대형 구조물의 상설 감지를 위한 감지기의 최적 위치

Optimal Transducer Placement for Health Monitoring of Large Structural System

황 충 열* 허 광 희**
Hwang, Chung-Yul Heo, Gwang-Hee

요 약

이 연구의 목적은 대형 구조물의 상설 감지를 위한 감지기의 최적 위치의 알고리즘을 개발하는데에 있다. 구조물의 진동을 이용한 감지 시스템은 장기적으로 계속해서 구조물을 자동으로 감지하는데에 좋은 방법 중의 하나이다. 하지만 구조물의 진동을 정확히 계측하기 위해서는 감지기의 위치나 감지기의 숫자에 큰 영향을 받는데, 이와 같은 일은 대형 구조물에 있어서 쉽지가 않다. 최적의 감지기 위치와 최소의 감지기로 가장 정확한 데이터를 획득하기 위하여 최적합한 감지기의 위치를 위한 알고리즘이 개발되어 수치적 그리고 실험적으로 유용성을 보인다. EOT가 개발되어 모형 교량에 적용하여 EIM과 비교 분석된다. 이들의 비교를 통하여, 이 연구에서 제안되어진 EOT가 적은 수의 감지기로 좋은 결과를 보여, 상설감지의 목적에 적합함을 보여준다.

Abstract

This research aims to develop an algorithm of optimal transducer placement for health monitoring of large structural system. The structural vibration response-based health monitoring is considered one of the best for the system which requires a long-term, continuous monitoring. In its experimental modal testing, however, it is difficult to decide on the measurement locations and their number, especially for complex structures, which have a major influence on the quality of the results. In order to minimize the number of sensing operations and optimize the transducer location while maximizing the accuracy of results, this paper discusses about an optimum transducer placement criterion suitable for the identification of structural damage for continuous health monitoring. As a criterion algorithm, it proposes the Kinetic Energy Optimization Technique (EOT), and then addresses the numerical issues which are subsequently applicable to actual experiment where a bridge model is used. By using the experimental data, it compares the EOT with the EIM(Effective Indefence Method) which is generally used to optimize the transducer placement for the damage identification and control purposes. The comparison conclusively shows that the EOT algorithm proposed in this paper is preferable when a structure is to be instrumented with fewer sensors for monitoring purpose.

Keywords : transducer, structural system, kinetic energy, optimization, energy matrix

* 충북대학교 구조시스템공학과, 교수
** University of New Mexico 토목과, 연구원

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1. Introduction

Aging infrastructural facilities like bridges which form the life line of our countrys economy are facing a severe crisis. Long service lives, inadequate designs and increasing traffic loads are responsible for the current state of affairs. However bridges must still operate without suddenly collapsing. Therefore, it is imperative that a continuous health monitoring system, as shown in Fig. 1, be developed. Structural dynamics based damage detection and monitoring have been successfully used for health monitoring[1-4]. Large civil structures in terms of structural parameters also have closely spaced mode shapes and resonance frequencies which presents an additional challenge, and high damping[5]. The primary transducer input for health monitoring systems consist of an array of accelerometers. However, in order to make the system cost effective and to acquire accurate modal parameters for large structural system, it is necessary to develop optimal transducer placement. This paper discusses an optimization technique based on the maximization of the modal kinetic energy.

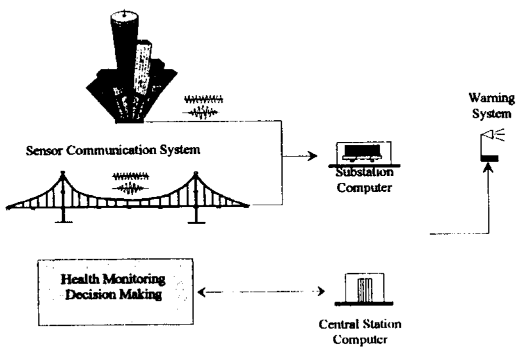

Fig. 1 Automated health-monitoring system (concept)

