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Contribution of Road Surface to Far-field Sound Noise Propagation from Moving Vehicle

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***Abstract*—This paper aims at predicting the sound noise generated by moving vehicle by using steady state Proudman volume integral broadband noise source (BNS) model considering road ground surface in mid-field. The steady and unsteady state CFD were performed to get the SST-turbulent RANS and LES simulations for Proudman BNS and unsteady pressure fluctuations respectively using commercial CFD code STAR-CCM+. The approximate sound pressure levels in volume term were obtained and that information is compared with the point sound pressure level in frequency spectral range in mid-field region. After evaluating the Proudman volume integral, the applicability and accuracy of it is discussed.**

***Index Terms*—computational aero-acoustic, vehicle, Broadband noise source model, Proudman volume integral, CAA.**

I. INTRODUCTION

The aerodynamic is one of important interest in design of vehicle. To reduce the drag and noise of it, significant researches are studied in car manufacturers. On the other hand, the aerodynamic around the vehicle can be an aero-acoustic sound noise source itself which is annoying and fatiguing to the driver. Many studies are now focuses on the efficient methods to reduce the acoustic quantities on the vehicle by numerical and experimental approach. The acoustic noise source on vehicle has complex characteristics. The wind tunnel facilities are accepted as a promising way to capture the acoustic noise signature. However in many cases, there are demands to get the information before manufacturing the vehicle or parts. Thus, they often try to use and develop the numerical method with wind tunnel acoustic experiment. Those can propose powerful tool for research and design process. In order to analysis the acoustic characteristics induced by aerodynamic, higher computing cost are necessary in advanced modeling and solving the acoustic generation and propagation phenomena occurring in realistic situations.

The noise generation sources that emitted from vehicle are tyre-road interaction [1-4], power-train and aerodynamics [5-10]. Regarding the predicting the noise propagation of traffic vehicle noise, it is rather difficult to distinguish the main contribution at distance by combination of large number of acoustic sources. Due to the significant progress has been achieved with respect to the sound radiation of the power train of vehicles, it can be said that the tire and aero-acoustic sources are more important than the engine and power-train mechanical source with the increasing vehicle speed. And the emitted noise propagates to the mid-to far-field within environment near the road. The highway noise is harmful pollution for residents. During propagation of emitted noise, it can be interfered by many effects of interactions including the solid structure, fluids, turbulence and viscosity and so on [11] in mid to far-field region also.

Among the acoustic noise sources, the computation fluid dynamics (CFD) and coupled computational aero-acoustic (CAA) can be used to analysis the acoustic generation and propagation in near to far-field regions. According to the view points, the acoustic problem can be further classified to near, mid and far-field problems. When the noise source and generations are main interest, it can be focused on the near-field region. The propagation of noise is the main interest in far-field problem without considering the effects of interactions. In mid-field problems, the generation and propagation of noise source are considered. Since the more numerical process and efforts are paid for the problems. Direct numerical simulation (DNS) and hybrid integration method (IM), such as those relying on, Lighthill [12] or Ffowcs-Williams & Hawkings (Fw-H) [13-15] can be used for near and far-field domain respectively. The Large Eddy Simulation (LES), unsteady Reynolds Averaged Navier-Stokes equations (URANS), or Detached Eddy Simulation (DES) can be used for near-field problems also.

It is well known that an A-pillar's separated flow produces strong vortex sources on the side window, and progresses a large scale vortex shedding in wake. An unsteady separated shear flow which was result in the periodic convection of vortices over the cavities can cause the buffeting noise due to the opened sunroof or side window. And the time varying vortex shedding on the vehicle body also can produce a low frequency sound noise. There are complex vertical structures impinging in local and global pressure fluctuations between vehicle body and road ground surface interaction, and feeds the acoustic fluctuation in low to high frequency ranges. And the trailing edge noise can be occurred due to the interaction of the boundary layers instabilities with the surface edges. This is attributed to time-varying flow separations and the breaking of large vertical structures into fine turbulent structures. Thus the flow-induced aero-acoustic noise has broadband spectral content ranging from tens of Hertz at low frequencies to a few hundreds or thousands of Hertz at mid-to-high frequencies in near to far-field domain. Thus, to account the various

The aero-acoustic noise source, the surface and volumetric terms, which were defined as dipole and quadruple, are noticed. The volumetric term is usually omitted in far-field hybrid integral method in low Mach number problem. And the road ground surface interaction also omitted in far-field propagation prediction because of the grid model complexity either. Actually, the vortex shedding interaction to the road ground surface is not negligible but important in mid-to

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far-field sound noise propagation. To account the road ground surface contribution in aero-acoustic, the mid-field fluid domain should be considered. However it is also not easy to simulate, but more numbers of grid are necessary.

The purpose of this paper is to investigate the effects and influences of mid-field region for far-field noise propagation. The contribution of an interaction between the vortex shedding and road surface to far-field noise propagations are main interests. The unsteady acoustic fluctuations were captured by using LES with Smagorinsky-Subgrid Scale (S-SGS) sub grid scales model. The sound noise propagation of far-field was obtained from the Fw-H method [13-15]. The commercial CFD code Star-CCM+ was used for CFD and CAA simulation in this study.

II. NUMERICAL METHOD

The acoustic wave, which was emitted from noise source, propagates to mid to far-field region. The dipole and quadruplole noise source terms generates the noise on surface and volume in space. Compared with surface dipole result in surface pressure loading, the volumetric term of quadruple is negligible to be considered for sound energy. The separated flow is initiated from the vehicle body on the trailing edges including A-pillar and rear trunk edge, and is the main source of periodic rotating vortex shedding. There can be an interaction of vortex between road surface in mid to far-field region. Usually the fluid domain should be continuous and fine grid for accurate CFD solution. The grid resolution affects significant effects on the CFD and CAA results. The low quality grid can not analysis the acoustic wave energy in high frequency region. However it is almost impossible to extend the grid model to far-field region continuously. Thus the fine grid model is available to be prepared for near-field region only. The direct numerical techniques can be used in near-field aero-acoustic problem with fine grid model. But it is not available for far-field problem. Thus efficient integral methods (IM) are usually adopted to predict the mid to far-field aero-acoustic which were emitted from near field noise sources. IM are based on Lighthill[29] or Ffowcs-Williams & Hawkings (Fw-H) [13-15] integration techniques.

Among them, the Fw-H acoustics integral formulation is the preferred strategy for mid-to far-field noise prediction. This model is combined with CFD simulation for acoustic pressure fluctuations in surface and volume, and the monopole, dipole and quadruple sound source terms are available in considering. The LES, DES or URANS are used to solve the unsteady flow. Because of the combination with CFD, Fw-H integration techniques are called as hybrid method. This model is able to calculate the mid- to far-field sound signal that is radiated from near-field flow data from a CFD solution using near field information with higher quality grid model for it. The FW-H equation is an exact rearrangement of the continuity and the momentum equations into the form of an inhomogeneous wave equation. And it gives accurate results even if the surface of integration lies in the nonlinear flow region. It is based on the free-space Green's function to compute the sound pressure at far-field region, where the aerodynamic flow is steady and virtually homogeneous. The goal is to predict small amplitude acoustic pressure fluctuations at the locations of each receiver. The IM methods can be one of CAA method which was adopted with CFD.

