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SYSTEM IDENTIFICATION OF STRUCTURES FOR THE PURPOSE OF STRUCTURAL HEALTH MONITORING AND DAMAGE DETECTION

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ABSTRACT

The goal of structural health monitoring (SHM) are effective recognition and identification of possible structural damage, estimation of the actual state of a structure, and its potential for further exploitation, and finally, assessment of the eventual need for reparation. This research attempts to describe steps and procedures for SHM in order to locate possible damages to the structural and non-structural elements of buildings due to earthquakes.

The target structure for SHM, in this study, is the Urban Disaster Prevention Research Center (UDPRC), located in Tsukuba, Japan. The SHM procedure is an addition to the regular monitoring of the UDPRC building for the purpose of detecting damage sustained since the building's original construction.

The SHM methodology, described in this paper, consists of analyzing strong motion acceleration records from the year 1999 till 2012, and microtremor acceleration records from 2009 and 2011. Dynamical properties of the structure (natural frequencies, damping ratios, mode shapes) and parameters related to stiffness are extracted from the records by applying parametric system identification methods (ARX, ARMAX and N4SID). The changes of these parameters in time indicate the possible occurrence of damage to the building. Damage detection and localization have been performed by tracing the history of changes in the extracted dynamical parameters and storey stiffness during the observed period. The results obtained demonstrate the tendency of natural frequencies and storey stiffness to decrease, and damping ratios to increase due to aging and exposure of the structure to strong ground motion. A loss in frequency and stiffness is most evident in the year 2011, after the Great East Japan earthquake.

1. INTRODUCTION

Damage involves any change in a system that is unforeseen and tends to decrease or disable a system's future safe and successful exploitation. Early detection, identification and repair of damage to structures are some of the most crucial challenges in engineering. The implementation of a strategy and methodology for damage detection in building structures and infrastructure, as well as structures and devices in mechanical, aero and aerospace engineering, is called structural health monitoring (SHM). Generally, the goal of SHM is to fulfill the following requirements: consideration of the occurrence of structural damage, locating the damage, evaluation of the severity, prediction of the remaining lifetime of the structure. Damage detection in structures requires a comparison of the dynamic parameters of the structure and storey stiffness, obtained at different times. The possibility of such a comparison provides a history of changes in these structural parameters and estimating possible damage location. System identification (SI) techniques play an important role in structural health monitoring processes. The structures in their physical nature can be observed as dynamic systems with

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their own dynamical properties. The SI procedures are based on digital data analysis and processing. They are subjected to various external influences that in system identification elaboration are called input. The input can be applied to structures according to various factors (ground motion, wind, etc.) in the form of signals. As a result of the input, the structures exhibit responses (output) with features dependent on the dynamic properties of the structure and input. The structural dynamical properties are resonant frequencies (or resonant periods), mode shapes and damping coefficients. Those properties in SHM processes may be recognized as damage sensitive features and may be utilized in process of detecting possible damage. The identification procedure usually requires high S/N (signal-to-noise ratio) and uncorrelated sources of excitation. The SI identification techniques on buildings for the purpose of SHM include ambient vibration (microtremor) measurements, strong motion measurements (in the case of earthquakes) and forced vibration measurements (shaker test). A high S/N ratio occurs with strong motion measurements and forced vibration measurements, so identification procedures can be considered as having a higher possibility of accuracy than with microtremor measurements, which usually contain a large number of disturbances compared to real input-output combinations (low S/N ratio).

2. SYSTEM IDENTIFICATION METHODS IN STRUCTURAL HEALTH MONITORING

In structural health monitoring procedures, mechanical signals, such as acceleration, velocity, displacement, force, etc. are of crucial importance for the identification of a of structure's dynamical and damage sensitive parameters. Measured signals in an observed system include input, output and noise. The analog signals are converted into digital signals after being cleaned up, using processes such as averaging, detrending and filtering. Building and complementing models from the signals is a process that is defined as system identification. The systems (buildings) can be analytically identified by using the mass, stiffness and damping ratios, estimated during the process of designing. However, the required parameters may differ from ones considered in the design, especially if there is reason to believe that external factors (earthquakes, harsh weather conditions, aging, etc.) may have caused imbalance within the initially estimated parameters. This imbalance may be considered damage. In such cases, system identification in operational modal analysis should be performed to complement the model. The full process of system identification, based on signal analyses, includes signal observation, signal cleansing, features extraction, diagnosis and prognosis.

