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A Study on the Sound Noise Emission of Moving Vehicle by Using Curle Surface Integral

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

***Index Terms*—computational aero-acoustic, vehicle, Curle surface integral, Broadband noise source model**

I. INTRODUCTION

The aerodynamic noise on the inside and outside of the vehicles important design consideration. To identify the source and intensity of aero-acoustic noise around the vehicle, a wind tunnel test was performed to investigate wind noise. However, the test was increasingly needed to develop the effective and accurate numerical method in obtaining the aero-acoustic noise in early vehicle design phase process with cost-effectiveness. Recently, the computational aero-acoustics (CAA) [1-8], which is fundamentally based on transient CFD (computation fluid dynamics) to get the time changing pressure fluctuation on vehicle body surface and flow field, is commonly used to simulate the aero-acoustic noise in automotive engineering fields [9-14] and etc by many research works. In another case, the acoustic environment in a vehicle cabin under the influence of high-frequencies aerodynamic sources has been studied using statistical energy analysis (SEA) for the analysis of structural acoustic systems [15]. The wind tunnel test could be time consuming and occasionally irrelevant to the rapid design changing process. Even though its accuracy and feasibility as aerodynamic noise is related to body shape, it is almost impossible to fundamentally improve the noise after finishing car design. Improvement items regarding aerodynamic noise are needed before making prototype cars [13, 14].

The CAA can be classified into two types which are aero-acoustic analogy [1] which models the propagation of sound waves by using integration techniques [1-7] and direct numerical simulation (DNS) for near-field propagation, according to the numerical method and process. Actually, this type aero-acoustic propagation can be simulated with the CFD method including DNS, LES (Large Eddy Simulation), unsteady RANS (Reynolds Averaged Navier-Stokes equations), or DES (Detached Eddy Simulation) with the advantage of accuracy. The integral method (IM) [1-7], which uses the aero-acoustic analogy, is fundamentally limited to near-field propagation. The results of steady or unsteady CFD analysis involving Reynolds Averaged Navier-Stokes (RANS) equations can be utilized to find the turbulence quantities. Consequently, these quantities can be used in conjunction with semi-empirical correlations and Light hill's acoustic analogy [1] to come up with some measures of the source of broadband noise. Thus these models are based on the assumptions implicit to RANS turbulence modeling. They are termed Broadband Noise Source (BNS) Models [2-4], which are strictly applied to turbulence-generated flow-noise and can be attributed to the classical aero-acoustic categorization of dipoles [2] and quadruples [3,4] in shear and jet flows respectively. Then, the sound wave propagation theory, such as those relying on Light hill [1] or Ffowcs-Williams & Hawkings (FWH) [5-7] integration techniques, is applied to estimate the sound in the far-field. Although such analogical methods make it possible to estimate sound at a low computational cost, its accuracy does not seem to be so high, since sound sources are assumed to be incompressible or the analogical model itself does not have enough reliability. Thus, the more accurate and directive to the sound sources and wave propagation direct simulations are preferred. But they need comprehensive computational efforts and cost and make the analysis to be impossible in performing in current hardware.

In considering the aero-acoustic, noise can cause passenger discomfort, and more importantly, it may lead to driver fatigue. It is important for the success of the vehicle to predict the aerodynamic noise at the design stage and control it within an acceptable level. In such a circumstance, the broadband noise source model can be used in development of new car design which focuses on the practical ways to identify and reduce the location and intensity of acoustic sources respectively in avoiding excessive computational cost in near-to-far field noise propagation. For turbulence generated noise, they will identify the location of flow generated aero-acoustic sources and approximate the associated sound power or dB level. They can provide a reasonable basis on which to compare one component design with another and decide where to apply mesh refinement ahead of a well-qualified transient calculation.

In low Mach number flow around a solid body, the quadruple volumetric noise sources have little contribution in noise propagation. Rather the far-field sound pressure is dominated by dipole sources. The dipole sources are created by unsteady surface pressure distributions due to the presence of a turbulent boundary layer in the vicinity of the solid body [12].

