MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

Analytical model for predicting transmission of vehicle horn sound using one-dimensional standing-wave model

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ABSTRACT
Vehicle horns need to satisfy sound pressure level (SPL) regulations in each country. To adhere to SPL regulations, the sound transmission of a vehicle through openings in its front grille has to be controlled by adjusting the location of the horn within the vehicle. To assist with the adjustment of horn placements in the early stages of vehicle development, this study aims to clarify relationship between the horn placements and the SPL. Therefore, an analytical model based on a one-dimensional standing-wave model is proposed to simplify the complex acoustic fields within the vehicle. First, to express the spectral shift of the SPL in response to horn position, the formation of the standing waves within the vehicles were analytically formulated based on one-dimensional acoustic wave equations. The formulated phenomena were measured in sample commercial vehicles. Next, the parameters of the analytical model were determined to accurately represent the acoustic fields within the vehicles. Finally, the analytical model was validated using measurements obtained in sample commercial vehicles. The spectral shifts obtained by the analytical model agree well with those measured in the sample commercial vehicles.

Keywords: Vehicle horn, Standing-wave model, low-fidelity model
I-INCE Classification of Subject Number: 75

1. INTRODUCTION

In highly competitive vehicle markets, the vehicle development process needs to be shortened. Therefore, a recent development process employs computer-aided engineering at an early stage, which is known as functional performance engineering [1]. As illustrated in Fig. 1, in comparison to the conventional development process, which places a heavy emphasis on the detailed phase and proto-type phase, the new development process (with functional performance engineering) reduces engineering

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refinements in the later stages and shortens the total development time. Therefore, it is important that a low-fidelity model is used for numerical computation in the early stages of development.

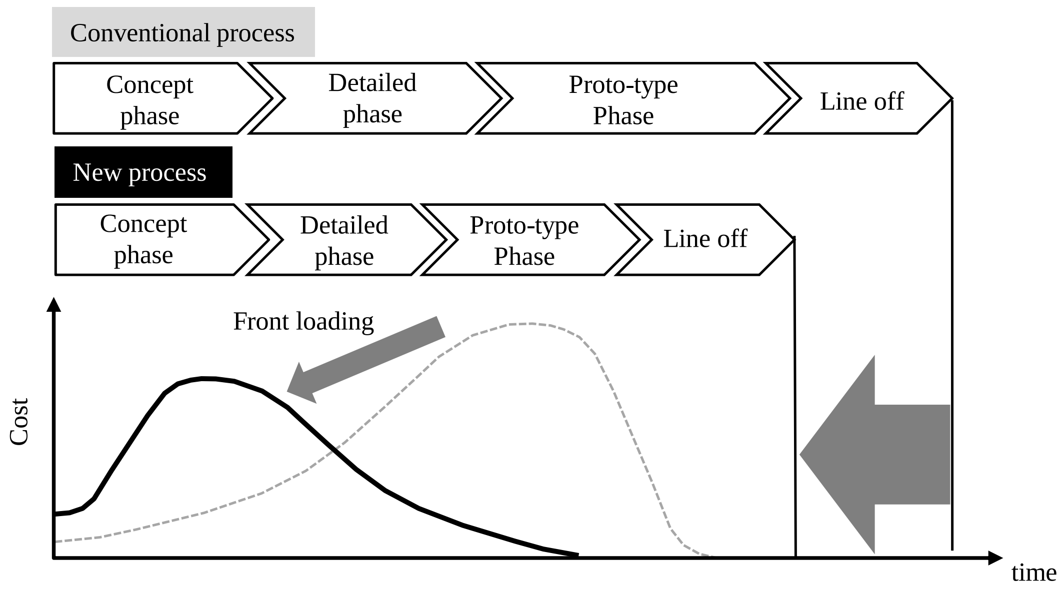

Fig. 1. Illustration of the contribution of employing low-fidelity models in the early stages of the vehicle development process.

