

A CFD Analysis Method for Prediction of Vehicle Exterior Wind Noise

Vinh Long Phan, Hiroshi Tanaka, Takaaki Nagatani, Mikio Wakamatsu, and Tsuyoshi Yasuki
 Toyota Motor Corporation

ABSTRACT

High frequency wind noise caused by turbulent flow around the front pillars of a vehicle is an important factor for customer perception of ride comfort. In order to reduce undesirable interior wind noise during vehicle development process, a calculation and visualization method for exterior wind noise with an acceptable computational cost and adequate accuracy is required. In this paper an index for prediction of the strength of exterior wind noise, referred to as Exterior Noise Power (ENP), is developed based on an assumption that the acoustic power of exterior wind noise can be approximated by the far field acoustic power radiated from vehicle surface. Using the well-known Curle's equation, ENP can be represented as a surface integral of an acoustic intensity distribution, referred to as Exterior Noise Power Distribution (ENPD). ENPD is estimated from turbulent surface pressure fluctuation and mean convective velocity in the vicinity of the vehicle surface. Therefore calculations and visualizations of ENP and ENPD can be implemented in an unsteady Computation Fluid Dynamics (CFD) simulation without extra cost for acoustical computation. Applications of ENP and ENPD in vehicle development process can provide not only quantitative information about the acoustic power of exterior wind noise in parts of vehicle but also an indication of the location of dominant sources of exterior wind noise as well as the associated turbulent flows. The information of ENP and ENPD are helpful in order to set targets for exterior wind noise around each part of vehicle and to establish countermeasure designs for reduction of exterior wind noise.

CITATION: Phan, V., Tanaka, H., Nagatani, T., Wakamatsu, M. et al., "A CFD Analysis Method for Prediction of Vehicle Exterior Wind Noise," *SAE Int. J. Passeng. Cars - Mech. Syst.* 10(1):2017, doi:10.4271/2017-01-1539.

INTRODUCTION

Innovation of powertrain technologies in recent years has led to significant reductions of the interior noise generated by transmission of vibratory forces and acoustical loads from the engine, tires and irregular road surface. Due to this, contribution of exterior wind noise induced by turbulent flow around the vehicle to the acoustic field inside the cabin at the high frequency range have become more dominant, particularly in high speed cruising conditions. Due to high customer demands for quietness and ride comfort, such exterior wind noises become the key factor for evaluation of quality and competitiveness of a vehicle, therefore must be continuously reduced.

While turbulent flow in many regions of a vehicle can contribute to exterior wind noise, the important contributors which have a major impact on interior noise come from surface pressure fluctuation around the vicinity of the front pillar and front side glass [1]. Such surface pressure fluctuation generated by vortices and separated flow around the front pillar and side mirror, contains both convective and acoustic pressure components [2] in which the acoustic component is typically very small in amplitude compared to the convective component but is the dominant contributor to high frequency interior noise due to coincidence effect of side glass [3, 4]. Based on the fact that acoustic pressure propagation is not only travelling towards the side glass and transmitting inside the cabin and reaching to the driver's ear but also reflected by boundary walls and radiating outward to form the acoustic far-field surrounding the vehicle [5], it

can be considered that the power of the acoustic component in exterior wind noise has a strong correlation with the power of the acoustic far-field.

In order to reduce development time and cost and to provide timely and reliable information, an efficient prediction method with adequate accuracy for exterior wind noise is required. A number of experimental and computational methods of representing exterior wind noise have been used and developed over the past several years in the automotive industry. In experimental approaches, a conventional beam-forming method using microphone array located far from vehicle, is one of the most common ways to assess the exterior wind noise [6, 7]. Measurements by this method can directly capture the far field acoustic pressure and its results can be inverted to predict the acoustic field around vehicle. However, it is not possible to provide in detail the distribution of wind noise sources on complex shapes of vehicle surface due to lack of resolution and limitation of the inverse algorithm in which acoustic propagations is assumed as plane waves or spherical waves [8, 9]. In recent years, in order to directly extract the acoustic pressure component from surface fluctuation pressure on side glass, another experimental approach using micro-electro-mechanical (MEMS) microphone array stuck on the side glass and filtered by wavenumber technique is under development [10]. However, the method for practical use still has to overcome a lot of difficulties such as removal of the interference of flow with microphones, or reduction of spatial aliasing and phase mismatch in measurement signals.