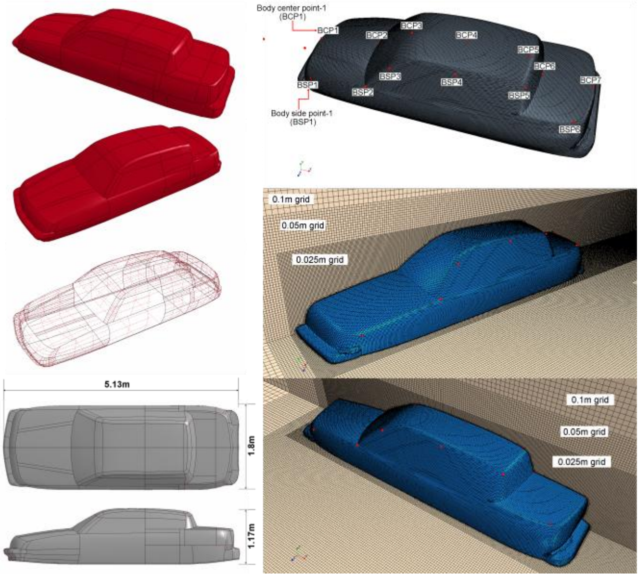

Fig.1 Geometry and grid definition of vehicle body

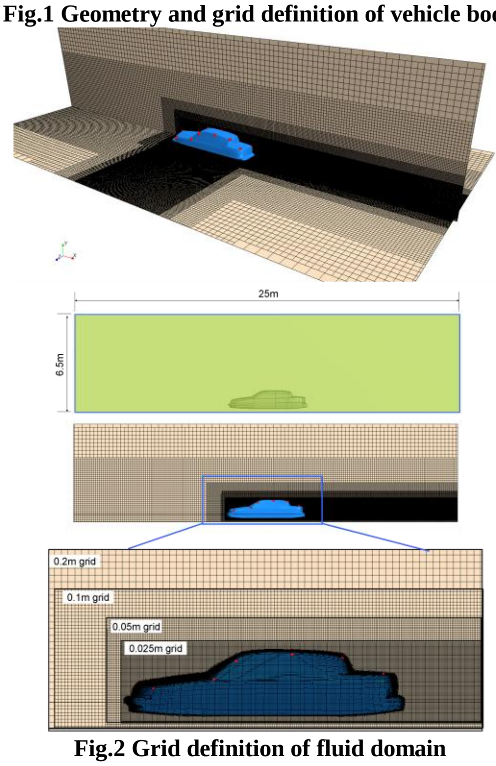

Fig.2 Grid definition of fluid domain

Thus, in this study, to investigate the applicability and feasibility of dipole which is caused broadband noise source model in near-field noise propagation, the Curle's surface integral model [2] was demonstrated which computes the sound generated by dipoles representing the fluctuating surface pressure with which the solid boundaries act on the. The model valuates the far field noise emitted by turbulent boundary layer flow over a solid body at low Mach number. The shear stress transport (SST) turbulent model was used to find the turbulence quantities in steady state RANS equation. Consequently, these quantities can be used in conjunction with semi-empirical correlations and Lighthill's acoustic analogy to come up with some measures of the source of broadband noise. Thus, these models are based on the assumptions implicit to RANS turbulence modeling. The obtained surface noise sources in turbulent boundary layer flow were compared with noise quantities which were represented in the frequency domain from unsteady pressure fluctuation results in near field which were obtained from transient LES simulation with Smagorinsky-Subgrid Scale (S-SGS) sub grid scales model. Finally, the characteristics of the Curle surface noise source, which is easy and approximate to be obtained, are discussed in comparison with the nature of noise in the frequency domain. The commercial CFD code Star-CCM+ was used for CFD and CAA simulation in this study.