One important design requirement for vehicle development is the exterior sound of a horn, which is attached as a warning device. If it does not exceed sound pressure level (SPL) regulations in each country (e.g.,[2,3]), the vehicle is not allowed to be sold. Therefore, horn placements are adjusted to adhere to the SPL regulations. These adjustments are difficult in the later stages of vehicle development because the horn placements are constricted strongly by other design requirements. Thus, the horn adjustment process requires numerical computation to optimize the placements of horns in the early stages of development.

In previous studies, numerical computation has been conducted to improve the sound quality generated from a horn [4-6]. These studies evaluate the sound of horns under the condition that they are not mounted inside vehicles. To apply the adjustment of the horn placements to such studies, the transfer characteristics of vehicles have to be modeled. In terms of the transfer characteristics of vehicles, the effect of horn placements on the interior sound quality was investigated using transfer path analysis [7]. In addition, the exterior sound of a warning device for electric vehicles was computed using both the boundary element method and the ray tracing method to investigate the effect of the positon of the device [8]. These methods are based on high-fidelity models, which are created using detailed geometries of acoustic fields obtained from the detailed phase of vehicle development. However, as detailed geometries are not present in the early stages of the development process it is necessary to employ low-fidelity models, which are constructed using limited parameters such as the distance between the front grille and the horn. To the best of our knowledge, low-fidelity models for the placement of horns in vehicles have not been developed. Therefore, horn placements are determined empirically in the early stage of the development process, and engineering refinements tend to increase in the latter stage of development.

This study aims to compute the SPL using the information given in the early stages of vehicle development, namely without using detailed geometries of acoustic fields. To realize this approach, an analytical model based on a one-dimensional (1D) standing-wave model is proposed to simplify the complex acoustic fields within a vehicle.

This paper is organized as follows. In section 2, the transfer characteristics from horns placed inside vehicles to the outside of the front grilles are measured using sample commercial vehicles, and effects of horn placements on these transfer characteristics are evaluated. In section 3, the relationship between the transfer characteristics of vehicles and the placements of horns are formulated using a 1D standing-wave model. In section 4 , the analytical model was validated using measurements obtained in sample commercial vehicles. Finally, discussion and conclusions are summarized in section 5.

2. Experimental measurements

2.1 Acoustic characteristics of SPL emitted from a vehicle horn

Fig. 2 shows the spectrum of the SPL emitted from a typical disk-type vehicle horn. The spectrum has two dominant peaks, at 2800 Hz and 3150 Hz. Thus, when this vehicle horn is employed, it is necessary to adjust its placement to maximize the transmission of these dominant frequencies. In this paper, analytical models for the prediction of the transfer characteristics in frequencies of these ranges are discussed.

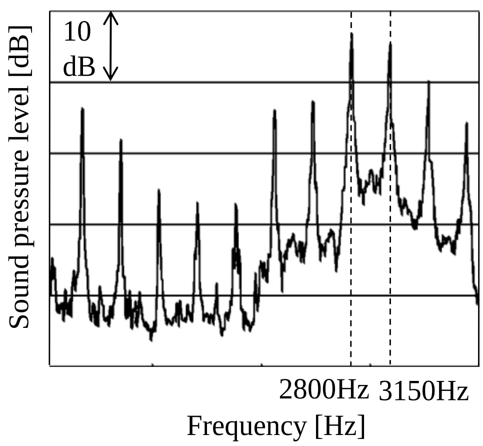

Fig. 2. Spectrum of sound pressure level (SPL) emitted from a vehicle horn

2.2 Measurements of transmission characteristics

Transfer characteristics from the position of a horn to the outside of the opening in a front grill are measured using sample commercial vehicles (Fig. 3). Generally, a vehicle horn is attached between the front grille and the radiator and these placements are adjusted in a horizontal direction. Therefore, the influence of the horizontal position of a horn on the transfer characteristics is investigated. A speaker with the same radius as a vehicle horn is employed as a sound source in place of a vehicle horn. The speaker generates a sweep sound in the frequency range of interest, and the SPLs transmitted from openings in the front grilles are measured using a microphone located 50 mm outside of the front grilles. These measurements are performed under the condition that the speaker moves closer to the front grill by Δl (10, 20, 30 mm) based on the initial horn placements l shown in Table 1.