According to the focus in the region and interest, the analysis method can be selected. For near-field region, the direct method is used for high frequency air flow. In this region, the dipole surface term is more important which has significant effects for SPL. The surface pressure loading has strong intensity of SPL and the acoustic wave generated mainly. The propagation of the emitted noise term is not concern fundamentally. Accordingly the limited size of near-field domain, there is little acoustic fluctuation information in volume space. Thus the quadrupole can not be accurately simulated. The effects of interfering of mid-fields can not be considered such as reflection, diffraction, convection, refraction, diffusion, absorption and so on. When adopting the IM Fw-H integration technique for far-field noise propagation, the mid-field, which is located between near-field and far-field, is neglected as steady and virtually homogeneous. However, in cases the mid-field region must be included in CFD and CAA, if the noise source is generated in mid-field region. Usually, solely near-field region is known as the noise source term. And the higher quality grid is used for near-field in CFD analysis. As explained, there is limitation in computing cost which limited to near field only for higher acoustic frequency range. But if the mid-field generates and emits the acoustic noise, it has to be considered in CFD analysis. But there are little researches has interested in mid field region. Actually, the mid-field region can be negligible. The contribution of it is little than dipole surface term. However it will have important information for aero-acoustic noise field to study the effects of mid-field especially the effects of interaction of vortex shedding to road ground surface. The initiated Vortices

The time varying vortex shedding on the vehicle body can produce a low frequency sound noise, and then the vortical structures impinging to road ground surface are occurred. The interaction between the vortex and road surface is secondary effects of flow. The low intensity and frequency in tonal range vortex flow feeds the acoustic fluctuation on the road ground surface will be the new noise source to be combined with already emitted sound wave. Those various emitted noise sources into the environment are difficult to be considered in general far-field propagation simulation with near-field information. The flow-induced aero-acoustic noise has broadband spectral content ranging from tens of Hertz at low frequencies to a few hundreds or thousands of Hertz at mid-to-high frequencies in near to far-field domain.

In this study, the hybrid Fw-H integral technique is used to predict the far-field noise propagation in both of dipole and quadrupole for surface and volume terms respectively. The contributions of mid-field were considered for dipole and quadrupole simultaneously. The unsteady acoustic pressure fluctuations were obtained from LES with with Smagorinsky-Subgrid Scale (S-SGS) subgrid scales model. The commercial Star-CCM+ code was used for CFD and CAA simulation for the studies.

The equations of Fw-H formulation are briefly reviewed as follows which is based on Farassat's Formulation [14,15], that is the non-convective form of Fw-H. The FW-H equation for pressure that is radiated into a medium at rest by a flow in a region or a set of surfaces is:

$$p'(\vec{x},t) = p'_T(\vec{x},t) + p'_L(\vec{x},t) + p'_Q(\vec{x},t) \quad (1)$$

Where,

$p'_T(\vec{x},t)$: the monopole term

$$p'_T(\vec{x},t) = \frac{1}{4\pi}\left(\left(-\frac{\partial}{\partial t}\right)\int_S\left[\frac{Q}{\left(r\left(1-M_r\right)\right)}\right]dS\right) \quad (2)$$

$p'_L(\vec{x},t)$: the dipole term

$$p'_L(\vec{x},t) = \frac{1}{4\pi}\left(\left(-\frac{\partial}{\partial x_i}\right)\int_S\left[\frac{L_i}{\left(r\left(1-M_r\right)\right)}\right]_{ret} dS\right) \quad (3)$$

$p'_Q(\vec{x},t)$: the quadrupole term

$$p'_Q(\vec{x},t) = \frac{1}{4\pi}\left(\left(-\frac{\partial^2}{(\partial x_i)(\partial x_j)}\right)\int_V\left[\frac{T_{ji}}{\left(r\left(1-M_r\right)\right)}\right]_{ret} dV\right) \quad (4)$$

With :

$$Q = \rho_0 U_i n_I \quad (5)$$

$$U_i = \left(1-\frac{\rho}{\rho_0}\right)v_i + \frac{\rho u_i}{\rho_0} \quad (6)$$

$$L_i = P_{ij} n_j + \rho u_i (u_n - v_n) \quad (7)$$

$$P_{ij} = (p - p_0)\delta_{ij} - \sigma_{ij} \quad (8)$$

$$T_{ij} = \rho u_i u_j + \delta_{ij}\left[(p-p_0) - c_0^2(\rho-\rho_0)\right] - \sigma_{ij} \quad (9)$$

Where,

u_i represents fluid velocity components in the x_i direction.

u_n is the fluid velocity component normal to the surface.

v_i represents surface velocity components in the x_i direction.

v_n is the surface velocity component normal to the surface.

n_i is the surface normal vector.

σ_{ij} is the viscous stress tensor.

ρ_0 is the far field density.

P_{ij} is the compressive stress tensor.

T_{ij} is the Lighthill stress tensor.

The space derivatives from Eqn. (2) and Eqn. (3) are transformed into time derivatives and afterwards, the time derivatives at the observer locations are moved into the integrals.

From equation (1), the surface Fw-H surface terms are derived as

$$p'_S(\vec{x},t) = p'_T(\vec{x},t) + p'_L(\vec{x},t) \quad (10)$$

When the integration surface coincides with the body, these terms are called:

$$p'_T(\vec{x},t) = \frac{1}{4\pi}\left(\int_{f=0}\left[\frac{\rho_0\left(\dot{U}_n + U_{\dot{n}}\right)}{r\left(1-M_r\right)^2}\right]_{ret} dS + \int_{f=0}\left[\frac{\rho_0 U_n\left\{r\dot{M}_r + a_0\left(M_r - M^2\right)\right\}}{r^2\left(1-M_r\right)^3}\right]_{ret} dS\right) \quad (11)$$

$$p'_L(\vec{x},t) = \frac{1}{4\pi}\left(\frac{1}{a_0}\int_{f=0}\left[\frac{\dot{L}_r}{r\left(1-M_r\right)^2}\right]_{ret} dS + \int_{f=0}\left[\frac{L_r - L_M}{r^2\left(1-M_r\right)^2}\right]dS + \frac{1}{a_0}\int_{f=0}\left[\frac{L_r\left[r\dot{M}_r + a_0\left(M_r - M^2\right)\right]}{r^2\left(1-M_r\right)^3}\right]dS\right) \quad (12)$$

Eqn. (11) describes the monopole source term using the advanced-time formulation.

Eqn. (12) describes the dipole source term using the advanced-time formulation.

$p'_T(\vec{x},t)$: known as the Thickness Surface Term, resulting from the displacement of fluid as the body passes. The term is defined in Eq. (11) for general flows and in Eq. (16) for flows with rigid body motion or moving reference frames.

$p'_L(\vec{x},t)$: known as the Loading Surface Term, resulting from the unsteady motion of the force distribution on the body surface. The term is defined in Eq. (12) for general flows and in Eq. (17) for flows with rigid body motion or moving reference frames.