Optimal placement of transducers on a structure has generated a lot of research[6-12]. Traditionally, large, flexible complex structures require precise transducer configurations for enabling the identification of their essential dynamics. This is computationally intensive and requires several hundred iterations for converging to the optimal configuration[12-13]. Various methods propose to minimize the invariant of the estimated error covariance matrix[14-15]. The error covariance matrix was adapted by Kammer into the Effective Independence Method (EIM), which was based on the spatial independence concept[14]. The degree of freedom in the candidate set can be reduced by eliminating locations that do not significantly contribute to the linear independence of the mathematical mode shapes. Basically, the EIM searches for transducer configurations where the rank of the measured matrix $[\Phi_S^T \Phi_S]$ is maximized to minimize the error covariance matrix. In other words, the Fisher Information matrix (Q) is maximized so that the covariance matrix between the displacement vector in the modal coordinate(q) and the estimated modal displacement($\bar{q}$) is minimized.

$$Min(Co) = E[(q-\bar{q})(q-\bar{q})^T] \quad (1)$$

$$Max(Q) = Max\{[\Phi_S^T \Phi_S]\} \quad (2)$$

where E denotes the expected value, Φ_S represents a reduced set of the mathematical mode shapes corresponding to the target modes. EIM optimizes and selects a set of target modes for identification of the structure based on FE analysis. An initial candidate set of transducer locations is also selected. These locations are ranked based on their contribution to the linear independence of corresponding FEM target mode partitions. Locations that do not contribute are removed from the candidate set[14]. EIM guarantees the linear independency of identified modes and is computationally efficient. However, the authors feel that optimizing the transducer set for maximizing of the kinetic energy of the structural system measured by the transducers will provide more information needed to identify the structural damage in high damping.

2. Kinetic Energy Optimization Technique

The energy optimization technique algorithm is designed to improve the modal information as maximizing the measured kinetic energy of the structural system. The spatial independence of the identified mode shapes is satisfied by the sensing configuration obtained with the EOT algorithm. The distribution of kinetic energy in the system is

$$KE = \Phi^T M \Phi \tag{3}$$

where Φ is the measured mode shape vector. After decomposition of the mass matrix, M, in upper and lower triangular Cholesky factors, the kinetic energy matrix can be derived as:

$$KE = \Psi^T \Psi$$

$$where: \Psi = U\Phi, \text{ and } M = LU \tag{4}$$

The matrix L and U denote the lower and upper triangular Choleskey factor, The projection of the mode shapes on the reduced configuration is denoted by

$$\overline{\Phi} = Projection(\Phi)$$

$$\overline{\Psi} = Projection(\Psi) \tag{5}$$

Similarly, the energy measured by a reduced set of transducers is obtained from the initial energy by removing the contribution of all transducers which have been eliminated

$$\overline{KE} = \overline{\Psi}^T \overline{\Psi} \tag{6}$$

The objective of the transducer placement is to find a reduced configuration which maximizes the measure of the kinetic energy of the structure. It is desirable to stop eliminating the transducers if it results in a rank deficiency of the energy matrix. The column rank N of the quantity $\overline{KE}$ is equal to the number of linearly independent projected vectors in matrix $\overline{\Phi}$, assuming that the mass matrix is non-singular. The problem is solved iteratively by the following procedure. The eigenvalues Λ and eigenvectors Ψ of the energy matrix are extracted.

$$\overline{KE}\Psi = \Psi \Lambda \tag{7}$$

Computin the eigenparis at each iteration of the EOT procedure does not significantly increase the computational cost because the matrix $\overline{KE}$ is a square, symmetric, and positive-definite matrix of size N. Then, the fractional contributions of each remaining transducers are assembled into the EOT vector:

$$EOT = \sum_{i=1 \ldots m} [\overline{\Psi} \phi \Lambda^{-\frac{1}{2}}]^2 \tag{8}$$