Computational Fluid Dynamics (CFD) simulations for aerodynamic sound or in other words the computational aero-acoustic simulation (CAA) is the other potential choice for exterior wind noise engineering based on expectation of its ability to contribute visualization and detailed information that enhance the understanding of the effect of vehicle shape features on turbulent flow and acoustic field around vehicle. Rapid progress in CFD simulation development recently has made it possible not only to model the exterior air flow around the vehicle to predict drag coefficients but also to calculate the turbulent pressure spectra on vehicle surface to use as sources for vehicle noise and vibration model [11, 19, 20]. The most direct simulation approach for exterior wind noise using CFD compressible simulation [12, 13] contains direct calculations of the acoustic pressure component. However, under evaluation conditions in wind noise development such as high frequency range and low Mach number, the direct calculation of acoustic spectrum in turbulent flow around vehicle is almost impossible without huge computational costs because of large difference in time and length scales of the turbulent flow and acoustic field. Another method in simulation approach is splitting the calculation in which each turbulent flow and acoustic field is computed separately [4, 14, 15]. The turbulent flow can be calculated in incompressible manner using fine CFD meshes and its results can be used for computation of the acoustic field based on, for instance, the acoustic analogies in coarser acoustic meshes. Even though significant reduction of computational cost is done in comparison with compressible simulation, calculation time of the method is still a concern when trying to match with rapidly changing design in the exterior development process. Another concern for the method occurs in the accuracy of data mapping of turbulent flow results in CFD simulation to acoustical computation due to the difference of mesh size used in each calculation. There is also a common difficulty in both the compressible simulation and splitting simulation which is that direct validation by measurement has not been conducted due to reliable measurement method for the acoustic pressure around vehicle is not available as mentioned in above paragraph.

One more method in CFD simulation approach uses approximate analytically solutions obtained by Curle's integral [16], an extension of Lighthill analogy [17] for aero-acoustical noise sources generated by the turbulent flow over a solid body. The method can be applied to obtain an approximation of the contribution from rigid boundaries of the solid body to the total acoustic power. Some applications of the method in basic models such as in a single model of side mirror [18] were carried out, but no application for the prediction of exterior wind noise in full scale production vehicle has been reported.

In this paper an index for prediction of the strength of exterior wind noise, referred to as Exterior Noise Power (ENP) is developed based on an assumption that the acoustic power of exterior wind noise can be approximated by the far field acoustic power radiated from vehicle surface. Using the well-known Curle's equation, ENP can be represented as a surface integral of an acoustic intensity distribution, referred to as Exterior Noise Power Distribution (ENPD) which can be estimated from surface pressure fluctuation and mean convective velocity in the vicinity of the vehicle surface.

This paper is organized as follows: In the next section theoretical derivations of ENP and ENPD are described. A procedure for numerical calculations of ENP and ENPD in an unsteady CFD simulation is introduced. The numerical validation and correlation of ENP results obtained from CFD simulation is discussed by comparison with experimental data in the third section. The fourth section describes the effectiveness of ENP and ENPD in order to predict and find the location of the dominant sources of exterior wind noise as well as to make detailed countermeasure designs for reduction of exterior wind noise are shown. In the last section, the benefits and limitations of ENP and ENPD as well as future works are summarized.

THEORETICAL BACKGROUND

Derivation of ENP

In this section, a theoretical derivation of a new index for prediction of exterior wind noise based on an assumption that acoustic far field can represent acoustic field around vehicle which has a direct impact on the interior noise is introduced.

First, we start with a formulation of the acoustic pressure at an observation point x located far from vehicle, in other words at the far-field observation point is given as following based on Curle's equation.

$$p_a(x, t) = \frac{1}{4\pi} \sum_{i=1}^3 \int_S \frac{(x_i - y_i)}{cR^2} \left[\frac{\partial P(y, t - R/c)}{\partial t} \right] n_i dS(y) \quad (1)$$

where y is a measurement point on vehicle surface and R, c, t, S, n denote the distance between x and y , sound velocity, time, an area of the region on vehicle surface including acoustic sources and the unit normal vector on the local area at measurement point y , respectively. Also, the subscript i ($i = 1, 2, 3$) is used to define directions in Cartesian coordinate. An image of the physical parameters mentioned above is shown in Figure 1.

Since the propagation of acoustic waves in the far-field can be regarded as locally planar, the acoustic intensity at the far-field observation point can be written in the next equation.

$$I = \frac{p_a(x, t)^2}{\rho c} \quad (2)$$

The exterior noise power (ENP) around the vehicle is defined as the acoustic power radiated to the far-field and then can be calculated as an integration of the far-field acoustic intensity over a closed surface which encloses the vehicle at large distance from vehicle.

$$W(t) = \iint \frac{p_a(x, t)^2}{\rho c} dS(x)_{Closed_Surface} \quad (3)$$

To simplify the calculation of ENP, we consider the closed surface as a spherical surface whose origin is at the center gravity of the vehicle as shown in Figure 1. Substitution of equation (1) into equation (3) the equation of ENP is rewritten as

$$W(t) = \frac{1}{16\pi^2\rho c} \oint \left(\sum_{i=1}^3 \int_S \frac{(x_i - y_i)}{cR^2} \left[\frac{\partial P(y, t - \frac{R}{c})}{\partial t} \right] n_i dS(y) \right. \\ \left. \times \sum_{j=1}^3 \int_S \frac{(x_j - y'_j)}{cR'^2} \left[\frac{\partial P(y', t - \frac{R'}{c})}{\partial t} \right] n'_j dS(y') \right) dS(x)_{Closed_Surface} \quad (4)$$