$p'_S(\vec{x},t)$: known as the Total Surface Term, resulting from the sum of the Thickness Surface Term and the Loading Surface Term. The term is defined in Eq. (10).

And

$$M_i = U_i / a_0 \quad (13)$$

$$r = x_{observer} - y_{face} \quad (14)$$

Where

$f \neq 0$ denotes a mathematical surface to embed the exterior flow problem $f > 0$ in an unbounded space.

$f = 0$ represents the emission surface and is made coincident with a body, impermeable surface, or permeable surface. If the data surface coincides with a solid surface, then the normal velocity of the fluid is the same as the normal velocity of the surface:

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$$u_n = v_n \tag{15}$$

In this case, Eqn. (11) and Eqn. (12) correspond to the Impermeable FW-H Surface type and some of the terms are eliminated.

The quadruple noise is a volume distribution of sources, which accounts for nonlinearities in the flow. These nonlinearities are of two types, as Lighthill described. First, the local speed of sound is not constant, but varies due to particle acceleration. Second, the finite particle velocity near the body (for example blade) influences the velocity of sound propagation. When strong shear layers exist in the flow or when the Mach number increases, the quadruple term is not negligible. Farassat and Brentner [14,15] have shown that the noise contribution from the quadrupole, $p'_Q(\vec{x},t)$, may be expressed as a "collapsing-sphere" formulation. Using this formulation, the space derivatives from Eqn. (4) are transformed into time derivatives:

$$p'_Q(\vec{x},t) = \frac{1}{4\pi}\left(\begin{array}{l}\left(\frac{1}{c}\right)\left(\frac{\partial^2}{\partial t^2}\right)\int_{-\infty}^{t}\left[\int_{(f>0)}\frac{T_{rr}}{r}d\Omega\right]d\tau + \left(\frac{\partial}{\partial t}\right)\int_{-\infty}^{t}\left[\int_{(f>0)}\frac{3T_{rr}-T_{ii}}{r^2}d\Omega\right]d\tau \\ +c\int_{-\infty}^{t}\left[\int_{(f>0)}\frac{3T_{rr}-T_{ii}}{r^3}d\Omega\right]d\tau\end{array}\right) \tag{19}$$

T_{rr} is the double contraction of T_{ij}.

r_i are the components of the unit vector in the direction of radiation.

T_{ij} is the Lighthill stress tensor.

Eqn. (19) can be transformed from a collapsing-sphere formulation to an advanced time formulation. In these equations, the time derivatives at the observer are moved into the integrals to prevent numerical time differentiation of the integrals. The "source-time-dominant" algorithm from [128] is used to allow the estimation of the volume term of the FW-H equation as follows:

$$p'_Q(\vec{x},t) = \frac{1}{4\pi}\left(\int_{(f>0)}\left[\frac{K_1}{c^2 r}+\frac{K_2}{cr^2}+\frac{K_{31}}{r^3}\right]_{ret} dV\right) \tag{20}$$

Where,

$$K_1 = K_{11}+K_{12}+K_{13}$$
$$=\left[\frac{\ddot{T}_{rr}}{(1-M_r)^3}\right]+\left[\frac{\ddot{M}_r T_{rr}+3\dot{M}_r\dot{T}_{rr}}{(1-M_r)^4}\right]+\left[\frac{3\dot{M}_r^2 T_{rr}}{(1-M_r)^5}\right] \tag{21}$$

$$K_2 = K_{21}+K_{22}+K_{23}+K_{24}$$
$$=\left[\frac{-\ddot{T}_{ii}}{(1-M_r)^2}\right]+\left[\frac{4\dot{T}_{Mr}+2T_{Mr}+\dot{M}_r T_{ii}}{(1-M_r)^3}\right]+\left[\frac{3\left[\left(1-M^2\right)\dot{T}_{rr}-2M_r T_{Mr}-M_i\dot{M}_i T_{rr}\right]}{(1-M_r)^5}\right]$$
$$+\left[\frac{6\dot{M}_r\left(1-M^2\right)T_{rr}}{(1-M_r)^5}\right] \tag{22}$$

$$K_3 = K_{31}+K_{32}+K_{33}$$
$$=\left[\frac{2T_{MM}-\left(1-M^2\right)T_{ii}}{(1-M_r)^3}\right]+\left[\frac{6\left(1-M^2\right)T_{Mr}}{(1-M_r)^4}\right]+\left[\frac{3\left(1-M^2\right)^2 T_{rr}}{(1-M_r)^5}\right] \tag{23}$$

Where

$T_{rr} = T_{ij}r_i r_j$, $T_{MM} = T_{ij}M_i M_j$, $T_{Mr} = T_{ij}M_i r_j$, $T_{\dot{M}r} = T_{ij}\dot{M}_i r_j$,

$\dot{T}_{Mr} = \dot{T}_{ij}M_i r_j$, $\dot{T}_{rr} = \dot{T}_{ij}r_i r_j$, $\ddot{T}_{rr} = \ddot{T}_{ij}r_i r_j$, $M_i = \frac{v_i}{c}$, $M_r = M_i r_i$,

$\dot{M}_r = \dot{M}_i r_i$, $\ddot{M}_r = \ddot{M}_i r_i$, $\ddot{M}_{rr} = \ddot{M}_i r_i r_j$, $r_i = \frac{x_i - y_i}{r}$

Where:

r_i denotes the unit vector in the direction of radiation.

A dot above a variable denotes the time derivative with respect to source time of that variable.

III. GEOMETRY AND METHODOLOGY

The aerodynamic over the vehicle causes the aero-acoustic noise generation. There are many studies about the near-field region for vehicle aero-acoustic problems [5-10]. Due to the limitation of computing capacity, the mid-field regions were not considered in their studies. As mentioned in references, Murad et al. [5,6] and Shojaefard et al. [7] used identical simplified geometry of car to study the near-field CAA simulation. The geometry of car was used to study the acoustic characteristics of near-field region of body surface. The detail parts of car were omitted and simplified. The steady state RANS CFD results, which contain the turbulent kinetic energy production in near wall as the noise source, were transferred to CAA solver in mapping process for unsteady aero-acoustics propagation through solving for the acoustic pressure. Using the acoustic source terms, the CAA solver determine the aero-acoustics propagation using the LEE approach, together with a time domain calculation conducted using a Quadrature Free Discontinuous Galerkin Spatial discretization approach [1,2]. Shojaefard et al. [3] adopted the approximate Curle Broadband Noise Source (BNS) model was used to solve the dipole surface SPL quantities with RANS CFD results using different grid model. To get the unsteady sound noise acoustic information in near-field and far-field, DNS or hybrid IM based on acoustical analogy can be used and well demonstrated. Nonetheless, as a first step, an accurate CFD simulation must be performed. The near-field problems were regarded as important interests in vehicle acoustic fields. Wang et al. [8], Dechipre and Hartmann [9] and Hamamoto et al. [10] were interested in unsteady vehicle acoustic problems of near-filed vehicle parts such as side mirror or A-pillar region details. To get the unsteady surface pressure distributions due to the presence of a turbulent boundary layer in the vicinity of the solid body, various direct numerical methods were used for their researches.