The system identification methods can be classified in two groups: non-parametric identification and parametric identification methods.

2.1 Non-parametric identification

The methods that identify transient response models and transfer function models are called nonparametric system identification methods. They do not involve direct estimation of physical or mathematical model parameters.

Transient response models can be expressed in the form of impulse response or step response. These two approaches provide a precise relationship between input and output. In cases of chosen and controlled input, the more complex steps in system identification are not necessary because the output is the identified model itself, directly revealing information of frequencies and damping ratios. In the case that transient response (impulse response) is defined, the basic non-parametric identification can be performed using an empirical transfer function estimate (ETFE) also known as a spectral ratio. An ETFE or spectral ratio is a model in the frequency domain that is actually a Fourier transform of a transient response model. However, since the noise function $v(t)$ is included in the Fourier transform of the output signal, the spectral ratio may not be sufficiently accurate. The spectral ratio defines the relationship between the input and output of the system, both expressed as a function of the frequency ω as shown in Eq.(1), where Y is an output and U is an input:

$$G(\omega) = \frac{Y(\omega)}{U(\omega)} \tag{1}$$

The damping can be easily obtained using two methods: the half-power method and random decrement method. The half-power method can be applied on microtremor, strong ground motion analysis and forced vibration analysis. Random decrement method can be applied only on microtremor measurement analysis.

2.2 Parametric identification

An instrumented civil structure requires a mathematical description of its behavior to describe the dynamical system in both an undamaged and eventually damaged structural state. Assuming the structural system to be linear and time-invariant, numerous system identification models can be calculated from digitized input-output data. Dynamic systems are usually described by ordinary or partial differential equations. For convenience, they can be replaced by difference equations. Parametric modeling is based on these difference equations. Parametric models use the data for determining the unknown parameters in models, obtained from the physical modeling. In parametric modeling, the objective is to simulate the output while minimizing the errors between the model's simulated output and the measured output. The most commonly used models are auto-regressive ARX and ARMAX models and state space N4SID (numerical subspace state space identification) models. This study is focused on understanding and applying these three models.

Mathematically, an ARX model is a linear difference equation equating weighted past observations of the system output, $y(k)$, with those of the system input, $u(k)$. The method is based on tracing the history of the sets of input and output. The main goal of the observation is obtaining the dynamic properties of the structure (mode shapes, frequencies, damping), as well as the changes of the storey stiffness. The output $y(t)$ can be directly expressed as a function of input $u(t)$ and residual error $e(t)$:

$$y(t) = \frac{B(q)}{A(q)} u(t) + \frac{1}{A(q)} e(t) \tag{2}$$

The term $B(q)/A(q)$ in Eq. (2) is the transfer function of the dynamic system. The transfer function directly and indirectly should contain the necessary information about the properties of the system (structure).

The ARMAX identification model is actually an extended ARX model that provides more flexibility for modeling noise using the C parameters (a moving average of white noise) (Eq. (3)).

$$y(t) = \frac{B(q)}{A(q)} u(t) + \frac{C(q)}{A(q)} e(t) \tag{3}$$

Just like in ARX model, The term $B(q)/A(q)$ is the transfer function of the dynamic system.
The system's mode shape frequencies can be extracted from the transfer function $B(q)/A(q)$, computed with both, ARX and ARMAX models by applying the Eq. (4), where ${}_z p_j$ is a root of $A(z)$ (pole) and Δt is the sampling interval. The damping ratio ς can be expressed as in Eq. (5). The mode shapes of the structure can be evaluated with the Eq. (6)

$$f_j = \frac{\sqrt{\left(\ln\left|{}_z p_j\right|\right)^2 + \left(\arg{}_z p_j\right)^2}}{2\pi\Delta t} \tag{4}$$

$$\varsigma_j = \frac{-\ln\left|{}_z p_j\right|}{2\pi f_j \Delta t} \tag{5}$$

$$\beta u_j = \Re\left[\frac{2\,{}_z r_j \sqrt{1-h_j^2}}{\Delta t(2\pi f_j h_j - i\,sign(\Im({}_z p_j))2\pi f_j(1-2h_j^2))}\right] \tag{6}$$

