Structural Damage Detection Using Sensors Optimally Located

Carlos Alberto Riveros, Edwin Fabián García, Javier Enrique Rivero

***Abstract*—**The measured data obtained from sensors in continuous monitoring of civil structures are mainly used for modal identification and damage detection. Therefore, when modal identification analysis is carried out the quality in the identification of the modes will highly influence the damage detection results. It is also widely recognized that the usefulness of the measured data used for modal identification and damage detection is significantly influenced by the number and locations of sensors. The objective of this study is the numerical implementation of two widely known optimum sensor placement methods in beam-like structures.

***Keywords*—**Optimum sensor placement, structural damage detection, modal identification, beam-like structures.

I. Introduction

SENSING technology has been widely developed and applied in the aerospace, automotive and defense industry, in civil structures the most widely used sensors for structural health monitoring are the accelerometers, but due to economic constraints, nowadays, it is impossible to completely instrument civil structures for continuous damage monitoring, this limitation cause that the number of sensors used in real applications is very small when is compared with the total degree-of-freedom corresponding to the Finite Element Model of the structure. Optimum sensor placement deals with two important factors: the optimum number of sensors to be used and the best locations for each sensor. The main idea is to find the best distribution of sensors when a limited number of sensors is used; in addition, in order to achieve a good distribution of sensors, the purpose of the optimization is also important (e.g. modal identification, damage detection).

Modal updating is also of importance due to simplifications when the response of a structure is predicted using numerical models. Recent structural failures have shown the importance of having reliable numerical models. In addition, simplification in reviewing processes may also benefit from data collected from a structure when the purpose of the numerical model is to increase its carrying capacity or update the structure to new codes requirements.

Identification of the location and degree of damage may require considerably dense array of sensors and perhaps sensors that provide more robust local information. In order to determine the presence of damage, in addition to the sensor selection, efficient and robust damage algorithms are needed. The goal of Vibration-based damage detection methods is to evaluate the dynamic structural characteristics, such as stiffness, damping, and mode shapes, and monitor changes in their values. The main purpose of continuous damage monitoring is to detect damage in an early stage. The type of damage that is aimed at detect is damage that causes a stiffness decrease in the structure.

Instrumented bridges have received much attention due to the potential economic impact and life-safety implications of early damage detection, unfortunately current methodologies for sensor placement is based on practical experience, in addition, it is widely known that the usefulness of the measured data depends significantly on the selection of number and locations of sensors,usually, sensors are located in the center of the spans, center of the half of the spans and supports without any additional consideration, the objective of this study is to numerically implement sensor placement techniques on beam-like structures, in this study two sensor placement techniques are selected based on the optimization of modal identification, damage detection and damage detection considering measurement noise.

Carlos Alberto Riveros,Edwin FabiánGarcía, and Javier Enrique Rivero are with the University of Antioquia, Medellín, Colombia (phone: 2198580; fax: 2195514; e-mail: carlos.riveros@udea.edu.co,edwin.garcia@ udea.edu.co,javier.rivero@ udea.edu.co).

II. Sensor Location

In placing the sensors, one must determine both the number of sensors needed for economic implementation, and the best location of those sensors. One should consider the ability of the sensors to measure the modes of interest. The characteristics of the excitation should be considered in the placement scheme, including the source, type and frequency range. Additionally, one should take into account the likelihood of damage in various regions of a structure if this information is available. Furthermore, the effectiveness of a placement methodology will be related to the requirements of the selected damage detection technique. Thus, the placement methodology should be tested in conjunction with the modal identification and the damage detection procedures adopted. This study will focus in the numerical implementation of two existing sensor placement techniques named the Eigenvector Sensitivity method and the Effective Independence method which are two methods that are commonly used to place sensors in damage detection studies.

