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Identification of vehicle interior noise sources based on wavelet transform and partial coherence analysis

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A B S T R A C T

Vehicle interior noise has an important influence on the physical and psychological perceptions of passengers and their perception of vehicle quality. The identification of potential noise sources is necessary to effectively reduce vehicle interior noise and/or improve perceived vehicle quality. In this paper, a subjective evaluation of interior noise and vibration measurements was conducted. The contributions of different noise sources, such as the engine, transmission, and structure-borne noises that radiate from the vibrations of the car body panels, were investigated using continuous wavelet transform and partial coherence analysis methods to identify major sources of vehicle interior noise. The continuous wavelet transform results indicated that most interior noise was low and middle-frequency noise. The partial coherence analysis of the vibro-acoustical signals showed that the structural vibrations responsible for structure-borne noise contribute more to interior noise than airborne noise. This case study shows that one of the main sources of interior noise in the sample vehicle is the structure-borne noise that radiates from the car body panels connected to the front sub-frame. This structure-borne noise resulted from the low vibrational isolation ratio of the rear engine mount. In addition, to validate the effectiveness of the proposed method, another vehicle was tested to identify interior noise sources. For this vehicle, the structure-borne noise clearly radiated from the panel suspension. These findings can be further applied to facilitate the reduction of vehicle interior noise.

1. Introduction

Currently, vehicles serve as a transport mechanism and as offices or places of leisure where people spend much of their time. Consequently, demands for vehicle quality are increasing. Excessive vehicle noise decreases the interior sound quality and negatively affects passenger psychology and physiology. Therefore, much attention has been paid to reducing interior noise and vibrations. The NVH (noise, vibration and harshness) performance of a vehicle has become a distinctive marketing and design criterion. Improving vehicle NVH can be achieved by considering three facets: the noise source, transfer path, and receiver. In this paper, vehicle interior noise sources are identified in the attempt to reduce noise levels and improve sound quality.

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Many factors influence vehicle interior noise. According to the characteristics of noise, the potential sources of noise can be divided into two categories [1]:

- Airborne noise sources: the noises generated by the vehicle systems and aerodynamic excitations that transmit through the cabin and are heard by the passengers.
- Structure-borne noise sources: the noises generated from the vibrations of the vehicle structure that stimulate vibrations in the cabin and result in structural noise radiation.

Generally, airborne noise is high frequency and can be reduced via the use of sound insulation and absorption materials in the vehicle [2,3]. Structure-borne noise is mainly low-to-mid frequency, i.e., less than 1 kHz, and may be controlled by suppressing structural vibrations [4]. To reduce vehicle interior noise more effectively, the noise sources should first be identified. In general, noise source identification methods can be briefly categorized into two classes, namely, simulation methods and experimental methods. The simulation method is based on numerical analysis and is well suited for quick system-level response predictions during the design stage of a product, and the experimental method is based on real data acquisition and analysis and is widely used in the analysis of dynamic responses at the mass production stage. Note that on some occasions, both methods can be combined for complementary use. A review of some of the relevant studies from recent years is provided below.

Simulation methods, such as the finite element method (FEM), boundary element method (BEM) and statistical energy analysis (SEA), are frequently applied to the prediction and identification of noise sources due to their convenient properties. The FEM subdivides a large problem into smaller, simpler parts called finite elements and uses simple equations that are assembled into a larger system of equations that models the entire problem to obtain a numerical answer. The FEM model was built by Sheng et al. [5] to predict low-frequency (2–200 Hz) structural vibrations and noise in cabins, and they used this model to analyze surface vibrations. Tijs et al. [6] developed the FEM using the particle velocity approach to evaluate the contributions of panel noise with fast and high resolution, and combined with measurements, the noise sources were visualized via sound pressure contours. BEM is an improved method of FEM and can more efficiently analyze complex problems. Mohanty et al. [4] investigated the contributions of structure-borne noise in specific modes to identify major sources of noise using the BEM. Note that the FEM and BEM can accurately predict only low-frequency noise problems because of the limitations of the element mesh.

To analyze high-frequency noises, SEA was introduced. In SEA, a system is represented in terms of a number of coupled subsystems, and a set of linear equations are derived that describe the input, storage, transmission and dissipation of energy within each subsystem. To support the sound package design and changes in the target vehicles, Teknos et al. [7] used SEA to predict high-frequency (>1000 Hz) interior noise at the source level. Moron et al. [8] optimized the acoustic goals of vehicle subsystems, such as the dash, floor, roof, and doors, using SEA. However, SEA is based on statistical energy theory, which requires a model with high modal density [9]; therefore, SEA is less effective for solving low- and middle-frequency noise problems because the modal density of a system in the low and middle frequencies is low.

Consequently, a combination of FEM and SEA, i.e. FE-SEA, has been applied in recent years to integrate the advantages of both methods [10]. Charpentier et al. [11] identified the transmission of mid-frequency structure-borne noise in a trimmed automotive vehicle using FE-SEA. To predict the low and middle frequencies of vehicle interior noise during the vehicle design and development stage, the hybrid FE-SEA method was used by Chen et al. [12], and the sound field of the interior noise was analyzed. Despite its numerous successful applications, the drawbacks of FE-SEA are that the modeling is complex and that the calculation efficiency is low.

Indeed, the construction of a vehicle is complex. Some hypotheses have been introduced to numerically analyze the dynamic characteristics of a vibro-acoustical system and have resulted in a significant simplification of the simulation models. However, the reliabilities of simulation results strongly correspond to the accuracies of the models. This trade-off makes the use of simulation analysis challenging and sometimes less effective. Experimental measurements and tests can occasionally provide better solutions.

In experiments, extracting signal characteristics precisely is very important for identifying noise and vibration signals [13]. Some advanced time-frequency analysis techniques, such as short time Fourier transform (STFT), wavelet transform (WT), Wigner-Ville distribution (WVD), and empirical mode decomposition (EMD), have been widely used in sound and vibration signal processing. Each of these methods has its own advantages and drawbacks [14–18]. In practical use, few signal processing methods perform overwhelmingly better than others. Therefore, the selection of a method mainly depends on the characteristics of the original signal and the purpose of the analysis. In the literature [19–23], STFT, WT and EMD have been successfully used to extract the noise characteristics of vehicle engine systems, exhaust systems and transmission systems. Note that the shapes of wavelet functions, such as Daubechies wavelets, are similar to the wave crests and troughs of vehicle noise or vibration signals, and this property is very useful for extracting the features of vehicle noise and vibration signals.

To identify the vibro-acoustical sources from vehicle components and quantitatively assess each noise source, the sound intensity, acoustic holography, singular value decomposition (SVD) and coherence analysis methods are applied. Sound intensity measurements can provide the amplitude and direction of a noise. Fan et al. [17] applied sound intensity techniques to analyze the interior noise distribution and recognized potential noise sources from the floor and window in a high-speed train. Acoustic holography has been proven to be a useful technique for identifying noise levels and noise origins