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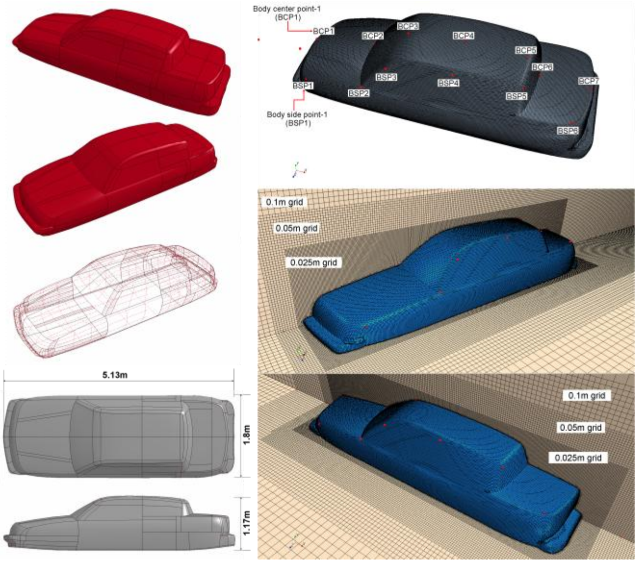

Fig.1 Geometry and grid definition of vehicle body

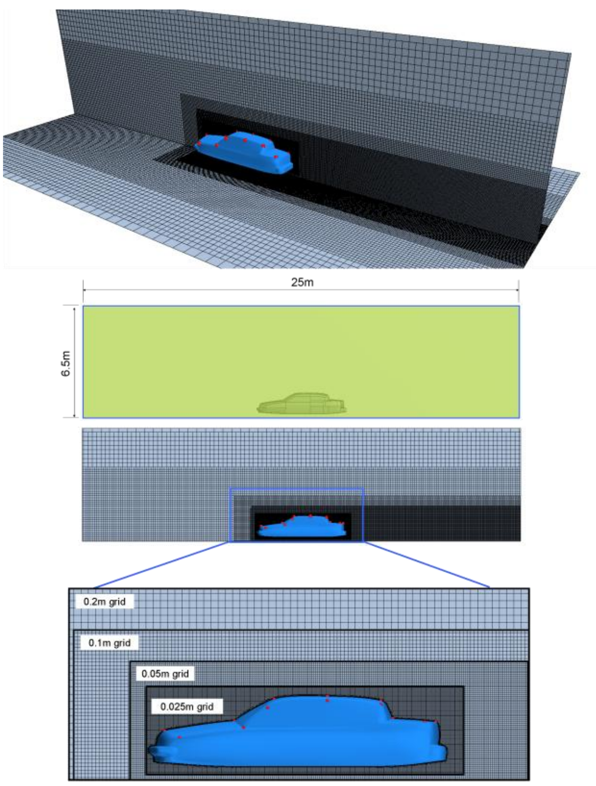

Fig.2 Grid definition of fluid domain

Wang et al. [8] and Hamamoto et al. [10] were interested in near-field acoustic problem of simplified side mirror geometries, and LES and DNS numerical methods were developed for their studies respectively. Dechipre and Hartmann [9] used the commercial CFD code of ANSYS to get the unsteady acoustic pressure fluctuation of near-field of A-pillar gutter by using an improved URANS method which can provide a LES-like behaviour in detached flow regions called as scale adaptive simulation (SAS) with the shear stress transport (SST) turbulent model was used for URANS equation.

A near-field problem can used more number of grids to improve the fluid domain quality far higher frequency range. The energy of acoustic energy is distributed over the broadband frequency range. Thus the fluid domain grid should account the sound wave length of required frequency range in unsteady transient analysis. In contrast long period flow phenomena of quadrupole in near to far-field flow such as buffeting, vortex shedding, near-field dipole sound noise contains higher frequency acoustic source in short time period. In such cases for surface dipole noise source term related acoustic problems, the higher quality grid resolution must be used for unsteady CAA analysis. The noise source is emitted from the vehicle body to the air flow. The sound energy is contained into the turbulent flow and highly influenced by the complex flow behaviors. From the limitation of computation resource of CFD, the unsteady direct simulations were usually limited to near-field problems which need higher grid quality. The characteristics of continuation of fluid make the analysis to be difficult for mid-to far-field problems. Nevertheless of higher quality of grid for acoustic problem, the quality of grid can not meet the near-field problem in mid-field acoustic problem fundamentally. Thus the interaction of flow in mid-field region can be in-accurate or evaluated underestimated SPL in tonal frequency range. The quality and number of grid usually could not meet the requirement sufficiently. In this study, the limited numbers of grids were considered. More numbers of grid for higher quality resolution will be adopted in the following studies.

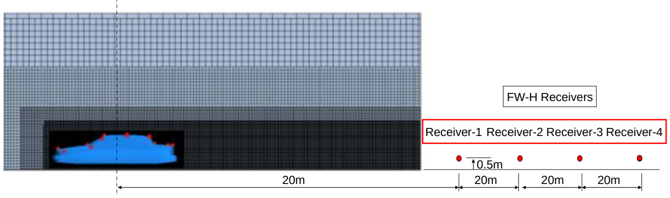

Fig.3 Point probes definition

Fig.1 and Fig.2 illustrates the geometry, point proves and grid model for this study. There are 7 and 6 numbers of probe points at the center and side of vehicle body surface in Fig.1. The domain size was extended to mid-to far area to account the effects of vortex shedding interaction between road ground surface. The length, height and width of vehicle are 5.13m, 1.8m and 1.17m respectively. The aero-acoustic characteristics were studied for car type vehicle. The fluid domain size was defined as 25m, 6.5m and 14m for length, height and width respectively. The grid unit length of surface of vehicle is defined as 25mm for trimmed grid model. The resulting total number of grids and nodes are 7,783,157 and 7,973,488 respectively. The effects of grid resolution for CFD solution are critical in mid-to far-field area. The preliminary parametric studies for grid resolutions were studies to determine the grid model. Fig.3 illustrates the locations point receivers in far-field. To see the effects of mid-field in dipole surface noise term which propagated into far-filed, 2-types of impermeable surfaces were defined. The impermeable surface-1 is only limited to vehicle body surface in near-field.

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And the impermeable surface-2 includes both of the vehicle body and road ground surface. The "no-slip" wall shear stress specifications were defined for both of surfaces.

IV. NOISE SOURCE OF HIGH SPEED VEHICLE

Fig.4 and Fig.5 show the surface Vorticity and streamline. The surface Vorticity in Fig.4 demonstrates the importance of road ground surface in dipole noise source which usually omitted in evaluating the aero-acoustic. The contour color of surface streamline in Fig.5 explains the wall shear stress. Since, blue and red colored streamline means lower and higher wall shear stress, or lower and higher near-wall flow velocity respectively. Higher speed flows are occurred at the edge of A-pillar region specially as shown in Fig.5. Since the separated flow with high speed transmits to rear edge side vehicle. There are high speed flows on the roof edge also.

