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# TRACKING DYNAMIC PROPERTIES OF CIVIL STRUCTURES WHILE SUBJECTED TO SEISMIC EXCITATIONS

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**ABSTRACT:** This article examines the variations of natural frequencies, equivalent damping ratios and the high frequency component of the response as damage indicators in reinforced concrete structures subjected to seismic excitations. Experimental and simulated data from a shake table test of a real scale reinforced concrete column subjected to a sequential load protocol of increased intensity is used for this purpose. Conventional methodologies that operate on the free decay and white noise excitation responses are engaged to estimate natural frequencies and damping ratios before and after each earthquake load. Model-free output-only methodologies based on the Continuous Wavelet Transform (CWT) and Fast Wavelet Transform (FWT) of the registered accelerations are used to track frequency shifts and detect anomalies in the high frequency component of the response, respectively. It was found that the frequency shifts identified in the CWT analyses could be partially related to severe inelastic excursions in the structure. Moreover, the FWT analysis at high frequencies was found appropriate to identify sudden damage occurrences, like rebar fractures. A second approach based on the Unscented Kalman Filter (UKF) resulted to be better suited to capture the natural frequency shifts, providing also an estimate of the instant damping ratio. Nevertheless, implementation of the UKF requires knowledge of the input excitations and a simplified model of the structure. Finally, it can be concluded that if the results from the different approaches evaluated are integrated, a more robust portrayal of the damaging process undergone by the structure is produced.

## 1. Introduction

A robust tracking of the shifts in natural frequencies and equivalent damping ratios in reinforced concrete (RC) structures subjected to seismic excitations may play an important role in any structural health monitoring system as such changes may be related to damaging processes undergone by the structure. Moreover, tracking of the dynamic properties variations while the structure is subjected to seismic accelerations is desirable rather than an estimation pre and post event, since in this last approach incidents between dynamic measures are lost and significant information can be missed (Montejo 2011). Todorovska and Trifunac (2007), for example, investigated the response of a six-story reinforced concrete structure severely damaged by the 1979 Imperial Valley earthquake, and detected a decrease in the system frequency of about 44% followed by a 35% increase at the end of the recorded shaking. In this case, if the assessment was to be performed based solely on the structural vibration properties estimated before and after the earthquake, the severity of damage would be largely underestimated.

In this article we explore the viability of using signal processing based (model free – output only) methodologies and Kalman Filter schemes for tracking the variations of natural frequencies and equivalent damping ratios. The different methodologies are evaluated using experimental and simulated data from a series of progressive intensity full scale shake table tests of a typical RC bridge column that allows the evaluation of a wide range of structural performance levels (from elastic response to near collapse conditions).

## 2. Experimental and simulated data used for validation

The experimental data used in this work was registered during a set of full-scale RC bridge column shaking table tests performed at the NEES - Large High Performance Outdoor Shake Table at the University of California, San Diego. The load protocol consisted of 10 records applied sequentially to the column covering a large range of inelastic demands, low amplitude white noises were applied between earthquakes for identification purposes. The column had a cantilever length of 7.32m with a circular cross section of 1.22m diameter, additional mass representing the superstructure was provided through a 2245kN reinforced concrete block at the top of the column (Fig. 1). Longitudinal reinforcement consisted of 18 No. 11 bars and butt-welded double No. 5 hoops spaced 152mm center to center were used as transverse reinforcement. Further details of the test, material properties, and specimen geometry are available in Schoettler et al. (2012).

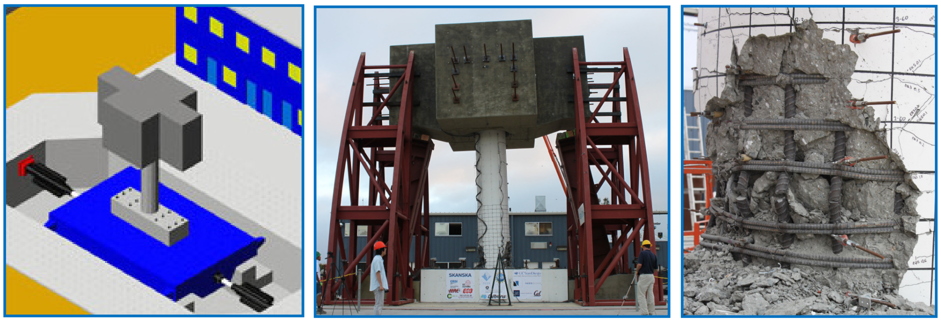

**Fig. 1 –Test setup scheme, column after EQ9 and rebar fracture close-up. Photos provided via NEEShub <https://nees.org/warehouse/project/987>**

A numerical model capable of closely replicate damaging episodes was developed and calibrated using the experimental data, this allow us to retrieve "target" structural parameters to evaluate the identification methodologies. The model was developed in OpenSees using a fiber based distributed plasticity approach. The column section was modeled using unidirectional fibers and constitutive-material relationships were specified for each kind of fiber (unconfined concrete, confined concrete and reinforcing steel). Second order effects were included using the OpenSees P-Delta coordinate transformation command and elastic damping was included as 2% tangent-stiffness-proportional damping. The strength degradation parameters for the reinforcing steel fibers were calibrated to capture the bar fracture episodes. Table 1 summarizes the tests results and Fig. 2 shows that the response obtained from the model is in close agreement with the recorded experimental response. Further information about the model and calibration process is available elsewhere (Aguirre et al. 2013).