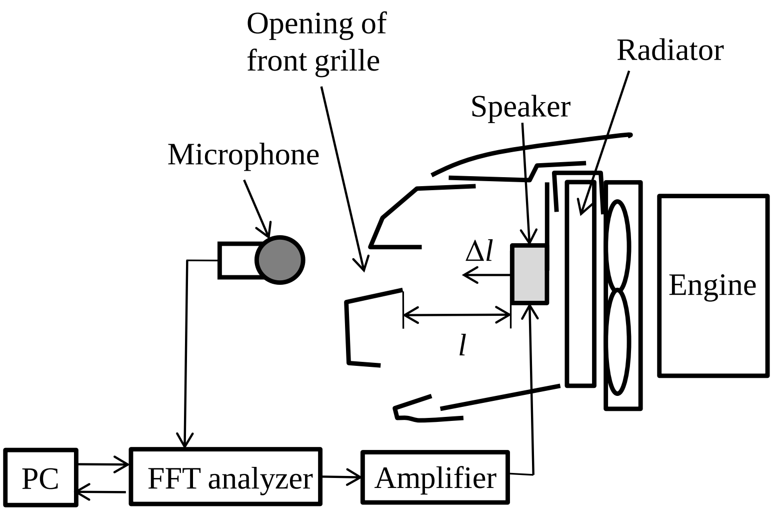

Fig. 3. Experimental set up

2.3 Spectra of transfer characteristics

Fig. 4 (a)–(b) show the spectra of the transfer characteristics in response to the change of the sound source placements. To evaluate the spectra of the two dominant horn sound frequencies, shown in Fig. 2, the spectra are shown in the frequency range from 2600 to 3300 Hz. Both spectra of the transfer characteristics shift depending on the position of the sound source. It seems that the position of the sound source contributes to the formation of a standing-wave within the vehicle.

Table 1 Horn placement of sample commercial vehicles I and II

	Vehicle I	Vehicle II
Horn placement l [mm]	97	116

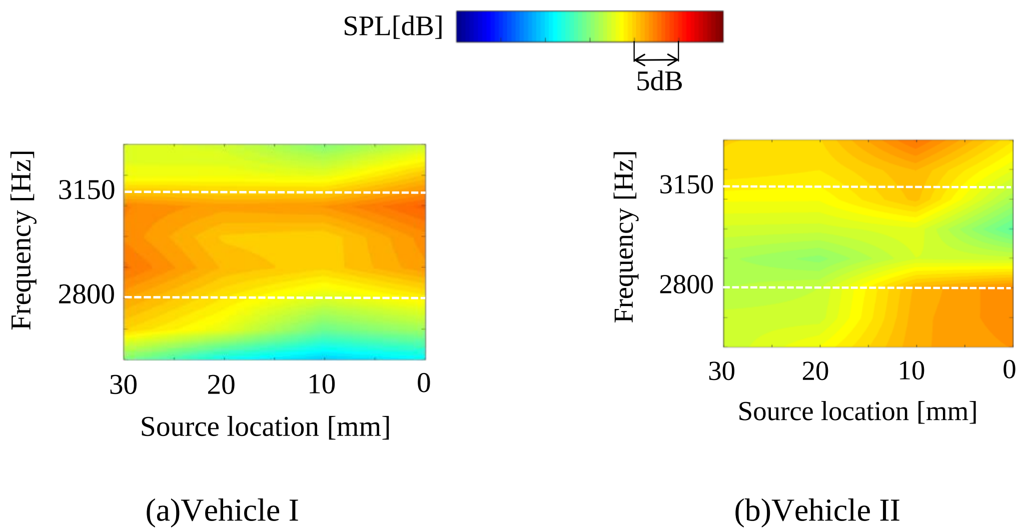

Fig. 4 Spectra of transfer characteristics from the position of the sound source to the outside of the front grilles of a vehicle

3. Formulations of transfer characteristics

This section provides analytical models to express the formation of a standing-wave within the vehicles. To simplify the acoustic phenomena, such as wave propagation, transmission, and reflection, several assumptions are proposed.

