4th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-4) 2009
22-24 July 2009, Zurich, Switzerland

Damage identification of civil infrastructures with array sensing under local excitation

Toshiyuki Oshima[1], Shuichi Mikami[1] , Yasunori Miyamori[1] , Tomoyujki Yamazaki[1] and Sherif Beskhyroun[2]

[1] Kitami Institute of Technology, Kitami, Japan
[2] University of Saskatchewan , Saskatoon, Canada

ABSTRACT: A method of damage identification for engineering structures based on strain energy is dealt with in this paper. The method is described theoretically and applied to the experimental data on structural members. Several damage scenarios were introduced to the members of the structure. Experimental results show that the proposed approach may be successfully implemented to detect damage and to locate regions where damage occurred. This research also aims at establishment of experimental environment to enable the verification of applicability and the effective evaluation of the structural health monitoring (SHM) technology that uses the high performance sensor system on real bridges. The primary goal of the project is development of test beds that meet wider requests for SHM experiments. Several steel bridges on an abolished railway in Hokkaido, Japan will be available for the establishment of the test beds. The test beds can be utilized by not only researchers of this project but also other researchers. The final goal of the project is international contribution by means of cooperative utilization of the test beds.

1 INTRODUCTION

In recent years there has been interest in the damage diagnosis and health monitoring of existing highway bridges using vibration based damage identification techniques. Most vibration-based damage detection theories and practices are formulated based on the assumption that failure or deterioration would primarily affect the stiffness and therefore, affect the modal characteristics of the dynamic response of the structure[1-5]. If this kind of changes can be detected and classified, this measure can be further implemented for a bridge monitoring system to indicate the condition, or damage, or remaining capacity of the structures. It can also be used to evaluate the seismic behavior of the structures. However, conventionally defined modal parameters have been shown to be mildly sensitive in the detection of various types of bridge damages. Furthermore, the modal parameters of conventional modal testing such as frequencies and modal damping are global parameters, which cannot locate the damages[6]. Research efforts have been made to detect structural damage directly from dynamic response measurements in the time domain, e.g. the random decrement technique[7], or from frequency response functions (FRF)[8]. Also, some damage detection methods have been proposed to detect damage using system identification techniques[9, 10]. In this paper, an algorithm based on changes in Power Spectrum Density(PSD) is presented. The algorithm is used to detect damage, locate its position and

monitor the increase in damage using only the measured data without the need for any modal identification or numerical models. The method is applied to the experimental data extracted from a railway steel bridge after inducing some defects to its members. The damage was introduced to the bridge through the increasing length of slits located on the members of the main girder and cross beam of the bridge. A future goal of a comprehensive bridge management system is to have a self-monitoring bridge where sensors feed measured responses (accelerations, strains, etc.) into a local computer. This computer would, in turn, apply a damage identification algorithm to this data to determine if the bridge has significantly deteriorated to the point where user safety maybe jeopardized. The local computer could then contact a central monitoring facility (via cellular phone) to notify the appropriate maintenance or safety officials of the bridge's current condition. If such a monitoring system is to be practical, it will have to identify the dynamic properties of the structure from ambient, traffic-induced vibration or using another controlled excitation technique. One difficulty with determining dynamic parameters of a structure through ambient vibrations is that the forcing function is not precisely characterized. In this paper, the implementation of piezoelectric actuators[11-13] as a local excitation source for large structures such as steel bridges is presented. The advantages of using piezoelectric actuators instead of shakers, hammers or ambient vibrations will be discussed in details in the following chapters.

2 THEORETICAL DESCRIPTION

Let $G_i(f)$ denote the Power Spectrum Density(PSD) magnitude measured at channel number i at frequency value f. The absolute difference in PSD magnitude before and after damage can be defined as

$$D_i(f)=\left|G_i(f)-G_i^*(f)\right| \tag{1}$$

where $G_i(f)$ and $G_i^*(f)$ represent PSD magnitude for the undamaged and damaged structures respectively. When the change in PSD is measured at different frequencies on the measurement range from f_1 to f_m, a matrix [D] can be formulated as follows