**TABLE 1 – Significant performance levels / main response parameters**

| Test | max(\|a\|) [g] bottom | Displacement ductility | max(\|a\|) [g] top | Observations |
|---|---|---|---|---|
| EQ1 | 0.20 | 0.68 | 0.21 | Hairline cracks |
| EQ2 | 0.43 | 1.44 | 0.29 | Rebar first yield |
| EQ3 | 0.53 | 4.07 | 0.38 | Concrete cover spalling |
| EQ4 | 0.43 | 1.88 | 0.17 | No significant changes |
| EQ5 | 0.53 | 6.28 | 0.37 | Deep concrete spalling / onset of rebar buckling |
| EQ6 | 0.53 | 5.44 | 0.34 | No significant changes |
| EQ7 | 0.66 | 6.27 | 0.37 | Initial concrete core crushing / rebar buckling |
| EQ8 | 0.83 | 6.77 | 0.34 | Rebar fracture (2 ct) |
| EQ9 | 0.83 | 7.13 | 0.29 | Rebar fracture (3 ct) |

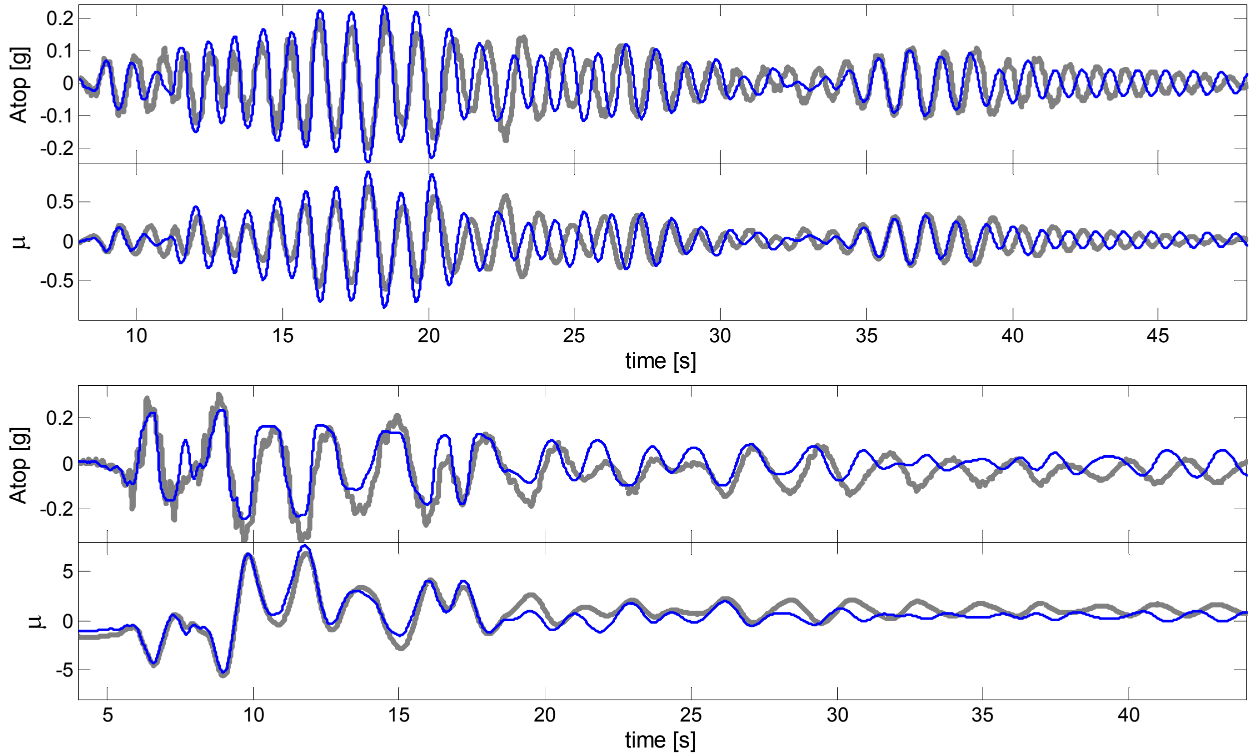

**Fig. 2 – Experimental (thick gray) and simulated (thin blue) acceleration and displacement ductility (*μ*) response for EQ1 – elastic range (top) and EQ8 – rebar fracture (bottom)**

## 3. Identification using white noise excitations and free decays

An initial identification of the column natural frequencies and damping ratios at the different test stages was performed using two different approaches. In the first approach, the free decay response is obtained by applying the Random Decrement Technique (RDT) and the Auto Random Decrement (ARD) to the white noise (WN) excitations to generate a Random Decrement Signature (RDS) as shown in Figs. 3 (left). The Hilbert Transform (HT) is then applied to the RDS to construct the so-called "analytic signal" from which the instant frequency (IF) and instant amplitude (IA) can be computed as shown in Figs. 3 (right). Finally, an average damping ratio is estimated from the slope in the linearized IA.