A. The Effective Independence Method

The Effective Independence (EI) method was proposed by Kammer [1] and it is basically related to the fact that sensors for conducting a modal test should be arranged such that the mode shapes obtained using the measured DOF are spatially independent of each other. The partition of the FE model eigenvector matrix, $[\phi]_{Nxm}$ is used to form the matrix, **A**:

$$[A]^{-1}_{mxm} = [\psi]^{T}_{mxm} \cdot [\lambda]^{-1}_{mxm} [\psi]_{mxm} \tag{1}$$

where λi and ψi are the ith eigenvalue and eigenvector of **A**, respectively. For this study the eigenvectors are mass-normalized. The so-called Prediction Matrix, **E**, can be generated as:

$$[E]_{NxN} = [\phi]_{Nxm} \cdot [A]^{-1}_{mxm} \cdot [\phi]^{T}_{mxN} = [\phi]_{Nxm} \cdot \left([\phi]^{T}_{mxN} \cdot [\phi]_{Nxm}\right) \cdot [\phi]^{T}_{mxN} \tag{2}$$

Taking the diagonal elements in the matrix **E**, a vector referred to as the effective independence distribution vector of the candidate sensor set, is obtained. Kammer[1] developed this method and considered the method in the cases of models with noise, measurements with noise, and sequentially assembled structures.

B. The Eigenvector Sensitivity Method

The Eigenvector Sensitivity (ES) method for sensor placement was developed by Shi et al. [2]. The mathematical derivation of the method is based on the model updating method proposed by Hemez [3]. To apply this approach we consider that the initial model corresponds to the undamaged structure, and the updated model corresponds to the damaged structure. The approach uses a truncated Taylor series expansion

$$\begin{Bmatrix} \tilde{\lambda}_i \\ \tilde{\phi}_i \end{Bmatrix} = \begin{Bmatrix} \lambda_i \\ \phi_i \end{Bmatrix} + [\mathbf{S}_i]\left(\{\tilde{\alpha}\} - \{\alpha\}\right) \tag{1}$$

where λi, ϕ_i and $\tilde{\lambda}_i$, $\tilde{\phi}_i$ are the ith eigenvalue and mode shape of the undamaged and damaged models, respectively, $\{\alpha\}$ and $\{\tilde{\alpha}\}$ are vectors of the elemental stiffness parameters of the undamaged and damaged models. The sensitivity matrix, **Si**, is defined by

$$[\mathbf{S}_i] = \begin{bmatrix} \dfrac{\partial \lambda_i}{\partial \alpha} \\ \dfrac{\partial \phi_i}{\partial \alpha} \end{bmatrix} \tag{2}$$

The Fisher information matrix as a distribution of strain energy **B** is defined as a summation of the contribution of the selected modes as shown in (5)

$$[\mathbf{B}_i] = [\mathbf{S}_i]^{T} [\mathbf{S}_i] \tag{3}$$

The diagonal terms are used to rank the importance of a particular DOF to the determinant of **Ei** for the selected sensor locations as defined by

$$\mathbf{E}_{\mathrm{i}} = ([\mathbf{S}_{\mathrm{i}}]\left[[\mathbf{S}_{\mathrm{i}}]^{\mathrm{T}}[\mathbf{S}_{\mathrm{i}}]\right]^{-1}[\mathbf{S}_{\mathrm{i}}]^{\mathrm{T}}) \tag{4}$$

Thus, if a particular DOF has a small contribution to the diagonal terms of **Ei,** this sensor position can be eliminated from the selected sensor locations, then the remaining sensor locations maximize the contribution to the Fisher Information matrix as a distribution of the strain energy **B** providing the most information for damage detection.

III. Modal Identification

The selected procedure is based on the Natural Excitation Technique (NExT) [4] and the Eigensystem Realization Algorithm (ERA) [5]. The first method is used to obtain a free vibration record from ambient vibration tests, allowing modal identification without knowing the forces exciting the structure. The ERA is used to obtain the modal parameters of the structure from the free vibration records.The choice of an excitation source is also guided by other additional criteria; if mass-normalized mode shapes are required, one cannot use ambient excitation. To obtain the correct scaling of the mode shapes, the applied force has to be known. For large structures, it becomes very difficult to apply sufficient artificial excitation to surpass the vibration levels from the ambient excitation which is always present. Therefore, if the purpose of the test is continuous monitoring, only ambient excitation can be used.

With ambient excitation, only a handful of natural modes would be identified. Because the main goal of this study is the implementation of continuous damage monitoring for cable-stayed bridges, we assume herein that traffic will be the main excitation source. This type of loading acts primarily to excite the vertical modes of a beam-like structure. Thus, in this study we focus on a select number of modes dominated by vertical motions and simulate the use of sensors capable of measuring only vertical components.