A state space model of combined deterministic-stochastic system can be represented by the Eq. (7)

$$\begin{cases} x_{k+1} = Ax_k + Bu_k + Ke_k \\ y_k = Cx_k + Du_k + e_k \end{cases} \tag{7}$$

And the frequencies, damping ratio and mode shape can be computed by set of Equations (8)

$$f_k = \frac{\left|\ln(\lambda_k)\right|}{2\pi\Delta t} \qquad \varsigma_k = \frac{-\operatorname{Re}[\ln(\lambda_k)]}{2\pi\Delta t} \qquad \varphi_k = \left|C\psi_k\right| sign\left[\operatorname{Re}(C\psi_k)\right] \tag{8}$$

where λ are the complex eigenvalues and ψ are eigenvectors of the system matrix A.

Stiffness coefficients $[K]$ can be estimated from mass-normalized measured mode shapes $[\Phi]$ (Eq. (9)) where $[\Phi]$ is determined from the modal participation function βu_j and frequencies $[\Lambda]$.

$$[\Phi]^T[M][\Phi] = [I] \tag{9}$$

$$[K] \equiv \left([\Phi][\Lambda]^{-1}[\Phi]^T\right)^{-1} \tag{10}$$

3. HEALTH MONITORING OF URBAN DISASTER PREVENTION RESEARCH CENTER (UDPRC) – A CASE STUDY

The subject of the study is health monitoring of the structure of the Urban Disaster Prevention Research Center (UDPRC) using parametric system identification methods.

The construction of the building was completed in March 1998, and since the beginning of its exploitation, strong motion acceleration sensors have been installed for the purpose of monitoring the state of the structure, and analyzing its behavior when affected by earthquakes. Microtremor measurements have also been periodically conducted for the purpose of tracing the history of changes in the structure’s dynamic parameters and stiffness. This study examines analyses of microtremors and strong motion by applying ARX, ARMAX and N4SID system identification methods for the purpose of detecting and locating damage that has occurred in the building’s structural and non-structural elements due to aging and frequent exposure to earthquakes since the time of its construction.

The Urban Disaster Prevention Research Center (UDPRC) is a part of the National Institute for Land and Infrastructure Management (NILIM). It is an eight storey steel-encased reinforced concrete structure with nearly constant floor masses.

Observational data derives from the strong motion records from several earthquakes from 1999 until 2012. Within this period, the UDPRC building was affected by several strong ground motion events, including the Great East Japan earthquake of March 11, 2011. The strong motion records for earthquakes with maximum peak ground acceleration not greater than 7.0 gals have been chosen. It has been assumed that such earthquakes are not strong enough to cause substantial damage or nonlinear behavior in the building, and consequently the dynamic properties and changes in the storey stiffness of the structure may be identified more clearly.

For the detection of damage in the UDPRC building due to the Great East Japan earthquake, microtremor measurements from December 2, 2011 were analyzed, and the results compared with the analyses of measurements that were conducted on Jun 26, 2009, almost two years before the earthquake. All three system identification methods (ARX, ARMAX and N4SID) were applied, and the adopted method for identification is the one that provided the first mode shape of the building that is closest to the expected one. The identification results from strong motion records are shown in Figure 1 and Figure 2. The identification results from microtremor measurements are shown in Figure 3.

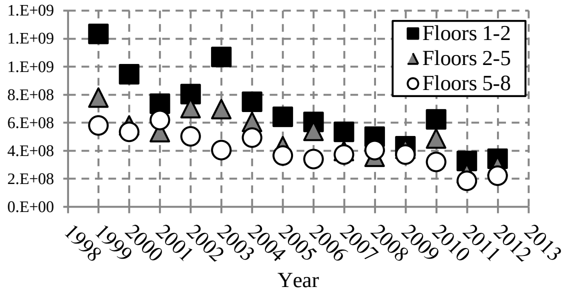

Figure 1. Second order storey pseudo-stiffness (N/mm), N-S direction (strong motion analysis)

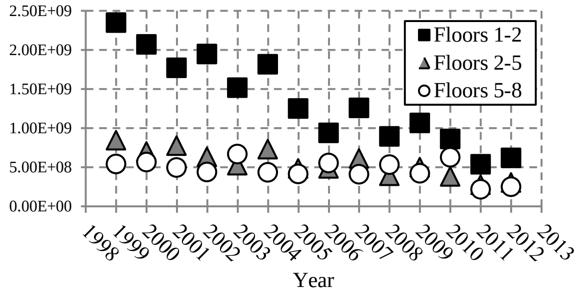

Figure 2. Second order storey pseudo-stiffness (N/mm), E-W direction (strong motion analysis)