$$D=\begin{bmatrix} D_1(f_1) & D_1(f_2) & \cdots D_1(f_j)\cdots & D_1(f_m) \\ D_2(f_1) & D_2(f_2) & \cdots D_2(f_j)\cdots & D_2(f_m) \\ \cdot & \cdot & \cdots\cdots & \cdot \\ D_i(f_1) & D_i(f_2) & \cdots D_i(f_j)\cdots & D_i(f_m) \\ \cdot & \cdot & \cdots\cdots & \cdot \\ D_n(f_1) & D_n(f_2) & \cdots D_n(f_j)\cdots & D_n(f_m) \end{bmatrix} \tag{2}$$

where n represents the number of measured points. In matrix [D], every column represents the changes in PSD at different measuring channels but at the same frequency value. The summation of PSD changes over different frequencies can be used as the indicator of damage occurrence and the increase in damage. In other words, the first damage indicator is calculated from the sum of rows of matrix [D] as

$$TC=\begin{Bmatrix} \sum_{j=1}^{m} D_1(f) \\ \sum_{j=1}^{m} D_2(f) \\ \cdot \\ \sum_{j=1}^{m} D_i(f) \\ \cdot \\ \sum_{j=1}^{m} D_n(f) \end{Bmatrix} \tag{3}$$

However it was found to be a weak indicator of damage localization. A statistical decision making procedure is employed to determine the location of damage. The first step in this procedure is the picking of the maximum change in PSD at each frequency value (the maximum value in each column of matrix [D]) and removing all other changes in PSD measured at other nodes. For example in matrix [D], if $D_3(f)$ is the maximum value in the first column the value will be used as $M_3(f_1)$ and other values in this column will be removed. The same process is applied to the different columns in matrix [D] to formulate the matrix [M] of maximum changes of PSD at different frequencies as shown in Eq. (4)

$$[M]=\begin{bmatrix} 0 & 0 & \cdots & 0 \\ 0 & M_2(f_2) & \cdots & 0 \\ M_3(f_1) & 0 & \cdots & M_3(f_m) \\ 0 & 0 & \cdots & 0 \\ \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot \\ 0 & 0 & \cdots & 0 \end{bmatrix} \quad (4) \qquad C=\begin{bmatrix} 0 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ 1 & 0 & \cdots & 1 \\ 0 & 0 & \cdots & 0 \\ \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot \\ 0 & 0 & \cdots & 0 \end{bmatrix} \quad (5)$$

In order to monitor the frequency of damage detection at any node, a new matrix [C] is formulated as shown in Eq. (5). The matrix consists of 0's at the undamaged location and 1's at the damaged locations. For example in matrix [C] , we put a value of 1 corresponding to the locations of $M_3(f_1)$, $M_2(f_2)$ and so on, as shown in Eq. (5) .

The total of maximum changes in PSD can be calculated from the sum of the rows of matrix [M] as

$$SM = \begin{Bmatrix} \sum_f M_1(f) \\ \sum_f M_2(f) \\ \cdot \\ \cdot \\ \cdot \\ \sum_f M_n(f) \end{Bmatrix} \quad (6) \qquad SC = \begin{Bmatrix} \sum_f C_1(f) \\ \sum_f C_2(f) \\ \cdot \\ \cdot \\ \cdot \\ \sum_f C_n(f) \end{Bmatrix} \quad (7)$$

And the total number of instances of detecting the damage at different nodes is calculated from the sum of the rows of matrix [C] as shown in Eq. (7)

The damage indicator (DI) is defined as the scalar product of { SMD } and { SCD } as shown in Eq. (8)

$$Damage_Indicator(DI) = \begin{Bmatrix} SM(1)\times SC(1) \\ SM(2)\times SC(2) \\ \cdot \\ \cdot \\ \cdot \\ SM(n)\times SC(n) \end{Bmatrix} \quad (8)$$

Damage indicator (*DI*) will be used to determine the damage location. On the other hand, total change in PSD (Eq. (3)) will be used to detect the occurrence of damage and assess the damage extent.

