

AMBIENT VIBRATION TESTING & MODAL IDENTIFICATION OF AN OFFICE BUILDING

Lingmi Zhang¹, Yukio Tamura², Akihiko Yoshida², Kangpyo Cho²,
Shinji Nakata³ and Shunichi Naito⁴

¹Institute of Vibration Engineering
Nanjing University of Aeronautics & Astronautics, China

²Dept. of Architectural engineering
Tokyo Institute of Polytechnics, Japan

³Housing Division
Asahi Chemical Industry Co., Ltd. Japan

⁴Taku Structural Design Co. Ltd. Japan

Abstract

Ambient vibration test and modal identification of a 15-story office building newly completed in Tokyo are described in this paper. There are 200 DOF's in the test model of the building with 48 real acceleration measurements and 152 virtual measurements under the rigid floor assumption. It took less one-day to finish all the ambient response measurements in four setups, 14-channel for one setup with two sensors as references. The Frequency Domain Decomposition (FDD) technique is adopted for ambient or output-only, modal identification. Within interested frequency range of 0 to 4.5 Hz, altogether 9 modes were accurately identified. As one of the major focus of the project, accurate damping estimation was conducted based on damping convergence with increasing frequency resolution of the PSD measurement. The identified modal frequencies and mode shapes were utilized for FE model correlation and tuning. Excellent agreement of modal parameters up to 9 modes has been achieved with respect to the final tuned FE model.

1 Introduction

Dynamic characterization of civil engineering structures (CES's) becomes increasingly important for dynamic response prediction, finite element modal updating, structural health monitoring, as well as passive and active vibration control of the high/middle-rise buildings, towers, long-span bridges, etc. A CES can adequately be excited by non-measurable ambient, or natural, excitation such as wind, turbulence, traffic, and/or micro-seismic tremors. Ambient vibration test has two major advantages compared to forced vibration test for obtaining dynamic characteristics of large civil engineering structures. One is that no expensive and heavy excitation devices are required, and, therefore ease and economic to implementation. The other advantage is

that All (or part) of measurement coordinates can be used as references, and therefore, the identification algorithm used for operational modal analysis must be MIMO. The closed-spaced or even repeated modes can easily be handled.

Structural system identification based on ambient response measurement has drawn great attention in civil engineering community in recent years for extracting dynamic characteristics, such as natural frequencies, damping ratios and mode shapes.

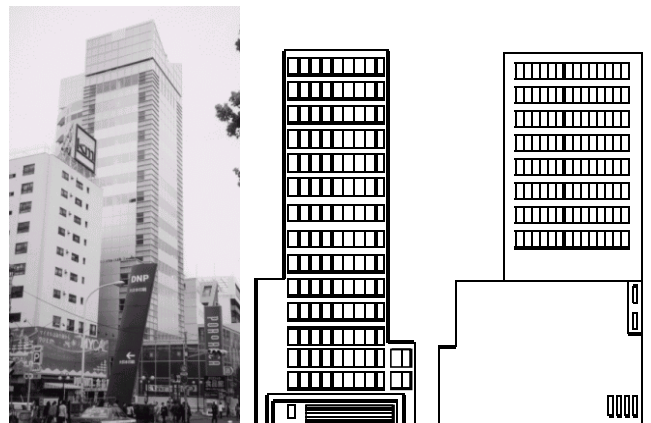


Fig. 1 CFT Building

A research project was launched for dynamic characterization of a newly design and constructed 15-story office building with the first author as project leader. Fig. 1 shows a photo and planner graph of the building. The building has columns with so called Concrete Filled Steel Tube (CFT), and beams with wide flange shapes. The CFT structural system was invented as the result of the New Urban Housing Project organized during 1985 - 1989 by the Ministry of Construction of Japan. The box-shape steel pipe is filled with high-

strength concrete, thus realizing high stiffness and high strength due to the confining effects of the steel pipe on the concrete.

In the research project, ambient response measurements of the CFT building in the field at different construction stages were planned in order to investigate the variation of its dynamic characteristics with the progress of construction. This was done in order to examine the separate contributions of the steel frames, the column concrete, the floor slabs, the external walls, and the internal walls, etc., to the dynamic characteristics of the building. Detecting the change in the dynamic characteristics with an additional structural members or architectural parts, more accurate quantitative evaluation of the contribution of these members and parts to the analytical finite element model (FEM) of the building can be obtained.

