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Structural damage detection by a new iterative regularization method and an improved sensitivity function

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ABSTRACT

A new sensitivity-based damage detection method is proposed to identify and estimate the location and severity of structural damage using incomplete noisy modal data. For these purposes, an improved sensitivity function of modal strain energy (MSE) based on Lagrange optimization problem is derived to adapt the initial sensitivity formulation of MSE to damage detection problem with the aid of new mathematical approaches. In the presence of incomplete noisy modal data, the sensitivity matrix is sparse, rectangular, and ill-conditioned, which leads to an ill-posed damage equation. To overcome this issue, a new regularization method named as Regularized Least Squares Minimal Residual (RLSMR) is proposed to solve the ill-posed damage equation. This method relies on Krylov subspace and exploits bidiagonalization and iterative algorithms to solve linear mathematical systems. For the majority of Krylov subspace methods, conventional direct methods for the determination of an optimal regularization parameter may not be proper. To cope with this limitation, a hybrid technique is introduced that depends on the residual of RLSMR method, the number of iterations, and the bidiagonalization algorithm. The accuracy and performance of the improved and proposed methods are numerically examined by a planner truss by incorporating incomplete noisy modal parameters and finite element modeling errors. A comparative study on the initial and improved sensitivity functions is conduced to investigate damage detectability of these sensitivity formulations. Furthermore, the accuracy and robustness of RLSMR method in detecting damage are compared with the well-known Tikhonov regularization method. Results show that the improved sensitivity of MSE is an efficient tool for using in the damage detection problem due to a high sensitivity to damage and reliable damage detectability in comparison with the initial sensitivity function. Additionally, it is observed that the RLSMR method with the aid of the hybrid technique successfully solves the ill-posed damage equation and provides better damage detection results compared with the Tikhonov regularization technique.

1. Introduction

Many existing civil engineering infrastructures were constructed several decades ago, which are still in service despite of their age and structural weakness. Deterioration and damage of these structures may cause irrecoverable economic losses,

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human injuries, and death. In order to prevent such undesirable issues, many attempts have been performed by researchers and engineers in the context of structural health monitoring (SHM) to assess the integrity of structures and detect any probable structural damage. Damage in a structure can occur with deviations in geometry configurations, boundary conditions, and deterioration of materials leading to cracks in concrete, loose bolts and broken welds in steel connections, corrosions, and fatigue. These adverse changes may cause undesirable stresses and displacements, unfavorable vibrations, failure and even collapse. The process of damage identification by vibration data is usually known as vibration-based damage detection, which is categorized into four levels including damage existence (level 1), damage localization (level 2), damage quantification (level 3), and damage prognosis (level 4) [1]. The primary idea behind vibration-based damage detection methods is that structural damage leads to inappropriate changes in the inherent physical properties of a structure such as mass, stiffness, and damping. Any deviation in these properties, therefore, changes dynamic characteristics or vibration responses of the structure.

Even though many innovative vibration-based methods have been proposed more recently, modal-based approaches are still widely used in the problem of damage detection. The underlying reason is that the modal parameters such as natural frequencies and mode shapes depend directly on the inherent physical properties regardless of the excitation sources. Some of these methods use direct changes in the natural frequencies [2,3] and mode shapes [4–6] for structural damage detection. However, the modal frequencies provide only global information about the condition of structure and typically fail to locate damage [7]. The modal displacements or mode shapes, on the other hand, are usually more difficult to measure accurately and are not extremely sensitive to moderate changes in structural stiffness [8].

Sensitivity-based damage detection methods using the modal parameters are other kinds of approaches relying on the sensitivity analysis of measurable dynamic outputs of the structure. The sensitivity analysis represents how dynamic characteristics vary based on changes in the physical properties of the structure [9]. A variety of methods have been developed to derive the sensitivity of modal parameters that can be found some of them in [10–13]. Additionally, the sensitivity of modal strain energy (MSE) is another efficient and useful sensitivity function that can be much more sensitive to damage. Various methods have been presented to establish different sensitivity formulations of MSE based on the direct difference and algebraic methods, the indirect methods, and the variation principle. Yan and Ren [14] proposed a direct algebraic method to determine the sensitivity of MSE for a real symmetric undamped system. Yan et al. [15] presented a statistic structural damage detection algorithm using the sensitivity of MSE for the process of damage detection based on ambient vibration measurements, where operational mode shapes is the only available data. Li et al. [16] proposed a sensitivity function of MSE using the variation principle in order to design structural parameters by Lagrange function.

An important issue regarding the sensitivity-based methods is to derive a well-established sensitivity function. For the damage detection problem, in general, the sensitivity formulation should be sensitive to damage. A salient characteristic of a well-established sensitivity function is damage detectability without applying any complicated mathematical techniques to solve damage equations. Furthermore, the incompleteness conditions of modal parameters provide limitations of using the sensitivity-based methods in detecting damage. In practice, there is no necessity to measure all modal frequencies from dynamic tests, because in the large-scale structures only low-order natural frequencies are measureable. As another limitation, the number of measured modes is normally less than the number of degrees of freedom (DOFs) resulting from practical and economic limitations of installing sensors at all DOFs. Under such circumstances, the sensitivity matrix gained by incomplete modal parameters may be sparse, rectangular, and ill-conditioned. Measurement errors in vibration response data are other obstacle to achieve successful damage detection results, because both measurement errors and ill-conditioned sensitivity matrix lead to an ill-posed damage equation [17]. This means that conventional mathematical methods based on inverse problems are not robustly able to solve an ill-posed problem.

To cope with this shortcoming, regularization methods are in general applied to guarantee the existence, uniqueness, and stability of the solution of ill-posed damage equation. The regularized solution of damage identification problem can be found in the article of Chen [18], who utilized a regularization method, truncated singular value decomposition (TSVD), for detecting damage in a 16-story braced frame building model. Weber et al. [19] applied Tikhonov regularization and TSVD methods to detect structural damage in a full-scale laboratory concrete frame. Li and Law [20] proposed an adaptive Tikhonov regularization approach for damage detection based on solving a nonlinear model updating inverse problem. In another research, Chen and Maung [21] presented a direct model updating method using dynamic perturbation theory of structural parameters and incomplete noisy modal data. For a regularized solution, they utilized Tikhonov regularization method along with the L-curve method for the determination of regularization parameter. Another application of regularized solution to vibration-based problems can be found in Aucejo [22], who introduced Generalized Iteratively Reweighted Least-Squares (GIRLS) algorithm to solve a generalized Tikhonov regularization problem for the identification of force sources using vibration measurements. Grip et al. [23] investigated a new regularization method based on the minimization of total variation for the damage detection problem based on the sensitivity-based model updating strategy. In their article, they compared the new regularization method with a well-established interpolation-based regularization approach.

Despite many research efforts in vibration-based methods using sensitivity functions and regularization techniques, one of the critical and challenging issues is how to robustly deal with the ill-posed problem with the sparse and ill-conditioned sensitivity matrix. Another prominent issue is to use a well-established sensitivity function regarding the damage detection problem. As a result, the main objective of this article is to propose a new sensitivity-based damage detection method using incomplete noisy modal data for locating damage and quantifying damage severity. To achieve these aims, the initial