3 STEEL BRIDGE MODEL

3.1 Experimental setup and equipment

Fig. 1 Bridge photo used for measurement(I beam, length: 3.55m)

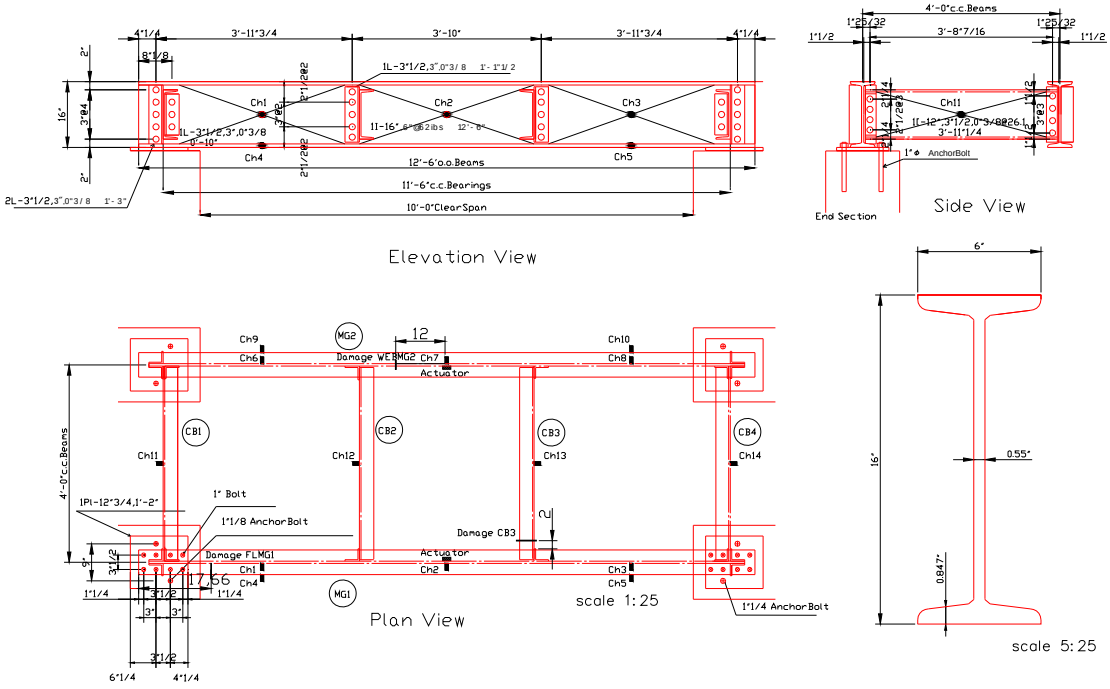

Fig. 2 Bridge dimensions

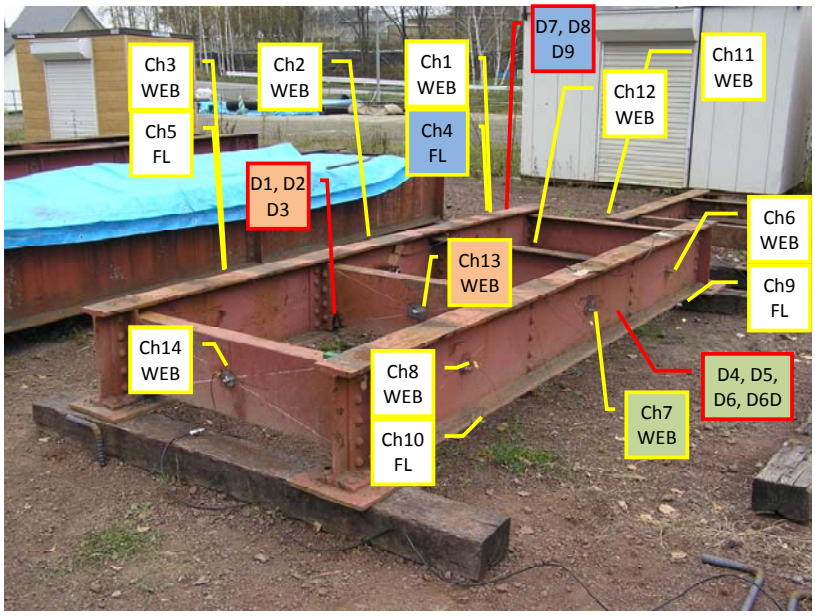

Fig. 3 Array sensor location and damage location

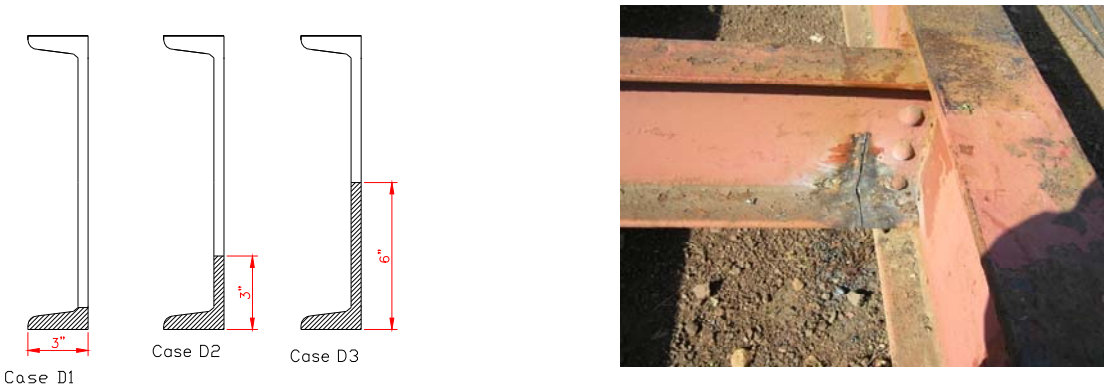

Fig. 4 Damage details on cross beam CB3 as damage D1-D3

Bridge which was constructed in the year of 1909, has elements of 2 main girders (I beams) and 4 cross beams (channels) and the bridge is supported on two wooden blocks without fixation. Sensors are 2 actuators on two main girders and 14 accelerometers.

Setup: 2 piezoelectric actuators are permanently fixed at the center point of the web of each girder from inside. 3 accelerometers are mounted at the geometrical center of gravity of each panel of the main girder's web , 2 accelerometers will placed on the each flange below the side accelerometers of the web , and 1 accelerometer will be mounted on the center point of each cross beam . Actuators and accelerometers are aligned in the horizontal direction. Actuators and accelerometers must not be removed from their locations until the end of the experiment.

Excitation: excitation force amplitude = 30 Kgf, excitation force direction: horizontal, Excitation wave form: sine sweep, excitation frequency: 1~500Hz, excitation time 15 sec, recording time: 20 sec, sampling rate: 1600 Hz.

Excitation with resonant frequency: select one resonant frequency with the highest magnitude at each measuring channel located on the web. Excite the structure with each selected resonant frequency. Excitation time: 8 sec, recording time: 10 sec, sampling rate: 1600 Hz.