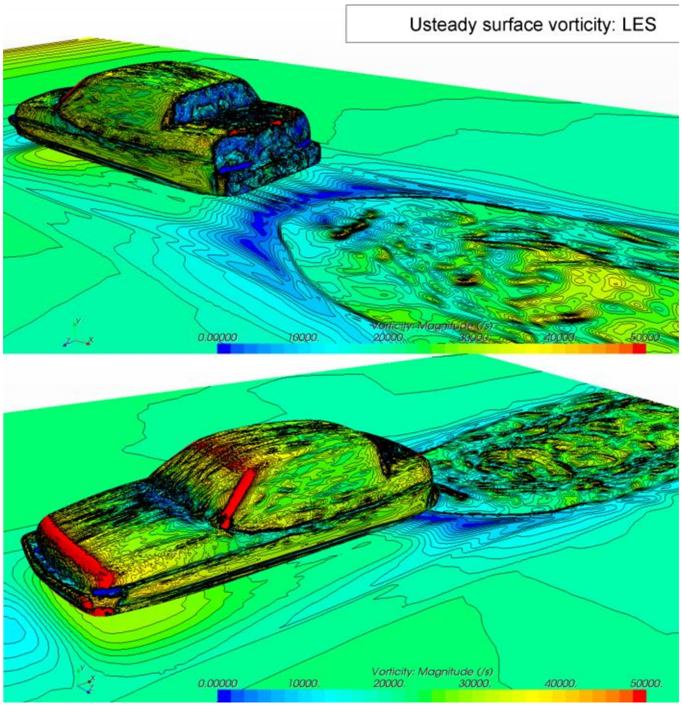


Fig.4 Surface Vorticity

Fig.6 shows the pressure results of vehicle and road ground surface. The instant, mean and unsteady pressure fluctuations were illustrated respectively in Fig.6 (a), (b) and (c). The time dependent acoustic and turbulent fluctuations are generated in differently. The acoustic fluctuation propagations to environment of far-field are produced as large scale spherical shape from the front, roof and side surface of vehicle body and road ground surface mainly. The many numbers of small unsteady turbulent pressure fluctuations are occurred at the rear of vehicle as small irregular small scale, where the large separated flows were developed into the beyond the turbulent boundary layer of near the wall. It is well known that the dipole acoustic source term has more important contribution to the SPL than quadrupole term. The volumetric quadrupole noise source term is contained in volumetric Vorticies or vortex shedding in wake with smaller acoustic wave energy. The volumetric sound wave is slower than dipole term in tonal sound without high frequency broadband.

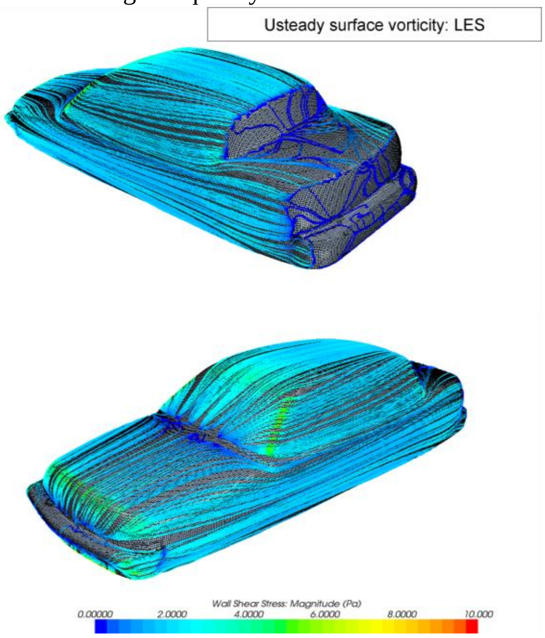
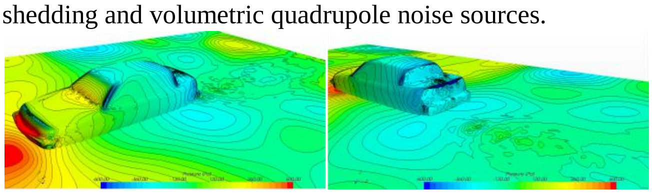


Fig.5 Surface streamline

Fig.7 shows the quadruple volumetric Fw-H noise term and corresponding vortex shedding shape which visualized as volumetric Vorticity and Q-criterion. As shown in Fig.7, the volumetric quadruple term was obtained in the Fw-H receiver-1 which was explained in Fig.3. The shape of it is good match with the turbulent flow in wake as vortex shedding shape of Vorticity and Q-criterion. Q-criterion is the second invariant of the velocity gradient tensor, often used for the detection of vortices. Vorticity is defined as the curl of the velocity, and it is equal to twice the rotation of the fluid at (x, t). Thus, the Vorticity can be used directly to identify vortices which are often thought of as regions of high Vorticity. But there is no universal threshold over which Vorticity is to be considered high. And a problem associated with this method is that Vorticity cannot distinguish between swirling motions and shearing motions. Nevertheless of their similarity and difference, both of them can represent the velocity field of flow. From Fig.7 the iso-surface of Vorticity and Q-criterion in unsteady state are similar in rear vehicle or wake which related far-field. There are not specific quantities of turbulent flow in velocity field. But it can be assumed that higher gradient or curl of velocity may contain the higher turbulent flow on them. Thus the Vorticity is mainly preferred as the representative characteristics which represent the vortex shedding and volumetric quadrupole noise sources.



(a) Instant pressure

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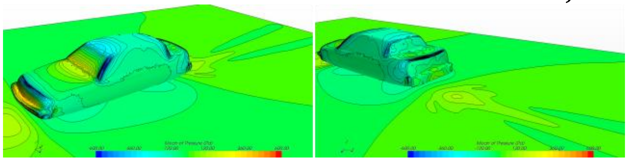
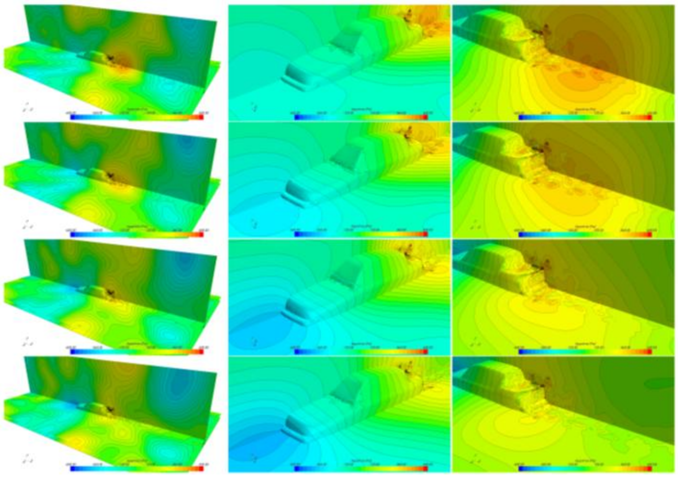


(b) Mean pressure



(c) Unsteady pressure fluctuation

Fig.6 Surface streamline

V. FW-H NOISE TERMS

The unsteady acoustic pressure fluctuation is directly calculated to evaluate the SPL (dB) on frequency range from Fourier transform in direct numerical method. The integral method does not calculate the acoustic pressure fluctuation on the space, but use the acoustic analogy of Lighthill [12]. There are steady and unsteady various methods for dipole and quadrupole noise source term. Fw-H integral technique [13-15], which is preferred for mid-to far-field aero-acoustic, is called as hybrid method because of combination with unsteady CFD simulation. It does not consider the effects of media between the noise generation and receivers which located from far distance. The far-field fluid is assumed as homogeneous and steady. Thus it can be approximate and inaccurate in cases in which those assumption can not keep. The mid-field field characteristics are the media between noise source and far-field. The effects of mid-field can affect the sound noise propagation to far-field.

