PREDICTION OF INTERIOR NOISE BY EXCITATION FORCE OF THE POWERTRAIN BASED ON HYBRID TRANSFER PATH ANALYSIS

S. J. KIM and S. K. LEE

Department of Mechanical Engineering, Inha University, Incheon 402-751, Korea

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ABSTRACT—In the early design stage of a vehicle, simulation of interior noise is useful for assessment and enhancement of the noise, vibration and harshness (NVH) performance. Traditional transfer path analysis (TPA) technology cannot simulate interior noise since it uses an experimental method. In order to solve this problem, hybrid TPA is employed in this paper. Hybrid TPA uses simulated excitation force as the input force, which excites the flexible body of a car at the mount points, while traditional TPA uses the measured force. This simulated force is obtained by numerical analysis of the finite element (FE) model of a powertrain. Interior noise is predicted by multiplying the simulated force by the vibro-acoustic transfer function (VATF) of the vehicle. The VATF is the acoustic response in the compartment of a car to the input force at the mount point of the powertrain in the flexible car body. The trend of the predicted interior noise based on the hybrid TPA corresponds very well to the measured interior noise, with some difference due to not only experimental error and simulation error, but also the effect of the airborne path.

KEY WORDS : Powertrain, Force prediction, FEM, Structure-borne noise, Vibro-acoustic

1. INTRODUCTION

Noise vibration harshness (NVH) technology in automobile engineering has become an important performance target in the search for vehicle comfort. In a vehicle, there are many noise and vibration sources that influence NVH performance, such as the powertrain, tires, wind, car body, suspension, etc. Among these sources, it is known that the powertrain is the dominant contributor to interior noise (Lee et al., 1994). Therefore, many researchers have tried to develop a simulation method to predict interior noise caused by a powertrain (Seki et al., 2001; Kim et al., 2007). Interior noise due to a powertrain is induced by two transfer paths: airborne (noise) and structure-borne (vibration). In order to predict interior noise due to the structure-borne transfer path, traditional transfer path analysis (TPA) has been used based on an experimental method (Wyckaert and Auweraer 1995; Lee et al., 2000). Although it is a useful tool for source identification, it is not convenient for modification of the powertrain structure for reducing interior noise since it uses an experimental method. This paper presents a hybrid method for the prediction of interior noise based on hybrid TPA. In order to solve the interior noise problem, the numerical model of a car body was used and the excitation force was measured (Auweraer et al., 2007). In another paper, we discussed the use of the numerical load combined with experimental FRSs (Marco et al., 2006). For calculation of the numerical load, we used the ADAMS model instead of the FE model of a real engine. The moving part components of the engine were all rigid and the powertrain was the virtual FE model built in ADAMS. Therefore, their results are not practical and do not simulate a real situation. However, the numerical load for a real engine is calculated based on the FE-model of a real powertrain by other authors (Lee et al., 2006) and the vibro-acoustic characteristic for a real car is measured for hybrid TPA. The simulation of the exciting force is validated by the measured exciting force. The measured exciting force is estimated by multiplying the dynamic complex stiffness of the mount rubber by the displacements measured on the mount bracket before and after the isolation of the mounting system of the powertrain. The dynamic complex stiffness of the rubber isolator is measured by the elastomer testing system with an electric actuator and isothermal reservoir. We also predicted the interior noise based on hybrid TPA. The simulated exciting force is used in the prediction of this interior noise. In order to predict the interior noise based on hybrid TPA, the VATF of the vehicle is also necessary and is measured by using the vibro-acoustic reciprocity method (Kim and Ih, 1993; Ko et al., 2006). The predicted interior noise is compared with measured interior noise. The trend of the predicted interior noise corresponds to the direct measured noise well, although there are some differences in the absolute magnitude.

*Corresponding author: e-mail: sangkwon@inha.ac.kr
2. THEORY OF HYBRID TRANSFER PATH ANALYSIS

The traditional TPA method is the experimental method to predict interior noise (Wyckaert and Auweraer, 1995). This method is useful for the identification of noise sources along the vibration transfer path. However, after identification of the noise source, if a design modification of the powertrain structure is necessary for the reduction of interior noise a simulation tool for the prediction of the interior noise is required. In this case, hybrid TPA is one of the best solutions. The prediction of interior noise inside a car based on traditional TPA is expressed as follows:

\[
p_i(\omega) = \sum_{j=1}^{n} \left[ p_j(\omega) \right] \phi_{ij} \]

\[
= \sum_{j=1}^{n} \left| f_j(\omega) \right| \left[ \frac{p_j(\omega)}{f_j(\omega)} \right] e^{i(\phi_{ij}(\omega) - \phi_{ji}(\omega))} + \sum_{k=1}^{n} \left| q_k(\omega) \right| \left[ \frac{p_k(\omega)}{q_k(\omega)} \right] e^{i(\phi_{kj}(\omega) - \phi_{jk}(\omega))}
\]

where \( p_i \) is the interior sound pressure at point \( i \) inside a car, \( f_i \) is the excitation force at the \( i \)-th path, \( q_k \) is the air-borne source at the \( k \)-th path and \( \phi \) is the phase corresponding to each source and response. The first term of equation (1) is related to the structure-borne path and the second term is related to the airborne path. Interior noise based on the traditional TPA for the structure-borne path is predicted by using the first term in equation (1). Therefore, equation (1) can be rewritten by neglecting the second term as follows:

\[
p_i(\omega) = \sum_{j=1}^{n} p_j(\omega) = \sum_{i=1}^{n} f_i(\omega) \times H_{ji}(\omega)
\]

where \( p_i(\omega) \) is the complex sound pressure due to the \( i \)-th path in the frequency domain. In equation (2) the vibro-acoustic transfer function of a vehicle, \( H_{ji}(\omega) \) is obtained by using the experimental method based on the theory of the vibro-acoustic reciprocity. The excitation force \( f_i(\omega) \) is calculated by multiplying the dynamic stiffness by the displacement difference based on traditional TPA. The mathematical expression for excitation force is given by,

\[
f_i(\omega) = k_i(\omega) \times \Delta x_i(\omega) = k_i(\omega) \left[ x_1(\omega) - x_2(\omega) \right]
\]

where \( k_i(\omega) \) is the complex dynamic stiffness measured by the elastomer testing system with electric actuator. In equation (3), the displacements \( x_1(\omega) \) and \( x_2(\omega) \) are measured on the mount bracket before and after isolation, respectively, while a car is being driven. In general, the powertrain is installed on the car body by using a mounting system as shown in Figure 1.

This mounting system consists of four mounts: engine (E/G) mount, front-roll (F/R) mount, rear-roll (R/R) mount, and transmission (T/M) mount. The mounting system is connected to the sub frame or the suspension frame of a vehicle. Therefore, these mounts are the major transfer paths of powertrain vibration for interior noise among many transfer paths in the vehicle. These mounts play the role of supporting the weight of the powertrain and absorbing vibrational energy. These mounts are composed of the isolation rubber and bracket. The combustion force due to the firing of the test engine excites the piston and its