

A New Method of Characterizing Wind Noise Sources and Body Response for a Detailed Analysis of the Noise Transmission Mechanism

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ABSTRACT

Interior noise caused by exterior air flow, or wind noise, is one of the noise-and-vibration phenomena for which a systematic simulation method has been desired for enabling their prediction. One of the main difficulties in simulating wind noise is that, unlike most other noises from the engine or road input, wind noise has not one but two different types of sources, namely, convective and acoustic ones. Therefore, in order to synthesize the interior sound pressure level (SPL), the body sensitivities (interior SPL/outer source level) for both types of sources have to be considered. In particular, sensitivity to the convective input has not been well understood, and hence it has not been determined. Moreover, the high-frequency nature of wind noise (e.g., the main energy range extends up to 4000 Hz) has limited the effective application of CAE for determining body sensitivities, for example, from the side window glass to the occupants' ears.

This paper presents a new approach to the analysis of wind noise which has been restricted by the intrinsic nature of the noise sources (i.e., a mixture of convective and acoustic components). To cope with this dual-input complexity, a new transmission model was built to treat noise sources characterized simply as "forces" impinging upon the body surfaces regardless of the type of source and noise transfer functions (NTFs) employed as body sensitivities to the forces. This model enables a quantitative synthesis of interior noise and also a contribution analysis of the sources and/or body sensitivities with high accuracy.

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INTRODUCTION

Improving passenger compartment quietness to enhance driver and passenger comfort is essential for strengthening the marketability of vehicles. In order to improve interior quietness especially during high-speed driving in Europe and the United States, it is necessary to reduce aerodynamic noise, i.e., wind noise, which is the dominant component at high speeds rather than engine or tire noise. Meanwhile, the use of thinner body panels and glass parts is being proposed as a way of promoting vehicle weight reductions for improving environmental performance, which is making it more difficult to insulate the passenger compartment from noise. Consequently, it has become necessary to reduce noise sources themselves. Against this backdrop, in order to both enhance quietness and reduce the vehicle weight, it is necessary to understand quantitatively the mechanism producing wind noise and the mechanism by which it is transmitted into the passenger compartment.

Many techniques have been proposed and reported for ascertaining wind noise quantitatively, including characterization of wind noise sources and the modeling of the transfer response system [1, 2]. The techniques employed in vehicle engineering, however, have yet to reach the level where they can satisfy all the requirements, including

good prediction accuracy up to high frequencies, reasonable computational time including model preparation, and acceptable cost, among other things. Statistical energy analysis (SEA) is an effective method for identifying high-frequency interior noise components with high accuracy, and there are examples in the literature of its application by vehicle manufacturers [3, 4]. However, it does not have sufficient spatial resolution to elucidate the mechanism causing wind noise, which is the issue of interest in our research, making it necessary to undertake an investigation of a new method.

Wind noise sources are characterized as being a mixture of two types, namely, pressure fluctuations due to convection (referred to here as pseudo-sound) and acoustic waves. Consequently, it is necessary to define a transfer function corresponding to each type. While qualitative hypotheses can be formed in this regard, the difficulty of proving them quantitatively poses a problem.

The method described here treats the excitation sources of wind noise as micro forces in terms of wall pressure fluctuations calculated by computational fluid dynamics (CFD) without separating them into pseudo-sound and acoustic waves. (The term excitation source is used here in a broad sense that includes noise sources.) A study was made of a new model for dynamically linking the excitation sources

and the transfer response system. As a result, the newly developed method makes it possible to treat wind noise phenomena quantitatively and visually from the perspective of detailed distributions of inputs and the transfer response system. Consequently, this method now enables interior wind noise to be analyzed quantitatively with high accuracy.

WIND NOISE OF INTEREST

Vehicle wind noise can be broadly divided into the two regions of narrowband and broadband noise components. For narrowband wind noise, which is also referred to as abnormal noise, measures are generally applied principally to the noise sources and rarely are measures, including soundproofing, applied to the transfer response system. In contrast, for broadband wind noise without any strange noise, it is necessary to apply comprehensive measures to both the noise sources and the transfer response system because the allowable noise levels perceivable by the driver and passengers have been determined. Consequently, it is necessary to identify clearly the mechanism of the excitation sources producing broadband wind noise and that of the transfer response system into the passenger compartment. This paper deals with broadband wind noise, which requires an effective approach from the dual aspects of the excitation sources and transfer response system.