Fig.8 and Fig.9 show the dipole and quadrupole noise source term at Fw-H receivers respectively. Fw-H integral method records the surface or volumetric noise fluctuation which can affect to far-field receivers.

As shown in Fig.8, the surface dipole term is highly affected by the body surface which is mainly perpendicular to the receiver locations. Thus the front and rear vehicle body surfaces are higher noise generation sources term, and their surface patterns are highly affected by the pressure distribution of Fig.6. The unsteady surface pressure is fluctuating in time domain. The information of surface pressure fluctuation is used in evaluating the acoustic power in receivers for Fw-H integration. Thus surface pressure fluctuation or similar quantities should contain the surface noise term for Fw-H integration.

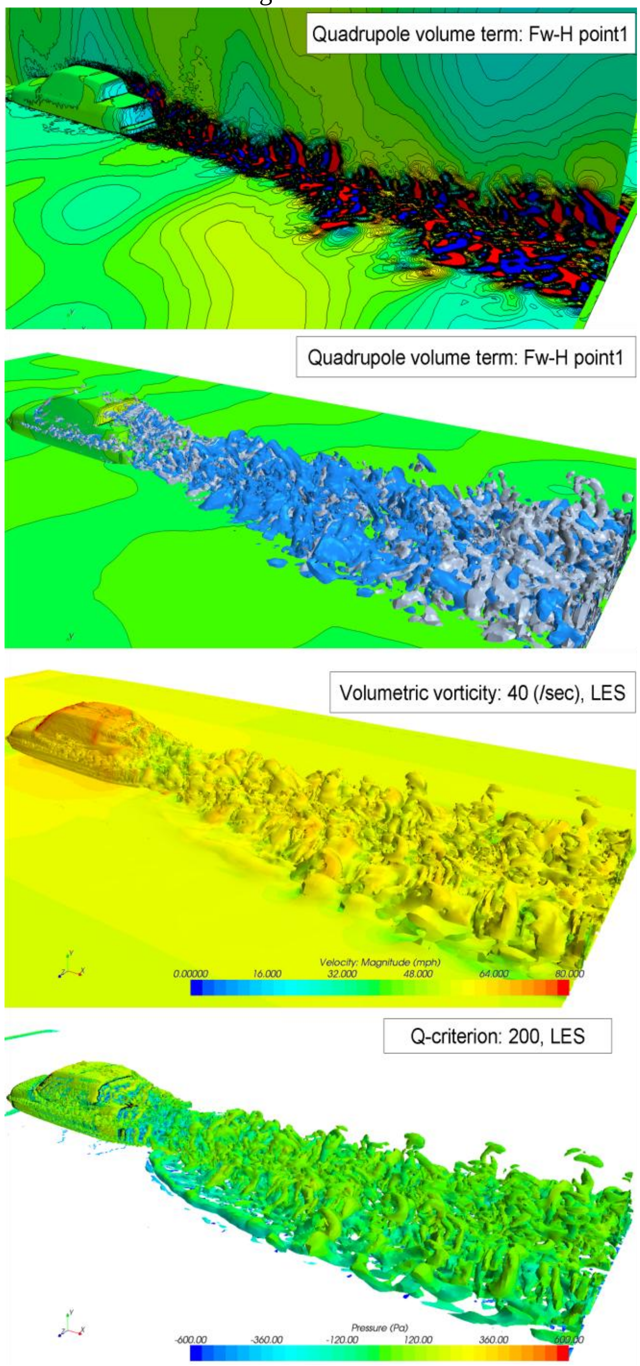


Fig.7 Quadrupole volumetric Fw-H term and vortex shedding

The surface dipole noise source contains the higher frequency noise energy and shows short time period of fluctuating. Thus surface dipole noise source term in Fig.8 is only for a specific instant time which is match with instant pressure of Fig.6 (a). There are wide areas of road ground surface which affect to the surface noise term. It is clear that the road ground surface has important effects to the dipole noise generation. However it is spread on the horizontal direction. Thus it's affect to the receiver which located to the far-field can be decreased.

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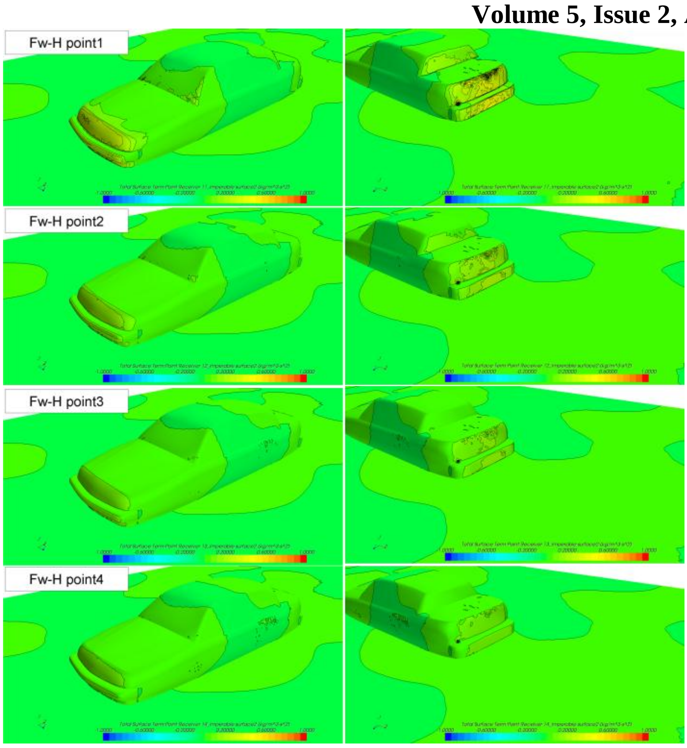
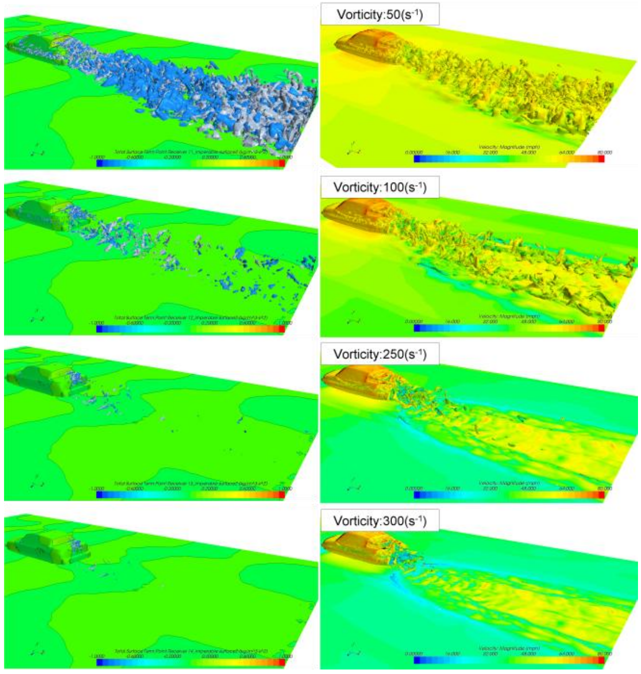