Details of damages : Cross beam (CB3)

Case D1: Cut of the whole lower flange, about 5 cm from the edge of the connecting angle.

Case D2: Continue the cut of case D1 to 1/4 of the web height.

Case D3: Continue the cut of case D2 to 1/2 of the web height.

[1] Piezoelectric actuator: A wave function generator is used to adjust the required excitation frequency range, the time in which the actuator reaches the maximum frequency and the excitation wave form. Then, the adjusted wave is transferred to the power supplier which in turn provides the actuator with the adjusted power. The actuator is fixed to the structure by a magnetic holder. This magnetic holder is suitable for fixing the actuator to steel structures; however, a thin steel plate must be mounted on the surface of concrete structures to attach the magnetic holder. A steel spring is fixed over the actuator to control the excitation force amplitude. The produced force amplitude is constant but the excitation frequency gradually increases over time until it reaches its maximum value after the designated time. It should also be noted that because the actuator is pressed but not glued to the test structure, the actuator provides pressure force only. The excitation frequency is gradually increasing over time until it reaches its maximum value after the designated time (15 seconds in this example). In this example, the excitation wave form is a sweep function.

[2] Piezoelectric accelerometer: The accelerometer has a nominal sensitivity of 10 mv/g, a specified frequency range of 5~4000Hz and an amplitude range of 200 m/s^2.

