Optimal Sensor Placement An Damage Detection In Health Monitoring

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Abstract:

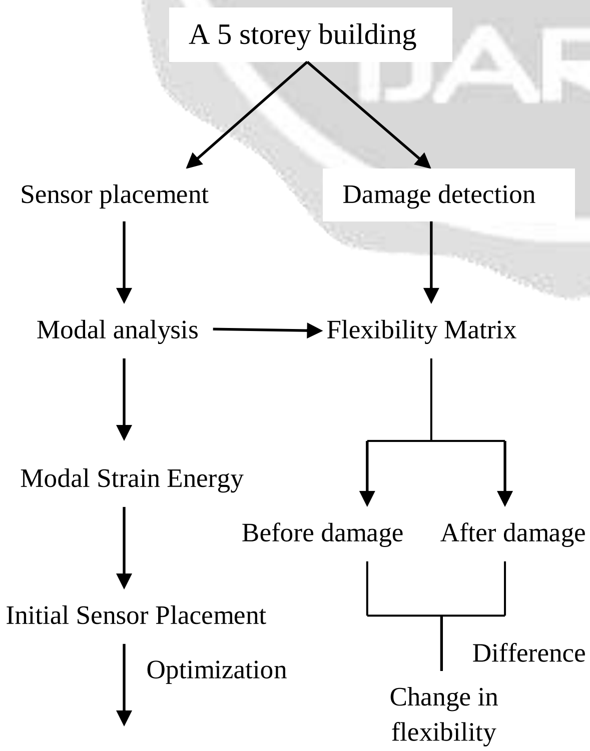
Advanced engineering technologies are an emerging research area with multiple applications such as medical fields, home appliances, transportations, electrical systems, civil and mechanical systems, all manufacturing industry like chemical, fabrics, electronics equipment, structural like buildings, bridges, towers and so on, in our lives. It relies heavily on the pervasive civil infrastructure in which industrialized nations have huge investments. Malfunctioning of civil infrastructure has caused tremendous economic loss and claimed numerous human lives. To properly manage civil infrastructure, its condition or serviceability must be assessed and to be monitored. So nowadays, a sophisticated sensor usage in all fields is increased to monitor the condition of the structures. Hence continuous monitoring of structures is necessary and it is monitored by using Structural Health Monitoring (SHM) systems. Considering cost, reliable data, accuracy of results, and computation time into account the proper deployment of sensors becoming a challenging task in SHM. There are several methods for optimal sensor placement and in this study, 'MSE' technique has been introduced for the sensor placement. Genetic algorithm, an evolutionary algorithm belonging to the area of artificial intelligence is used for the optimization of the number of sensors.

