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Design sensitivity analysis of a system under intact conditions using measured response data

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ABSTRACT

Design sensitivity requires knowledge of the accurate characteristics of system dynamics to determine the solution parameters—eigenvalues or eigenvectors. This paper presents a new form of sensitivity analysis based on transmissibility functions that can indicate the appropriate candidate node for minimal design modification. The proposed sensitivity analysis uses only measured response data and is performed under intact conditions without any system identification. The feasibility of the proposed sensitivity analysis is first verified through both an experiment and a computer-aided analysis of the uniaxial vibration of a notched beam; then its methodology is investigated by simulation involving a 5-degrees-of-freedom system.

1. Introduction

Sensitivity analysis for design is aimed to find the best design modification with respect to the assigned design goal and scope. Engineers can approach to the core re-design process directly without sacrificing much effort to solve design problem under heuristic manner, i.e., trial and errors.

The design sensitivity analysis is the main strategy employed for dealing with design modifications related to engineering problems, and several methodologies have been published to date on this topic. Despite the various methodologies—i.e., finite-difference, analytic, or semi-analytic methods [1–5]—accurate dynamic information such as eigenvalues and eigenvectors is required for the efficient implementation of a sensitivity analysis and thereby, much effort should be paid to obtain the reliable dynamic parameters during the analytic process. In addition, a responsible engineer inevitably compromises between the accuracy of the result and the cost of the computation during a sensitivity analysis. The sensitivity analysis is still being investigated for several engineering design cases. The direct differentiation method of sensitivity analysis was implemented using the finite element code [6] and the combination of the adjoint variable method [7,8]. In addition, the complex variable method [7,9,10] was suggested for the structural optimization by calculating the eigenvalue sensitivities related to size and shape design variables [11]. For the response sensitivity, new formulation of sensitivity method with Hessian matrix analysis were proposed for the planar frames under an earthquake excitation [12] and the uniformly modulated evolutionary random excitation based on PSD function [13]. In addition, the sensitivity analysis was applied to the design verification of nuclear turbo-sets through screening out insignificant source of uncertainty [14] and the wave-based method was used for a structural–acoustic semi-coupled problem [15].

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It is very difficult to apply the existing analyses directly under the intact condition; however, solving the design sensitivity problem under an intact condition may guarantee a reliable analytic result as well as a simple implementation. If it is possible to directly perform the sensitivity analysis using only measured in-situ response data, significant savings can be achieved in both the process time and cost. In addition, the accuracy of the analysis can be considerably enhanced in the actual experimental condition, i.e., the accurate characteristics of the joint property [16,17] or the altered dynamic effect of the feedback controller [18,19], during system identification.

On the other hand, the concept of transmissibility function (or output-only data) has been widely applied to dynamic analyses because it has the important advantage of being able to seamlessly maintain all the system dynamics under the intact condition of the system. The feasibility of transmissibility function properties for a multi-dof system was investigated [20], and other studies [21–23] revised the concept of transmissibility function in order to predict the unknown response sets. Some studies [24–27] proposed practical operational modal analysis (OMA) using the measured transmissibility function of the dynamic system, even when the loading case was not given as a stochastic formula, such as ideal white noise. In addition, the measured transmissibility functions were used to update a finite element model [28]. Recently, it was proposed that the transmissibility concept could be applied to transfer path analysis [29], and the identification of modal parameters using the measured transmissibility function was investigated [30]. The application of transmissibility function was also extended for the structural damage detection by proposing the damage sensitivity functions based on a general multi-dof spring–mass–damper system [31] or transmissibility damage indicator [32].

The aim of this paper is to present a new design sensitivity analysis under intact conditions using only measured response data to find the appropriate location of slight design modification. The claimed originality of this method is to quantify the nodal sensitivity of unknown linear system over the variation of design parameters, i.e., mass, damping and stiffness, using transmissibility function without any pre-knowledge about the system or additional identification process.

This paper presents a new type of intact design sensitivity analysis based on the transmissibility function that is defined as the change in the nodal response with respect to a small design modification. The concerned transmissibility function is related to the transmissibility function from a concerned node to a reference node as well as the response of the concerned node itself. The main concept of the proposed sensitivity analysis is presented and validated by two different cases, the numerical finite element (FE) model and the analytical model of a five-degrees-of-freedom (5-dof) system. First, the proposed sensitivity analysis is applied to the uniaxial vibration test of a simple notched beam; then, the feasibility of the proposed sensitivity analysis is discussed with both a CAE analysis and the experiments. Second, the 5-dof systems are introduced for simulation of the different loading condition as well as several modified system cases. The simulation result reveals that the proposed sensitivity analysis serves as a sound guideline to determine which node is the best candidate for the design modification strategy. In addition, this new methodology is proven to be robust enough to the location of excitation as well as that of the reference node by deriving a similar sensitivity index under different analytic conditions.

2. New intact design sensitivity analysis

In this paper, a new design sensitivity analysis is proposed, which is based on the transmissibility function from a concerned node to a reference point. The principle of the analysis can be described using a one-dimensional vibration path with several nodes (Fig. 1). In this system, the transmissibility function $T_{(i)}$ from a node i to the reference node 0 can be expressed as

$$T_{(i)} = \frac{r_0}{r_i} \tag{1}$$

The response of the reference node can be expressed as the product of the transmissibility function and the response of node i, as shown in Eq. (2). The transmissibility function can be expressed as a polar coordinate, as shown in Eq. (3)

$$r_o = T_{(i)} r_i \tag{2}$$

$$T_{(i)} = V_i e^{i\theta_i}, \tag{3}$$

where V_i and θ_i are the magnitude and phase of the transmissibility function given in Eq. (1).

If there is a small design modification in the system, the corresponding response variation can be expressed by r'_i, r'_0, and $T'_{(i)}$, as given by

$$T'_{(i)} = \frac{r'_o}{r'_i} = (V_i + \Delta_{V_i}) e^{i(\theta + \Delta_{\theta_i})} \tag{4}$$

Here, Δ_{V_i} and Δ_{θ_i} are the magnitude variation and the phase variation, respectively.

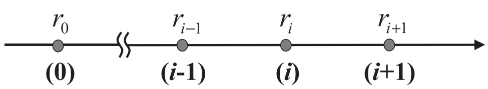

Fig. 1. One-dimensional system: r_o denotes the response at the reference node, and r_i denotes the response at node i.