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DESIGN SENSITIVITY ANALYSIS AND OPTIMIZATION OF AN ENGINE MOUNT SYSTEM USING AN FRF-BASED SUBSTRUCTURING METHOD

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The FRF-based substructuring method is one of the most powerful methods in analyzing the responses of complex built-up structures with high modal density. In this paper, a general procedure for the design sensitivity analysis of a vibro-acoustic system has been presented using the FRF-based substructuring formulation. For an acoustic response function, the proposed method gives a parametric design sensitivity expression in terms of the partial derivatives of the connection element properties and the transfer functions of the substructures. The derived noise sensitivity formula is combined with a non-linear programming module to obtain the optimal design for the engine mount system of a passenger car. The objective function is defined as the area of the interior noise graph integrated over a concerned r.p.m. range. The interior noise variations with respect to the dynamic characteristics of the engine mounts and bushings have been calculated using the proposed sensitivity formulation and transferred to a non-linear optimization software. To obtain the FRFs, a finite element analysis was used for the engine mount structures and experimental techniques were used for the trimmed body including the cabin cavity. The optimization based on the sensitivity analysis gives the ideal stiffness of the engine mount and bushings. The resultant interior noise in the passenger car shows that the proposed method is efficient and accurate.

1. INTRODUCTION

There are many tools that can be used to get the optimum design of a dynamic system. Among them, a sensitivity analysis combined with a mathematical programming technique has been a practical tool for design engineers when a large and complex system is considered. The design sensitivity analysis is a study of the rate of changes in system characteristics with respect to design parameter variations. Haug *et al.* [1] summarized the general procedures of the design sensitivity analysis for a structural system. For dynamic problems, the design sensitivity analysis has focused on the changes of the natural frequencies and modal vectors [2, 3] where the sensitivity information of a system response was obtained from the derivatives of the natural frequencies and modal vectors using modal superposition. To calculate the sensitivity of the response directly, researchers developed the design sensitivity formula of the frequency response functions (FRF). Akiyama *et al.* [4] introduced a structural modification concept in the transfer function synthesis method. Lin and Lim [5] developed a design sensitivity formula of the frequency response function from the experiments.

Dynamic substructuring technique is a method that predicts the dynamic behavior of a structure based on the dynamic behavior of the composing substructures. A method that calculates the frequency response functions of a structure composed of several substructures from the FRFs of the substructures is called the transfer function synthesis method or the FRF-based substructuring method (FBSM) [6, 7]. The FRF-based substructuring method is one of the most powerful methods available for the analysis of the response of a complex built-up structure with high modal density. Its superiority comes primarily from the ability to incorporate experimental FRFs into the formulation. It can predict the response of the total structure from the FRFs of the substructures, but it cannot give the systematic guides for the structural modification or optimal design. A design sensitivity analysis for the dynamic problem provides valuable information that the designer cannot predict by intuition or experience. However, little attention has been paid to the design sensitivity analysis in the frame of the substructuring method. Heo and Ehmann [8] presented a substructural sensitivity synthesis method by using component modal sensitivities. Santos and Arruda [9] also derived the joint stiffness sensitivity formula of a component mode synthesis model. Recently, Lallemand *et al.* [10] proposed a semi-analytical sensitivity analysis method in a component mode synthesis framework. As a direct approach, Jee [11] derived a response function sensitivity by differentiating the frequency response function formed by the transfer function synthesis method with respect to the substructure receptance function. Chang and Park [12] extended Jee's method and applied it to the structural dynamic modification.

In this paper, a general procedure for the design sensitivity analysis of vibro-acoustic problems is presented using the FRF-based substructuring formulation. By introducing the direct differentiation approach for the reaction forces on the interface elements, we derive a parametric noise sensitivity formula, in which algebraic linear equations can be solved. The present method is very powerful since the system matrix that is inverted for the sensitivity analysis is the same one used for the calculation of the system response by the transfer function synthesis method. In the formula, the additional term to be calculated for the sensitivity analysis is only a vector that consists of partial derivatives of substructure FRFs and connection element properties. To verify the efficiency of the proposed method, it is applied to a realistic problem related to the engine mount system of a passenger car. The sensitivities of a response with respect to the stiffness or damping coefficients of the connecting elements are calculated and compared with those from the conventional finite difference approach. To obtain the ideal stiffness of the engine mounts and bushings, an optimization problem is defined for the engine mount system of the real passenger car, and the solution is obtained by using the derived sensitivity formula in the non-linear optimization software.

2. DESIGN SENSITIVITY ANALYSIS USING THE FBSM

For the analysis of the structure-borne noise in a passenger car, the FRF-based substructuring method is more accurate due to its ability to combine the experimental