II. GEOMETRY AND METHODOLOGY

To evaluate the aero-acoustic characteristics of the high speed vehicle, the geometry and grid model were defined in Fig. 1 and Fig.2. The length, height, and width of the vehicle are 5.13m, 1.8m and 1.17m respectively as shown in Fig.1. The fluid domain size was defined in Fig.2 as 25m, 6.5m and 14m for length, height, and width respectively. The grid unit length of surface of the vehicle is defined as 25mm for the trimmed grid model. The resulting total number of grids and nodes are 18,160,000 and 18,540,000 respectively. Wheels, side mirrors, and details of the vehicle body are omitted to simplify the geometry in computing the approximate surface noise source information from Curls [2] BNS models. The effects of a side mirror or A-pillar gutter in aerodynamic noise were studied in references [12-14] using finer grid resolutions for relatively small parts. The effects of grid resolution for the Curle surface integral are not significant when the proper grid model is used. Because they are not time dependent to the time or frequency domain but surface pressure distribution to calculate. However, the fluid domain grid should account the sound wave length of required frequency range in unsteady transient analysis because the sound energy is continuously distributed over a broad range of frequencies. In this study, to investigate accurate separated turbulent flow near the wall, the SST turbulence model was considered in the simulation. After obtaining steady state turbulent flow results in CFD, the dipoles noise source was calculated using Curls surface integral in the BNS model.

III. CURLE BROAD NOISE SOURCE MODEL

The turbulent boundary layer flow over a solid body is often interest for generating far-field sound noise in near field region. The Curle's integral based on acoustic analogy can be used to approximate the local contribution from the body surface to the total acoustic power [1,2]. In this paper, the boundary layer noise source model was used in order to predict acoustic power level in vehicle body surface. This Lighthill Stress Tensor feature interrogates the flow field and compiles velocity derivatives, which make up the Light hill Stress Tensor. It is a scalar with vector components. By observing Lighthill results, it is possible to identify the

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location of flow-generated aero-acoustics sources. Lighthill's inhomogeneous wave equation governing the sound propagation is derived from conservation of mass and momentum.

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho v_i)=0 \quad (1)$$

$$\frac{\partial \rho}{\partial t}(\rho v_i)+\frac{\partial}{\partial x_j}(\rho v_i v_j + p_{ij})=0 \quad (2)$$

where, ρ : density; v_i , v_j : the velocity components; p_{ij} : the stress tensor.

$$p_{ij} = -\sigma_{ij} + (p - p_0)\delta_{ij} \quad (3)$$

where, p : the thermal dynamic pressure of the flow field; δ_{ij} : the Kronecker delta; σ_{ij} : the viscous stress tensor.

$$\sigma_{ij} = \mu\left(\frac{\partial v_i}{\partial x_j}+\frac{\partial v_j}{\partial x_i}-\frac{2}{3}\frac{\partial v_i}{\partial x_i}\delta_{ij}\right) \quad (4)$$

Using Einstein notation, Lighthill's equation can be written as:

$$\frac{\partial^2 \rho}{\partial t^2}-c_0^2(\nabla^2 \rho)=\frac{\partial^2 T_{ij}}{(\partial x_i)(\partial x_j)} \quad (5)$$

Where T_{ij} is the "Lighthill turbulence stress tensor" for the acoustic field, and it is denoted by substituting stress tensor p_{ij} in T_{ij},

$$T_{ij} = \rho v_i v_j + -\sigma_{ij} + \delta_{ij}\left[(p-p_0)-c_0^2(\rho-\rho_0)\right] \quad (6)$$

where, δ_{ij} : the Kronecker delta; σ_{ij} : the viscous stress tensor; ρ_0 : far field density. In laminar flow, the stress tensor is given by:

$$\sigma_{ij} = \sigma_{ij,lam} = \mu\left(\frac{\partial v_i}{\partial x_j}+\frac{\partial v_j}{\partial x_i}-\frac{2}{3}\frac{\partial v_i}{\partial x_i}\delta_{ij}\right) \quad (7)$$

In turbulent flow, the stress tensor is given by:

$$\sigma_{ij} = \sigma_{ij,lam} + \sigma_{ij,turb} = \mu_{eff}\left(\frac{\partial v_i}{\partial x_j}+\frac{\partial v_j}{\partial x_i}-\frac{2}{3}\frac{\partial v_i}{\partial x_i}\delta_{ij}\right) \quad (8)$$

where the effective viscosity $\mu_{eff} = \mu + \mu_t$ is , the sum of the laminar and turbulent viscosities.