ISSUES INVOLVED IN DEFINING AND EVALUATING THE EXCITATION SOURCE AND TRANSFER FUNCTION

In attempting to elucidate the mechanism of wind noise, there are issues involved in defining and evaluating the excitation sources, comprising a mixture of two types of noise sources in terms of pseudo-sound and acoustic waves, as well as in their corresponding transfer response system. With regard to the excitation sources, it is possible, for example, to measure pressure fluctuations on vehicle body surfaces using surface microphones, but it is difficult to evaluate accurately the excitation source distribution for the reasons explained below.

Figure 1 shows the sound pressure levels measured at the same place on the same vehicle using two microphones with different diaphragm diameters. The microphone with the larger diaphragm tended to evaluate the higher frequencies at a lower level [5]. The reason for that is because the number of vortices (pseudo-sound) on the diaphragm of a microphone is influenced by the microphone size and wind velocity as shown in Figure 2. The frequency of a Pseudo-sound captured by a microphone is defined here as the number of vortices passing over the diaphragm in one second. The distance between vortices becomes increasingly smaller at higher frequencies, so the number of vortices on the diaphragm increases. As the number of vortices becomes larger, the diaphragm is increasingly cancelled, with the result that lower pressure levels are shown at higher frequencies and by microphones with a larger acoustic pressure receiving area. This effect is specific to pseudo-sound that is characterized by high wave numbers.

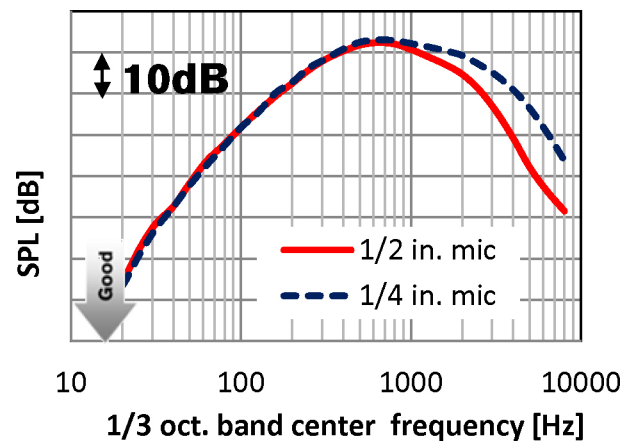


Figure 1. Example of the excitation source measured with surface microphone.

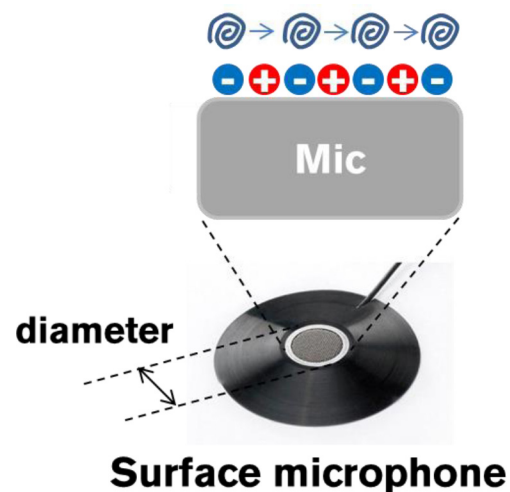


Figure 2. Conceptual representation of pressure fluctuation distribution measurement using a surface microphone

Figure 3 shows the interior wind noise level that was calculated by multiplying the pressure fluctuation [Pa] measured with a surface microphone by the transmission loss (expressed as Pa/Pa). It is seen that the predicted value is at least 20 dB higher than the measured value, making it inconsistent with the actual noise level in the interior. The reason for this difference is that the transmission loss is an index that expresses the sensitivity of the vehicle body to acoustic waves but not its sensitivity to pseudo-sound, which is the main component of the pressure fluctuations measured with a surface microphone. In short, the sum of the sound pressure levels measured with external microphones and the interior noise level do not correlate very well [6]. This inconsistency stems from the fact that suitable transfer functions have not been defined for acoustic waves and pseudo-sound respectively, which constitute the excitation sources of wind noise, as indicated in the model in Figure 4.

