograms recorded at Colfiorito, Italy during the 1997 Umbria Marche earthquake. During the experiment the absolute displacements of the markers were recorded by the 3D_vision system and analyzed by the Crystal Clear Stochastic Subspace Identification (CC-SSI) to identify the modal parameters. The fig. 2.2 displays the ARTEMIS geometry and the first three modes identified by the CC-SSI analysis [5]. The first mode at 2.18 Hz is not a physical mode of the structure, it is the base table motion at the dominant frequency of the earthquake with rigid motion of the drum-vault macro element; the second is the first flexural mode of the drum-vault at 6.31 Hz responsible of the vault damages and the third mode is the torsion mode at 13.91 Hz. responsible of the damages of the large windows.

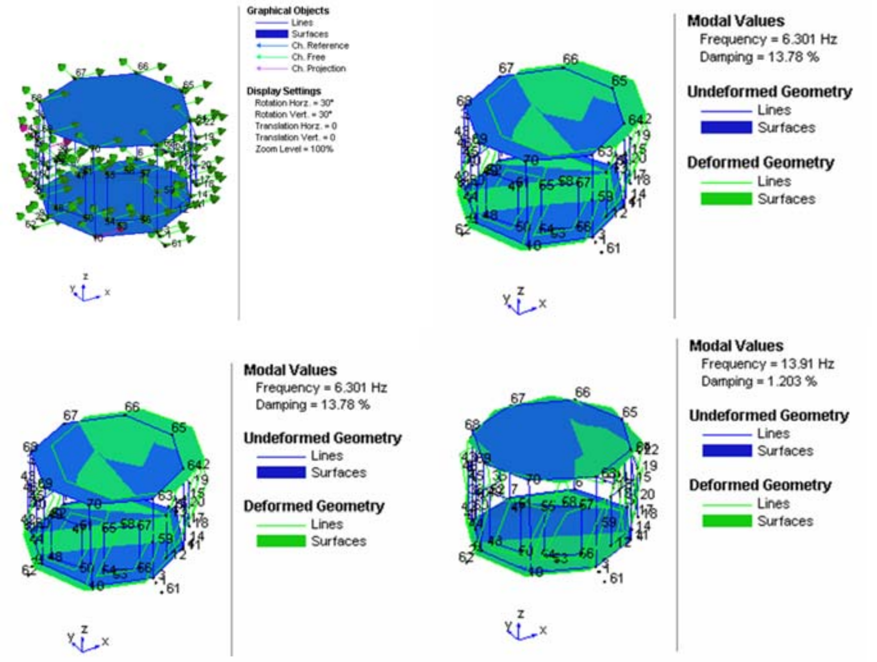


Fig. 2.2-a) X,Y acquisition channels of the markers displacements for the CC-SSI; Fig. 2.2-b) Translational mode associated at the shaking table dominant frequency;Fig.2.2- c) First flexural mode of the drum-vault;Fig.2.2- d) First torsion mode of the drum-vault

The natural frequencies and damping ratios values are displayed on the right side of the figures 2.2-a, 2.2-b and 2.2-c The modal parameters estimation was realized in two range of frequency: the first two modes at low frequencies in the range 0-10 Hz, the third mode in the range 10-20 Hz. The resulting stabilization diagrams are displayed in the fig. 2.3 and fig.2.4

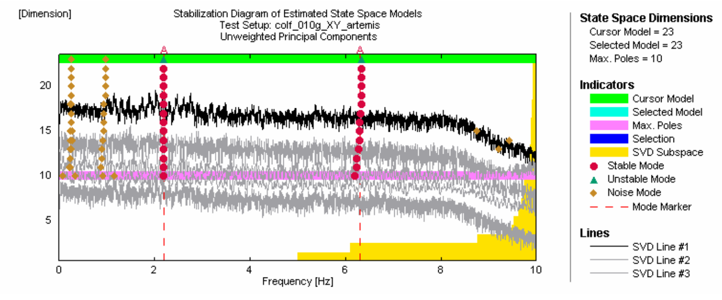


Fig. 2.3 Stabilization diagram of the low frequency estimated state space models.

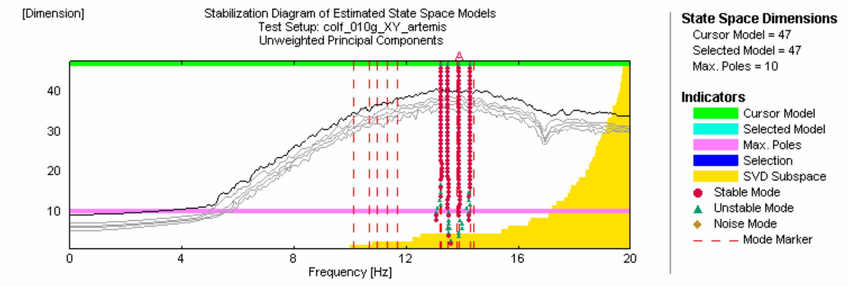


Fig. 2.4 Stabilization diagram of the estimated high frequency state space model.