3.1 One-dimensional standing-wave model

The standing-wave formations within a vehicle are formulated by dividing the acoustic fields within the vehicle into the front grille side (acoustic field 1) and the radiator side (acoustic field 2), as shown in Fig. 5.

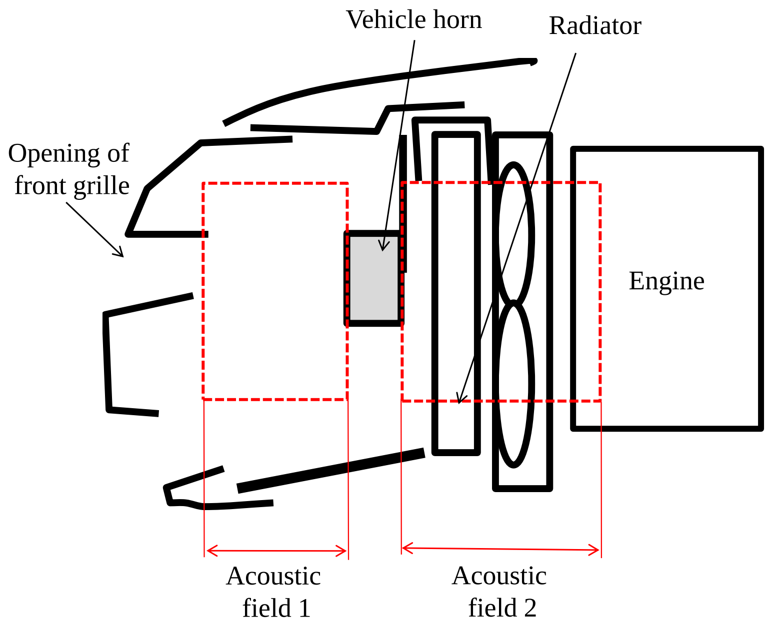

Fig. 5. Classification of acoustic wave fields within a vehicle

First, assuming that acoustic wave fields are represented by the 1D acoustic wave equation, the acoustic fields within a vehicle are expressed as follows [9]:

$$\frac{\partial^2 p}{\partial t^2} - c^2 \frac{\partial^2 p}{\partial x^2} = 0 \,, \tag{1}$$

where, p is pressure, t is time, x is the coordinate axis of the direction of wave propagation and c is velocity. The general solution of Equation 1 is given by

$$\begin{aligned} p &= \{Ae^{-jkx} + Be^{jkx}\}e^{j\omega t} \\ &= p_+ \quad + p_- \end{aligned} \,, \tag{2}$$

where, j is an imaginary unit, and p^+, p^- are positive and negative propagating waves, respectively. A and B are the pressure and amplitude of each wave, respectively, and k is the wave number.

Next, the formations of standing-waves are expressed based on two acoustic fields connected using transmission and reflection coefficients as shown in Fig. 6. The amplitude of propagating waves changes by propagation, reflection, and transmission. This phenomenon is expressed as follows:

$$\begin{Bmatrix} A_1' \\ B_2' \\ A_2' \\ B_2' \end{Bmatrix} = \begin{bmatrix} 0 & r_{1L} & 0 & 0 \\ r_{1R} & 0 & 0 & t_{21} \\ t_{12} & 0 & 0 & r_{2L} \\ 0 & 0 & r_{2R} & 0 \end{bmatrix} \begin{bmatrix} e^{-jk_1l_1} & 0 & 0 & 0 \\ 0 & e^{-jk_1l_1} & O & 0 \\ 0 & 0 & e^{-jk_2l_2} & 0 \\ 0 & 0 & 0 & e^{-jk_2l_2} \end{bmatrix} \begin{Bmatrix} A_1 \\ B_1 \\ A_2 \\ B_2 \end{Bmatrix} , \tag{3}$$