During the structural construction, three sensors were used to obtain fundamental natural frequencies and damping ratios. Free decays of fundamental transverse (x and y directions) and torsional modes were obtained via random decrement technique with band-pass filtering. Logarithmic decrement was then employed to calculate natural frequencies and damping ratios of the first three modes.

After completion of the building, full measurements were taken, and higher order modes with not only natural frequencies and damping ratios, but also mode shapes, were identify. Newly developed and more accurate technique—Frequency Domain Decomposition (FDD) was adopted for ambient modal identification of the completed building.

Ambient response measurement and modal identification of the CFT building newly constructed in Tokyo is presented in this paper. Ambient test planning, data acquisition and signal procession are described. There are 200 DOF's in the test model of the building with 48 real acceleration measurements and 152 virtual measurements under the rigid floor assumption. It took less one-day to finish all the ambient response measurements in four setups, 14-channel for one setup with two sensors as references. Within interested frequency range of 0 to 4.5 Hz, altogether 9 modes were accurately identified via enhanced Frequency Domain Decomposition (EFDD) technique ^[1]. The identified modal frequencies and mode shapes were utilized for FE model correlation and tuning. Excellent agreement of modal parameters up to 9 modes has been achieved with respect to the final tuned FE model.

2. Ambient Response Measurement & Signal Processing

2.1 Test Planning

The building to be tested is a middle-rise 15-story office building with height of 53.4 m, located in Ichigaya, Tokyo. The lower six stories are larger in floor plan from the remainder 9 stories, external irregular setback to the main body of the building at the three sites at the different floors below 6th floor.

In order to have sufficient spatial domain resolution and correlate with finite element analysis, a test model with 200 DOFs in two lateral directions was established. There are 14 measurements for one setup with two sensors at coordinators 91x and 91y at the 15th floor as references for all four setups (Fig. 2). It is reasonably assumed that the floor satisfies rigid body motion. The measured vibration was translated into equivalent motions at the five desired corners. Altogether 53 real measurements are taken, and 147 “ virtual measurements” are added via constrain equations.

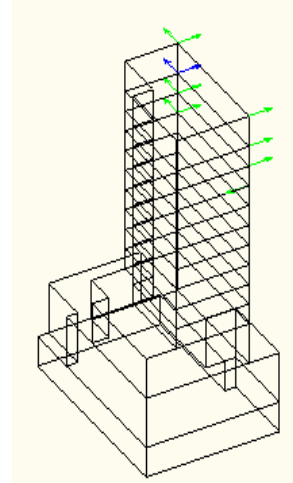


Fig. 2 Test model

2.2 Ambient Response Measurement

2.2.1 Sensors placement

Fourteen (14) server-type accelerometers (RION Corp) with relevant signal conditioners were used for ambient response measurement. With high sensitivity and 10^{-6} V/g acceleration resolution, sufficient response signal can be obtained. Two of them were allocated as reference accelerometers, the rest of 12, 12, 12 and 10 accelerometers were used as roving sensors for the 1st, 2nd, 3rd and 4th setups, respectively. Three accelerometers were typically placed in the southeast (x direction) and northeast corners (x and y directions) from 7th floor to the 15th floor and the roof. Six (6) accelerometers are placed at 2nd, 4th and 6th floor, respectively. Fig. 3 gives photos of the accelerometers with signal conditioner. Fig. 4 shows sensor placement at different floors.