IV. Damage Detection

Deterministic damage detection techniques, which rely only on the modal parameter information, might have the drawback that the damage locations and amount may not be uniquely determined from the estimated modal data. Models with differently assumed damage locations and amount can produce identical modal parameters. These models are referred to as output equivalent models. In real applications, multiple hypotheses need to be examined, because the modal testing measures the dynamic responses at limited points and estimates only a few fundamental modes, the number of output equivalent models can increase, and in the presence of the modeling error and the measurement noise, some erroneous models could have modal parameters closer to the estimated modal parameters than the model with the correct damage locations and amount. Sonh and Law [6] proposed the Bayesian Probabilistic approach for damage detection, which is based on an output error, which is defined as the difference between the estimated vibration parameters and the theoretical ones from the analytical model.

The main idea behind the Bayesian Probabilistic approach is to search for the most probable damage event by comparing the relative probabilities for different damage scenarios, where the relative probability of a damage event is expressed in terms of the posterior probability of the damage event, given the estimated modal data sets from a structure. The formulation of the relative posterior probability is based on an output error, which is defined as the difference between the estimated modal parameters and the theoretical modal parameters from the analytical model.

V. Numerical Implementation

A. Numerical Model

To evaluate the performance of the two sensor placement techniques presented, numerical simulations are performed using a limited number of structural responses to simulate the use of measurements from sensors with locations defined by these techniques. A continuous beam model is then selected. By using this model we are intended to simulate the dynamic behavior of the main span of a bridge. This model is used to simulate the dynamic behavior of a typical configuration of a highway bridge, the FE model of the intact beam has 30 Euler-Bernoulli elements, each element is of 1 meter long; the main span consists of 16 elements and both side spans have 7 elements. Nodes 8 and 24 are simply supported, and nodes 1 and 31 have only restriction in vertical direction, each node has three dregree-of-freedom (translational, vertical and rotational), the FE element has a cross-section of 0,4 m x 0,4 m, a density of 2.5e-3 Kg/m^3, a moment of inertia of 2,1e-3 m^4 and a Young Modulus of 2.5e10 N/m^2.

The objective of numerical simulation here is to investigate the performance of the two sensor placement techniques previously presented using limited number of sensor and computed mode shapes contaminated by noise.The previous FEM model is used. The effectiveness of the resulting sensor configurations is studied using the Bayesian probabilistic approach for damage detection, this method can locate and quantify structural damage using the measured mode shapes, only vertical degree-of-freedom are considered to place sensors. The Bayesian Probabilistic Approach can perform damage detection using limited number of sensors; herein two sensor configurations and two level of noise in the computation of mode shapes are used for all cases presented in this section. The Bayesian Probabilistic Approach is implemented by using the graphical user interface DAMTOOL developed by Lynch et al. [7].

B. Sensor Placement Results

The first four mode shapes are used to optimally locate sensors for each sensor placement technique. The main reason for these four modes being selected is that with ambient excitation sources we can only identify a few low frequency modes. It is also important to note that different configuration of sensors can be obtained if different modes are considering for sensor placement, therefore these modes must be carefully selected in order to improve the quality of damage detection analysis. The resulting placement schemes are shown in Figs.1-4.

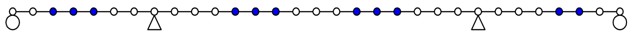

Fig. 1 11 Sensor Configuration Effective Independence Method

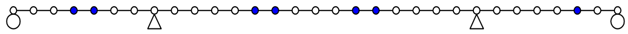

Fig. 2 7 Sensor Configuration Effective Independence Method

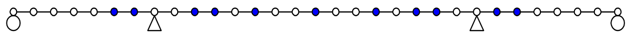

Fig. 3 11 Sensor Configuration Eigenvector Sensitivity Method

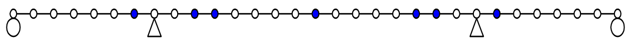

Fig. 4 7 Sensor Configuration Eigenvector Sensitivity Method

C. Modal Identification

Independent broad-band random excitations are generated for simulation of the beam model response. The excitation is applied to all the vertical DOFs of the nodes of the beam model. A linear simulation of the beam is performed using the state-space representation of the beam. A sampling frequency of 1 KHz and sample length of 1 minute are used in the simulation. After the simulation the acceleration records were resampled to 125 Hz. This approach allows us to identify modes up to 75 Hz, covering the first 8 vertical modes of the beam.