In inviscid flow, the stress tensor is $\sigma_{ij} = 0$. Each of the acoustic source terms from the Lighthill stress tensor in T_{ij} may describe a significant role in the generation of sound as:

$\rho v_i v_j$: describe unsteady convection of flow(or Reynold's stress); σ_{ij} : describe sound shear; $\delta_{ij}\left[(p)-c_0^2(\rho)\right]$: describe nonlinear acoustic generation processes.

The Curle surface integral computes the sound generated by dipoles representing the fluctuating surface pressure with which the solid boundaries act on the fluid. The model valuates the far field noise emitted by turbulent boundary layer flow over a solid body at low Mach number. Specifically, this model computes the surface acoustic power to evaluate the local contribution to the total acoustic power per unit area of the body surface. This model can be used in steady and unsteady (transient) analyses. It is compatible with all Reynolds-Averaged Navier-Stokes (RANS) models that can provide turbulence time and length scales. This model is preferable for steady-state solutions. The Curle boundary layer model is the Curle integral [11] based on Lighthill's theory, which determined the equations of sound propagation in a medium at rest from the equation of continuity and momentum. The Curle surface integral is:

$$\rho'(x,t) = \frac{1}{(4\pi a_0^3)}\int_S\left[\frac{(\bar{x}-\bar{y})}{r^2}\frac{\partial p}{\partial t}\left(\bar{y},t-\frac{r}{a_0}\right)\right]\bar{n}dS(\bar{y}) \quad (9)$$

Where, $t-r/a_0$: the emission time; p : the surface pressure; ρ' : the acoustic pressure; a_0 : the far-field sound speed.

On the assumption of small perturbations and an adiabatic problem, then:

$$\frac{p}{\rho^{\gamma}} = ct \quad (10)$$

Which can be used to relate variations in acoustic pressure with density perturbations:

$$p' = a_0^2 \rho' \quad (11)$$

Then Equation becomes:

$$p'(x,t) = \frac{1}{(4\pi a_0)}\int_S\left[\frac{(\bar{x}-\bar{y})}{r^2}\frac{\partial p}{\partial t}\left(\bar{y},t-\frac{r}{a_0}\right)\right]\bar{n}dS(\bar{y}) \quad (12)$$

The acoustical directional intensity per unit surface of the solid body on the far field prediction is approximated with :

$$\overline{p'^2} \approx \frac{1}{16\pi^2 a_0^2}\int_S \frac{(\cos\theta)^2}{r^r}\overline{\left[\frac{\partial p}{\partial t}\left(\bar{y},t-\frac{r}{a_0}\right)\right]^2} A_C(\bar{y})dS(\bar{y}) \quad (13)$$

Where, A_C is the correlation area, $r = (\bar{x}-\bar{y})$ ($r = |\bar{x}-\bar{y}|$), θ is the angle between r and the $\bar{n}$ wall-normal direction. The measure of the local contribution to acoustic power per unit surface area can be computed from

$$SAP = \frac{1}{\rho_0 a_0}\left[\int_0^{2\pi}\int_0^{\pi}\overline{p'^2} r^2 \sin\theta d\theta d\gamma\right]$$
$$= \int_S I(\bar{y})dS(\bar{y}) = \int_S \frac{A_C(\bar{y})}{(12\rho_0 \pi a_0^3)}\overline{\left(\frac{\partial p}{\partial t}\right)^2} dS(\bar{y}) \quad (14)$$

where, $I(\bar{y})$ is the directional acoustic intensity per unit surface.