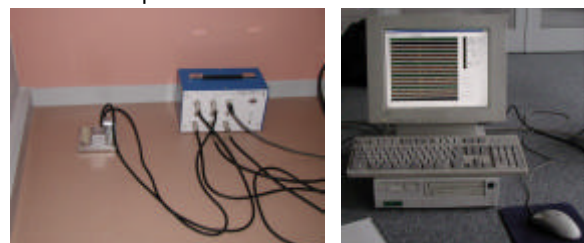


Fig. 3 Field measurement equipments

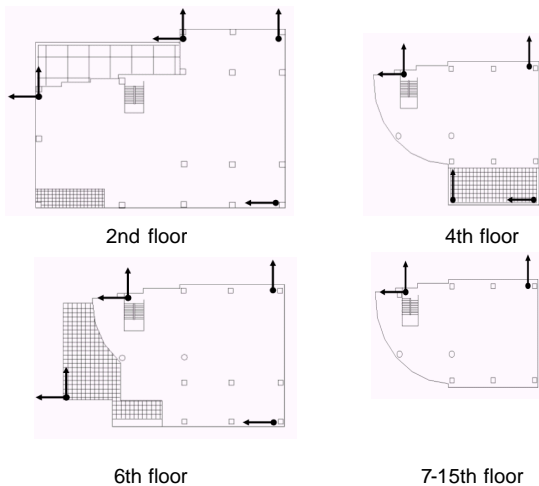


Fig. 4 Sensor placement at different floors

2.2.2 Data Acquisition

14-channel data acquisition system (National Instrument) is used to transfer analog signal to digital data, and to data recording in hard disc of a PC. Sampling rate is selected as 20 Hz, with Nyquist frequency of 10 Hz. Duration of each record is 1,800 sec. Time series of each channel has 36,000 points. Ambient response measurements and data acquisition were conducted in May 8, 2001 by the research team. It took less than 6 hours to finish all 4-setup measurements in the same day

2.3 Data Processing

The ambient data recorded at the field was processed in frequency domain. Power Spectral Density (PSD) was estimated using total time period with a frame of 1024 data points. 512 spectrum lines, with frequency resolution of 0.01953 Hz, were obtained. Hanning windows are applied as usual with 66.7 % overlapping to increase the number of average.

3. Ambient Modal Identification

3.1 Modal frequency & mode shape Identification

A dedicated commercial software for ambient response test and modal identification, ARTEMIS, developed by SVS*, was employed in this project. ARTEMIS consists of 5 major modular: project management, data processing, FD ambient modal identification via FFD, TD ambient modal identification via Stochastic Subspace Technique (SSI), and Modal validation.

Two input files are required for project manager—a configuration file with sampling interval parameter, geometry of the structure under test, basic description of measurement for different setups and constrain equation for virtual measurements, and data files corresponding different setup.

The main advantage of the classical FD approach compared to sophisticated TD approaches, such as two-stage time domain identification technique such as Ibrahim Time Domain (ITD)^[2], Polyreference Complex Exponential (PRCE)^[3], ITD/CF and PR/CF^[4] System Realization techniques, such as ERA^[5], ERA/DC^[6], and Stochastic Subspace Identification techniques^[7] (Unweighted Principal Component, Principal Component and Canonical Variance Analysis algorithms). It is fast, simple to use, and gives the user a “feeling” of the data he or she is dealing with.

PSD was computed based on digital Fourier Transform via data processing modular, which has other capability, such as decimation, filtering, etc., and FDD modal identification technique was then employed to obtain modal frequencies and mode shapes^[2].

The basic FDD ambient modal identification has most advantages of the classical frequency domain technique, or Peak-Picking of PSD, such as simplicity and ease of use, but without the difficulty of dealing with close-spaced mode.

In the FDD technique, the PSD matrix is formed at first from ambient response measurements. Instead of using PSD directly, as it does by classical FD technique, the PSD matrix is decomposed at each frequency line via Singular Value decomposition (SVD). SVD has a powerful property of separating noisy data from disturbance caused by unmodeled dynamics and measurement noise. The Singular Value (SV) plot, as functions of frequencies, calculated from SVD can be used to determine modal frequencies and mode shapes.

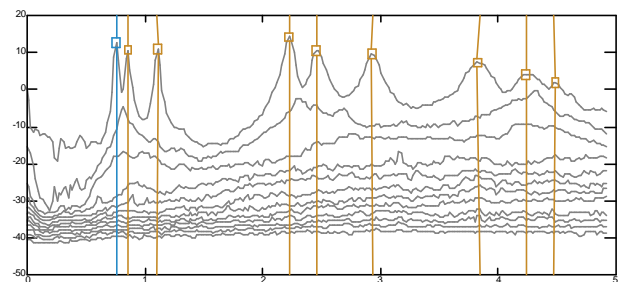


Fig. 5 SV plot of the CFT Building

It has been proved^[2] that the peaks of singular value plot indicate the existence of structural modes. The singular vector corresponding to the local maximum singular value is unscalled mode shape. It is exactly true if the excitation process in the vicinity of modal frequency is white noise. One of the major advantages of the FDD technique is that close-spaced modes, even repeated modes can be dealt with without any difficulty. Only approximation is that orthogonality of the mode shapes is assumed. Fig 5 presents the SV Plot of the CFT building. Table 1 gives identified 9 modal frequencies and damping ratios. Fig.6 depicts corresponding 9 mode shapes.