Keywords*: Structural Health Monitoring, Optimal Sensor Placement*

I. INTRODUCTION

Civil infrastructure includes buildings, bridges, tunnels, factories, conventional nuclear power plants and geotechnical structures, such as foundations and excavations and they are erected to serve for the serviceability of the society. Depending on importance, ownership, use, risk and hazard, continuous inspection and monitoring of structures are essential. The effectiveness of maintenance and inspection lies in the fact that they intimate the damage before the structure proves to be more dangerous. Manual inspection techniques like non destructive methods may not be useful all times[1]. Hence automated systems have to be developed for monitoring the general health of the structure. Today, wired connections are slowly being replaced by different latest emerging wireless technologies[2]. Emergence of new wireless technologies has helped to bring out many new ideas and applications to the society. Wireless technology is a broad term that incorporates all procedures and forms of connecting and communicating between two or more devices using a wireless signal. Likewise, sensor placement method also focuses on wireless technology. A sensor is a device used for detecting and signaling a changing condition which are widely used in different applications and has become an enabling technology in many instances especially in wireless networks. But where the sensors should be located in a structure is a challenging task. Identifying the points of sensor location that gives the maximum details with high efficiency is desirable. If the sensors are located at many points, more is the information obtained. But placing many sensors is uneconomical. Therefore limiting the number of sensors is wise. That is called as 'Optimal Sensor Placement'. Optimization is the process of making things better .Optimization can be defined as the science of determining the 'best' solutions to mathematically defined problems which are often models of physical reality. The fundamental principle of optimization algorithm is "search for an optimal state". Optimization aims for efficient allocation of scarce resources. The sensor placement optimization is a kind of combinatorial optimization problem that can be generalized as "given a set of n candidate locations, find m locations, where $m < n$, which may provide the best possible performance." For this optimization problem various criteria has been introduced. Singular Value Decomposition analyzes discrete FRF data. The corresponding principal directions show how the energy is distributed in the system. Like mode shapes, principal directions are the fundamental shapes that represent the system's dynamics[3]. Another criteria is that the kinetic energy contained in the DOFs for each mode is measured and the energy stored in the modes before and after damage is evaluated. The locations with high amplitudes of responses are noted for sensor placements[4]. Fisher information is a key concept in the theory of statistical inference and the FIM matrix provides the maximum likelihood estimator on how far the damaged mode shapes lie on the undamaged mode shape of the structure [5]. The Modal Assurance Criterion is defined as scalar constant which provides a useful criterion to evaluate the correlation of modal vectors[6]. Apart from the criteria, there are also several optimal sensor placement techniques. A technique called 'effective independence (EI) method' in which a number of candidate sensor positions are eliminated or added according to their ranks evaluated by the determinant of a Fisher information matrix (FIM) is given by Kammer[5]. Six different optimal sensor placement in buildings namely . EFfective Independence (EFI), Optimal Driving Point (ODP), Non-Optimal Driving Point (NODP), Effective Independence Driving Point Residue (EFI-DPR), Singular Value Decomposition (SVD) and the Sensor Set Expansion (SSE) methods is proposed by Pelin Gundes Bakir [3]. Also a integrated methodology [7] has also been presented by Pelin Gundes Bakir for efficient sensor placement and robustness of each technique is also presented. Carne and Dohrmann[8] proposed a famous algorithm called minMAC by distinguishing one modal vector from another to realize modal parameter identification. All of these algorithms have their own limitations so we go for traditional algorithm such as simulated annealing method [9], Particle Swarm Optimization[10], Genetic algorithm [11]. Among the above-mentioned heuristic algorithms, Genetic Algorithm (GA) seemed to be an effective approach to sensor placement problems. Genetic Algorithms (GAs) are adaptive heuristic search algorithm based on the ideas of selection and genetics. Genetic algorithms are a type of optimization algorithm that are used to find the optimal solution to a given computational problem and it yields the 'fittest' of the solutions. The "traditional" GA is composed of a fitness function, a selection technique, and crossover and mutation operators which are governed by fixed probabilities [12]. Modal Assurance Criterion(MAC) is defined as the objective function and the sensor positions is designated as the design variables. The fitness function is evaluated by the root mean square of the MAC matrix. The mode shapes of the structure is used to find the modal strain energy. Strain energy is the energy stored by a system undergoing deformation. The MAC matrix is also obtained from the mode shape matrix [6].Any damage is characterized by changes in the dynamic characteristics of a structure. Loss of a single member in a structure can result in changes in the fundamental natural frequency of one to as much as thirty percent [13]. A further improved method to determine the location of damage is from the curvature of the mode shape [14]. The changes in flexibility matrix has also proved to be a better damage index for determining the location and the extent of damage [15]. This study focuses on the optimal sensor placement and damage detection of the structures.

II. METHODOLOGY OF THE STUDY



Genetic Algorithm

Fig. 1: Flowchart depicting sensor placement and damage detection

An essential problem in SHM is the sensor location optimization. This problem consists of an arrangement of a limited number of sensors over the structure that guarantees the best estimates of the structural properties, such as mode shapes. Mode shapes and their derivatives have been proven to be sensitive in capturing structural dynamic changes. A significant change in the mode shape implies possible damage. By comparing changes, and by identifying the sensor location where the maximum changes occur, we can obtain possible damage-sensitive locations.