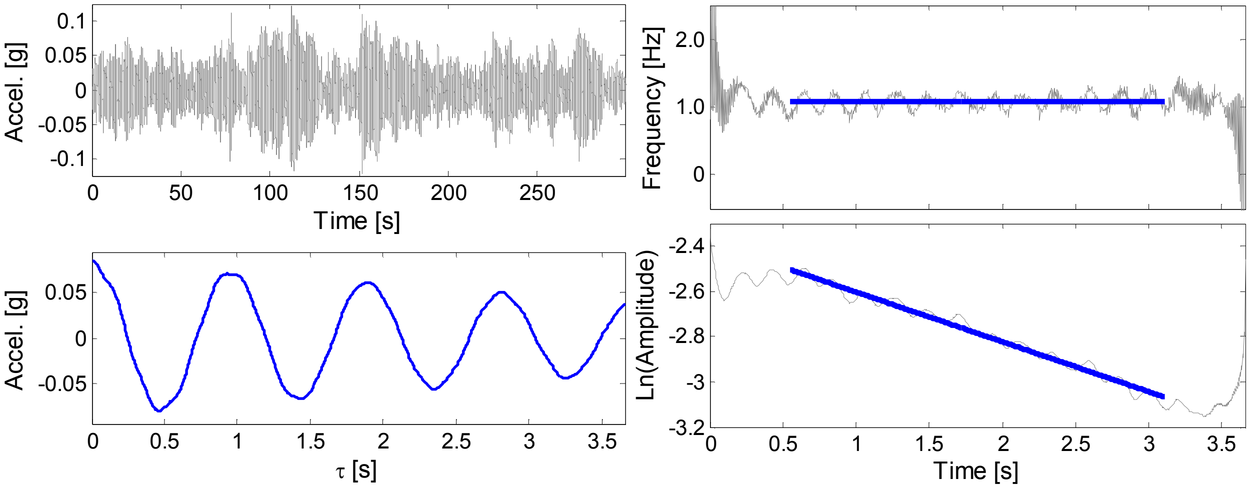

**Fig. 3 – Response to white noise excitation and extracted RDS (left), and identification of instant frequency and amplitude using the HT approach (right).**

The second approach implemented utilizes the free decay oscillations extracted from the column response to the earthquakes once the strong motion part has faded away. In this case, the decay signal is analyzed via the Continuous Wavelet Transform (CWT) using the Complex Morlet Wavelet. Since the function used to compute the CWT is complex, the resulting wavelet coefficients are also complex and extracting the CWT coefficients along the retrieved skeleton (Fig. 4) would provide us with a complex signal that is proportional to the analytic signal and can be used to identify instant frequencies and average damping ratios. Further details on the two approaches implemented are available in Aguirre and Montejo (2014). Fig. 5 summarizes the variations in natural frequencies and damping ratios obtained from low amplitude oscillations at the different load stages, it is seen that while there is a clear tendency on the natural frequency to decrease as the inelastic demand and induced damage increase, such tendency tends to saturate at large levels of ductility demand (*μ>4*). On the other hand, the damping ratios tend to remain constant around 3%.