where, A and B are the amplitude of the positive and negative propagating waves, respectively, and r and t are the reflection and transmission coefficients, respectively. Subscripts L and R denote the left and right boundary of i th acoustic wave fields, respectively. For convenience, equation (3) is expressed as:

$$\mathbf{A}' = \mathbf{SDA} \,, \tag{4}$$

where, **S** and **D** are scattering and propagating matrices, respectively. The wave amplitude vector emitted from horns, $\mathbf{A}_{\mathrm{Horn}}$, is defined by:

$$\mathbf{A}_{Horn} = P_{Horn}[0 \quad 1 \quad \zeta \quad 0]^{\mathrm{T}} \,, \tag{5}$$

where P_{Horn} is the SPL emitted from the horn to the front grille side and ζ is the ratio of SPL emitted into the radiator side to SPL emitted into the front grille side. Namely, it corresponds to directional characteristics of vehicle horns. The emitted waves form the standing-waves because of repeated propagation and scattering. The amplitude vector of the standing-wave is formed by superposition of a set of scattering waves and is given by the following equation [10]:

$$\mathbf{A}_s = \sum_{i=0}^{\infty} (\mathbf{SD})^i \mathbf{A}_{Horn} = (\mathbf{I} - \mathbf{SD})^{-1} \mathbf{A}_{Horn}, \quad (6)$$

where, $\mathbf{I}$ is the identity matrix and i is the number of scattering. Using an incident component of standing-waves $\mathbf{A}_s(2)$, the transfer characteristics can be expressed as follows:

$$\alpha_T = \frac{|t_G \mathbf{A}_s(2)|^2}{|P_{Horn}|^2}, \quad (7)$$

where, t_G is the transmission coefficient of the front grille. In the following section, t_G is analytically defined using the exterior view.

