LESSONS LEARNED FROM TWO DYNAMIC MEASUREMENTS FOR VERY TALL BUILDINGS

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Abstract

Dynamic measurements using accelerometers in the natural environment were carried out on 25- and 42-story concrete buildings to extract their inherent properties such as natural frequencies, mode shapes and damping ratios. For the operational modal analysis, the FDD and SSI methods, currently considered as the most advanced techniques in frequency and time domains respectively, were used in addition to the more classical ANPSD method. The extracted modal parameters were also compared with those from the FE analysis made at the initial phase of design. Due to the similarity of dimension or stiffness in the principal axes of the building, very close modes of vibration were observed in both buildings, while the significant coupling between torsion and transverse motions was maintained in a 25-story building. In overall sense, acceptable representation of the building behavior was acquired from measurement through FDD and SSI although higher natural frequencies were noted in lower modes when compared with the results predicted by the FE models. It is deduced that this difference might be from the crudeness in the FE modeling. Discussions were made for improving the quality of measurements and for correlating with the results by the FE analysis in the future study.

1 Introduction

Operational Modal Analysis to identify the dynamic characteristics of large civil engineering structures such as high-rise buildings using dynamic measurements is becoming more important due to almost the impossibility of measuring the input source, resulting in the more realistic representation of their behavior based on a variety of conditions. The accurate assessment of dynamic properties for such structures is indispensable in further developing the procedures of finite element model (FEM) updating, structural health monitoring (SHM), structural vibration control (SVC), etc.

In view of many advantages occurring from the consideration of the natural environmental condition as an excitation source, such as no elaborate arrangement of equipment, no simulation of boundary conditions and no possible damage on the structure, the natural or ambient vibration test is more preferable in many areas than the forced vibration one. It measures only the response and in turn, requires the so-called output-only modal or system identification techniques that have still been a challenging research area, particularly associated with very noisy data normally expected in high-rise building structures. (Ref [1])

This paper examines three modal identification methods commonly used for large civil engineering structures by extracting the dynamic properties of 25- and 45-story concrete buildings from sets of acceleration records measured at a number of floors using the scheme of reference and roving sensors. Comparisons between identified properties from measurement and analyzed from the FE models currently adopted in practice are also made to demonstrate how close or different they are.
so that structural engineers can utilize this information to deepen the understanding of the dynamic behavior for such very tall buildings.

2 Description of Buildings

A 25-story reinforced concrete building under consideration called DWD building and located in Gwangju, Korea, poses a hollow type of structural configurations, consisting of a core wall on the north side of the building throughout. The additional walls and frames on the remaining three sides were placed in stories above and below ground, respectively as shown in Fig. 1. This ensures the structural symmetry only in the NS direction. (see Fig. 2) It contains the residential units in the tower, with dimensions 37 m by 38 m and the commercial areas in the lower three stories with the extended floors, 54 m by 51 m in plan. A 5-story underground parking garage is located beneath the building and the overall elevation above the ground level is 104 m. The footprint of this building is nearly square, while it includes the central void throughout above the 4th floor where the full story-height transfer girders are placed in the perimeter of the tower. The mat foundation is used over piles reaching the sedimentary rock. The construction of this building was completed in 2005.

The other 42-story reinforced concrete building under consideration, called DLA building and located in Pyungchon, Korea, contains towers in pair with the common and enlarged floor areas in the lower six stories, as shown in Fig. 3. To this, the full story-height transfer girders have to be provided over the tower areas between levels 7 and 8. Each tower, 64 m by 28 m in plan, consists of a core wall connected to external columns by outrigger beams with some irregularity, because both bays between parallel external frames and a core wall in the long or NS direction have opposite setbacks every two stories on each transverse side in a stepped manner from levels 26 to 40. This results the anti-symmetrical structure in the tower. (see Fig. 4) There are residential units in the tower and commercial spaces in the lower stories. The building is 162 m in height from the ground level and a 5-story parking garage is located below ground over the area combining twin towers. The foundation used is the mat type with supporting piles, and this building has been built very recently. Only one tower was measured.