The results of the displacement based approach for the CC-SSI identification were used to validate the Finite Element Model of the vault - drum macro element and the results of the numerical calculation of the modal model are given in the fig. 2.5: the fig. 2.5-a is the numerical flexural mode at 4.18 Hz , the fig. 2.5-b is the numerical torsion mode at 14.90 Hz and the fig. 2.5-c displays the normalized strain energy patterns associated at the torsion mode.

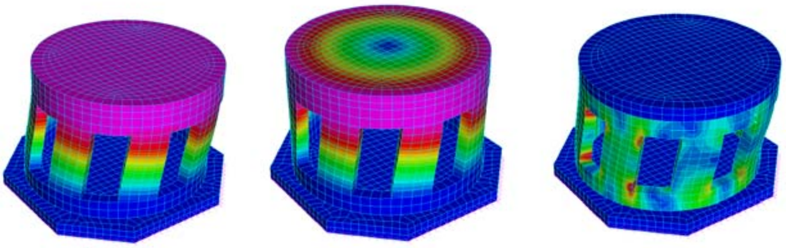


Fig. 2.5-a) Numerical flexural mode at 4.18Hz; Fig. 2.5-b) Numerical torsion mode at 14.90 Hz; Fig.2.5-c) Associated pattern of the normalized strain energy.

3 Estimation of the dynamic modal parameters of a steel frame building

The second experimental campaign was carried out on a 5 storey steel frame structure weighting 2ton. The estimation of the modal parameters has been performed imposing a white noise time history at the base of the table; the displacements data of the markers were recorded by the 3D_vision displacement tool and analyzed by ARTEMIS CC-SSI.

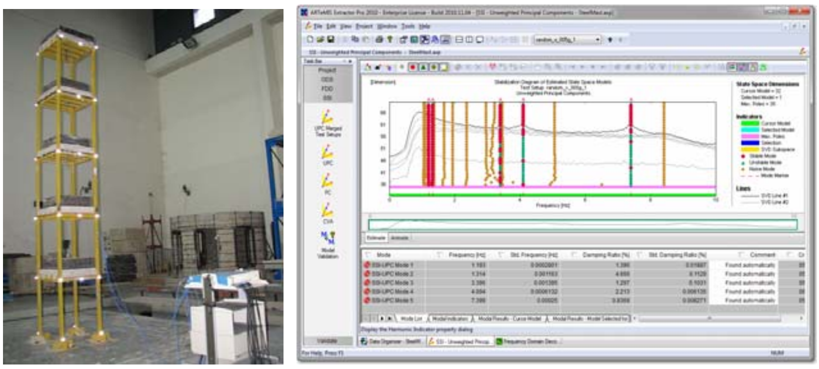


Fig. 3.1 a) Steel frame on the shaking table for the structural identification tests; Fig.3.1-b)Stabilization diagram of the CC-SSI estimated modes.

The Fig. 3.1-a displays the 5 storey steel frame positioned on the shaking table for the structural identification tests. The drum-vault model analyzed in the previous chapter is also visible. The stabilization diagram of the estimated modal parameters is in Fig.3.1-b; note that mode 2 in the stabilization diagram shows too high damping and its mode shape doesn't look good due to high noise, therefore has not been validated. Mode shapes and frequencies of the first four modes of the structure are shown in the Fig.3.2-a,b,c,d.

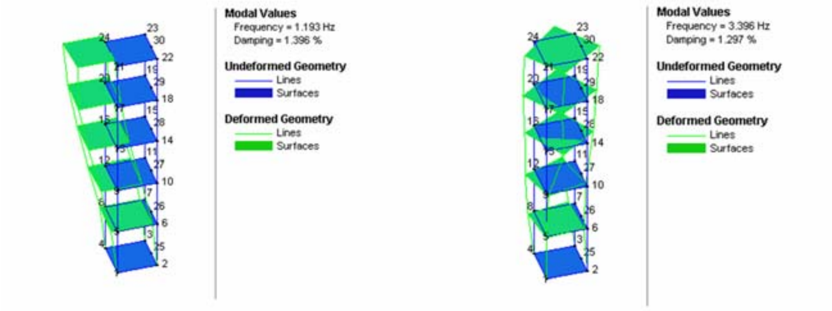


Fig. 3.2 a) 1st flexural mode shape at 1.193 Hz; b) Torsion mode shape at 3.396 Hz.