A. Modal analysis

The modal analysis of the structure is carried out to calculate the mode shapes and the natural frequencies.

B. Mode Shapes and Natural Frequency

Each mechanical structure has a number of specific vibration patterns at specific frequencies. These vibration patterns are called mode shapes. All bodies have a natural frequency. Natural frequency is the frequency at which a system tends to oscillate in the absence of any driving or damping force. Free vibrations of any elastic body is called natural vibration and happens at a frequency called natural frequency.

1) Modal strain energy (MSE) of the system

Modal strain energy is a damage index which is proposed for the initial sensor placement. The energy stored in the modes during deformation is called as modal strain energy. The MSE is obtained from the mode shape matrix and stiffness matrix it is given by,

$$MSE=\phi^T K\phi \qquad (1)$$

where, ϕ is the mode shape matrix and K is the stiffness matrix. The main idea behind initial sensor placement is to reduce the searching space by identifying degree of freedoms with large MSE as the sensor location. The sensors are placed at points of high MSE.

C. Optimization using GA

Optimization can be defined as the process of finding the best solutions that satisfy given constraints and achieve the objective at its optimal value.

1) Genetic Algorithm

Genetic algorithms are a type of optimization algorithm, meaning they are used to find the optimal solution(s) to a given computational problem. It imitates the biological processes of reproduction and natural selection to solve for the `fittest' solutions.

2) Representation of a chromosome

In this study, binary coding is done for the chosen random population.

3) Fitness function

Modal Assurance Criterion (MAC):

The Modal Assurance Criterion is defined as scalar constant which provides a useful criterion to evaluate the correlation of modal vectors. MAC matrix is defined as

$$MAC = \frac{(\Phi_i^T \Phi_j)^2}{(\Phi_i^T \Phi_i)(\Phi_j^T \Phi_j)} \qquad (2)$$

where ϕ_i and ϕ_j are the *i*th and *j*th column vectors in the modal shape matrix ϕ. The off-diagonal elements in the MAC matrix is more significant in expressing the correlation between two modal vectors.

Fitness function using MAC:

Fitness function should be problem specific. Fitness can be quantified by single numerical fitness in single objective optimization or as multiple measures in multi-objective optimization problem. The fitness function is obtained from the MAC matrix and it is constructed as,

$$f = 1 - \text{RMS} \quad (3)$$

where, RMS is the root mean square of the off-diagonal elements in the MAC matrix.

4) Parameter processing in the algorithm

Genetic algorithm (GA) presented initially in searches for a global optimal solution using three main genetic operators in a sequence selection, crossover, and mutation. Roulette wheel selection strategy is used for the selection of individuals based on their fitness. The individuals with a higher fitness have a higher probability of reducing offspring. An elitist strategy is employed to retain the best individual for the subsequent generation.

5) The way of terminating the algorithm

The algorithm is terminated with the condition in the fitness evaluation. If the fitness function nearly equals 1 then the algorithm is terminated. Else selection, crossover and mutation is carried out until a sensor number whose fitness function corresponds to 1 is obtained.

D. Damage detection based on flexibility matrix

For the purpose of damage detection, Flexibility Matrix Based Technique(FMBT) is introduced. It has been proved that the presence of damages increase the flexibility of the structure. The flexibility matrix F is the inverse of the stiffness matrix K relating the applied static forces $\{f\}$ to resulting structural displacements $\{u\}$ as

$$\{u\} = [F]\,\{f\} \quad (4)$$

The relationship between the flexibility matrix and the dynamic properties of the structure is obtained by,

$$\{f\} = \frac{1}{\omega^2}\Phi_i\,\Phi_i^T \quad (5)$$

where φ_i is the mode shape and ω is the natural frequency of the structure .