, where y and y' are pressure measurement points on the surface of the vehicle and the subscripts i, j indicate direction of Cartesian coordinate. Due to independence between y and y' the product of the integral with respect to y and the integral with respect to y' in equation (4) can be replaced by a double integral as follows.

$$W(t) = \frac{1}{16\pi^2\rho c^3} \oint \sum_{i,j=1}^3 \int_S \int_S \frac{(x_i - y_i)}{R^2} \frac{(x_j - y'_j)}{R'^2} \left[\frac{\partial P(y, t - \frac{R}{c})}{\partial t} \right] \\ \times \left[\frac{\partial P(y', t - \frac{R'}{c})}{\partial t} \right] n_i n'_j dS(y') dS(y) dS(x)_{Closed_Surface} \quad (5)$$

From far-field positions the vehicle can be treated as a point, so the next approximation can be obtained $(x_i - y_i)(x_j - y'_j) \approx x_i x_j$ and ENP can be represented as

$$W(t) = \frac{1}{16\pi^2\rho c^3} \oint \sum_{i,j=1}^3 \int_S \int_S \frac{x_i x_j}{R^4} \left[\frac{\partial P(y, t - \frac{R}{c})}{\partial t} \right] \left[\frac{\partial P(y', t - \frac{R'}{c})}{\partial t} \right] \\ n_i n'_j dS(y') dS(y) dS(x)_{Closed_Surface} \quad (6)$$

Hereby, we define a local area on vehicle surface around measurement point referred to as $S(y)_{correlation}$ where surface pressure fluctuation at any measurement point y' belonging to the area correlates with the surface pressure fluctuation of the measurement point y . Based on the fact that correlation area in high frequency range is very small in comparison with characteristic area of vehicle ($S_{correlation} \ll 1$) the following approximations are established.

$$y' \approx y \quad (7)$$

$$n'_i \approx n_i \quad (8)$$

$$\frac{\partial P(y', t - \frac{R'}{c})}{\partial t} \approx \frac{\partial P(y, t - \frac{R}{c})}{\partial t} \quad (9)$$

, where the measurement point y' belongs to the correlation area at the measurement point y .

From the above relationships time averaging of equation (6) can be transformed in the following manner.

$$\overline{W(t)} = \frac{1}{16\pi^2\rho c^3} \oint \int_S \int_S \frac{(\sum_{i=1}^3 x_i n_i)^2}{R^4} \left[\frac{\partial P(y, t)}{\partial t} \right]^2 S(y)_{correlation} dS(y) dS(x)_{Closed_Surface} \quad (10)$$

, where the bar indicates averaging operation.

Based on the fact that the closed surface at the far-field is spherical, the following equation is obtained.

$$\oint \frac{(\sum_{i=1}^3 x_i n_i)^2}{R^4} dS(x)_{Closed_Surface} = \frac{(\vec{x} \cdot \vec{n})^2 \times 4\pi R^2}{R^4} = \frac{4\pi}{3} \quad (11)$$

Substituting equation (11) into equation (10), the time averaging of ENP can be rewritten as follows

$$\overline{W(t)} = \frac{1}{12\pi\rho c^3} \int_S \left[\frac{\partial P(y, t)}{\partial t} \right]^2 S(y)_{correlation} dS(y) \quad (12)$$

Because evaluation of wind noise is often discussed in frequency bands, the calculation equation of ENP in this manner is given by using subscript f which shows the frequency band with center frequency at f . Using the features of trigonometric function in a frequency band the next relation between power spectrum of time derivative of surface pressure fluctuation and power spectrum of surface pressure fluctuation is obtained

$$\left[\frac{\partial P(y, t)}{\partial t} \right]^2_f = 4\pi^2 f^2 \overline{P(y)_f^2} \quad (13)$$

Substituting the relationship (13) into equation (12), ENP is rewritten in term of power spectrum of surface pressure fluctuation as follows

$$\overline{W_f} = \int_S \frac{\pi f^2}{3\rho c^3} \overline{P(y)_f^2} S(y)_{correlation} dS(y) \quad (14)$$

The integrand part of the above equation is denoted as exterior noise power distribution (ENPD) within a frequency band and is given by

$$I_f(y) = \frac{\pi f^2 \overline{P(y)}_f^2 S(y)_{\text{correlation}}}{3\rho c^3} \quad (15)$$