3.2 Modal damping estimation

One of the major objectives of the research project was to estimate modal damping of the CFT building rather accurately. An enhanced FDD algorithm in the ARTEMIS is adopted. The Basic idea of the EFDD is as follows^[8].

| Mode # | Freq. (Hz) | Std. Freq. (Hz) |
|--------|------------|-----------------|
| 1 | 0.760 | 0.0025 |
| 2 | 0.855 | 0.0018 |
| 3 | 1.111 | 0.00097 |
| 4 | 2.230 | 0.0032 |
| 5 | 2.468 | 0.0061 |
| 6 | 2.939 | 0.0072 |
| 7 | 3.849 | 0.018 |
| 8 | 4.255 | 0.013 |
| 9 | 4.474 | 0.037 |

Table 1 Identified modal frequencies

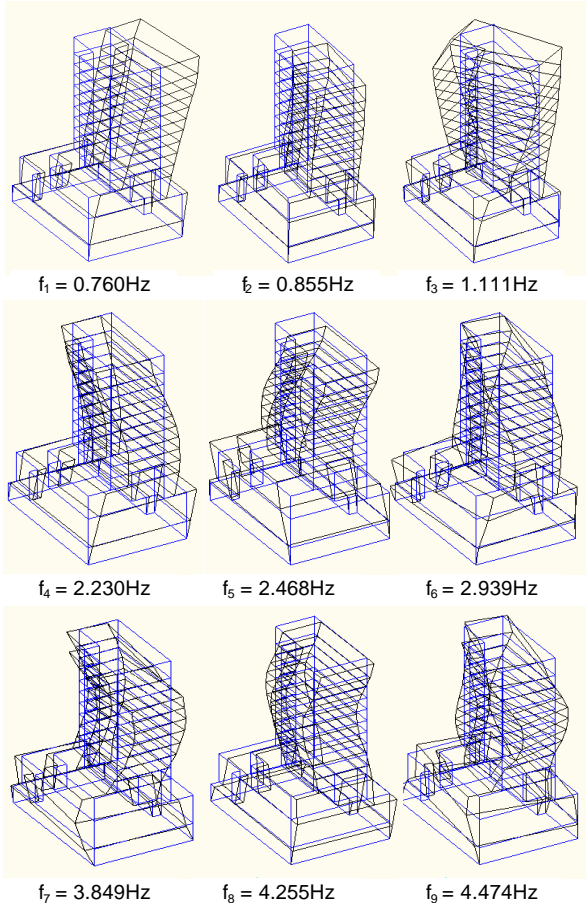


Fig. 6 Identified 9 mode shapes of the CFT building

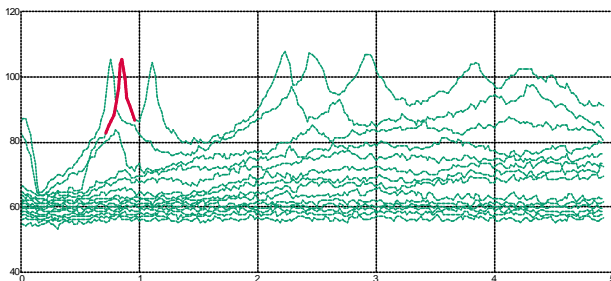


Fig. 7 SV plot, the “bell” shows the data of second mode as SDOF system in FD

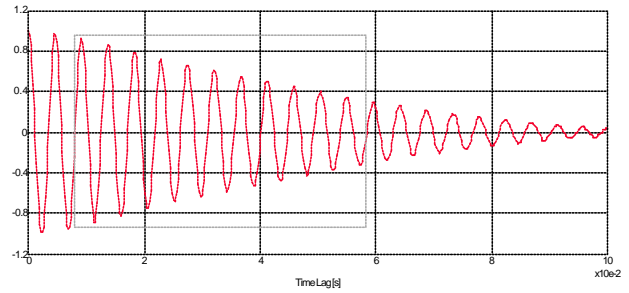


Fig. 8 Correlation function of the second mode

The singular value in the vicinity of natural frequency is equivalent to the power PSD function of the corresponding mode (as a SDOF system). This PSD function is identified around the peak by comparing the mode shape estimate with the singular vectors for the frequency lines around the peak. As long as a singular vector is found that has high MAC value with the mode shape, the corresponding singular value belongs to the SDOF function. If at a certain line none of the singular values has a singular vector with a MAC value larger than a certain limit value, the search for matching parts of the PSD function is terminated. Fig. 7 gives a typical “bell” of the SDF system—the second mode of the CFT building. The remaining spectral points (the unidentified part of the PSD) are set to zero. From the fully or partially