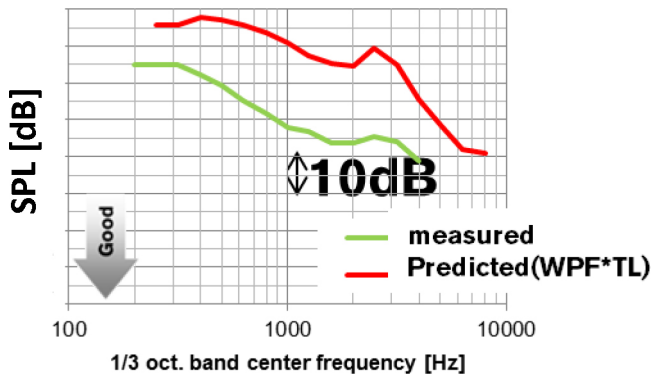


Figure 3. Present level of wind noise prediction accuracy

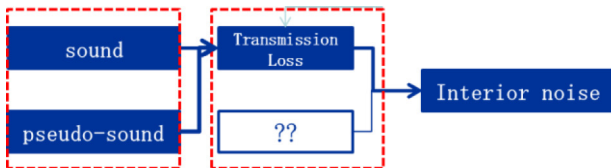


Figure 4. Interior noise model without separation of excitation sources into acoustic waves and pseudo-sound (model in Figure 3.)

Method of Analyzing Interior Noise Quantitatively

Therefore, an investigation was undertaken to determine if this issue could be resolved by using body sensitivity (i.e., noise transfer function, NTF, expressed as Pa/N) as a suitable transfer response system in relation to the interior noise model in Figure 4. The difficulty with the model in Figure 4 is that it is necessary to define separate transfer response systems for acoustic waves and pseudo-sound. In the interior noise model shown in Figure 5, acoustic waves and pseudo-sound are interpreted as “forces” acting on local body surfaces, rather than separating them. It was reasoned that this approach would allow the model to be replaced by the one in Figure 6 in which the excitation sources (i.e., input force) and Transfer function (NTF) are linked dynamically.

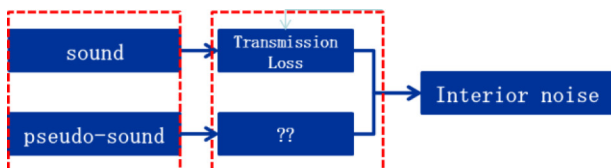


Figure 5. Interior noise model with separation of excitation sources into acoustic waves and pseudo-sound

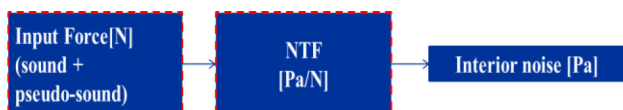


Figure 6. New dynamic interior noise model without separation of excitation sources

TEST VEHICLE VERIFICATION

The interior noise model in Figure 6 was then verified using a test vehicle. As the first step in the verification process, the excitation forces were calculated from the wall pressure fluctuations extracted by CFD calculations. The result was multiplied by the experimentally measured body sensitivity (NTF) to predict the interior noise level. The predicted value was then compared with the data measured in a wind tunnel test.

Evaluation Conditions and Specifications

A midsize Nissan sedan was used for the calculation model and in the wind tunnel measurements. The vehicle velocity (wind velocity) was 120 km/h in the straight-ahead direction, and the evaluation point was the noise at the driver's outer ear where the input force was applied. In order to evaluate only the input to the front door window glass in the wind tunnel test, soundproofing material was used to mask all other parts of the test vehicle.

Excitation Source Evaluation: Excitation Force [N]

The analysis software used in the excitation force evaluation was EXA's PowerFLOW®, which is based on non-steady-state Lattice-Boltzmann equations. The wall pressure (input force [N]) on the door window glass was extracted at an average spacing of approximately 1.5 mm (Figures 7 and 8).

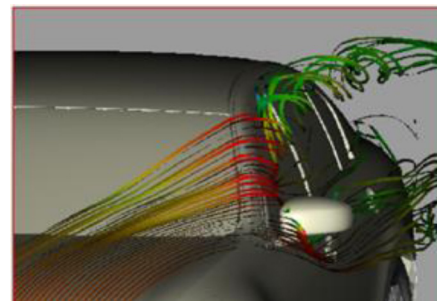


Figure 7. CFD simulation

As one example of an excitation source distribution, Figure 8 shows a snapshot of the instantaneous wall pressure fluctuations at 2500 Hz. Strong pressure fluctuations are observed rearward of the A-pillar together with a clustering of plus or minus pressure values. These results indicate that a salient pseudo-sound exerted pressure on the window glass surface.

The force input [N] to the front door window glass was calculated by multiplying the wall pressure fluctuation at each individual point by a minimal wall area (referred to here as an element). The size of all the elements was assumed to be a square of 10 mm x 10 mm. This element size coincided with the measurement interval of the noise transfer function (NTF) that will be explained later.