Damages are artificially introduced in the structure and the flexibility matrix for the damaged case is found[15]. Now the change in flexibility is given by,

$$\Delta f = \{f_d\}-\{f_h\} \quad (6)$$

where $\{f_d\}$ is the flexibility matrix of the damaged case and $\{f_h\}$ is the flexibility matrix of the healthy structure.

III. Result Analysis

A 5-storey building is taken for the study. As the first step, the modal analysis of the building is carried out by assuming the mass and the stiffness matrices. The mode shapes and the modal strain energy of the building are as shown in Fig. 2 and Fig. 3.

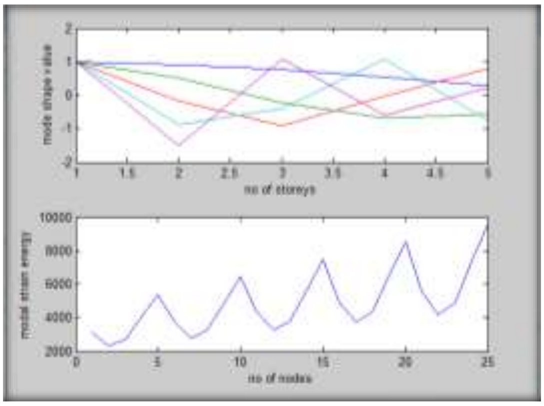


Fig.2: Output of mode shape and modal strain energy

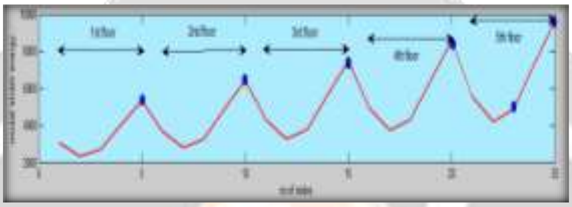


Fig.3: Initial Sensor Placement

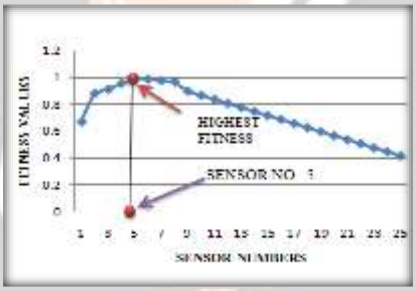


Fig.4: Optimization

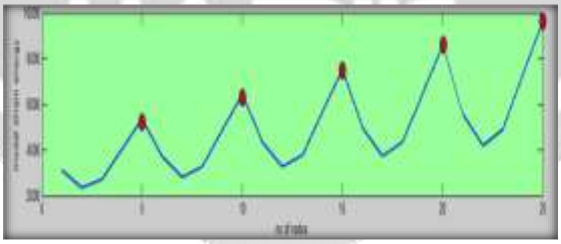


Fig:5 Final Sensor Placement

From Fig. 3 it is evident that 6 points are chosen as the high energy points of the structure. Inorder to optimize the number of sensor points, optimization is carried out using Genetic Algorithm. The result of optimization has showed that 5 is the optimal number. Hence 5 number of sensors are sufficient for monitoring the assumed structure.

Damages are introduced in the 1^{st},4^{th} and 5^{th} storeys of the building. The flexibility matrix of the original structure is first calculated and the flexibility plot is as shown in Fig. 6. The flexibility plots of the three damage cases are shown in Fig.7, Fig.8 and Fig.9 respectively.