identified SDOF spectral density function, the natural frequency and the damping can be estimated by taking the PSD function back to time domain by inverse FFT as correlation function of the SDOF system, as showed in Fig. 8. From the free decay function, the natural frequency and the damping are found by the logarithmic decrement technique.

| Nt | 256 | 512 | 1024 | 2048 | 4098 | 8196 |
|-----------------|------|------|------|------|------|------|
| 1 st | 3.05 | 1.60 | 0.95 | 0.65 | 0.54 | 0.51 |
| 2 nd | 2.81 | 1.58 | 0.99 | 0.74 | 0.67 | 0.58 |
| 3 rd | 2.06 | 1.29 | 0.98 | 0.84 | 0.80 | 0.87 |
| 4 th | 1.52 | 1.24 | 1.11 | 1.10 | 1.08 | 1.06 |
| 5 th | 1.91 | 1.64 | 1.65 | 1.56 | 1.62 | 1.29 |
| 6 th | 1.90 | 1.73 | 1.66 | 1.67 | 1.72 | 1.68 |
| 7 th | 2.37 | 2.23 | 2.18 | 2.15 | 2.11 | 1.63 |
| 8 th | 1.57 | 1.60 | 1.38 | 0.85 | 0.78 | n/a |
| 9 th | 1.91 | 1.92 | 1.62 | 1.25 | 0.86 | n/a |

Table 2 Identified modal damping ratios

In the enhanced FDD, power spectral density functions should be estimated via DFT at first before the SVD. It is well known that leakage error in PSD estimation always takes place due to data truncation of DFT. Leakage is a kind of bias error, which cannot be eliminated by windowing, e.g. by applying Hanning window, and is harmful to the accuracy of damping estimation, which is rely on the PSD measurements.

The bias error caused by leakage is proportional to the square of the frequency resolution [9]. Therefore increase frequency resolution is a very effective way to reduce the leakage error. Thanks to the enough data taken at field response measurements, we can afford to use more data, i.e. increase frequency resolution, in PSD computation.