3.2 Damage identification results on the steel bridge structure

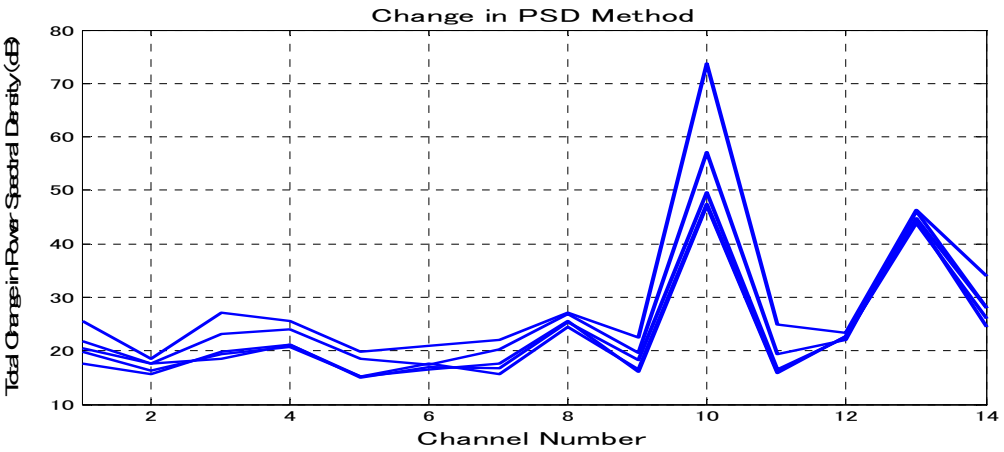

Fig. 4 *TC* distribution over channels in damage case of D1

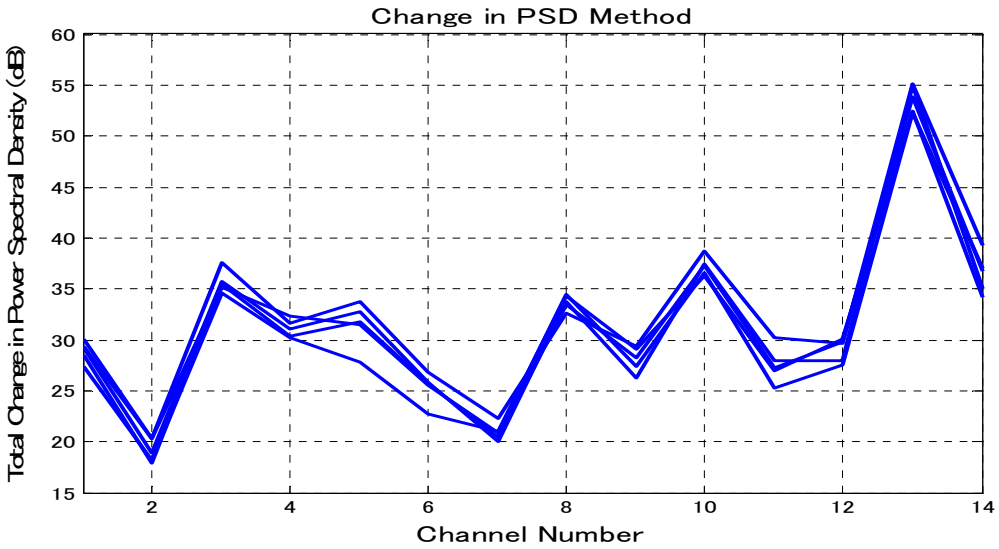

Fig. 5 *TC* distribution over channels in damage case of D3

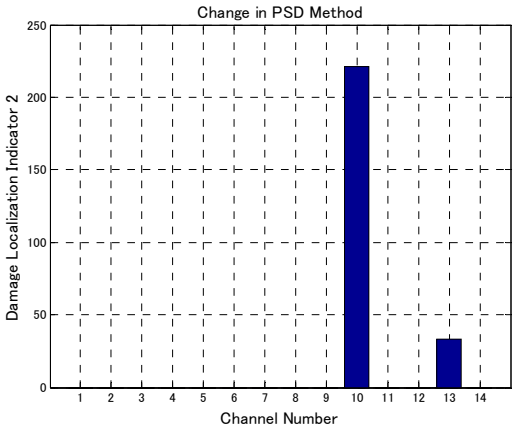

Fig.6 *DI* in damage case of D1

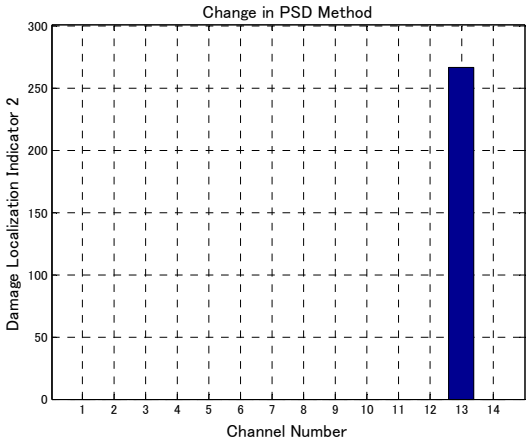

Fig. 7 *DI* in damage case of D3

Analyzed results for *TC* by Eq. (3) and *DI* by Eq. (8) are shown in Figures 4 -6 in cases of damages D1 and D3. Information of damage existence in case of smaller damage D1 is given at channel 10 which locates on lower flange of main girder. On the other hand, in case of larger damage D3 dominated influence of damage locates more close at channel 13 which locates on web plate of cross beam. By array distribution measurement through local excitation of external force we can get clear information on damage even if damage is smaller. Decision of array distribution of sensors is important in the area of suspected damage region of structure.

