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A damage identification technique based on embedded sensitivity analysis and optimization processes

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ABSTRACT

A vibration based structural damage identification method, using embedded sensitivity functions and optimization algorithms, is discussed in this work. The embedded sensitivity technique requires only measured or calculated frequency response functions to obtain the sensitivity of system responses to each component parameter. Therefore, this sensitivity analysis technique can be effectively used for the damage identification process. Optimization techniques are used to minimize the difference between the measured frequency response functions of the damaged structure and those calculated from the baseline system using embedded sensitivity functions. The amount of damage can be quantified directly in engineering units as changes in stiffness, damping, or mass. Various factors in the optimization process and structural dynamics are studied to enhance the performance and robustness of the damage identification process. This study shows that the proposed technique can improve the accuracy of damage identification with less than 2 percent error of estimation.

1. Introduction

Various structural health monitoring (SHM) techniques have been developed for detection, location, and quantification of damages in a structural system. Damage identification techniques that utilize vibration signals are among the most studied SHM techniques. Doebling et al. [1] and Sohn et al. [2] reviewed these techniques. Many of these studies are based on sensitivity analysis, finite element model (FEM) updating, and optimization techniques. Friswell and Mottershead [3] reviewed and summarized the major FEM updating techniques. These techniques usually iterate to minimize the difference between the modal parameters measured from the real structure and the corresponding analytical predictions. A damage detection method using a genetic algorithm (GA) was suggested by Chou and Ghaboussi [4]. These researchers used static measurements of displacements in a few degrees of freedom to identify changes in the characteristic properties of structural members. A global-local optimization (GLO) approach was adopted by Meo et al. [5]. They employed the Coordinate Modal Assurance Criterion (COMAC) and Frequency Response Assurance Criterion (FRAC) in the objective functions. A method for damage assessment in beams and plates using a dynamic computer simulation technique was suggested by Shih et al. [6]. A multi-criteria procedure using the modal flexibility and the modal strain energy method was proposed in this study. Begambre et al. [7] proposed a damage identification procedure based on a hybrid particle swarm optimization-simplex

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Nomenclature

Symbols

C_{mn}	damping between dofs m and n
f_k	input force at k
H_{jk}	frequency response function
K_{mn}	stiffness between dofs m and n
M_{0m}	m-th mass
N_{dof}	number of dofs
N_{iter}	number of iteration
x, y	displacement in physical coordinate
ω	angular frequency
dof	degree(s) of freedom
FRF	frequency response function

algorithm (PSOS). They proposed a strategy for the control of the PSO parameters based on the Nelder–Mead algorithm. Algorithms using the multi-objective approach were introduced by Jung et al. [8] to improve the robustness of the damage identification algorithm. The effects of noise in the measurement on the accuracy of identification approach were explored using numerical examples of truss structures under static loading. The sensitivity of the dynamic response of a structure under sinusoidal, impulsive, and random excitations was analyzed by Lu et al. [9]. These researchers verified the effectiveness and accuracy of the proposed methods through solutions obtained with the penalty function method using regularization.

Many of the techniques discussed above use the measured and calculated dynamic or static responses of the system. The finite element updating method would be more beneficial for typical continuous system which cannot be reasonably discretized such as beams, plates, and shells. One of the drawbacks of these techniques is the large number of unknowns to be estimated. These techniques in the literature that use finite element model updating to estimate perturbed parameters for all elements in the model can be time consuming (1–30 h and hundreds of computational iterations) and ill-conditioned, even for relatively simple structures. For this reason, a physically meaningful optimization result is not guaranteed using these techniques. These techniques also require a full finite element model for each structure to be monitored because of the variability between structures.

The proposed method utilizes measured data (Frequency Response Functions) obtained from the structures using accelerometers. Therefore, the structure will be discretized by the number of sensors used in the test rather than by the finite element size resulting in fewer parameters that must be estimated. Although the resolution with which damage can be localized may not be as high as in the finite element updating methods, the proposed method is much faster than those techniques and efficient enough to be used in real structures using a relatively small number of sensors for which structural health monitoring is typically conducted. The iteration number of the optimization process for the examined case is about 10–20 and the elapsed time is about 10–30 s when five to ten parameters in the structure are considered. An embedded sensitivity technique developed by Yang and Adams [10–14] and an optimization method are used in this study to identify structural damages. The perturbed frequency response function (FRF) is calculated using Taylor series expansion in terms of the baseline system and the embedded sensitivity functions. The optimization process minimizes the difference between the measured FRFs of the damaged structure and the perturbed FRFs calculated from the baseline structure. Structural perturbations are often characterized by a change in some mechanical parameters such as stiffness, mass, and damping. Embedded sensitivity functions offer a means of determining the path that is followed from the baseline to the perturbed FRF of the structure. These functions are proven to be useful tools for the identification of perturbations. The accuracy of estimation of damages can be obtained within the range of 2 percent error with various enhancements applied to the technique.

2. Damage identification technique and process

2.1. Embedded sensitivity functions

The frequency response function (FRF) between $y_j(t)$ and $f_k(t)$, $H_{jk}(\omega)$, is used to model the relative amplitude and phase between the steady-state structural response at degree-of-freedom (dof) j and the excitation at dof k. The FRF is defined in terms of the response and excitation spectra and is given by

$$H_{jk}(\omega) = \frac{Y_j(\omega)}{F_k(\omega)}. \tag{1}$$

The embedded sensitivity functions were previously developed and applied to study noise and vibration in an automotive structure [10]. Equations were derived by calculating the partial derivatives of system FRFs with respect to the mass, damping, and stiffness parameters. The general equation to calculate the embedded sensitivity functions for multi-dof systems is given in the following equation:

$$\frac{\partial H_{jk}(\omega)}{\partial K_{mn}} = -\left[H_{jm}(\omega) - H_{jn}(\omega)\right]\left[H_{km}(\omega) - H_{kn}(\omega)\right] \tag{2a}$$