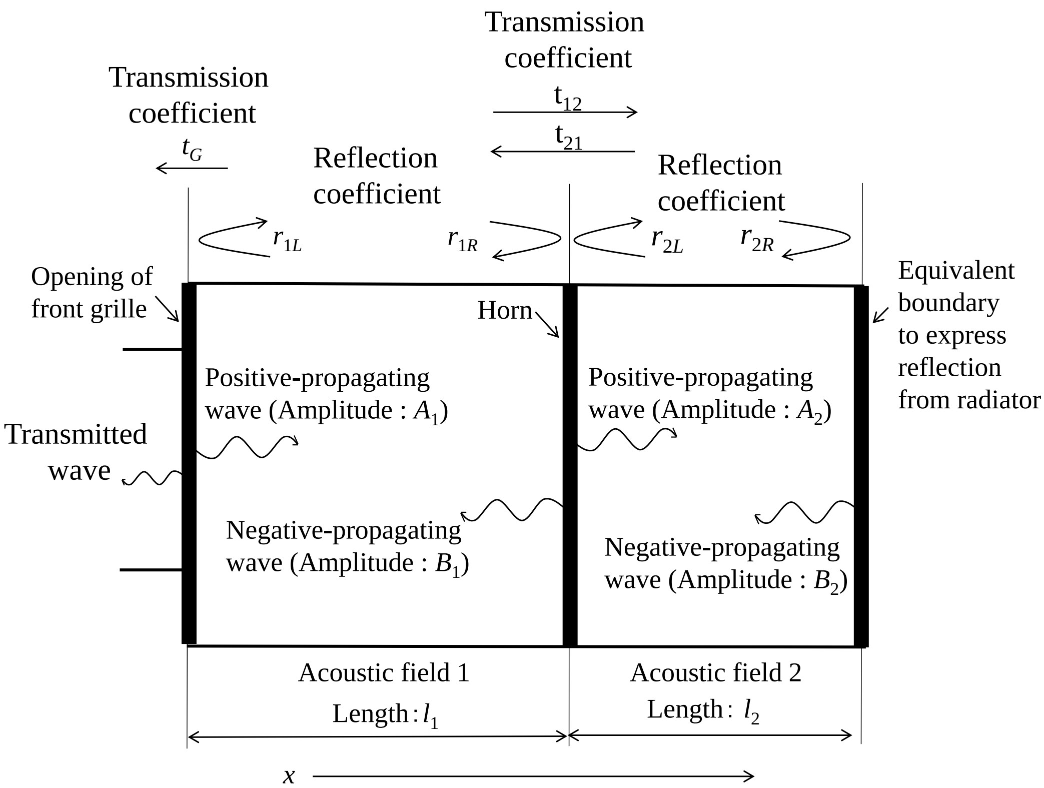

Fig. 6. Analytical model of acoustic fields within a vehicle

3.2 Acoustic field of the front grille side

To express the acoustic field on the side of the front grille (acoustic field 1), the length of the waveguide and the reflection and transmission coefficients of the boundary are defined.

First, the distance between the front grille and the horn l_1 is defined. If the horn placement is adjusted by Δl in a horizontal direction, based on initial horn placements $l_{1,ini}$ as shown in Fig. 3, the distance l_1 is expressed as follows:

$$l_1 = l_{1,ini} - \Delta l \,. \tag{8}$$

This equation corresponds to the adjustments of the placement of a sound source in the experimental measurements shown in Fig. 3, and $l_{1,ini}$ are the horn placements l of the sample commercial vehicles shown in Table 1.

Next, the reflection and transmission coefficients, r_{1L}, t_G, of openings in the front grilles are analytically defined. As only exterior views of front grilles are decided in the early stages of vehicle development, detailed geometries of the front grilles cannot be used. Therefore, information about the external view of the front grilles is replaced with a simple parameter such as transmission and reflection coefficients. The reflection and transmission are expressed as follows:

$$B_0 = t_G A_1 ,\ B_1 = r_{1L} A_1 , \tag{9}$$

where, A_1 B_1 and B_0 are incident, transmitted and reflected waves amplitudes, respectively. To represent the reflection and transmission at openings in the front grilles, it is assumed as a boundary with two waveguides that have different cross sectional areas (S_o and S_h), as shown in Fig. 7. These cross sectional areas are determined from exterior views of front grilles, as shown in Fig. 8. Using the cross sectional areas, the reflection and transmission coefficients of the boundary are expressed as follows [11]:

$$\begin{aligned} t_G &= \frac{B_0}{B_1} = \frac{2S_h}{S_h + S_o} = \frac{2}{1+M} , \\ r_{1L} &= \frac{A_1}{B_1} = \frac{S_h - S_o}{S_h + S_o} = \frac{1-M}{1+M} , \end{aligned} \tag{10}$$

where ratio of the open area of the front grilles to the grille surface is $M = S_o / S_h$. In practice, as the ratio M does not express the differences in impedance at the openings in the front grilles accurately, a weighting factor, α, is employed as follows:

$$m = \alpha M \ . \tag{11}$$

The weighting factor, α, is identified by comparing the transfer characteristics obtained by experiment and those obtained by calculation. The ratio of the open area, m, given in Equation 11, is used to calculate the transmission and reflection coefficients instead of M in Equation 10.

Finally, the reflection and transmission coefficients r_{1R} and t_{12} of the boundary of the horn are set as 1 and 0, assuming the reflection and absorption at horn placements are small.

