Thesis Summary
論文の内容要旨

Title : **System Identification of Bridges Using Seismic Records and Their Performance Evaluation**
論文題目 (**地震記録からの長大橋の構造同定と構造特性の理解**)

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Vibration based testing procedure as a means for structural assessment of instrumented bridges has been long explored. The analysis involves obtaining dynamic responses and employing mathematical model for estimation of dynamic parameters of bridge based on measurement data. Dynamic parameters obtained from this test are necessary to describe the actual dynamic properties of a bridge, and based on their characteristics and changes, the actual bridge behavior and integrity can be evaluated.

The most common and widely used techniques are ambient vibration and test forced vibration test. However, while both of these tests provide valuable information for modal identification and verification of analytical model, their small excitation amplitudes do not always serve well for investigation of structural behavior during a large excitation. It has been observed from records that the dynamic properties of many bridges are quite different during response to relatively small excitation of ambient and forced vibration than in strong excitation such as earthquake ground motion. Hence, there is a strong interest and importance of system identification of instrumented bridges subjected to strong ground motion.

The main objective of this study is to develop a systematic procedure to analyze seismic records of instrumented bridge using system identification and to use the results of identification as a tool for structural investigation especially seismic performance of instrumented bridges. The study consists of four main parts namely: 1) theoretical development of system identification, 2) numerical studies and verification, 3) application to instrumented bridges and 4) performance evaluation based on system identification results.

In the first part of the study theoretical development of system identification is addressed. The system identification is developed as a data-driven algorithm, which requires neither prior information of structural model besides the measured input-outputs data, nor the iteration procedure for optimization. It employs a state-space based realization using correlation of ground motion acceleration and structural accelerations as input and output of the system. It is developed using a platform of System Realization using Information Matrix (SRIM), and is later improved to achieve a better computational performance. (See Figure 1).

Numerical verification of the methodology is provided in the second part. Using simulation of 2D and 3D benchmark cable-stayed bridge, the accuracy, efficiency and practical application of system identification are investigated. Numerical simulations have shown that the system identification algorithm used in this study performs very well in capturing the global behavior of structure in terms of modal parameters such as natural frequency, damping ratio and mode shapes. Accuracy of modal parameters obtained from system identification was exceptional, even in the case where noise presents and for the case of limited number of sensor. In the benchmark problem of 3D Cable-stayed Bridge, it was found that using relatively small number of sensor (10-15) most of the first low-order modes (i.e. 42 modes) can be identified. Furthermore, numerical issues in identification such as effect of measurement noise, and limited number of output sensor, data length, and inclusion of input sensor are also discussed.