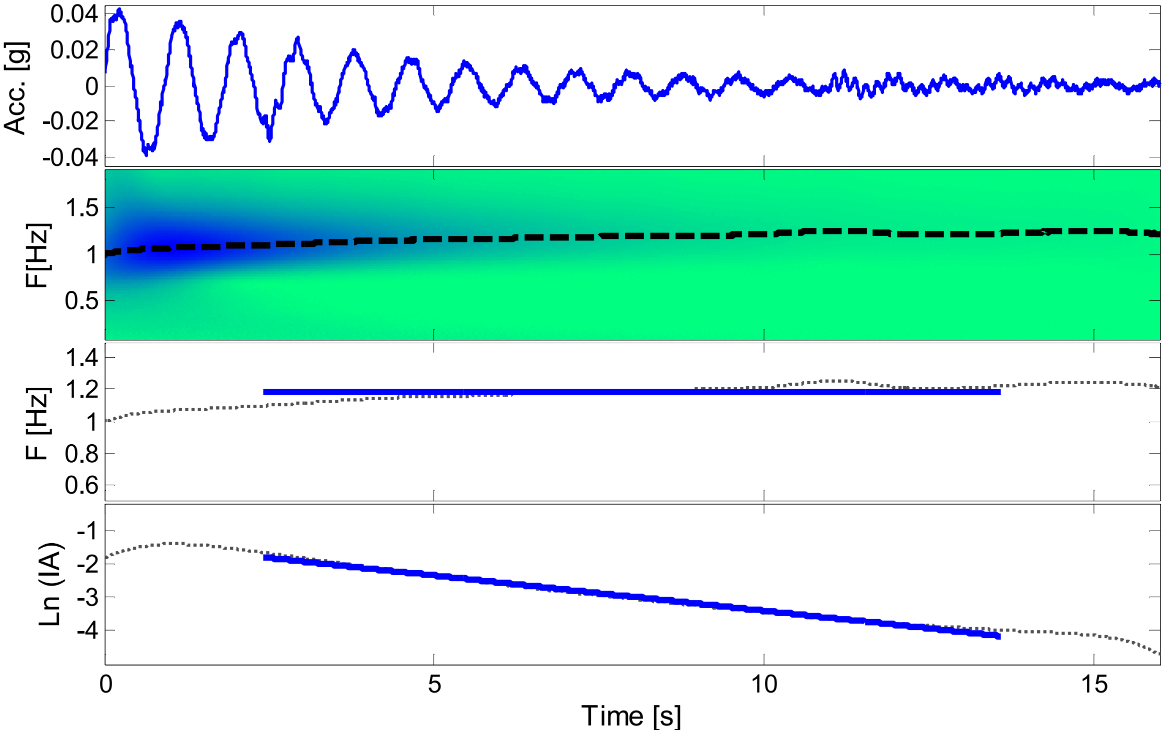

**Fig. 4 – Identification of instant frequency and amplitude via CWT analysis of the structure free decay after the strong motion part fades away.**

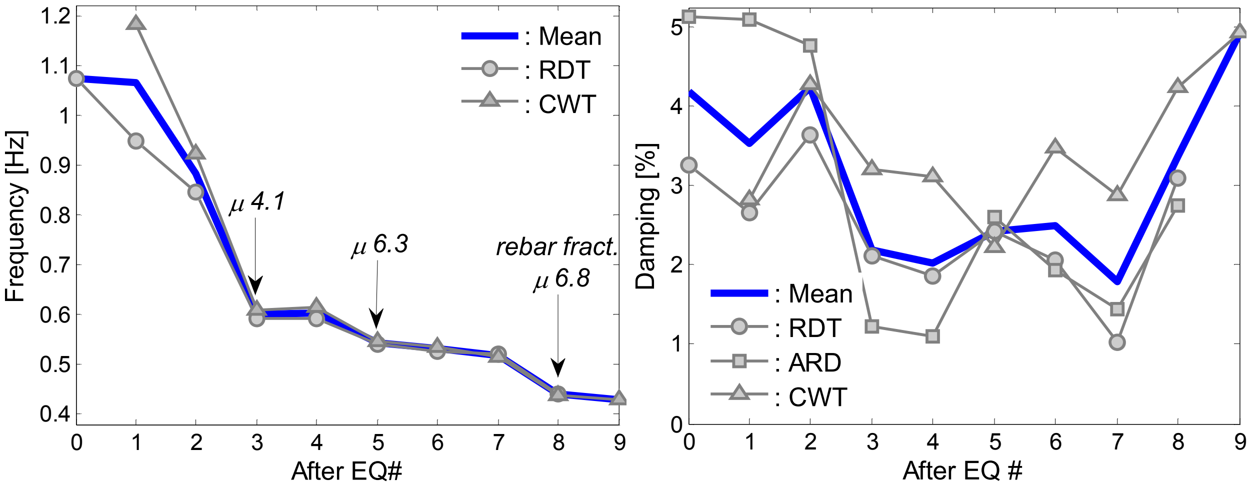

**Fig. 5 – Summary of frequency and damping ratios identified after each earthquake record.**

## 4. Wavelet based tracking of vibration frequencies and identification of singularities during the seismic excitation

Signal processing based techniques have the potential for near-real time identification of dynamic parameters and damage episodes from the analysis of the nonlinear-nonstationary characteristics of the dynamic response of the structure (usually accelerations) to the damaging event (e.g. Quiñones et al. 2105). The analysis is performed using mathematical tools that allow a time-frequency examination of the signal, like Wavelet or Hilbert-Huang Transforms (e.g. Montejo 2011, Montejo and Vidot 2012).

In this work two types of Wavelet analyses are performed: (1) an analysis at low frequencies via CWT (i.e. in the frequency range of the structure natural frequencies) and (2) an analysis at high frequencies (i.e. well above the structure frequencies of vibration and close to the signal Nyquist frequency) through the study of the so-called "detail functions" obtained via Fast Wavelet Transform (FWT).

The objective of the low frequency analysis is the identification of shifts in the vibration frequencies presumably caused by damage induced degrading stiffness. The objective of the high frequency analysis is to identify "sudden" irregularities in the response caused, for example, by large inelastic excursions or fracture of the rebar. The CWT analyses are performed using the Complex Morlet Wavelet with parameters $f_c=1$ and $f_b=2$. Computation of the FWT is accomplished using the Biorthogonal (6.8) Wavelet. Further details on the mathematical background and the computational implementation of these analyses is available elsewhere (Aguirre et al. 2013, Gaviria and Montejo 2014).

A representative sample of the results obtained is presented in Figs. 6 and 7, which shows (from top to bottom) the column acceleration response, the time history of displacement ductility, the tracking of vibration frequencies via CWT of the accelerations (Wavelet map), and the detail functions via FWT (i.e. the high frequency component of the acceleration response).

