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Structural damage detection-oriented multi-type sensor placement with multi-objective optimization

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ABSTRACT

A structural damage detection-oriented multi-type sensor placement method with multi-objective optimization is developed in this study. The multi-type response covariance sensitivity-based damage detection method is first introduced. Two objective functions for optimal sensor placement are then introduced in terms of the response covariance sensitivity and the response independence. The multi-objective optimization problem is formed by using the two objective functions, and the non-dominated sorting genetic algorithm (NSGA)-II is adopted to find the solution for the optimal multi-type sensor placement to achieve the best structural damage detection. The proposed method is finally applied to a nine-bay three-dimensional frame structure. Numerical results show that the optimal multi-type sensor placement determined by the proposed method can avoid redundant sensors and provide satisfactory results for structural damage detection. The restriction on the number of each type of sensors in the optimization can reduce the searching space in the optimization to make the proposed method more effective. Moreover, how to select a most optimal sensor placement from the Pareto solutions via the utility function and the knee point method is demonstrated in the case study.

1. Introduction

Structural health monitoring (SHM) systems have been developed and implemented in many infrastructures for ensuring their functionality and safety during their long service life. The performance of these systems for structural damage detection mainly depends on the damage detection algorithm and the feature of the sensor system, such as the number of sensors, the type of sensors and the spatial locations of sensors. The number of sensors is often limited due to cost and sometimes inaccessibility of locations for measurement. Previous studies have revealed that arbitrary sensor placement could lead to false damage identification [1,2]. Significant efforts have been spent on optimal sensor placement (OSP) in the last few decades, and many OSP methods have been proposed for various purposes including damage detection [3–5]. However, most of the OSP methods are applied for single-type sensors only. Although the design can be carried out independently for each type of sensors, the final sensor configuration by combining the individual designs could not avoid redundant measurement and exhibit holistically optimal performance [6–9].

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The proper selection, installation and use of multi-type sensors become important for the SHM of structures [10–14]. Various types of sensors (e.g., accelerometer, displacement transducer and strain gauge) are installed in a structure to measure multi-type structural responses. Acceleration responses can be easily measured with a high signal-to-noise ratio and contain higher kinetic energy in higher-order vibrational modes. By contrast, displacement responses contain more kinetic energy in lower-order vibrational modes. Strain or stress responses are sensitive to local changes closer to the sensors but not sensitive to local changes far away from the sensors. Because of the different merits and limitations of these sensors, the joint use of multi-type sensors complicates the optimal sensor placement for structural damage detection.

Some efforts have been devoted to optimizing the performance of multi-type sensors in a unified framework. Zhang et al. [7] suggested an extended EfI OSP method for two types of sensors, in which the displacement transducers are integrated with the strain gauges for better response estimation. Zhu et al. [8] and Xu et al. [12] carried out further studies on multi-type sensor optimal placement for response reconstruction in terms of the Kalman filter. This method was later extended to the situations with the reconstruction of unknown external excitation [15] and applied for damage detection of an overhanging beam structure [13]. Yuen and Kuok [6] proposed a Bayesian sequential sensor placement algorithm for multi-type sensors optimization based on robust information entropy such that the overall performance of various types of sensors can be assessed. Recently, a data correlation analysis-based OSP method combined with a bone energy algorithm [9] was studied with different types of sensors deployed for less redundant measured information in a large spherical lattice dome-like structure. However, all the above works were based on the optimization of a single objective function with a unique optimal sensor configuration.

Different merits and limitations of multi-type sensors often lead to the requirement of multi-objective functions in the optimization. In multi-type sensor and multi-objective OSP problems, conflicted objectives are very common because of the limited number of sensors and the complex nature of problem [16,17]. The simultaneous optimization of the conflicting objectives may lead to a set of compromised solutions known as the non-dominated or Pareto-optimal solutions, and these non-dominated solutions represent the trade-offs amongst different objectives. An efficient Pareto sequential sensor placement (PA-SSP) algorithm with multi-objective functions [18] was developed for model updating. This algorithm was proved to be more efficient than the strength Pareto evolutionary algorithm (SPEA). The non-dominated sorted genetic algorithm-II (NSGA-II) was used for the optimal contaminant sensor network design in Ref. [19] and the optimal sensor configuration design of water distribution networks in Ref. [20]. Also, Kim et al. [21] used the NSGA-II to tackle a surveillance sensor placement problem. Moreover, Mathakari et al. [22] proposed the reliability-based optimal design of electrical transmission towers using multi-objective genetic algorithms. For active control systems of buildings, Cha and his colleagues [23–25] investigated the optimal placement of both actuators and sensors by developing a novel multi-objective genetic algorithm (NS2-IRR GA) through the integration of the NSGA-II and the implicit redundant presentation (IRR) GA. To enhance the capability of structural damage detection, optimal accelerometer placement with multiple objectives in terms of information entropies computed by multiple mode-shapes was reported in Ref. [26]. Additionally, the damage detection was investigated in Ref. [27] by adopting an advanced multi-objective optimization algorithm with two objectives in terms of the differences of two sets of modal strain energy (MSE) before and after damage occurring although the single type sensor of accelerometers are not optimally placed. However, the exploration of multi-type sensor optimal placement with multiple objectives for structural damage detection is still rarely found.

For the response covariance based damage detection with a limited number of sensors, two dilemmas were identified in Refs. [28,29]: (1) optimizing only the response covariance sensitivity can reach an OSP which is sensitive to damage but cannot exclude redundant (very close to each other) sensors; and (2) optimizing only the response independence can lead to an OSP with more evenly distributed sensors to fully capture the spatial information of a structure but the OSP's sensitivity to damage is not guaranteed. To solve the dilemmas, these two conflicted objectives are combined and a structural damage detection-oriented multi-type sensor placement method with multi-objective optimization is proposed. Section 2 describes the equation of motion of a structure in state space. Section 3 introduces the multi-type response covariance sensitivity-based damage detection method. Section 4 presents the multi-objective multi-type sensor optimal placement problem and the Pareto-optimal solutions of the problem using the tailored NSGA-II. Section 5 proposes a utility function based method with equal weighting to find the “best” OSP from the Pareto front and presents a numerical case study using a nine-bay three-dimensional frame structure to examine the feasibility and effectiveness of the proposed method. Section 6 proposes a knee point based method to find the “best” OSP from the Pareto front and demonstrates the merits of the proposed method by comparing with a Fisher information matrix based OSP method for traditional response sensitivity based damage detection. Some conclusions are drawn in Section 7.

2. Equation of motion

The equation of motion of a linear-elastic structural system with N degrees-of-freedom (DOFs) can be written as

$$\mathbf{M}\ddot{\mathbf{z}}(t) + \mathbf{C}\dot{\mathbf{z}}(t) + \mathbf{K}\mathbf{z}(t) = \mathbf{L}_{\mathrm{f}}\mathbf{f}(t) \tag{1}$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are, respectively, the $N \times N$ mass, damping and stiffness matrices of the structure; $\mathbf{z}(t)$, $\dot{\mathbf{z}}(t)$, and $\ddot{\mathbf{z}}(t)$ are, respectively, the displacement, velocity and acceleration response vectors of the structure at time t; $\mathbf{f}(t)$ is the excitation force vector; and $\mathbf{L}_{\mathrm{f}}$ is the mapping matrix relating the excitation forces to the corresponding DOFs of the structure.