TABLE I
IDENTIFIED NATURAL FREQUENCIES FOR 11 SENSOR CONFIGURATIONS

		EIGENVECTOR		EF. INDEPEND.	
Frq.	Exact (Hz)	Identified (Hz)	Error (%)	Identified (Hz)	Error (%)
1	3,6197	3,6273	0,2100	3,6249	0,1437
2	9,9338	9,9216	0,1228	9,9262	0,0765
3	14,1830	14,3690	1,3114	14,1870	0,0282
4	16,4620	16,4190	0,2612	16,4480	0,0850
5	24,6410	24,6240	0,0690	24,6070	0,1380
6	38,9900	38,9930	0,0077	39,0110	0,0539
7	50,3180	50,2840	0,0676	50,3200	0,0040
8	54,4060	54,3780	0,0515	54,4110	0,0092

D. Damage Detection

Two different levels of measurement noise are considering for each sensor configuration, based in previous results, 1% noise with 7 measurement sets and 2% random noise with 7 measurement sets are selected. Tables II and III show the damage detection results obtained from the numerical implementation. The Effective Independence method configurations do not follow a logic trend. For the Eigenvector Sensitivity method configurations there are some regions located near the supports and in the center of the spans where damage identification is not successful, for regions located near the supports, it is expected that small displacements in the mode shapes led to small changes due to damage, therefore when noise is introduced to the analysis the damage can be completely masked and almost impossible to identify. In the case of elements located near the center of the span, the mode shapes in these regions are very sensitive to any damage inflicted in other elements due to the support conditions of the beam model, for example, if one or more elements, in the main span near the supports, are damaged, it will cause change in the mode shapes similar to the changes in the mode shapes produced by damage near the center of the span.

TABLE II
DAMAGE DETECTION RESULTS EFFECTIVE INDEPENDENCE METHOD

Number of sensors	Level of Noise	Number of Cases Correctly Identified				
		Rank 1	Rank 2	Rank 3	Rank 4	Total
7	1% and 7 sets	10	-	-	1	11
	2% and 7 sets	5	1	1	-	7
11	1% and 7 sets	8	1	1	2	12
	2% and 7 sets	4	-	2	-	6

TABLE III
DAMAGE DETECTION RESULTS EIGENVECTOR SENSITIVITY METHOD

Number of sensors	Level of Noise	Number of Cases Correctly Identified				
		Rank 1	Rank 2	Rank 3	Rank 4	Total
7	1% and 7 sets	14	-	1	-	16
	2% and 7 sets	7	-	-	-	7
11	1% and 7 sets	14	-	1	-	16
	2% and 7 sets	4	-	2	1	7

VI. CONCLUSIONS

In this paper the numerical implementation of two existing optimum sensor placement methodologies on beam models was presented. Some differences were found in damage detection analysis for different number of sensors and levels of noise, according to the numerical results presented in this study the Eigenvector Sensitivity method seems to perform the best when compared with the Effective Independence Method, but in the case of modal identification there is no significant difference among the sensor placement methods presented in this paper.

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REFERENCES

[1] D.C. Kammer. "Effect of model error on sensor placement for on-orbit modal identification of large space structures". *Journal of Guidance, Control and Dynamics*, 15(2):334-341, March-April 1992.
[2] Z.Y. Shi, S.S. Law, and L.M. Zhang. "Optimum sensor placement for structural damage detection", *Journal of Engineering Mechanics,* Volume 126, Issue 11, pp. 1173-1179, 2000.
[3] F.M. Hemez and C. Farhat. "An energy based optimum sensor placement criterion and its application to structure damage detection" *Proc. 12th Conf. on Int. Modal Analysis (Honolulu, HI: Society of Experimental Mechanics),* pp. 1568–75, 1994.
[4] C.R. Farrar, and G.H. James III. "System identification from ambient vibration measurement on a Bridge", *Journal of Sound and Vibration*, Vol.205, No1, pp. 1-18, 1997.
[5] J.N. Juang, and R.S. Pappa. "Effects of Noise on Modal Parameter Identification"*, Journal of Guidance*, pp. 295-303, 1986
[6] H. Sohn and K.H. Law. "Bayesian probabilistic approach for structure damage detection". *Earthquake Engineering and Structural Dynamics*, 26:1259-1281, 1997.
[7] J.P. Lynch, H. Sohn, and K.H. Law. The development and application of a damage detection toolbox for matlab, *The 5th US National Congress on Computational Mechanics,* University of Colorado at Boulder, CO, USA, August 4-6, 1999.