As a result, ENP can be expressed by the integration of ENPD over vehicle surface as follows

$$\overline{W}_f = \int_S I_f(y) dS(y) \quad (16)$$

Calculation of equation (15) and (16) requires detailed information of the correlation area of surface pressure fluctuations at all measurement points on the vehicle surface. The correlation area can be computed directly by using the following coherence function of surface pressure fluctuation at each measurement point.

$$\text{coh}(y, y')_f = \frac{|\overline{p_f(y')p_f(y)}|^2}{|\overline{p_f(y')}|^2 \times |\overline{p_f(y)}|^2} \quad (17)$$

However, those calculations for all measurement points on vehicle surface require huge computational resources that make it somewhat impractical. To simplify the calculation of correlation area, the next analytical approximation is applied

$$S(y)_{\text{correlation}} \cong \frac{\pi L(y)^2_{\text{correlation}}}{4} \cong \frac{\pi k^2 \overline{U}(y)^2}{4f^2} \quad (18)$$

, where k is a constant coefficient, $L(y)_{\text{correlation}}$ is the characteristic length scale of correlation area and $\overline{U}(y)$ is the local convective mean velocity in neighborhood of surface measurement point y . The above approximation is based on the fact that signal of surface pressure fluctuations is shifted by $\overline{U}$, that is for instant pressure information at the point at time t will arrive in the point $(y + \Delta y)$ at time $(t + \Delta y/\overline{U}) = (t + k\Delta y/(f \times L(y)_{\text{correlation}}))$. Due to that the phase change in signals at y and $(y + \Delta y)$ is $2\pi k\Delta y/L(y)_{\text{correlation}}$ and the coherence function within an octave frequency band in equation (17) can be neglected approximately at $y' = \pm L(y)_{\text{correlation}}$. Substituting the above approximation into equation (15) and (16), the final expression of ENPD and ENP are obtained by the next equation (19) and (20) respectively

$$I_f(y) = \frac{\pi^2 k^2 \overline{P(y)}_f^2 f^2 \overline{U}(y)^2}{12\rho c^3 f^2} = \frac{\pi^2 k^2 \overline{P(y)}_f^2 \overline{U}(y)^2}{12\rho c^3} \quad (19)$$

$$\overline{W}_f = \int_S \frac{\pi^2 k^2 \overline{P(y)}_f^2 \overline{U}(y)^2}{12\rho c^3} dS(y) \quad (20)$$

It can be noted that for the mean velocity the order of magnitude of surface pressure is

$$\overline{P(y)}_f^2 \propto \overline{U}(y)^4 \quad (21)$$

, the well-known sixth power law of acoustic power for dipole sources generated by surface pressure fluctuation around vehicle can be reproduced in ENPD calculation as follows.

$$I_f(y) \propto \overline{U}(y)^6 \quad (22)$$

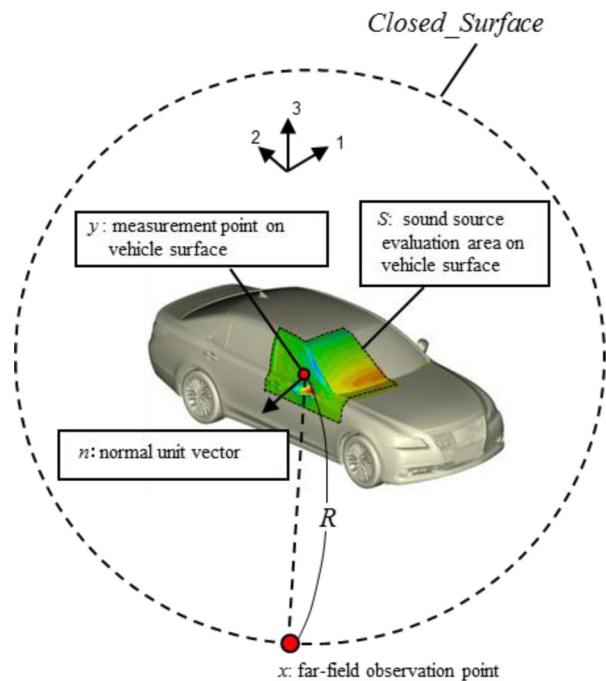


Figure1. Acoustic far field radiated from sound sources around vehicle

Computation Procedure of ENP

Computation of ENP and ENPD can be applied directly in an unsteady CFD simulation where the calculation of equations (19) and (20) are conducted by using a script that operate arithmetically simulation results of the surface pressure fluctuation spectrum and mean velocity in each surface mesh to derive ENPD and to integrate ENPD results over surface areas in each vehicle part for ENP calculation. The detail steps of computational procedure for calculation of ENP and ENPD are shown in Figure 2. As mentioned above, this computation procedure has no extra requirements for acoustical computation so it has advantages over other aero-acoustic simulation methods in term of evaluation of exterior wind noise with low computational costs.