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Relative sensitivity analysis of responses using transmissibility

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ABSTRACT

To identify the most effective position for solving vibrational problems, it is necessary to analyze the system sensitivities. In this study, new sensitivity indices based on the concept of transmissibility are proposed for analyzing the relative sensitivities of the responses with respect to the design variables that are used to indicate the sensitive positions where small design modifications can be applied, and analyze the effect of these modifications on the responses. The transmissibility concept is applied after differentiating the equation of motion to consider the crosstalk effects. More important information regarding the relative sensitivity characteristics of a system with easily measured response data to reduce unintended responses can be acquired by using the proposed indices. Further, the proposed indices are applicable to the variables of mass, stiffness, and damping. The indices are validated analytically and numerically, and the results demonstrate the effectiveness of the proposed indices.
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1. Introduction

A general approach to improve the vibrational characteristics of a system with problems involves making small design modifications to the system parameters. For this, it is necessary to analyze the relationship between the dynamic responses and design variables. It is important to indicate the appropriate location where design modification can be applied to improve the vibrational characteristics of system and to consider how the design variable on the sensitive position affects the other responses to avoid unintended responses. They should be analyzed before application of design modifications to the system. Sensitivity analysis is the study of the variations in specific physical quantities with respect to the design variables, and it indicates the positions where small design modifications could be applied to improve the vibrational characteristics. Sensitivity analysis is widely used to indicate the direction for the optimal design of a system using an iterative process.

The framework of sensitivity analysis has been studied by several researchers [1–5]. Numerous studies have examined the sensitivities of eigenvalues and eigenvectors [6–8], frequency responses [9–11], and dynamic responses [12–15]. Furthermore, sensitivity analysis is increasingly used in various branches of dynamic analysis such as damage detection [16,17], model updating [18,19], and structural-acoustic problems [20]. This article focuses on the sensitivity analysis of dynamic responses. Haug and Arora [12] developed an efficient method to calculate the derivatives of the responses of elastic structures by adopting the adjoint variable method. Zhang and Der Kiureghian [13] presented a finite element method-based solution for analyzing the response sensitivities of inelastic structures. Liu et al. [14] proposed a new algorithm for a more efficient calculation of the response sensitivities and Hessian matrix, with respect to earthquake excitation. Further, they [15] utilized the Gauss precise time step integration method to obtain the derivatives of the dynamic response under a transient loading condition. There

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have been efforts to enhance the accuracy of the algorithms used for calculating the derivatives. Kirsch and Papalambros [21] adopted a combined approximation approach to develop an efficient method for approximating the response and response derivatives. Kirsch et al. [22] formulated an improved and efficient solution for calculating the displacement derivatives using global finite differences, as they can be implemented more effectively than analytical derivatives. Bogomolni et al. [23] calculated the response sensitivities using the displacement and sensitivities of eigenvectors, under a dynamic loading condition. The proposed approach simplified the differential equations so that they could be solved more efficiently. Several authors have proposed employing the time-domain approach for performing the sensitivity analysis of dynamic responses. Su and Xu [24] presented an explicit time-domain formulation for dynamic responses under a non-stationary random excitation. Hu et al. [25] developed a more efficient and concise expression by using the direct differentiation method.

Recently, Kim et al. [26] have proposed a new approach for sensitivity analysis that can indicate the proper position for a design modification using only the response data, without identifying the system characteristics under intact conditions. They used the concept of transmissibility to derive the sensitivity index of response. Transmissibility is defined as the ratio of the frequency response functions when an input force is applied at the same position [27]. Therefore, it is expressed as the ratio of two values of the response data, excluding the force effect, which could cause a measurement error. They used only the output data to derive the equation for the nodal sensitivity, without system identification. They also investigated the effect of the position where the external force was applied, and concluded that the result indicated the proper position where the mass modification could be applied, although a small deviation was possible. However, it was assumed that the response variation of the reference node with respect to a small mass modification applied to another node was extremely small and could be ignored. This suggests that the crosstalk effects were not considered. Thus, the index gives imperfect results and is applicable only to the mass variable. In practical situations, the responses at the other nodes will be affected by the design modification at other nodes. Therefore, crosstalk effects should be considered in the approach to accurately indicate the position where the design modification is required to be applied.

The present study does not merely adopt the concept of transmissibility to calculate the relative sensitivity of responses, but also considers the crosstalk effects between the nodes. Indices that include the crosstalk effects could yield relevant information about the relative sensitivity of the responses. In this study, two types of indices applicable to each design variable are proposed, namely, sensitivity indices of the response at specific nodes with respect to the design variables, and the sensitivity indices of responses with respect to the design variables at specific nodes. The former indicates the appropriate position where the design variable could be modified, whereas the latter predicts the effect of a specific design variable on the responses. The proposed indices are analytically and numerically investigated to determine whether they adequately reflect the relative changes in response to small design modifications. The analytical model and two numerical beam models are used to validate the indices.

2. Theory

In this study, a method is proposed to analyze the sensitivity characteristics of responses using transmissibility. The purpose of this method is to indicate sensitive positions in a component with respect to design variables at a specific position by only using the response data.

A general system composed of three different coordinates is considered as shown in Fig. 1. An external force is applied to the i coordinate, and a small design modification is applied to the j coordinate. The target set is indicated as the t coordinate. The equation of motion using the apparent mass ($\mathbf{M}_{\text{app}}$) and acceleration is

$$\mathbf{M}_{\text{app}}\mathbf{a} = \mathbf{F}, \tag{1}$$

where apparent mass ($\mathbf{M}_{\text{app}}$) is expressed as

$$\mathbf{M}_{\text{app}} = \mathbf{M} - \frac{(\mathbf{K} + \mathrm{j}\omega\mathbf{C})}{\omega^2}. \tag{2}$$

$\mathbf{M}$, $\mathbf{C}$, $\mathbf{K}$, ω, $\mathbf{a}$, and $\mathbf{F}$ denote the mass, viscous damping, stiffness, angular frequency, acceleration, and force, respectively. A direct differentiation method is applied to Eq. (1), to derive the response sensitivity with respect to design variable as follows:

$$\frac{\partial \mathbf{M}_{\text{app}}}{\partial v}\mathbf{a} + \mathbf{M}_{\text{app}}\frac{\partial \mathbf{a}}{\partial v} = \frac{\partial \mathbf{F}}{\partial v}, \tag{3}$$

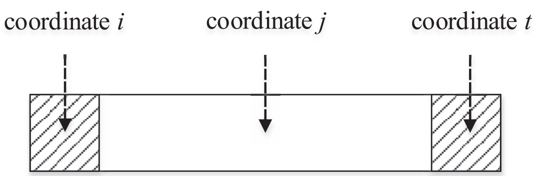

Fig. 1. Schematic model of system.

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