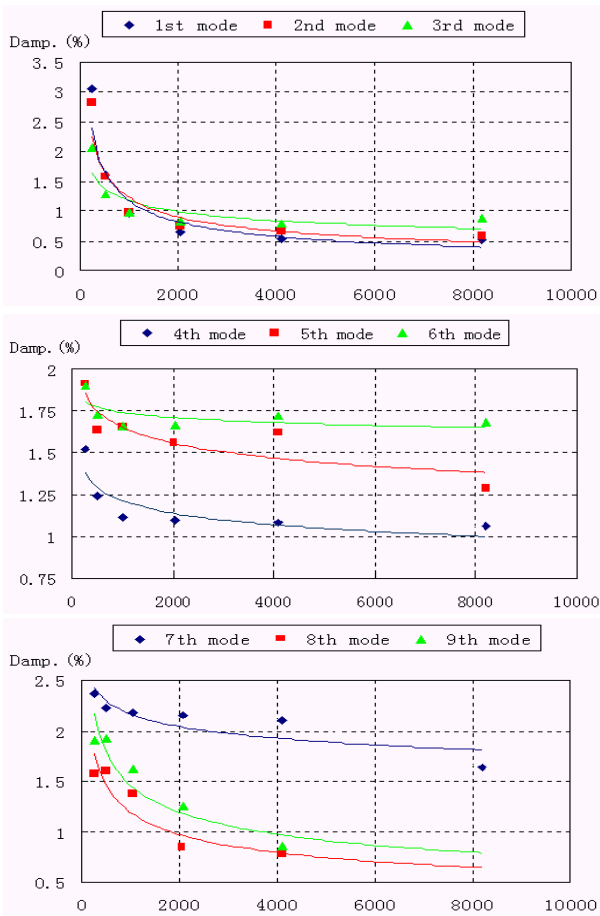


Fig. 9 Changes of modal damping vs. data points

In order to show the influence of the frequency resolution to the accurate of damping estimation, 256, 512, 1024, 2048 and 4096 data points were used to calculate PSD functions. Corresponding frequency resolution were 0.0783, 0.0392, 0.0195, 0.00977 and 0.00488 Hz, respectively. Table 2 shows estimated damping ratios of all 9 modes via EFDD with respect to these four cases. Fig. 9 presents the changes of the damping ratios with the number of data points used for PSD calculation. It is very interesting to observe that, as predicted by the theory of random data procession, damping ratios of all modes are decrease while number of data point, or frequency resolution, is increasing! It looks that damping estimates converge when the number of data points is large enough (reach to 4096 and 8192), or frequency resolution is fine enough (equal to 0.00488 and 0.00244 Hz)!

Application to FE model Correlation

A finite element model was built via SAP 2000 for CFT building in the research project. The FE model of CFT building consists of 1226 coordinate with three translational directions.

FEM was tuned according to the modal correlation of modal frequencies and mode shapes computed by FEA and identified from ambient test. By taking into consideration of the stiffness of non-load-bearing walls, such as an inside-

and-outside wall, excellent agreement with ambient identified modal characteristics has been obtained. Table 3 gives comparisons of the natural frequencies of all 9 modes. It can be seen the maximum error of the frequencies up to 9 modes is less than 5 %.

| Mode # | FEM (Hz) | EMA (Hz) | Error (%) |
|--------|----------|----------|-----------|
| 1 | 0.756 | 0.760 | -0.53 |
| 2 | 0.874 | 0.855 | 2.22 |
| 3 | 1.150 | 1.111 | 3.51 |
| 4 | 2.141 | 2.230 | -3.99 |
| 5 | 2.532 | 2.468 | 2.59 |
| 6 | 3.022 | 2.939 | 2.82 |
| 7 | 3.851 | 3.849 | 0.05 |
| 8 | 4.264 | 4.255 | 0.21 |
| 9 | 4.666 | 4.474 | 4.29 |

Table 3 Comparison of FEM and EMA

Concluding Remarks

Ambient Response Test and modal identification of a 15-story office building with CFT columns newly constructed in Tokyo is presented.

In order to have sufficient spatial domain resolution and correlate with finite element analysis, a test model with 200 DOFs in two lateral directions was established. Altogether 48 real measurements were conducted and 152 virtual measurements were added to characterize transverse and torsional vibration of the building.

The basic Frequency Domain Decomposition (FDD) technique via dedicated software ARTeMIS was employed for ambient modal identification of the CFT building. All natural frequencies and mode shapes of nine modes—three sets of transverse (in two direction) and torsional modes—were accurately identified in the frequency band of interest.

Enhanced FDD technique was adopted to estimate modal damping. It was very interesting to find that the damping ratios of all 9 modes decreased while frequency resolution in PSD calculation is increasing. When data points used for DFT reach to 4096, i.e. the frequency resolution equals to 0.00488 Hz, the modal damping of all 9 modes converge to constants.

The modal characteristics of the CFT building obtained by the ambient response test and modal identification was applied to correlation with finite element model. Excellent agreement of the natural frequencies and mode shapes up to 9 modes has been reached between updated FE model and test model obtained from ambient modal identification.

According the experiences gained from modal identification of the CFT building, the Frequency Domain Decomposition technique is showing promise in application to civil engineering structure, not only in FE model updating, but also in dynamic response prediction, structural health monitoring and structural control.

Acknowledgement

The first author of this paper would like to express his appreciation of the support of the National Science Foundation of China for the research project No. 50075038.

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