The transducer location with the minimal contribution in the EOT vector is then selected for removal. Subsequently, the contribution of the removed transducer to the kinetic energy matrix is deleted and the new matrix is checked for rank deficiency. If the removal of the transducer produces a rank deficiency it implies that the transducer location in question cannot be removed. If removal of the transducer did not produce a rank deficiency then the transducer location is removed from the candidate set and the process repeated until one arrives at the required number of transducers. The quantity between brackets in equation (8) represents a linear combination of the measured mode shapes which is designed to achieve orthonormal vectors, since it can be verified that.

$$[\overline{\Psi}\phi\Lambda^{-\frac{1}{2}}]^T[\overline{\Psi}\phi\Lambda^{-\frac{1}{2}}] = I \qquad (9)$$

Furthermore, each EOT of the vector is a heuristic measure of the contribution of each transducer to the measured energy. The normalization factor $\Lambda^{-\frac{1}{2}}$ prevents the contribution of high frequency modes from dominating those of the low modes. In theory, the number of remaining transducers is equal to the size of the target modal set. However, the apparent rank is often increased due to noise in the experimental data, and more than M transducers are required to identify N independent modes.

3. A Numerical Simulation of the Asymmetrical Long Span Bridge

In order to prove the concepts developed in this research it was necessary to perform experiments on an actual structure. A model of a simply supported long span bridge was built towards this end. In real life, long bridges are characterized by very low closely spaced resonance frequencies[5, 16]. This is primarily due to large span over width ratios and structural redundancies which in turn introduce non-linearity in the dynamic behavior of structure. The guiding design principle behind the model bridge was to be able to simulate this real life behavior of actual bridges[16]. The design process was based on a dynamic simulation on I-DEAS (SDRC)[17-18] where different combinations of geometrical parameters like span, width, beam sizes and configuration, slab thickness and boundary conditions were simulated to obtain acceptable mode shapes and frequencies. In spite of the best of efforts, it was not possible to obtain the low closely spaced resonance frequencies that typify actual complex bridges. This was to maintain constructional simplicity. But we felt that it was enough to prove the optimal transducer placement concept developed in this research. The model structure that was finally chosen is shown in Fig. 2. Both the FEM results of the model showed in Fig. 3(a) and typical FRF from experimental test showed in Fig. 3(b) showed closely spaced mode shapes and resonance frequencies which presents an additional challenge, and high damping as characteristics of large structural systems.

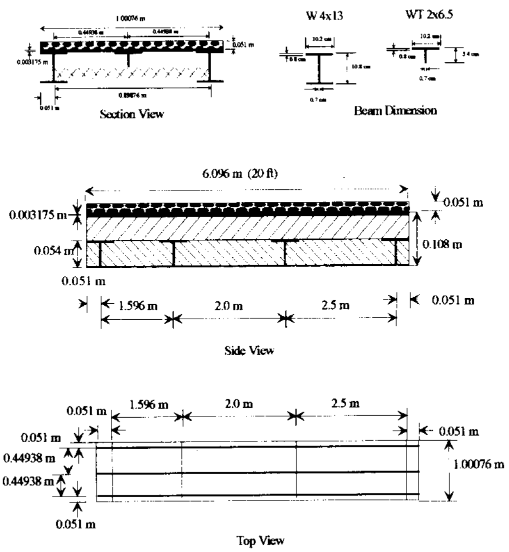

Fig. 2 Description of the asymmetrical bridge (all dimension in m)