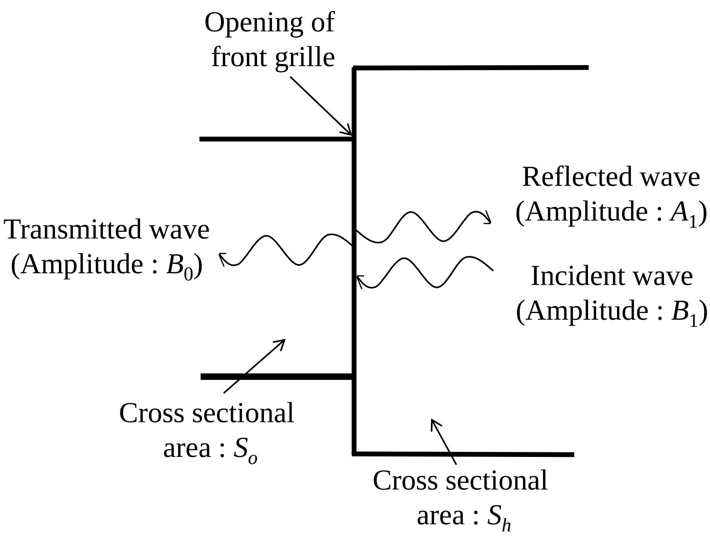

Fig. 7. Analytical modeling to obtain the reflection and transmission coefficients of openings in the front grille

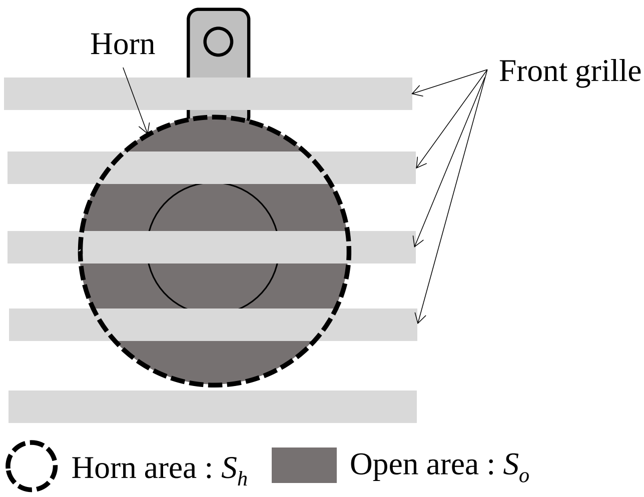

Fig. 8. Exterior view of the front grille

3.3 Reflection from the radiator

The acoustic field on the radiator side (acoustic field 2) is formulated. As the sound field on the radiator side has a complicated boundary, such as radiator mesh and the engine surface, it is difficult to estimate the reflection coefficient and the length of the waveguide from the geometry of the vehicle. Therefore, an equivalent boundary representing the reflection from the radiator is introduced.

First, the distance between the horn and the equivalent boundary is defined as follows:

$$l_2 = l_{2,ini} + \beta \Delta l \, , \tag{12}$$

where Δl is the adjustment length of horn placement, $l_{2,ini}$ is the initial distance between the horn placements and the equivalent boundary, and β is the sensitivity to which adjustments of horn placements affect the distance. Parameters $l_{2,ini}$ and β are estimated by comparing the transfer characteristics obtained by experiment and by calculation.

Finally, the reflection and transmission of each boundary are determined. Those of the left boundary, r_{2L},$t_{21,}$ are set as 1 and 0 for the same reasons as described in the previous section. The reflection coefficient of the right boundary, $r_{2\mathrm{R},}$ is set as 1, neglecting sound absorption in the radiator.

4. Validation of analytical models

4.1 Parameter estimation

First, the parameters obtained from the geometry of the vehicle are explained. As mentioned above, the ratio of grille openings to the horn surface, *M*, can be obtained from the exterior view of the front grilles (Fig. 8). Those of vehicles I and II are 0.62 and 0.49, respectively. In addition, the initial distance between the front grille and the horn, $l_{1,ini}$, can be decided in the early stage of the development process because the space allowed for attaching the horn can be estimated from the vehicle size. Those of vehicles I and II have been shown in Table 1 as parameter *l*.