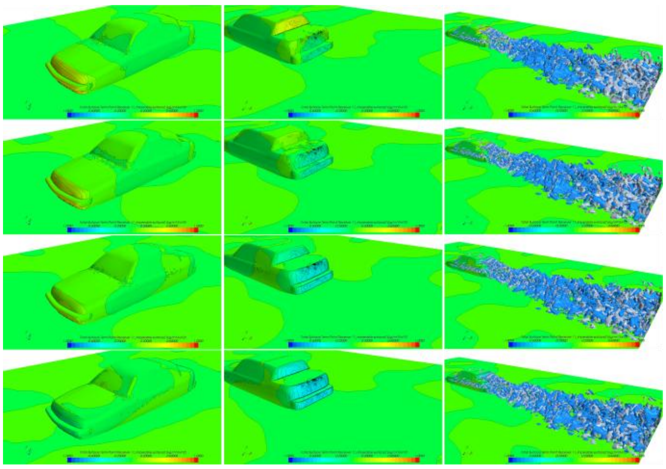
Fig.8 Fw-H acoustic terms for surface total term

Fig.9 shows the volumetric quadrupole noise source term in comparison with volumetric Vorticity. In Fig.9 (a), the surface contour demonstrates the surface dipole acoustic power which explained in Fig.8, and shows the influences of vortex shedding to the volumetric quadrupole noise source in nature. Usually the quadrupole noise source term is omitted in evaluating far-field noise source term because of it's little contribution to the intensity of acoustic SPL. Thus the mid-field characteristics of turbulent flow are not the concern and interest which could be omitted. But when the mid-field region is not considered, the global flow generation can not be considered related to the acoustic noise source generation. During the propagation of noise in mid-field, the secondary noise can be occurred by the interaction of there turbulent flow of voetex shedding. From Fig.9, it can be seen that the volumetric vortex shedding contains the volumetric quadrupole noise source, and the characteristics of long time period of vortex shedding and volumetric noise source. According to the distance and location of receivers, the intense and volumetric noise source is clearly defined in Fig.9. Fig.10 illustrates the surface and volumetric acoustic fluctuation respectively.

Fig.11 and Fig.12 explain the surface dipole and volumetric quadrupole SPL (dB) at far-field receiver for impermeable surface1 and impermeable surface2 respectively. As shown in Fig.11, the surface term has broadband frequency range beyond 1K Hz. The impermeable surface1 was defined for the vehicle body surface only. And the impermeable surface2 includes both of vehicle body and road ground surface. Thus SPL of impermeable surface2 is higher than impermeable surface1 as shown in Fig.11. The SPL of Fig.11(b) must include the influences and contributions of road ground surface. As a result, the SPL graph of receiver1 for impermeable surface2 (Fig.11(b)) is higher than impermeable surface1 (Fig.11(a)). And those are shown in broadband frequency region beyond 1K Hz.



(a) Fw-H Quadrupole volume term (b) Vorticity
Fig.9 Fw-H acoustic terms for volume term



(a) Fw-H surface term (b) Fw-H volume term
Fig.10 Acoustic fluctuations in surface total and quadrupole volume terms for Fw-H point1

The surface dipole noise source term contains the high frequency range of acoustic energy. Thus the effects of impermeable surface are shown only in higher frequency region. But the effects of road ground surface are not significant for the other receivers. Since, it can be said that the mid-field's surface dipole has limited effects to the far-field receivers, even though wide area of road ground surface which has acoustic pressure fluctuations.

Fig.12 shows the volumetric quadrupole SPL graph for impermeable surface1 and impermeable surface2 respectively. The volumetric quadrupole is the volumetric term which

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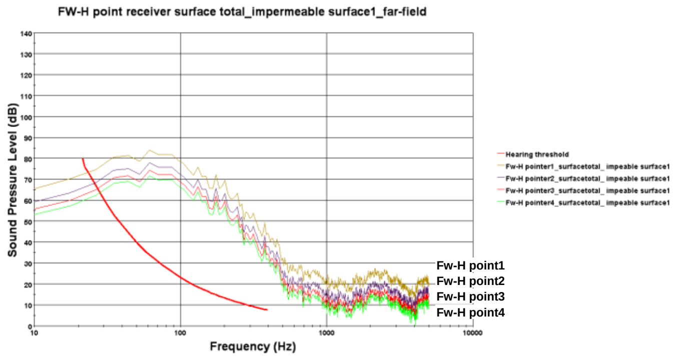
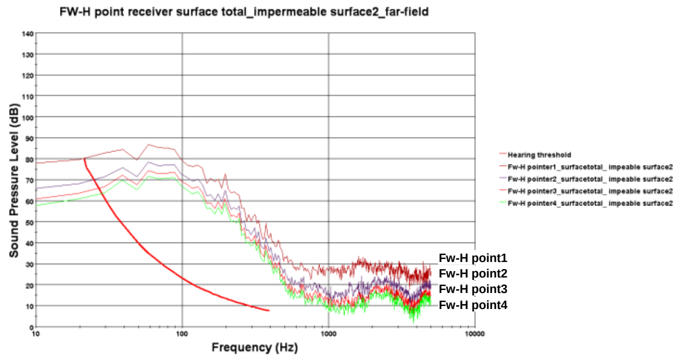
contained in vortex shedding mainly not the surface dipole. Thus the acoustic SPL graphs of both impermeable surfaces show identical result. And those are tonal sound noise which under 500 Hz frequency. There are no-acoustic sound noise energy beyond 1K Hz in contrast to surface dipole term of Fig.11. Since the volumetric terms are little influences for total intensity of aero-acoustic SPL as a whole.