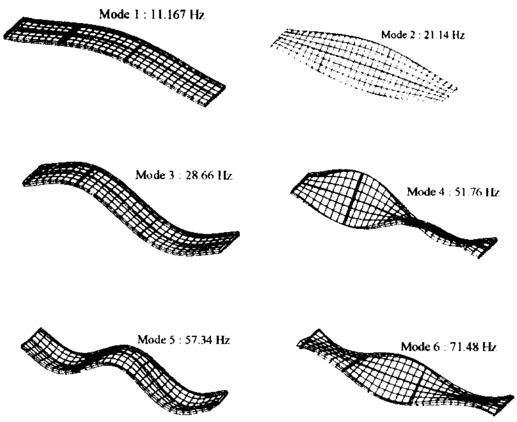

Fig. 3 (a)FE results of the bridge

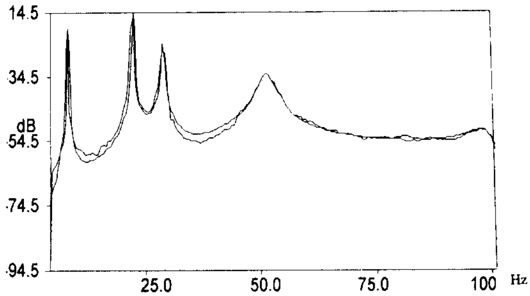

Fig. 3 (b) A typical FRF with curve fitting

4. Numerical Comparison of Optimal Transducer Configuration

To determine the relative efficiencies of the kinetic energy technique and the EIM a bench mark test is carried out on a model of a simulated bridge above. The initial candidate set shown in Fig. 4 consists of 87 transducer locations positioned to identify six eigenmodes and eigenvectors. transducers are eliminated with the EIM and the EOT until a rank deficiency is created in the Fisher information matrix and the Energy matrix.

A plot of the relative performance of EIM and EOT as a function of the number of transducer locations deleted is shown in Fig. 5. Both the methods start out with the same number of transducers, and after each iteration the value of the determinant of the Fishers information matrix and the energy matrix is computed. This new value of the determinant is then compared to the old value and presented in the form of a percentage and has been plotted on the y axis as a function of the number of iterations. As seen in Fig. 5 both the methods are very stable, but the EOT appears to have a distinct advantage as the number of removed transducers increases.

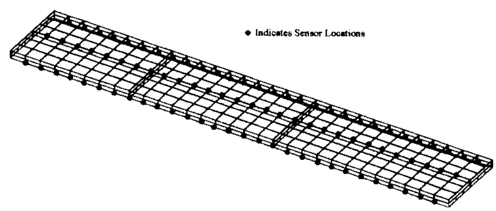

Fig. 4 Initial candidate transducer set (87 transducers) positioned to identify six eigenmodes and eigenvectors

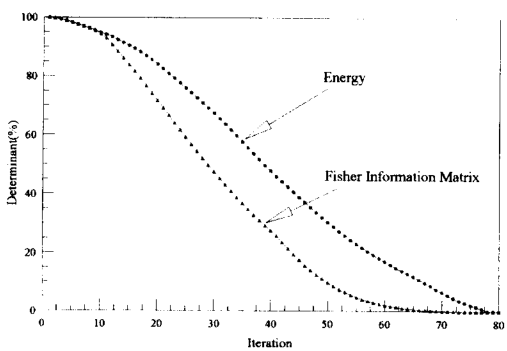

Fig. 5 Determinant of fisher information matrix and kinetic energy

5. Experimental Test Results

The above comparison was based on a numerical simulation only. In order to further investigate the efficiencies of the two methods, an experimental analysis was performed on the long span bridge model with simply supported B.C. The experimental setup as shown in Fig. 6 consisted of Dytran 3187B1 accelerometers and a 32 channel Zonic 7000 data acquisition system. The data acquisition process was controlled by Zeta, a proprietary data acquisition software developed by Zonic Corp. The data was obtained in the form of FRFs and stored in a universal file format. Subsequently the data was processed by MEscope(Vibrant Technology Inc.) to obtain the mode shapes, frequencies and damping ratios.