Next, since the parameters α, β, and $l_{2,\,ini}$ do not relate to vehicle geometry, these parameters are estimated to obtain the appropriate transfer characteristics. For evaluation of the validity of transfer characteristics, the correlation coefficient, C_{spl}, between experimental and computational images of spectral shifts of the transfer characteristics is employed as follows:

$$\mathrm{C}_{spl} = \frac{\sum \mathbf{P}_{ana}(\alpha, \beta, l_{2,ini}) \sum \mathbf{P}_{\exp}}{\sqrt{\sum \mathbf{P}_{ana}(\alpha, \beta, l_{2,ini})^2 \sum \mathbf{P}_{\exp}{}^2}} \times 100[\%] \, , \tag{13}$$

where $\mathbf{P}_{ana}$ (α, β, $l_{2,ini}$) and $\mathbf{P}_{exp}$ are images of spectral shifts of transfer characteristics obtained by analytical model and by experimental measurements, respectively. Table 2 shows the parameters estimated to maximize the correlation coefficient.

Table 2 Estimated parameters of analytical models

	Vehicle I	Vehicle II
α	1.6	
β	0.3	
$l_{2,ini}$	0.23	0.20

4.2 Transfer characteristics

Fig. 9 (a) and (b) show the transfer characteristics of vehicles I and II calculated using the parameters estimated in Table 2. The C_{spl} of vehicles I and II are 80.5% and 80.2%, respectively. These high correlation coefficients indicate that the proposed analysis model adequately expresses the phenomenon of standing-wave formation within the vehicles. In the early stage of the vehicle development process, the transfer characteristics predicted using the proposed analytical models contribute to the optimization of the horn location.

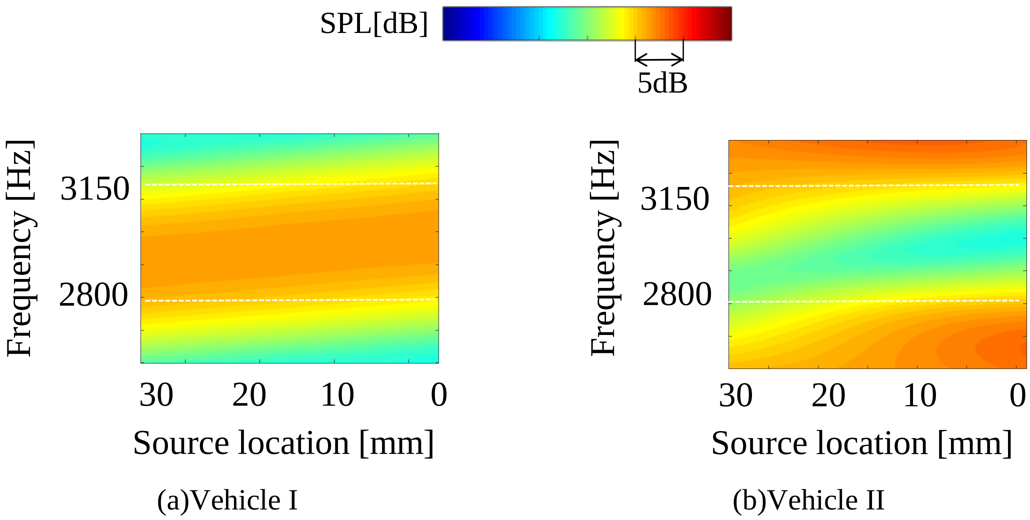

Fig. 9. Spectral shifts computed by the analytical models

5. Conclusion

In this paper, an analytical model has been proposed to simplify the geometry of the acoustic fields within a vehicle for adjustments of the position of a horn in the early stage of vehicle development. In section 2, spectral shifts of the transfer characteristics with respect to the position of a sound source were experimentally obtained using sample commercial vehicles. Section 3 proposed analytical models to express the spectral shifts in transfer characteristics that were obtained. In section 4, the parameters of the analytical models were estimated by comparing the transfer characteristics obtained by experiment and by calculation. The images of spectral shifts of the transfer characteristics obtained by the analytical model agree well with those measured in the sample commercial vehicles. The analytical models can contribute to the optimizing the placement of horns in the early stages of the vehicle development process.

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