4 FINAL REMARKS

It is shown that by array sensing through local excitation using piezoelectric actuator we can get local damage information properly. This research also aims at establishment of experimental environment to enable the verification of applicability and the effective evaluation of the structural health monitoring (SHM) technology that uses the high performance sensor system on real bridges. The primary goal of the project is development of test beds that meet wider requests for SHM experiments. Several steel bridges on an abolished railway in Hokkaido, Japan will be available for the establishment of the test beds. The test beds can be utilized by not only researchers of this project but also other researchers. The final goal of the project is international contribution by means of cooperative utilization of the test beds.

References

1) Doebling S. W., C. R. Farrar, M. B. Prime, and D. W. Shevitz, 1996. *Damage Identification and Health Monitoring of Structural and Mechanical Systems from Changes in their Vibration Characteristics*, A Literature Review, Los Alamos National Laboratory Report, LA-13070- MS .
2) Farrar C. R. et al., 1994. *Dynamic Characterization and Damage Detection in the I-40 Bridge Over the Rio Grande*, A Literature Review, Los Alamos National Laboratory Report, LA-12767- MS .
3) Farrar C. R. and D. A. Jauregui, 1996. *Damage Detection Algorithms Applied to Experimental and Numerical Model Data from the I-40 Bridge*, Los Alamos National Laboratory Report, LA-12979-MS .
4) Sampaio R. P. C., Maia N. M. M. and Silva J. M. M., 1999. Damage detection using the frequency-response-function curvature method, *Journal of Sound and* Vibration, 226(5), pp. 1029-1042 .
5) Peeters B., Maeck J. and De Roeck G., 2001. Vibration-based damage detection in civil engineering: excitation sources and temperature effects, *Smart Materials and Structures*, 10, pp.518-527 .
6) Xue S. T. , N. Fujitani, Z.B. Wei and H.S. Tang, 2006. Comparison of variations of natural frequencies for wooden structural models with and without damages part 2, shaking table based results, *Proceedings of the international conference on Structural Health Monitoring and Intelligent Infrastructure*, China, pp 1101-1104 .
7) Yang J. C. S. , J. Chen and N. G. Dagalakis, 1984. Damage detection in offshore structures by the random decrement technique, *Journal of Energy Resources Technology*, American Society of Mechanical Engineers 106, 38-42 .
8) Flesch R. G. and K. Kernichler, 1988. Bridge inspection by dynamic tests and calculations dynamic investigations of Lavent bridge, *workshop on Structural Safety Evaluation Based on System Identification Approaches* (H. G. Natke and J. T. P. Yao, editors), 433-459, Lambrecht/ Pfalz, Germany: Vieweg & Sons.
9) Masri S. F. , R. K. Miller, A. F. Saud and T. K. Caughey, 1987. Identification of nonlinear vibrating structures, *Journal of Applied Mechanics 54*, 923-929: Part I-formulation .
10) Natke H. G. and J. T. P. Yao, 1990. System identification methods for fault detection and diagnosis, *International Conference on Structural Safety and Reliability*, American Society of Civil Engineers, New York, 1387-1393 .
11) Oshima T., Yamazaki T., Onishi K. and Mikami S., 2002. Study on damage evaluation of joint in steel member by using local vibration excitation, (In Japanese), *Journal of Applied Mechanics JSCE*, Vol.5, pp.837-846 .
12) Beskhyroun S., Oshima T., Mikami S., Yamazaki T., 2003. Damage detection and localization on structural connections using vibration based damage identification methods, *Journal of Applied Mechanics, JSCE*, Vol.6, pp. 1055-1064 .
13) Beskhyroun S., Mikami S., Oshima T. and Yamazaki T., 2004. Modified damage identification algorithm based on vibration measurements, *Journal of Applied Mechanics, JSCE*, Vol.7, pp. 97-107 .
14) MATLAB *Reference Guide*, 2003. The Math Works, Inc., Natick, MA .
15) MATLAB *User's Guide*, 2003. The Math Works, Inc., Natick, MA .