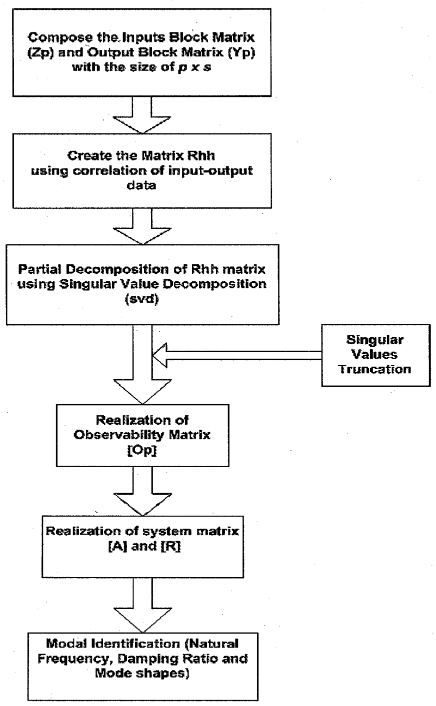


Figure 1. Flowchart of System Identification

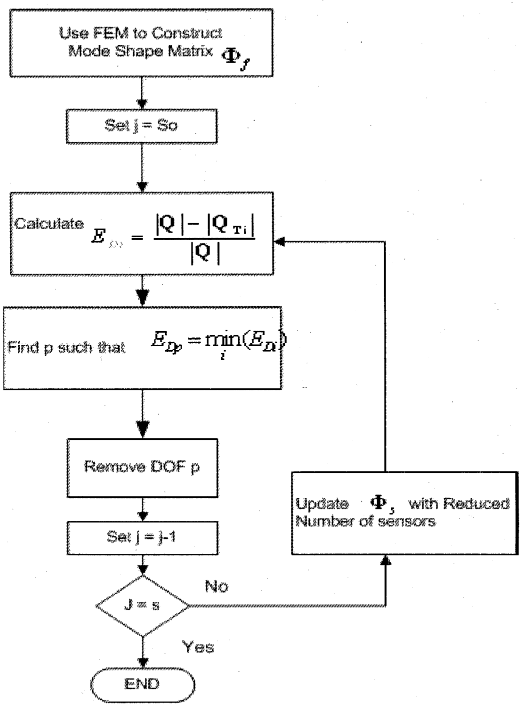


Figure 2. Flowchart of optimum sensor placement

In addition to numerical issue of identification, sensor placement for system identifiability is also investigated. Two issues of sensor placement were addressed namely: the minimum number of required sensor and the optimum placement for identification of certain set of modes using limited number of sensor. An optimum sensor configuration is defined as a selection of sensor that minimizes the required size of observability matrix while still maintaining its full rank. Mathematical relationship is developed to define the contribution of a sensor in one position to the mode identifability. Using Effective Independence index (EfI) the optimum sensor placement is determined by iteratively by omitting degree-of-freedom that do not contribute significantly to the degree of effective independence, until all the important degree-of-freedoms are retained (Figure 2). Example of application is given numerically using 3-D Cable-Stayed Bridge models.

The third part presents the application of system identification to the instrumented bridges. Five long span bridges are investigated in this study namely: Yokohama Bay Bridge, Rainbow Bridge, Tsurumi-Tsubasa Bridge, Minato Bridge and Katsushika-Harp Bridge. Modal parameters of these bridges are estimated using system identification and the analysis of identified modes from several seismic records are presented. In the case of Yokohama-Bay Bridge global trend of modal parameters are observed using the results of identification from various earthquakes from 1990 to 2004. Results of identification have shown that natural frequencies and mode shapes observed earthquake records were identified within good agreement when compared to the results from the finite element model, ambient and forced vibration test. Results of identification show that the system identification used in this study has outperformed other conventional system identification methods and other tests in terms of efficiency and identifiability. Later, using series of earthquake with different input amplitude, trends of amplitude-dependency of modal parameters were observed.

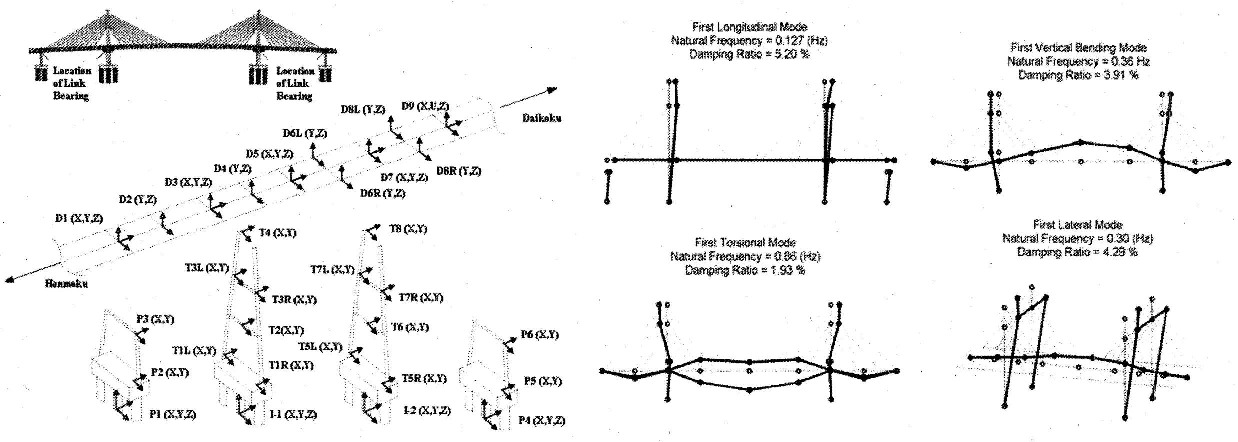


Figure 3. Example of Sensor arrangement and the results of System Identification of Yokohama-Bay Bridge