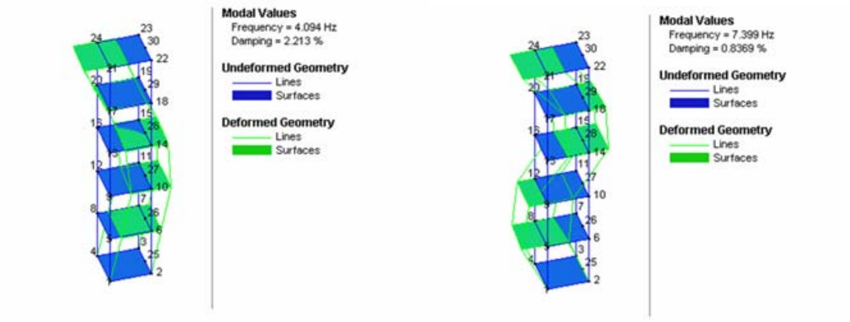


Fig. 3.2 c) 2nd flexural mode shape at 4.094 Hz; d) 3rd flexural mode shape at 7.399Hz.

The results of the CC-SSI analysis of the displacements data have been compared with the Frequency Response Function (FRF) between the accelerations recorded at the base table and top of the structure

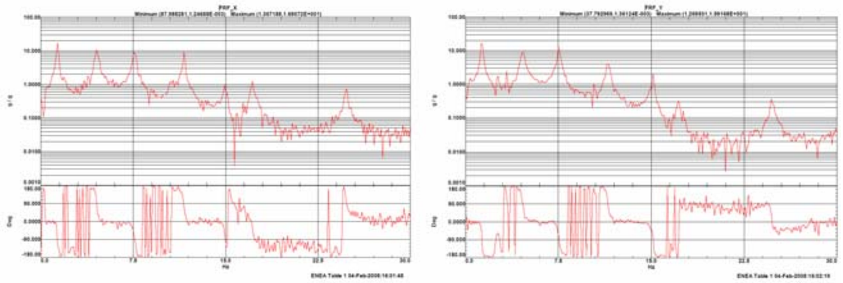


Fig. 3.3: a)FRF_X (A5_X/At_X); b)FRF_Y (A5_Y/At_Y).

The graphs in the fig. 3.3 represent the frequency response functions FRF_X (fig. 3.3-a) and FRF_Y (fig. 3.3-b) between base and top of the structure. The first three peaks of the FRFs agree with the CC-SSI flexural modes at 1.193Hz, 4.094 Hz and 7.399 Hz. Also the first torsion mode at 3.396 Hz has its signature in the FRF graphs, (see fig. 3.3-b).

Table 3.1 comparison between modal parameters estimations by CC-SSI and FRF analysis

Mode	CC-SSI Frequency Hz	CC-SSI Damping. %	FRF Frequency Hz	FRF Damping. %
1st flexural	1.190	1.396	1.35	1.90
1st Torsion	3.396	1.297	3.40	0.92
2ndflexural	4.094	2.213	4.68	1.62
3rdflexural	7.399	0.834	7.58	0.73

Conclusions

The modal parameters estimation of two structures has been performed by means of efficient time domain data-driven Crystal Clear Stochastic Subspace Identification (CC-SSI) of the displacements data recorded by a new, innovative, high resolution 3-D optical movement detection and analysis tool, tracking the dynamic displacements of several selected points of the structures during the shaking table tests. The two structures were a 1:6 reduced scale model representative of the drum-vault macro element of a church and a 5 storey steel frame structure. The validation of Finite Elements models of the structures by means of data assimilation during the shaking table tests and the comparison of the estimated modal parameters with the numerical modal analysis calculation and the FRF analysis of the experimental data showed the robustness of the modal parameters estimation.

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REFERENCES

[1] Zingone G, De Canio G, Cavaleri A (2006) On the improvement of monumental structure safety: a case study III European Conference on Computational Mechanics Solids, Structures and Coupled Problems in Engineering C.A. Mota Soares et.al. (eds.) Lisbon, Portugal, 5–8 June 2006

[2] De Canio G, Caponero M, Colucci A, Roselli I (2008). Innovative high resolution 3-d vision and optical fiber sensors for data acquisition during experimental earthquake tests The 14th World Conference on Earthquake Engineering October 12-17, 2008, Beijing, China.

[3] Mongelli ML, De Canio G, Roselli I, Colucci A, Tatì A (2010) 3D motion capture and FEM analysis for shaking table tests at ENEA Casaccia Research Center" 14 ECEE Aug. 30 - Sept 3 2010, Ohrid, Macedonia

[4] Roselli I, Mencuccini I, Mongelli ML, Beone F, De Canio G, Di Biagio F (2010) The DySCo virtual lab for Seismic and Vibration Tests at the ENEA Casaccia R.C. 14 ECEE Aug. 30 - Sept 3 2010, Ohrid, Macedonia.

[5] Dohler M,Andersen P and Mevel L (2010) Data Merging for Multi-Setup Operational Modal Analysis with Data-Driven SSI. 28th International Modal Analysis Conference (IMAC) Jacksonville, Florida USA, 2010.