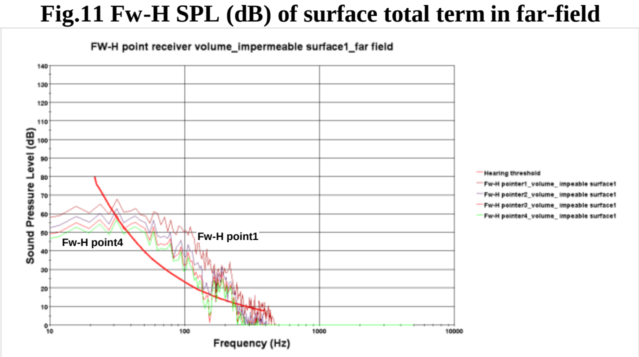


(a) Surface total term for impermeable surface1

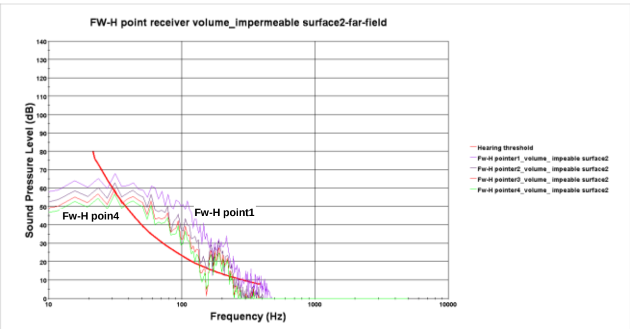


(b) Surface total term for impermeable surface2

Fig.11 Fw-H SPL (dB) of surface total term in far-field



(a) Quadrupole volume term for impermeable surface1



(b) Quadrupole volume term for impermeable surface2

Fig.12 Fw-H SPL (dB) of quadrupole term in far-field

VI. CONCLUSION

Fw-H integral technique was adopted to investigate the noise propagation of far-field region considering mid-field region of road ground surface. It is assumed that the interaction of the vortex shedding to the road ground surface has contribution to the noise propagation of far-field region. The unsteady acoustic fluctuations were captured by using LES with Smagorinsky-Subgrid Scale (S-SGS) subgrid scales model. The commercial CFD code Star-CCM+ was used for CFD and CAA simulation in this study.

The dipole and quadrupole noise sources were obtained successfully using unsteady LES simulation in time domain. The surface pressure fluctuations were recorded and converted to the dipole noise generation source, and they were contributed to the high frequency range in broadband region. The influencing vehicle surface was highly affected by the locations of Fw-H receivers which are higher in perpendicular than tangential. The road ground surface is spread on horizontal to the environment. Thus the road surface influence for noise generation to far-field was limited and not significant as long as far away from the dipole noise source, even though significant evidence of vortex shedding in wake. Only Fw-H receiver-1 shows the influences of road ground surface to the SPL by 5 dB higher than impermeable surface1 which is defined by vehicle body only. The other Fw-H receivers show nearly identical acoustic SPL. However it can influence the mid-field noise generation and propagation. The recorded dipole acoustic SPL of Fw-H integral technique in frequency range shows that there are lacks of information beyond 1K Hz frequency. After 1K Hz, there are continuous sound energy in SPL. Thus the far-field dipole noise propagation can be regarded as tonal noise in low frequency range.

The volumetric quadrupole noise scource was highly related to the vortex shedding which can make interaction of impinging to the road ground surface. However the acoustic energy of vortex shedding in volume for far-field is not significant or important which is limited to tonal sound noise below 500Hz. It is clear that even though, there are important role of vortex shedding to the interaction to road ground surface, the acoustic energy of volumetric term which contained mainly in vortex shedding are not significant but rather negligible. As a result, the far-field noise propagation is highly influenced by the vehicle body than road ground surface, because of the intensity and direction of acoustic emission. The vortex shedding has little contribution to far-field noise propagation which emitted volumetric quadrupole noise source. In the following, the effects of the wall condition of vehicle and road ground surface and grid quality will be discussed for the acoustic SPL in mid-to far field region.

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REFERENCES

[1] U. Sandberg, "Road traffic noise—The influence of the road surface and its characterization", Applied Acoustics, vol. 21, pp.97-118, 1987.

[2] M. Brinkmeier, U. Nackenhorst, S. Petersen, and O. Estorff, "A finite element approach for the simulation of tire rolling noise", Journal of Sound and Vibration, vol. 309, pp. 20–39, 2008.

[3] D. J. O'Boy, and A. P. Dowling, "Tyre/road interaction noise—Numerical noise prediction of a patterned tyre on a rough road surface", Journal of Sound and Vibration, vol. 323, pp. 270–291, 2009.

[4] G. Liao, M. S. Sakhaeifar, M. Heitzman, Ra. West, B. Waller, S. Wang, and Y. Ding, "The effects of pavement surface characteristics on tire/pavement noise", Applied Acoustics, vol. 76, pp. 14–23, 2014.

[5] N. Murad, J. Naser, F. Alam, and S. Watkins, "Computational fluid dynamics study of vehicle A-pillar aero-acoustics", Applied Acoustics, vol. 74, pp. 882-896, 2013.

[6] N. Murad, J. Naser, F. Alam, and S. Watkins, "COMPUTATIONAL AERO-ACOUSTICS OF VEHICLE A-PILLAR AT VARIOUS WINDSHIELD RADII", Fifth International Conference on CFD in the Process Industries CSIRO, Melbourne, Australia 13-15, December 2006.

[7] M. H. Shojaefard, K. Goudarzi and H. Fotouhi, "Numerical Study of Airflow around Vehicle A-pillar Region and Wind noise Generation Prediction", American Journal of Applied Sciences, vol. 6(2), pp. 276-284, 2009.

[8] Y. P. Wang, J. Chen, H. C. Lee, and K. M. Li, "Accurate simulations of surface pressure fluctuations and flow-induced noise near bluff body at low mach numbers", The Seventh International Colloquium on Bluff Body Aerodynamics and Applications (BBAA7), Shanghai, China, September 2-6, 2012.

[9] H. Dechipre, and M. Hartmann, "Aero acoustics Simulation of an Automotive A-Pillar Rain Gutter", EASC 2009 4th European Automotive Simulation Conference. 2009.

[10] N. Hamamoto, M. Yoshida, Y. Goto, A. Hashimoto, and Y. Nakamura, "Direct Simulation for Aerodynamic Noise from Vehicle Parts", SAE International, 2007-01-3461, 2007.

[11] S. Redonnet, "Aircraft Noise Prediction via Aero acoustic Hybrid Methods – Development and Application of Onera Tools over the Last Decade: Some Examples", Onera Aerospace Lab. Journal, Aero acoustics, AL07-07, pp.1-16, 2014.

[12] M. J. LIGHTHILL, "On Sound Generated Aerodynamically. I. General theory / II. Turbulence as a source of sound", Proc. Roy. Soc. London, vol. A 222, 1954.

[13] J. E. Ffowcs Williams, and D. L. Hawkings, "Sound generation by turbulence and surfaces in arbitrary motion," Philos Transact A Math Phys Eng Sci, vol. 264(1151), pp. 321-42, 1969.

[14] K. S. Brentner, and F. Farassat, "An Analytical Comparison of the Acoustic Analogy and Kirchhoff Formulations for Moving Surfaces," AIAA Journal, vol. 36(8), pp. 1379-1386, 1998.

[15] K. S. Brentner, and F. Farassat, "Modeling aerodynamically generated sound of helicopter rotors," Progress in Aerospace Sciences, vol. 39, pp. 83-120, 2003.

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