3 Measurement and Processing

Eight force-balanced type accelerometers by Gurlap (CMG-5U: 100 Hz natural frequency, 5 V/g sensitivity and 130 dB dynamic range) were used, two for references and the remaining six for roving with two floors in a setup. Using the $\pm 0.05 \, g$ high gain option in sensors and the adjustable gains up to 80 in the data acquisition, the signal can be amplified up to 1600 times. The resolution of the sensors that can be obtained with RogaDAQ16 having a 16bit A/D converter is 0.038μg. All measurement parameters were controlled by DasyLab that enabled various low sampling rates, screen monitoring through graphics, filtering, triggering, etc. Measurements were taken in two locations on each floor beginning from the roof down to the ground floor by two floors at a time, resulting in a total of thirteen setups for DWA building. For DLA building, a total of ten setups were obtained by skipping every two stories between setups.

Data were sampled at a rate of 100 Hz with 16 times over-sampling and the anti-aliasing filter had a cut-off frequency at 40 Hz in an 8th order Butterworth type. Each setup lasted about 30 to 40 min. In the field, data recorded were detrended, filtered and decimated, and then processed to estimate PSDs (Power Spectral Density) with a frame of 1024 or 2048 data points, 66.7% overlapping with Hanning or Rectangular windows. Before applying more complicated identification methods,
particularly SSI, it is desirable to reduce data as much as possible to avoid the problems associated with memory shortage.

4 System Identification

The identification was carried out by ANPSD (Average Normalized PSDs), FDD (Frequency Domain Decomposition) and SSI (Stochastic Subspace Identification) methods with the help of ARTeMIS for FDD and MACEC for others, although the former offers the EFDD (Enhanced FDD) and three variants of the data-driven SSI described below.

4.1 Average Normalized PSD

The estimation of ANPSD starts from converting measured accelerations to frequency domain values by DFT (Discrete Fourier Transform), and then normalizing the PSD for each record to the sum of all PSDs within the frequency range of interest and averaging all normalized spectral densities for selected sets of records. (Ref [4]) The values of a coherence function close to one for two simultaneously recorded output signals indicate the natural frequencies at the peaks or the vicinity of the corresponding ANPSD. The coordinates for mode shapes can be determined by the values of transfer functions at the natural frequencies, defined as the ratio of the responses measured by a roving sensor to a reference sensor. This process is more valid when modes are sufficiently separated and damping is lower, so requires user’s significant engineering judgment to be able to derive the meaningful results for other cases, although it is fast.

4.2 Frequency Domain Decomposition

The FDD is an extension of the classical frequency domain approach, ANPSD. In the FDD, the spectral densities are first calculated from measured responses using simple signal processing like DFT. However, instead of using them directly as in the ANPSD, the spectral density matrix is formed and decomposed at every frequency line using SVD (Singular Value Decomposition), resulting in a set of auto spectral density functions, each corresponding to a single degree of freedom (SDOF) system. This is exactly true in cases when the unknown input is white noise, the structure is lightly damped, and the mode shapes of close modes are geometrically orthogonal. The singular vectors in the SVD are used as the mode shape vectors, and the natural frequencies are estimated by taking each individual SDOF auto spectral density function back into time domain by the inverse DFT. Then, the frequency and the damping can be simply estimated from the crossing times and the logarithmic decrement of each SDOF auto correlation function. (Ref [5])