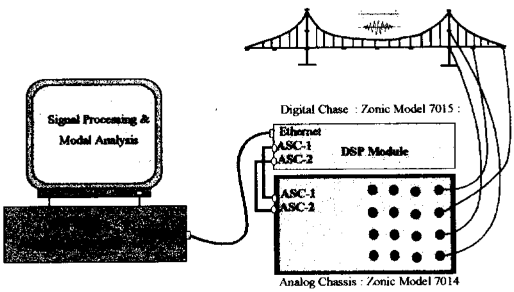

Fig. 6 Data acquisition setup

Transducer locations based on the EIM and the EOT were identified for the first six modes for a set of 15 transducers as shown in Fig. 7 and 8 respectively. The above transducer locations were used to obtain the response of the structure from forced excitation. A typical FRF is shown in Fig. 3(b) with high damping. The modal parameters from FE results are shown in Fig. 3(a). In comparison of the modal frequencies and damping ratios for the FE results, the EIM and the EOT are shown in Table 1. Both the EIM and the EOT results closely agree with each other. However there is some discrepancy between the FE results and the experimental results. This has been attributed to inaccurate modeling of the support rigidity.

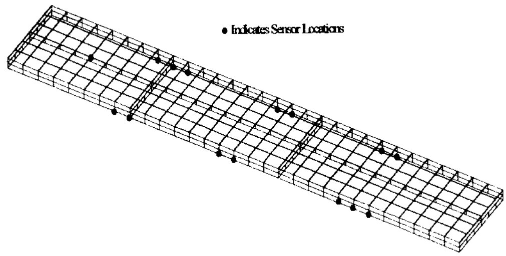

Fig. 7 Optimal sensor locations for the first 6 modes based on EIM

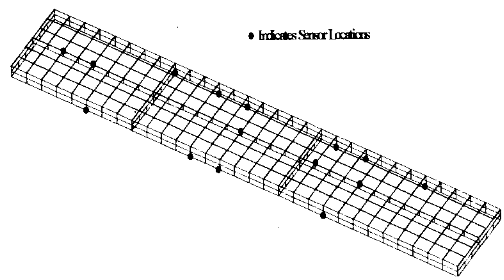

Fig. 8 Optimal sensor locations for the first 6 modes based on EOT

Frequency comparison is only one of the ways of comparing the EIM and the EOT results. A more objective way of comparing the results is comparing the actual mode shapes which can be identified by each of these methods. A tool called the modal assurance criteria (MAC) is an effective way of comparing two sets of structural dynamic data and devising a correlation measure. Popular measures of the correlation are the frequency relative errors

Table 1 Comparison of modal frequencies between EIM and EOT

	Frequency(Hz)				
	Analytical	EIM Exp. Test		EOT Exp. Test	
Mode	Freq. (Hz)	Freq. (Hz)	Damping (%)	Freq. (Hz)	Damping (%)
1	11.167	8.251	0.009	8.265	0.009
2	21.14	22.047	0.0236	22.11	0.038
3	28.66	28.534	0.149	28.58	0.146
4	51.76	50.497	1.482	50.814	1.481
5	57.34	55.334	3.002	55.084	1.855
6	71.48	67.535	0.412	66.768	0.529

and MAC, which is sometimes referred to as the modal correlation coefficient and is defined as

$$MAC(i,j)=\frac{\left|\sum_{j=1}^{n}(\Psi^{a})_{i}(\Psi^{e})_{j}^{*}\right|^{2}}{\left(\sum_{j=1}^{n}(\Psi^{e})_{i}(\Psi^{e})_{j}^{*}\right)\left(\sum_{j=1}^{n}(\Psi^{a})_{i}(\Psi^{a})_{j}^{*}\right)} \quad (10)$$

where a means analytical data and e means experimental data. MAC is calculated to quantify the correlation between measured mode shapes during the different tests and to check the orthogonality of measured mode shapes during a particular test. MAC uses the orthogonality properties of the mode shapes to compare either two modes from the same test or two modes from different tests. If the modes are identical, a scalar value of one model is calculated using MAC. If the modes are orthogonal, a value of zero is calculated. Ewins[15] opints out that correlated modes will yield a value greater then 0.9 and uncorrelated modes will yield a value less then 0.005 MAC is not affected by a scalar multiple.