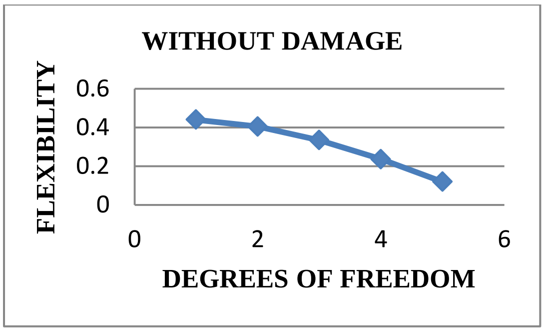


Fig.6: Flexibility plot of the original structure

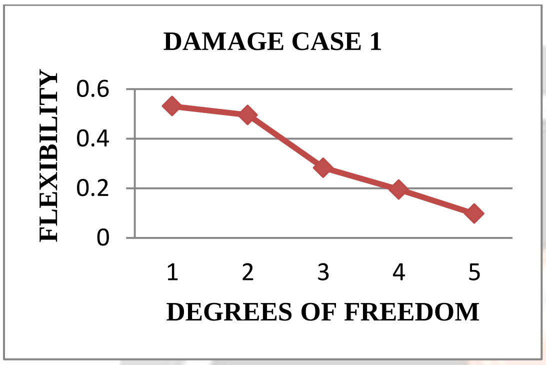


Fig.7: Flexibility plot for damage case 1

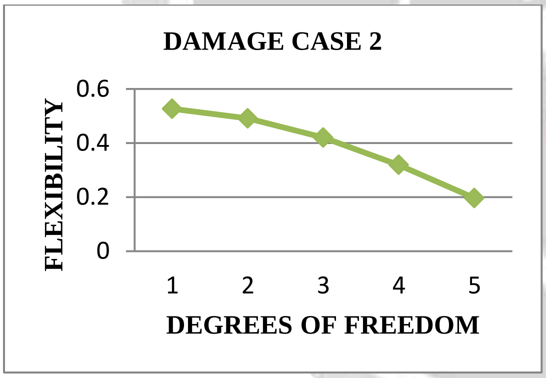


Fig.8: Flexibility plot for damage case 2

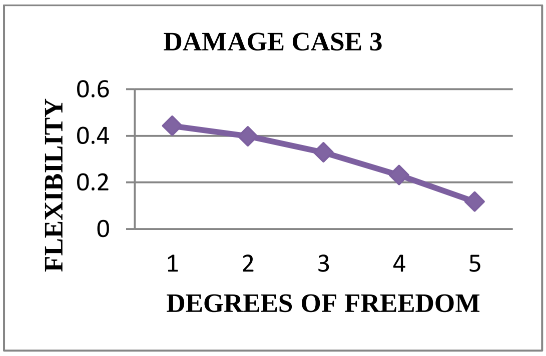


Fig.9: Flexibility plot for damage case 3

Based on the difference between the flexibility values of the original structure and the flexibility values of the damaged ones, the change in flexibility is noted as shown in Fig. 10. The change in flexibility values indicate the level of damage and the storey which is more affected by damage.

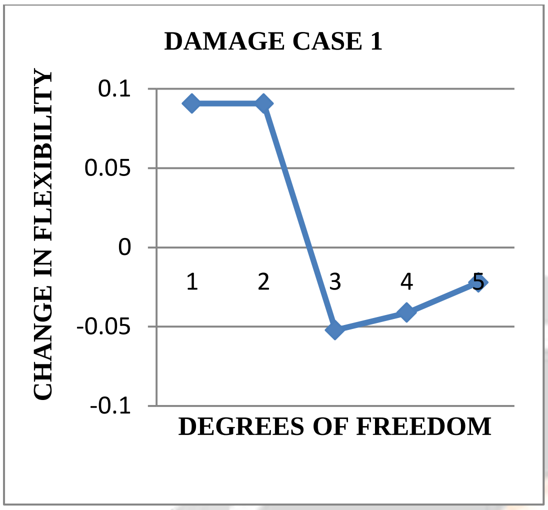


Fig.10: Change in Flexibility for damage case 1

IV. CONCLUSION

In this study a hybrid optimization and damage detection strategy is introduced and hereby a 5 storey building is taken for the study. The conclusions made are summarized as follows,

(i) The initial sensor placement is done by using MSE technique. The number of sensors obtained from initial sensor placement is optimized using Genetic Algorithm. This genetic algorithm makes use of the fitness function which is acquired from the root mean square of the MAC matrix.

ii) The search space for the location of sensors is reduced by 'MSE' technique. This concept of reducing the number of locations for the sensor placement superseded the older OSP techniques.