4.3 Stochastic Subspace Identification

Subspace methods identify state-space models from output data by applying robust numerical techniques such as QR factorization, SVD, and least squares. (Ref [6]) In contrary to the covariance-driven SSI, the data-driven SSI method avoids the computation of covariances between the outputs by projecting the row space of future outputs into the row space of past outputs. In fact, covariances and projections are closely related, so both are for removing the noise. The projection is computed from the QR factorization of a big data Hankel matrix. A significant data reduction is achieved with only a part of the R factors being needed in the subsequent algorithm. Both methods then proceed with SVD. This decomposition reveals the order of the system and the column or row space of the corresponding matrix. Several variants of the data-driven SSI exist. They differ in the weighting of the data matrices before the application of SVD. This weighting determines the state-space basis in which the identified model will be identified. Well-known variants are Canonical
Variate Analysis (CVA), Principal Components (PC) or Unweighted Principal Components (UPC). In practical applications, no differences in accuracy can be seen in any of the variants of SSI in view of the identified modal parameters. Herein the data-driven SSI with CVA was adopted.

5 Comparison and Discussion

With three identification methods, the values of the first 9 structural mode peaks for DWD building
and the first 10 structural modes for DLA building, representing the natural frequencies of the building, are listed in Tables 1 and 2.

The ANPSD diagrams for DWD and DLA buildings were obtained from thirteen and ten setups respectively, each setup consisting of eight channels and measuring for about 30 to 40 min. To better represent the frequency range of interest, decimation with the factor 4 or 5 was made and a time window of 2048 points was normally applied before estimating ANPSD. Although this nonparametric method now seems to be quite out-of-date, all the peaks comprising the dominant dynamics of a building can be well included in the ANPSD. However, high subjectivity exists in selecting peaks as to which one is the structural frequency.

The FDD peak picking editor in ARTeMIS provided the distribution of singular values of the spectral density matrix for each building as shown in Fig. 5. This also needs some judgment of users in selecting the peaks, but noise can be further reduced through SVD and clearer mode shapes can be obtained using singular vectors, compared with ANPSD.

Figs. 6 show 3D wireframe views of the first 9 modes of vibration for DWD building by FDD. Even though the spatial distribution of the sensors is not enough to clearly define the mode shapes, a simple linear interpolation based on the rigid floor motion helps provide a clear picture of the nature of each mode identified in the analysis. For DWD building, the modes are well defined in the NS and torsion directions, while the ES motion is significantly coupled with torsion after its lowest mode due to the asymmetry of wall placement. In addition, it is noted that the NS transverse and torsion modes are very close because of the similarity between the corresponding stiffnesses. Ten modes were obtained for DLA building, clearer than DWD building due to some difference in stiffness between transverse motions. However, the NS direction mode is more coupled with the torsion than the EW motion, indicating more asymmetry from setbacks apparent in the NS direction. This makes sense that because of long dimension, the effect of asymmetry becomes more evident although both directions have a similar degree of anti-symmetry in stiffness.

From previous experience with SSI, it is suggested to sufficiently overspecify the model order, and then to eliminate the spurious numerical poles afterwards by constructing a stabilization diagram. A series of modal parameters can be obtained from increasing the order of the model while eliminating smaller singular values correspondingly, and then can be plotted in the form of a diagram as stated, with some acceptance criteria such as below 1% difference for eigenfrequencies, 5% for damping ratios and 1% for mode shape vectors between previously and currently estimated values. In a new version of MACEC, an additional criterion, the so-called modal transfer norm, from model reduction theory is implemented that seems to be promising for further development of the full automation process, resulting from the automatic selection of stable poles in a stability diagram.

The stabilization diagram for one typical setup for DWD or DLA building is shown in Fig. 7. All frequencies with higher model orders corresponded to those obtained from FDD reasonably, and acceptable mode shapes were animated in both buildings. However the SSI method required the significant computational time although some setups that seem to have contamination or for other reasons were intentionally removed, resulting in seven and eight setups for DWD and DLA buildings, respectively. Tables 1 and 2 also include natural frequencies from the FE analyses on two buildings by MIDAS, a general purpose program developed domestically for the analysis of building structures. (Ref [7]) The FE models incorporated here represent the normal practice widely adopted in the design offices in Korea. The core wall was modeled by an assembly of plane stress elements, and stick elements were used for columns and beams. At the connections between a core wall and beams, the rotational degrees of freedom for beams were restrained by increasing the flexural stiffness of extended beams for compatibility. Non-structural elements such as in-filled
Table 1 Comparisons of identified results for DWD building