In the Wavelet maps the dashed lines on the sides of the figures denote the end-effects zone, results obtained beyond these lines are no reliable. The horizontal lines denote at the beginning and end denote the target frequency values (obtained from the previous CWT and RDT analyses). A more precise estimation of the instantaneous dominant frequencies is obtained by identifying a ridge in the time-frequency plane (yellow lines). As expected, the identified ridges tend to be unstable close to the end regions, which is a reflection of the poor quality of the Wavelet coefficients in this zone. A smoothed version of the identified ridges obtained by applying a 1 second window running average is also displayed in these figures (black dashed line). It is seen from the wavelet maps that frequencies identified by the CWT at the beginning and end of the motion coincide with the target values. Moreover, there are time instants where the identified frequency drops substantially below the final target frequency, this phenomenon is investigated in the next section with the aid of the numerical model developed and a Kalman based identification scheme.

The detail functions are presented in its absolute values and are standardized by subtracting the mean and dividing by the standard deviation. To avoid the identification of spurious spikes, a threshold value of 6 is adopted, i.e. the instants at which the absolute amplitude deviates more than 6 standard deviations (horizontal red line) from the mean value, are treated as damage instants. It is seen that the irregularity detected during EQ3 coincides with the first large inelastic excursion, however, further inelastic excursions occurring during the same and further excitations (EQs 4 to 7, not shown in here for space constrains) are not detected. The next high frequency irregularities are detected during EQ8, where two large spikes emerge with normalized magnitudes about 4 times larger than the spike in EQ3. It is inferred that each spike is pinpointing the rebar fracture episodes that occurred during this load stage. It is also noticed that these instants coincide with the points where the vibration frequency detected substantially decreases. Moreover, analysis of the ductility demand time history reveals that the fracture of the longitudinal bars took place at 14.6 and 18 seconds at intermediate levels of ductility, after two large inelastic excursions in the opposite direction have occurred.