(iii) FMBT technique is used for damage quantification and damage localization. Its performance is checked by inducing damages at various storeys of the building and change in flexibility for each storey is noted.

(iv) Change in flexibility is obtained from the difference between the flexibility values of the healthy structure and that of the damaged structure.

REFERENCES

1. Azevedo, S.G., Mast, J.E., Nelson, S.D., Rosenbury, E.T., Jones, H.E., McEwan, T.E., Mullenhoff, D.J., Hugenberger, R.E., Stever, R.D., Warhus, J.P. and Wieting, M.G. HERMES: "A high-speed radar imaging system for inspection of bridge decks-Non destructive Evaluation Techniques for Aging Infrastructure and Manufacturing", SPIE 294(6), 195–204, 1996.
2. Aygün, Bengi, and Vehbi Cagri Gungor, "Wireless sensor networks for structure health monitoring: recent advances and future research directions." *Sensor Review* 31.3,pp. 261-276, 2011.
3. Pelin GÜNDEŞ BAKIR, "Evaluation of optimal sensor placement techniques for parameter identification in buildings", Mathematical and Computer Applications, Vol. 16, No. 2, pp. 456-466, 2011 .
4. Ting-Hua Yi and Hong-Nan Li, "Methodology Developments in Sensor Placement for Health Monitoring of Civil Infrastructures", 7 August 2012.
5. Md Zakirul Alam Bhuiyan, Guojun Wang, Jiannong Cao, "Deploying Wireless Sensor Networks with Fault-Tolerance for Structural Health Monitoring", VOL. 64, NO. 2, 2015.
6. M. Brehm, V. Zabel and C. Bucher, "An automatic mode pairing strategy using an enhanced modal assurance criterion based on modal strain energies", J. of Sound and Vibration, 329 ,5375-5392, 2004.

7. Pelin GUNDES BAKIR, "An integrated methodology for damage detection in existing buildings using optimal sensor placement techniques", the 14th World Conference on Earthquake Engineering, 2008.
8. Carne T G, Dohmann C R ,"A modal test design strategy for modal correlation", in Proceedings of the 13th International Modal Analysis Conference, pp. 927–933, Schenectady, NY, USA, 1995.
9. Chiu P L & Frank Y S Lin , " A simulated annealing algorithm to support the sensor placement for target location", Electrical and Computer Engineering, Canadian Conference , Vol. 2, pp. 867-870 ,2004.
10. Xun Zhang, Juelong Li, Jianchun Xing, Ping Wang, Qiliang Yang, RonghaoWang and Can He, "Optimal Sensor Placement for Latticed Shell Structure Based on an Improved Particle Swarm Optimization Algorithm", Mathematical Problems in Engineering, Article ID 743904, pp 1-12, 2014.
11. H. Gao and J. L. Rose, "Sensor placement optimization in structural health monitoring using genetic and evolutionary algorithms," in Smart Structures and Materials, vol. 6174 of Proceedings of SPIE, pp. 1687–1693, San Diego, Calif, USA, 2006.
12. M. Srinivas and L. M. Patnaik, "Adaptive probabilities of crossover and mutation in genetic algorithms," IEEE Transactions on Systems, Man and Cybernetics, vol. 24, no. 4, pp. 656– 667, 1994.
13. Stubbs, N. and Osegueda, R., "Global non destructive damage evaluation in solids. Modal Analysis", The International Journal of Analytical and Experimental Modal Analysis, 5(2), 67–79, 1990.
14. Pandey, A.K., Biswas, M. and Samman, M.M. (1991), "Damage detection from changes in curvature mode shapes", Journal of Sound and Vibration, 145(2), pp. 321–332,1991.
15. M. Montazer and S.M. Seyedpoor, "A New Flexibility Based Damage Index for Damage Detection of Truss Structures", J. of Shock and Vibration , Article ID 460692, 12 pages,2014.