iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 4 **Issue:** V **Month of publication:** May 2016

DOI:

International Journal for Research in Applied Science & Engineering Technology (IJRASET)

Optimal Sensor Placement Techniques in Structural Health Monitoring Using Various Optimization Criteria

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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. However, engineering structures are designed to last longer; they go beyond their design life span. Because these structures are combined with day today lives which leads to slow deterioration. 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 they are discussed in this paper with their deployment criteria. And also, this paper gives the historical background of SHM, the recent deployed sensor placements methods.
Keywords: Structural Health Monitoring, Optimal Sensor Placement

I. INTRODUCTION

Today, wired connections are slowly being replaced by different latest emerging wireless technologies. 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 signalling 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. It can also be defined as the process of finding solutions that satisfy given constraints and achieve the objective at its optimal value. 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."

II. CURRENT STATUS OF OPTIMAL SENSOR PLACEMENT

Detecting damages is one of the most important task to be carried out in any engineering creation be it a machine or a building. Among the engineering creation,civil engineering structures need a continuous monitoring to check their operations,performance and the health status of the structures. Hence Structural Health Monitoring (SHM) aims to develop automated systems for the continuous monitoring, inspection, and damage detection of structures with minimum labour involvement. Inorder to achieve this, sensors are deployed to enable predictive monitoring of the general health of a structure.One of the fundamental requirements of SHM is sensor location optimization[6,12].

In past few years many traditional technology have been developed to achieve OSP mainly include a review concerning the differences and relationships of the sensor placement methods was provided by Yi and Li, Kammer presented an 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)[17], Li et al. determined the existence of a relationship between the effective independence method and the modal kinetic energy method and presented a quick computation of the effective independence method through QR downdating, Carne and Dohrmann considered that distinguishing one modal vector from another is essential to realize modal parameter identification and proposed a famous OSP method named minMAC. All of these algorithms have their own limitations so we go for traditional algorithm such as simulated annealing method , PS algorithm, Genetic algorithm etc.

Various criteria have been introduced for the optimization problem. Singular Value Decomposition has been introduced by , in which discrete FRF data were analyzed using the Singular Value Decomposition (SVD). The 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. Optimization can also be done by calculating the measured energy per mode. Generally the kinetic energy of a structure is usually not evenly distributed into the modes of the structure. The measured DOFs are expected to capture a large part of the total kinetic energy of the structure, and the energy contained in the measured DOFs for each mode should be a significant portion of that mode to satisfactorily measure the modes. This criterion helps to select those sensor positions[9,21]. Fisher information is a key concept in the theory of statistical inference and it says how the damaged mode shape is diverted from the original mode shape. The Modal Assurance Criterion is defined as scalar constant which provides a useful criterion to evaluate the correlation of modal vectors. The off-diagonal elements in the MAC matrix is more significant in expressing the correlation between two modal vectors. The minimization of the off-diagonal terms in the MAC matrix gives a good MAC index that can guarantee the orthogonality of the measured modal vectors and increase the amount of modal information obtained from the collected data. The possible range of the MACs is from zero to unity such that two modes are the same when it is unity, while both are in no correlation when it is zero.

For the purpose of optimal sensor placement, various techniques have been introduced. P.L.Chiu et al has proposed Simulated annealing algorithm method which is a probabilistic technique for approximating the global optimum of a given function[1]. Specifically, it is a metaheuristic for approximate global optimization in a large search space. We can apply this algorithm to generate a solution to combinatorial optimization problems. It consists of a successor function that returns a "close" neighboring solution given the actual one. A target function to optimize that depends on the current state of the system. This function will work as the energy of the system. But this method has some disadvantages like repeated annealing is very slow, the method cannot conclude whether it has found an optimal solution, they are problem-specific or take advantage of extra information about the system.

R.Reberhart et al and M.R.Rapai et al has found a solution for optimizing a problem called Particle Swarm Optimization (PSO) which is a computational method which tries to iteratively improve a solution with regard to a given measure of quality[5,7]. It is inspired by the social behavior of bird flocking or fish schooling. PSO optimizes a problem by having a population of valid solutions and it moves these particles around in the search-space. It uses simple mathematical formulae that consists of the particle's position and velocity as the parameters. Each particle's movement is influenced by its local best known position and it is guided toward the best known positions in the search-space. This is expected to move the swarm toward the best solutions.

T.H.Yi et al has proposed Monkey algorithm (MA) is one of the evolution algorithms for optimization problems with continuous variables. The monkey algorithm (MA) was designed from the inspiration of mountain-climbing processes of monkeys[10]. It assumes that there are many mountains in a given field and in order to find the highest mountain top which is the maximal value of the objective function, monkeys need to climb up from their respective positions. The algorithm mainly consists of climb process, watch-jump process, and somersault process in which the climb process is employed to search the local optimal solution. But disadvantages include meta-heuristic, there are no guarantees that the found solutions are the optimal ones, and usually more than one execution of the algorithm needed and hence it is time consuming and difficult.

According to Dorigo et al, the ant colony algorithm is an algorithm for finding optimal paths that is based on the behavior of ants searching for food[11]. It uses a colony of artificial ants that behave as a population in a mathematic space where in they search for food and pave pathways (solutions) in order to find the optimal ones . At first, the ants wander randomly. When an ant finds a source of food, it walks back to the colony leaving marks that show the path has food. When other ants come across the marks, they are likely to follow the path with a certain probability. The path with the highest population of ants is derived as the optimal solution.

Mehdi Nashat et al has proposed artificial fish swarm optimization method, AFSA as one of the best methods of optimization among the swarm intelligence algorithms. It is based on the collective movement of the fish and their various social behaviors[12]. The fish always try to maintain their colonies and they are reflected in their intelligent behaviors. Searching for food, immigration and dealing with dangers all happen in a social form and interactions between all fish in a group will result in an intelligent social behavior. This algorithm has many advantages including high convergence speed, flexibility, fault tolerance and high accuracy. Disadvantages include high time complexity, lack of balance between global and local search, in addition to lack of benefiting from the experiences of group members for the next movements.

Subhadhip Samanta and Mitchell M has given their contribution in the field of artificial intelligence namely, genetic algorithm (GA) which is a search heuristic algorithm that mimics the process of natural selection. This heuristic is routinely used to generate useful solutions to optimization and search problems. It is a global optimization algorithm derived from evolution and natural selection. It follows a very interesting path to select an optimum solution of any problem[2,3]. By generations it chooses and keeps the best and fittest solutions as survivor and discards the rest other options. This is a continuous and almost flawless process to find out the most optimum result. This process works for the "Survival of the Fittest".

The most important stage is the selection of appropriate optimization algorithms for optimal sensor placement. As an effective alternative approach to the above-mentioned heuristic algorithms, the use of genetic algorithm (GA) has been proposed by several subsequent investigators and it is proved to be efficient.

III. CONCLUSION

To make efficient placement in SHM, a hybrid optimization strategy named MSE-AGA is found to be efficient. Generally, the damage is characterized by changes in the Eigen parameters, i.e., natural frequency, damping values and the mode shapes associated with each natural frequency. Hence this approach makes use of the mode shape of the structures. The modal strain energy method is adopted to conduct the initial sensor placement. Finally, the adaptive genetic algorithm (AGA) is utilized to determine the optimal number of sensors, which uses the root mean square of off-diagonal elements in the modal assurance criterion matrix as the fitness function. It is concluded that MSE-AGA has short computation time and high efficiency.

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Volume 4 Issue V, May 2016
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

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