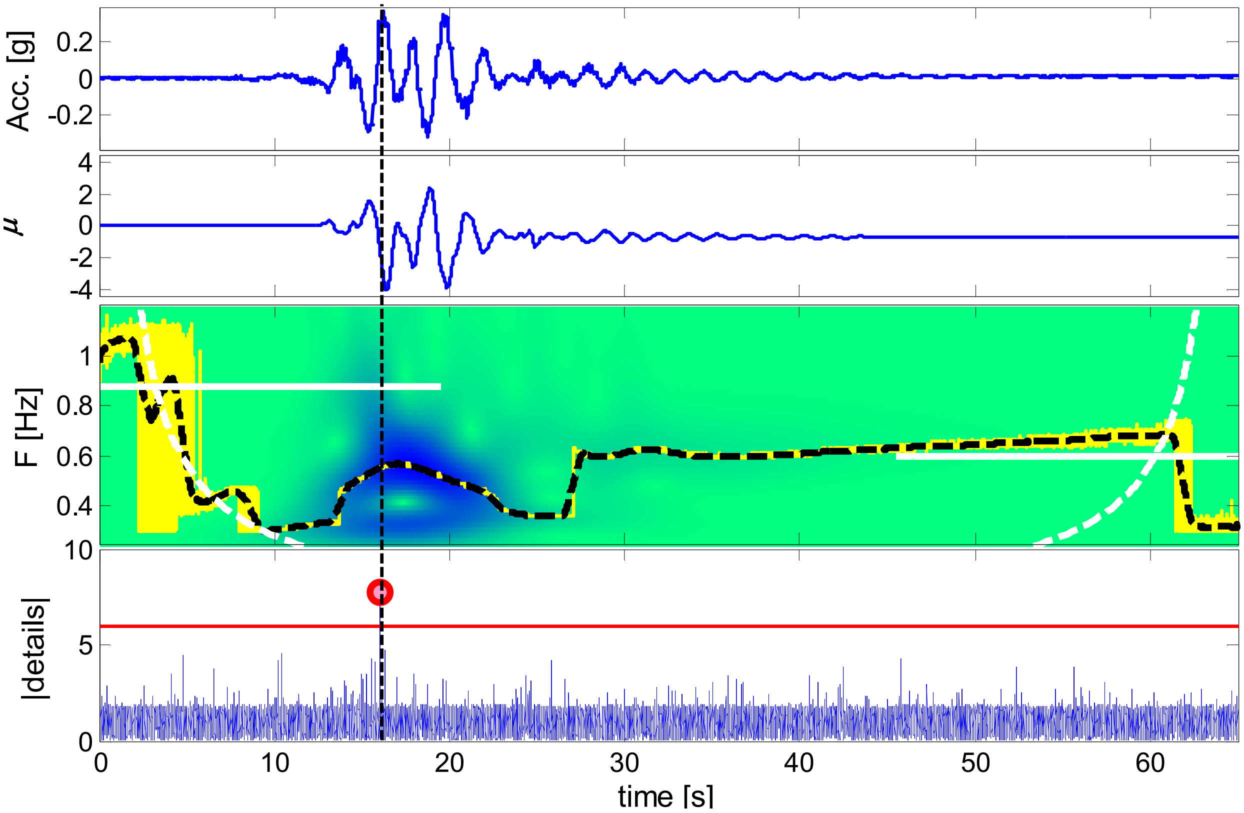

**Fig. 6 – Frequency tracking and high freq. singularities detection for EQ3**

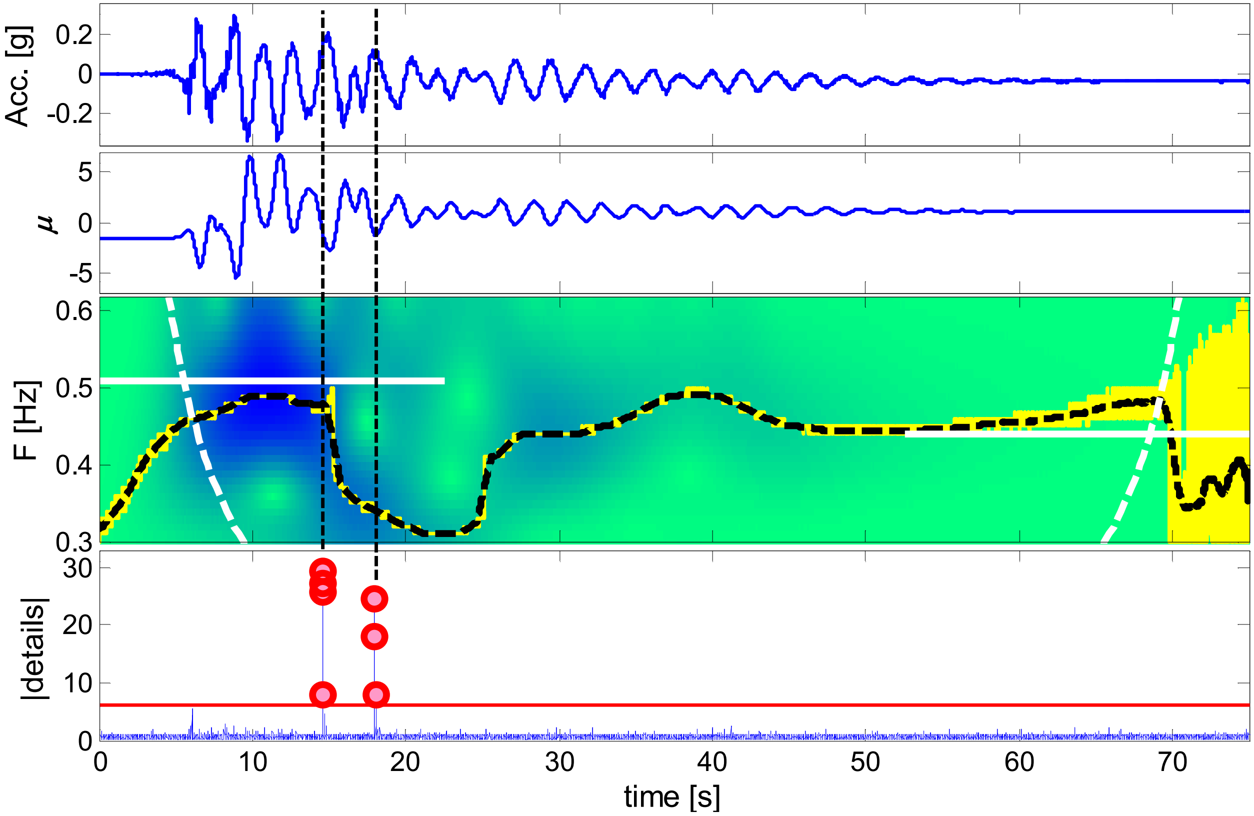

**Fig. 7 – Frequency tracking and high freq. singularities detection for EQ8**

## 5. UKF based tracking of natural frequencies and equivalent damping ratios

The signal processing based methodologies described in the previous sections are quite appealing for damage detection and health-monitoring applications as they only require the dynamic response of the structure to operate. Nevertheless, two important limitations are worth noticing: (1) the identified frequency shifts are based on vibration frequencies that not necessarily coincide with the structure natural frequencies and (2) the damping ratios are estimated at low amplitude oscillations after the strong motion part of the earthquake fades away. Therefore, these damping estimates can hardly provide any information regarding the energy dissipated during the structural response to the strong motion.

This section presents the results obtained using an Unscented Kalman Filter (UKF) based scheme for the identification of the properties of the UCSD column. Moreover, the UKF is used to statistically optimally update a simple piece-wise linear model of the structure implemented to track the changes in the structural/dynamic properties as the structure is subjected to the seismic excitations. It shall be noticed that in addition to the acceleration response, this approach requires knowledge of the input/base accelerations as well as the development of a numerical model of the structure. For simplification of the identification process, degrees of freedom associated with rotation are not considered in the model. Thus, the actual behavior of the structure is forced to match an “equivalent shear building’ model, i.e. the column is modeled as an elastic SDOF with properties updated each time within the UKF scheme. The nonparametric representation of the non-linearity avoids assumptions about nonlinear hysteretic behavior of the structure and adjusts to a wide range of possible behaviors (Ghanem and Ferro 2006). This also implies a reduced number of parameters to be estimated during the analysis compared to other nonlinear approaches. For example, considering that in the SDOF model the mass is known, only the stiffness and damping coefficients need to be identified, significantly less than the ~9 parameters needed to define a hysteretic Bouc-Wen like model. Further details on the development and implementation of the UKF-based scheme is available in Gaviria and Montejo (2015).