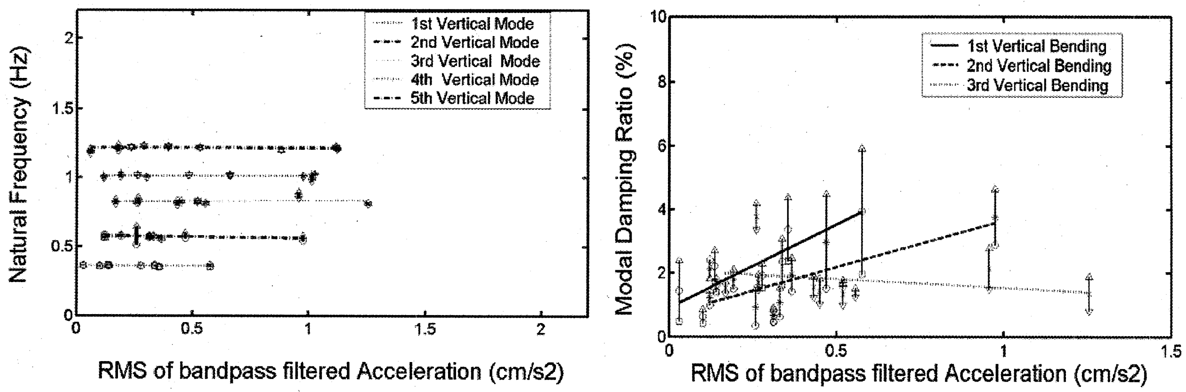


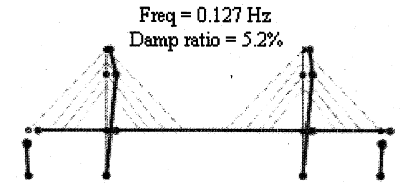
Figure 4. Trend of modal parameters of Yokohama-Bay Bridge with respect to input amplitude
(identified from 8 earthquakes)

Observation of the results shows that natural frequencies remain almost constant with respect to the earthquake magnitude. Modal damping ratios, on the other hand, indicate the magnitude dependency, especially for several low-order modes (Figure 4). Most of damping ratios were identified with the average values between 0.5-5.5%. Using series of seismic records from Chuetsu-Niigata earthquake significant decrease of natural frequency when compared to the results from previous earthquake in year 1990 was observed. The average decrease of natural frequencies with the range between 1 – 7% was observed. These changes are statistically significant since their values are larger than the margin of error for individual mode, the error that might have resulted from the variation in system identification. The decrease here implies that structural properties or stiffness have changed, which is due to the completion of additional deck. The results suggest that additional deck contribute largely as an additional mass to the whole structure system, rather than additional stiffness. Hence, the decreases of 5-7% of natural frequency especially for lower vertical modes were observed.

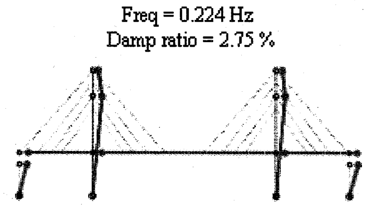
The last part of study deals with the performance evaluation of Link-Bearing Connection (LBC) of Yokohama-Bay Bridge. The link bearing is designed to function as perfectly hinged connection during bridge movement in the bridge longitudinal axis. This implies that the girder and pier cap acting as separated units and therefore the force from superstructure will not be transmitted into the pier. In designing of the end-piers this assumption is employed. Using System Identification, Response analysis, and Finite Element Model seismic performance of LBC is studied from eight earthquakes. The investigation of link-bearing connection using seismic records is particularly important since this type of motion is only observed during earthquakes and is not measurable during ambient motion measurement and dynamic testing using exciters.

Three typical first longitudinal modes were found from system identification with the main focus on the relative modal displacement between end-piers and girder. They are: the slip-slip mode, mixed slip-stick mode and the stick-stick mode. (Figure 5) The response analysis of relative displacement between the end-piers and girder confirm these findings. It was observed that during the small earthquake the link-bearing connection has yet to function as a full-hinged connection. Therefore a stiffer connection with higher mode was observed. The full-hinged type of connection at both of end-piers was only observed during the large earthquake. This slip-slip mode suggests that the link-bearings have performed as the intended fully hinged function.

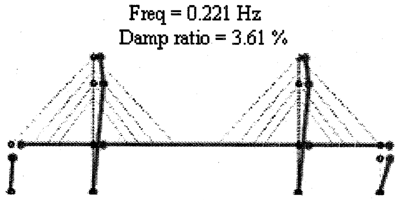
To study the behavior of link-bearing connections and their sensitivities to the modal parameters a finite element model of the Yokohama-Bay Bridge is constructed. Since the main focus of this analysis is on the first longitudinal mode, the model is built in 2-Dimensional system.



Slip-Slip Mode (Feb 20,1990 earthquake frame #1)



Stick-Stick Mode (Feb 2,1992 earthquake frame#2)