Comparison of the MAC data is shown in Tables 2 and 3, and Fig. 9 and 10. The MAC results for the EIM show a very high correlation between the first four modes with the correlation dropping off for the 5th and 6th modes. In comparison, the EOT shows a very high correlation between the first 4 modes, with the correlation dropping off for the 5th and 6th mode also. However, the correlation coefficients for the 5th and 6th modes of the EOT is much higher than the 5th and 6th modes of the EIM. The EOT technique however appears to be picking up off diagonal terms. Based on the results obtained from both the numerical simulation and the experimental data it can be inferred that the EOT has some distinct advantages over the EIM.

Table 2 Comparison of mode shape(MAC) for EIM

Mode	1	2	3	4	5	6
1	0.090	0.002	0.003	0.009	0.002	0.008
2	0.001	0.993	0.005	0.004	0.070	0.171
3	0.005	0.011	0.992	0.000	0.006	0.030
4	0.008	0.002	0.000	0.984	0.417	0.013
5	0.042	0.002	0.005	0.046	0.334	0.225
6	0.005	0.179	0.012	0.005	0.096	0.582

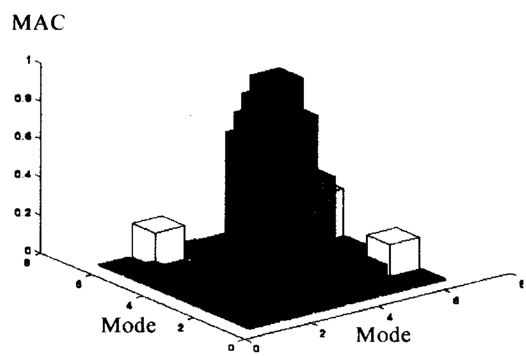

Fig. 9 Comparison of mode shape(MAC) for EIM

Table 3 Comparison of mode shape(MAC) for EOT

Mode	1	2	3	4	5	6
1	0.988	0.013	0.007	0.002	0.002	0.011
2	0.019	0.990	0.004	0.002	0.113	0.621
3	0.007	0.001	0.971	0.041	0.078	0.056
4	0.007	0.010	0.054	0.961	0.3	0.043
5	0.007	0.008	0.001	0.007	0.561	0.027
6	0.000	0.404	0.008	0.002	0.121	0.788

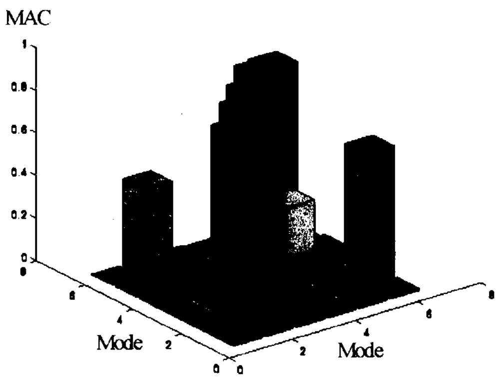

Fig. 10 Comparison of mode shape (MAC) for EOT

6. Conclusions

In this research, the Energy Optimization Technique is proposed to place transducers effectively and econmically in large structural system, and is compared to EIM. We numerically and experimentally show that the EOT with fewer transducers has more advantages in picking up the mode shapes in several ways. Both numerical simulation and experimental data prove that with the same number of transducer locations the EOT identifies the mode shapes better than the EIM. As the number of transducers ae reduced and the mode number increases, the difference between the two techniques become quite apparent. We therefore conclude that the EOT algorithm is preferable when a structure is to be instrumented with fewer sensors for monitoring purpose.

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