The UKF approach was applied to the simulated data, rather than the experimental, so that the actual structural properties can be retrieved from the model at each time step and used for validation purposes. The data was contaminated with Gaussian noise histories with 1% g RMS to recreate conditions that are more realistic. Figs. 7 and 8 show the results obtained for EQ3 and EQ8, respectively. These figures show from top to bottom: acceleration time history, displacement ductility time history, frequency shifts estimates in top of the Wavelet map and the equivalent damping ratio variations. Estimated frequencies and damping ratios presented have been smoothed using a 0.9 s running average. The estimated frequencies are calculated based on the stiffness values adjusted each time step by the UKF, frequencies are presented rather than stiffness so that a comparison can be made with the results obtained from a CWT analysis. Total equivalent damping ratios from the numerical model results are calculated as the specified elastic damping ratio plus the hysteretic damping estimated using the Jacobsen’s approach without any corrections factors (e.g. Priestley et al. 2007, Montejo et al. 2009). The following observations applied for the results obtained in both cases:

- The closest estimates are obtained for the accelerations since this is the only measure used to update the model
- The displacement histories obtained closely resemble the actual displacements variations, including matching of the peak displacements. However, the residual displacement is not captured due to the elastic nature of the model employed.
- The frequencies estimated via UKF are closer to the ones reported by the model than the obtained through the CWT. As mentioned earlier, any signal processing based procedure will identify vibration frequencies that may or not concur with the structural natural frequencies. This is reaffirmed by the fact that once the strong motion part vanishes, i.e. when the response of the structure is mostly a free decay, both estimates coincide with the actual frequency from the simulation. Moreover, it is revalidated that during the large inelastic demands the structure can reach natural frequencies significantly lower than the exhibited at the end of the excitation.
- The viscous damping ratios estimated via UKF and their variations are in close agreement with the total equivalent damping ratios computed from the simulated response. Moreover, the maximum damping ratios obtained during each excitation seem to correlate well with the peak inelastic demand.