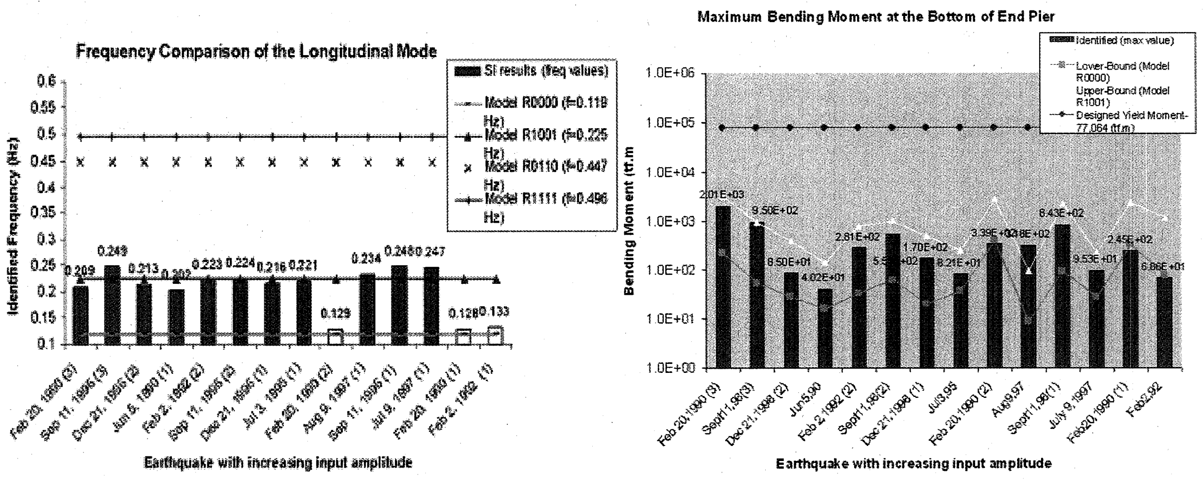


Slip-Stick Mode (July 3,1995 earthquake)

Figure 5. Three typical first longitudinal mode

Six first modes are considered in dynamic analysis namely the first longitudinal mode and the 1st to the 5th vertical modes. This is to compare the individual mode in the model with those that identified from the measurement.

Performance of link-bearing connection between end-pier and tower to the girder is modeled using two extreme scenarios namely a hinged and a fixed scenarios. In the hinged scenario the connection's stiffness in shear and bending directions are assumed to be zero, while in the fixed scenario the connections provide bending as well as shear stiffness whose values are equal to those of the columns below. Considering the fact that girder is a continuous rigid body, there are four possible extreme scenarios of end-pier and tower link, namely: 1) both end-piers and both towers are hinged (R0000), 2) both end-piers are fixed while both towers are hinged (R1001), 3) both end-piers are hinged while both towers are fixed (R0110), and 4) both end-piers and both towers are fixed (R1111). Comparison of the FEM and system identification results reveals that in small and medium earthquake end-pier LBC are still fixed or rigidly connected to the girder as evidence from their natural frequencies that are closer to the model R1001, while the all hinged type of connection was observed only during large earthquake (See Figure 6).



(a) (b)

Figure 6 (a) Comparison of frequencies of the model and system identification results (b) Maximum bending moment at the end-piers

Behavior of link-bearing connection and its longitudinal mode affects bending moment at the end-pier. When the pier and girder is rigidly connected, large portion of force will be imparted into the end-pier and this will result on a greater bending moment at its bottom. To investigate this effect maximum bending moment at end-pier due to type of LBC mode is calculated. For comparison, maximum bending moments of the two models R000 and R1001 are also presented. The maximum moment of model R0000 serves as the Lower-Bound values while the R1001 provides the Upper-Bound values.

Observation of end-piers' bending moment subjected to fourteen frames of earthquakes shows the importance of link-bearing performance to overall load distribution. It is shown that while the maximum moment observed during the largest earthquake is still far below the moment capacity, a difference in link bearing mode creates an unexpectedly larger load distribution to the pier that might damage the structure. It was found that the change from a fixed connection to a hinged connection results in a tremendous change in maximum moment (10-18 times). The results of moment computation also show how end-piers sustain higher bending moment even when earthquake amplitude are smaller because of the sticking of link bearing connections. This investigation shows that during earthquake connection might not perform as it is predicted in an analytical model. And this deviation or unwanted mechanism would have not been discovered without the vibration based system identification. Investigation shows that using seismic monitoring data of bridges one can evaluate bridge performance and utilize this information as feedbacks for future structural improvement.

Applications of system identification adopted in this study have shown the merit of the methodology. The benefits of this method are: (1) it identifies modal characteristics, such as natural frequencies, modal damping ratios and mode shapes with efficient use of relatively short earthquake record, (2) it is a data driven algorithm, which requires no prior knowledge of structural information, and (3) it allows the identification for SIMO system as well as MIMO system, therefore well-suited for application to the large and complex structures with multi inputs and multi outputs. Using system identification procedure, this study shows that it is possible to capture the global behavior of the bridge such as amplitude-dependency of modal parameters during earthquake and at the same time investigating the performance of its local components such as link-bearing connection. The advantages and effectiveness of system identification addressed in this study might lead for a promising future application of system identification for structural assessment and monitoring during seismic loading.