<table>
<thead>
<tr>
<th>Mode</th>
<th>FEM(Hz)</th>
<th>PP(Hz)</th>
<th>FDD(Hz)</th>
<th>SSI (Hz)</th>
<th>Damping (%)</th>
<th>(Dir)</th>
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<tr>
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<td>0.918</td>
<td>0.919</td>
<td>0.6</td>
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<tr>
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<td>2.222</td>
<td>2.213</td>
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</tr>
<tr>
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<td>1.407</td>
<td>2.417</td>
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<tr>
<td>6</td>
<td>1.606</td>
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<td>2.734</td>
<td>2.738</td>
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<td>2Tor</td>
</tr>
<tr>
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<td>3X &gt; 3Tor</td>
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Table 2 Comparisons of identified results for DLA building

<table>
<thead>
<tr>
<th>Mode</th>
<th>FEM(Hz)</th>
<th>PP(Hz)</th>
<th>FDD(Hz)</th>
<th>SSI (Hz)</th>
<th>Damping (%)</th>
<th>(Dir)</th>
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<tr>
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<td>3.345</td>
<td>3.330</td>
<td>2.612</td>
<td>0.7</td>
<td>4X-trans</td>
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</table>

masonry walls, stairways, flexible floors, and soil stiffness were not modeled. Any modifications have not been made so far for better correlation with measured results. Comparing measured and analyzed results, it is surprising that there is nearly the two times difference in natural frequencies in the lower three modes at least. This simply means that the stiffness of a real structure was modeled four times less. However, on the other hand this might be possible from fact that the previous research reported the seven times increase in the lateral stiffness of a three story infilled frame compared to a similar bare frame. (Ref [8]) It is also known that the accurate modeling of a
building structure is quite difficult due to many complexities and uncertainties. Until now, definite conclusions about this have not been reached, however the possible candidates are non-structural elements such as in-filled masonry panels and stairways, a box type behavior of the unit enclosed by top and bottom slabs and both side walls cast in the monolithic way, increased strength of concrete and some structural changes from the time of an analysis. More investigation on these is needed.

6 Conclusion

It has been demonstrated that the structural properties of a real building can be extracted with some degree of confidence from natural response vibration by using the output-only modal analysis such as FDD and SSI methods. Both methods seem to be reliable in identifying the natural frequencies, mode shapes and damping ratios in that they are providing consistent results. The former seems to be more efficient in view of the computational time required, although more detailed information is sacrificed due to the nature of algorithm. To a higher degree of reliability for the identified results, the most accurate measurement has to be ensured first, and then very careful interpretation between identified and measured results is necessary. The use of a 24 bit A/D converting unit along with the analog anti-aliasing filter at the lower frequency might be a solution to further increase the signal-to-noise ratio in the present testing configuration.

Comparing the structural properties extracted from dynamic measurement and analyzed from the FE analysis on two very tall buildings, the large difference between them about two times is apparent from some unknown reasons so far. It can be judged that the crudeness of the FE model at the initial phase of design might be the main reason, from the fact that non-structural elements such as in-filled panels and stairways, a box type behavior of the unit enclosed by top and bottom slabs and both side walls cast in the monolithic way, increased strength of concrete and some structural changes were not properly considered. More study on the FE model updating is necessary in the future study.

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7 References


(b) 0.791Hz  
(c) 0.918Hz  
(d) 2.222Hz  
(e) 2.417Hz

(a) 0.713Hz  
(f) 2.739Hz  
(g) 3.945Hz  
(h) 4.678Hz  
(i) 4.971Hz

Fig. 6 Mode shapes for DWD by FDD

Fig. 7 Stability diagrams by SSI for DWD and DLA