The model can be enabled for steady and unsteady cases with Reynolds-Averaged Navier-Strokes (RANS) models which can provide turbulence time scale, turbulence length scale and wall shear stress necessary to compute $\overline{(\partial p/\partial t)^2}$, the mean-square time derivative of the source surface pressure. The acoustic power per unit surface can be reported in dimensional units (W/m^2) and in dB :

$$SAP(dB) = 10\log\frac{SAP}{P_{ref}} \quad (15)$$

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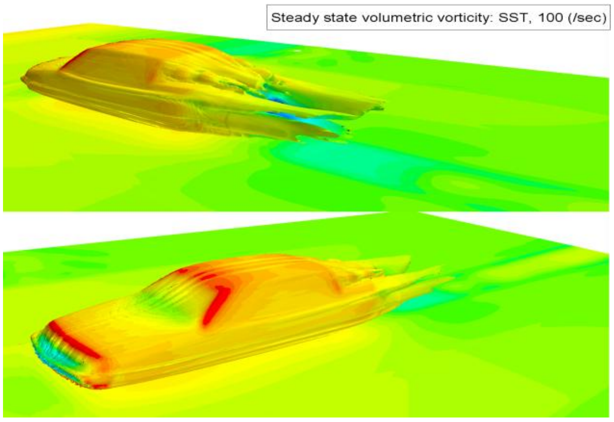
Where P_{ref} is the reference acoustic power. $P_{ref} = 1.0E^{-12}(W/m^2)$

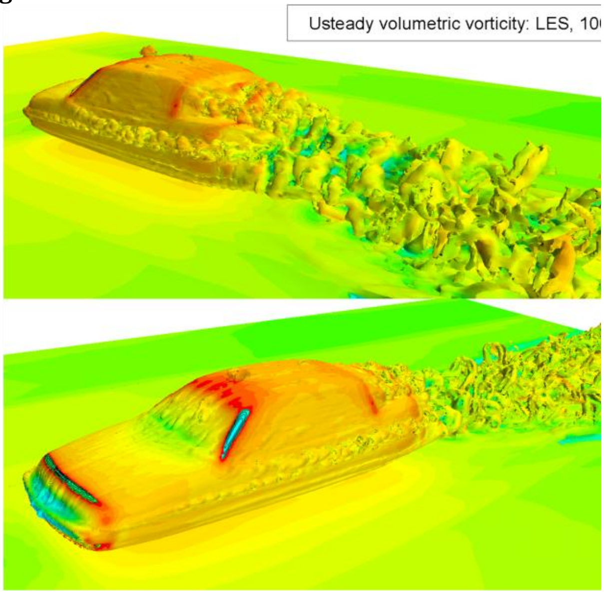
IV. VEHICLE NOISE SOURCES

The high speed vehicle emitted aerodynamic sound noise from the body and interacting road ground surface. Among the aero-acoustic sound noise sources, the main mechanisms of sound generation in the presence of solid structures can be classified as vortex shedding noise, turbulence-structure interaction noise, and trailing edge noise [20]. 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. The vortex shedding noise is related to the Vorticity that is released from a bluff body in a flow. The time varying circulation on the body due to vortex shedding induces a fluctuating force on the body itself, which is transferred to the fluid and propagates as low frequency sound noise is generated near the vehicle body. This periodic convection of large-scale vortices over the cavities where an unsteady shear flow exists, e.g., buffeting noise due to an open sunroof or window. The vortical structures impinging on a solid surface generate local pressure fluctuations on the body surface which feed the acoustic far field and produce the high frequency turbulence-structure interaction noise where vehicle body details of the flow interaction between the outside rear-view mirror and the A-pillar. The trailing edge noise is important for all rotating blade technologies, 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. The aero-acoustic noise is induced by the aerodynamic characteristics of vehicle body. It is clear that the unsteady turbulent flow around the body causes the periodic separation and reattachment.

The approximate aero-acoustic noise source could be identified by using BNS models. Dipoles and quadruples are noise source related to the origin. To get the dipoles or quadruple noise sources, the Curle [2] or Proudman [3] BNS models could be adopted according to the surface or volumetric terms.