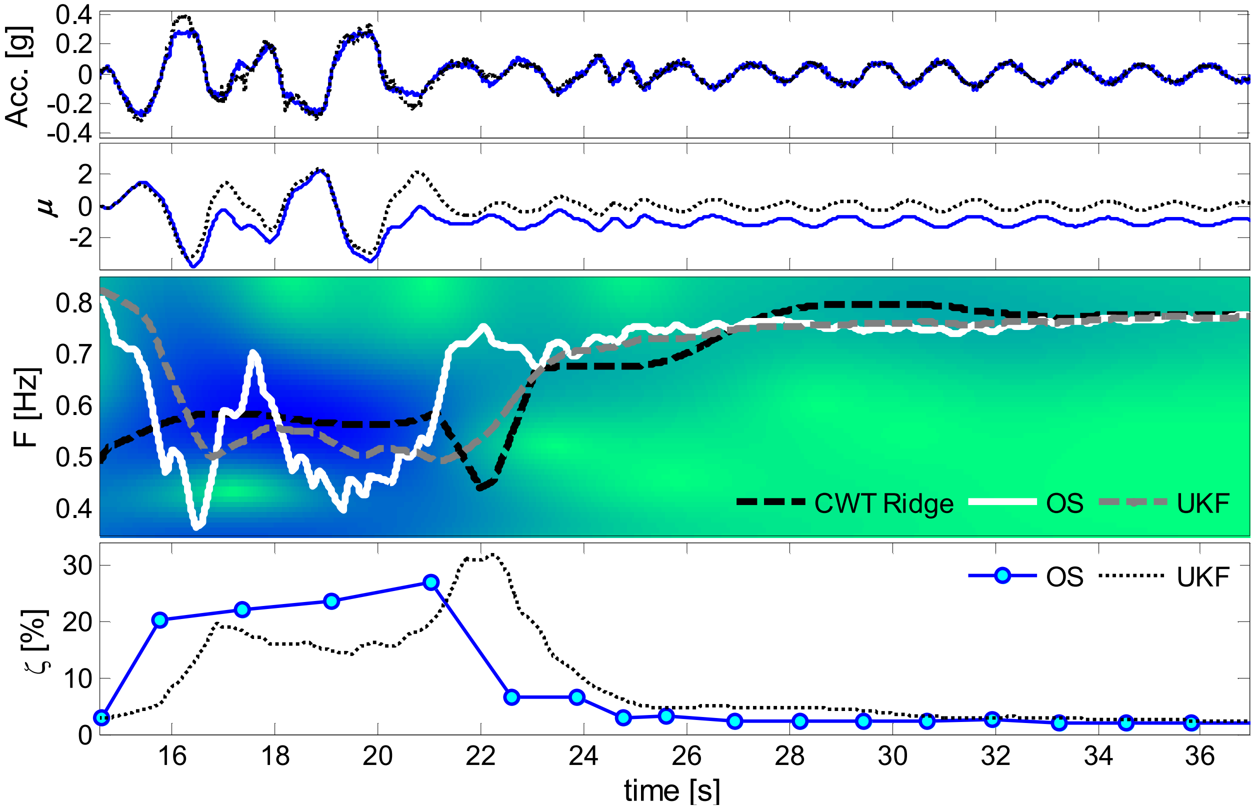

Fig. 8 – Acceleration, displacement, frequency and damping tracking for EQ3

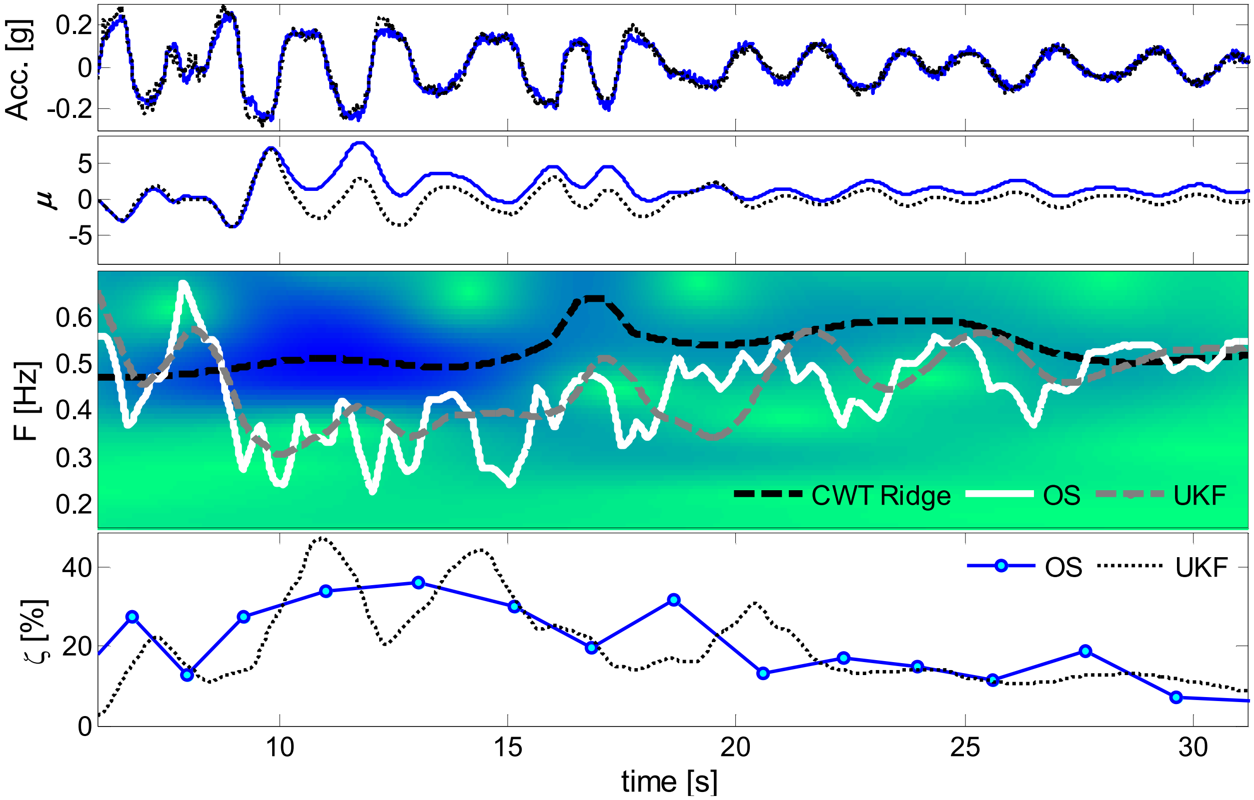

Fig. 9 – Acceleration, displacement, frequency and damping tracking for EQ8

## 6. Conclusions

Damage assessment based on the comparison of the structure dynamic properties before and after the damaging event can largely underestimate the level of damage undergone by the structure. While post-event natural frequencies do exhibit a tendency to decrease as the level of lateral demand increases, the observed frequency shifts tend to saturate at large levels of ductility demand making it troublesome to differentiate between moderate and severe levels of damage. Therefore, it is desirable to complement these type of analyses with methodologies that allow tracking of the properties from the response of the structure to the damaging event.

Tracking of frequencies from a simultaneous time-frequency representation of the dynamic response of the structure during forced vibrations must be handled thoughtfully as the identified vibrational frequencies not necessarily concur with the structure natural frequencies. Conversely, the UKF approach, while more computationally demanding, is aimed to directly track the variations on the structure parameters that can be used to provide estimates of the time variations of natural frequencies and equivalent damping ratios.

## 7. Acknowledgements

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