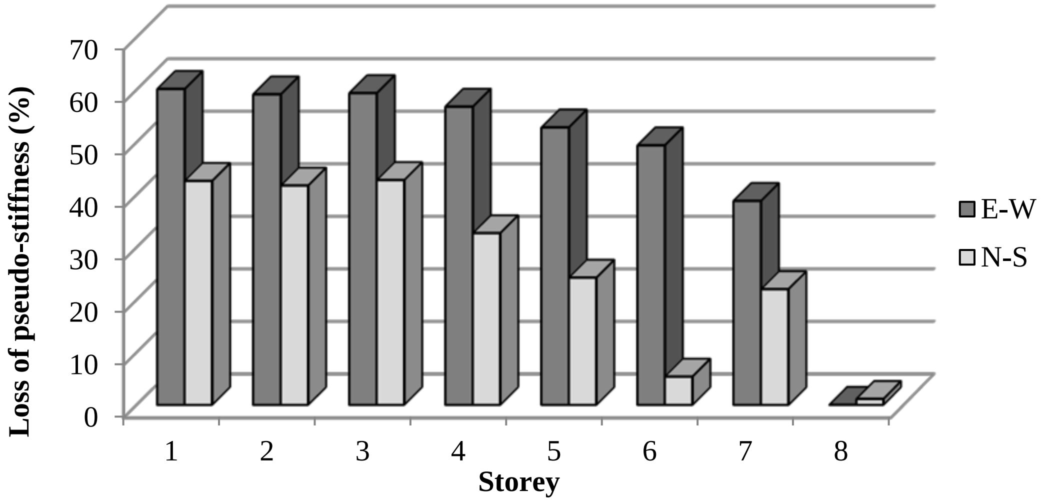

Figure 3. Loss of first order storey pseudo-stiffness of the UDPRC building due to the Great East Japan earthquake from March 11, 2011

From the results presented above, we can see that the UDPRC building suffered severe damages due to the Tohoku earthquake (structural or nonstructural) resulting in a loss of stiffness in nearly every storey in both east-west and north-south directions. The lower storeys suffered more severe damage than upper ones. This damage effect the structure’s stiffness in an E-W direction more than in a N-S direction.

4. CONCLUSIONS

Structural health monitoring strategy has been investigated and implemented on the building of Urban Disaster Prevention Research Center (UDPRC) using strong motion data records and microtremor records analysis, excluding soil-structure interaction effects. The obtained modal frequencies were as expected, and their values are the most stable results. Changes in the modal frequencies are the initial indicator for loss of structural stiffness, which can be considered as damage. Issues with all three computational methods applied (ARX, ARMAX and N4SID) are less stable results for other parameters, such as damping, mode shapes of the structure and the first order pseudo-stiffness, as a final result of the analysis. Further study needs to be made on algorithms for more precise structural identification projects. From the application of the three parametric system identification method, as well as tracing the history of changes in modal frequencies, damping coefficients and first order storey pseudo-stiffness, it can be concluded that:

- Modal frequencies and storey stiffness tend to decrease and damping coefficients tend to increase due to aging of the structure and its frequent exposure to earthquakes.
- For system identification and vibration-based structural health monitoring procedures, the information about the excitation data (microtremor or strong motion), chosen number of degrees of freedom of the structure and number of identified mode shapes are of crucial importance.
- For system identification and damage detection procedures, strong motion data is more convenient for analysis than microtremor data due to the high signal-to-noise ratio. The number of identified mode shapes, obtained from strong motion data, is usually higher than that one obtained from microtremor analysis. This facilitates obtaining a higher order of storey pseudo-stiffness values and implies more stable values for obtained storey pseudo-stiffness, closer to actual values of storey stiffness. However, for an accurate diagnosis, the compared states of the structure need to be based on records with nearly the same values of peak ground acceleration (PGA).
- Microtremor requires careful attention when the model order is chosen, and often more complex identification methods than ARX due to the low signal-to-noise ratio (ARMAX or N4SID).

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