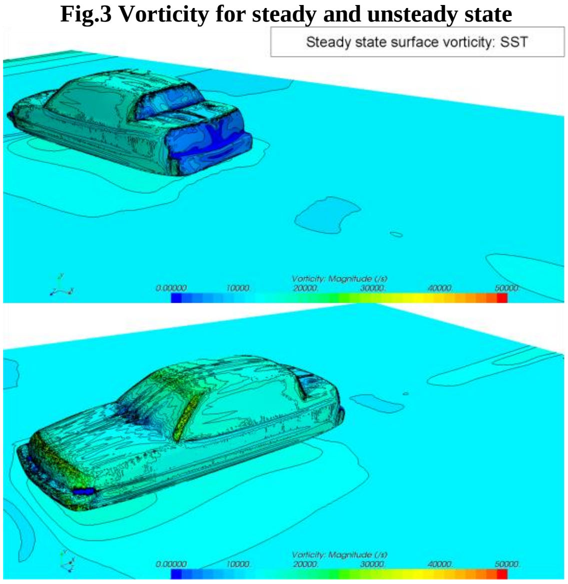


(a) Steady state (RANS)

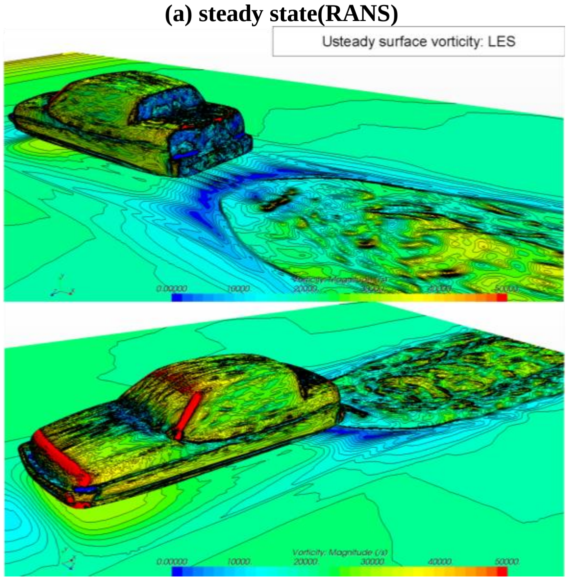


(b) unsteady state(LES)

Fig.3 Vorticity for steady and unsteady state



(a) steady state(RANS)



(b) unsteady state(LES)

Fig.4 Surface Vorticity for steady and unsteady state

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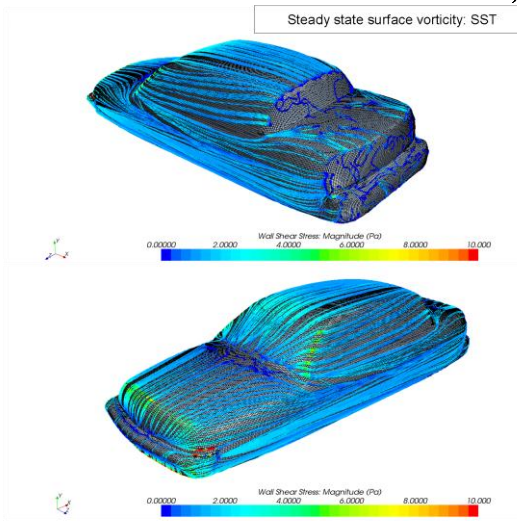
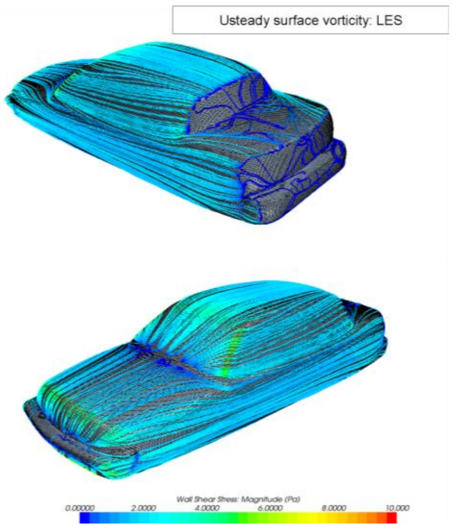
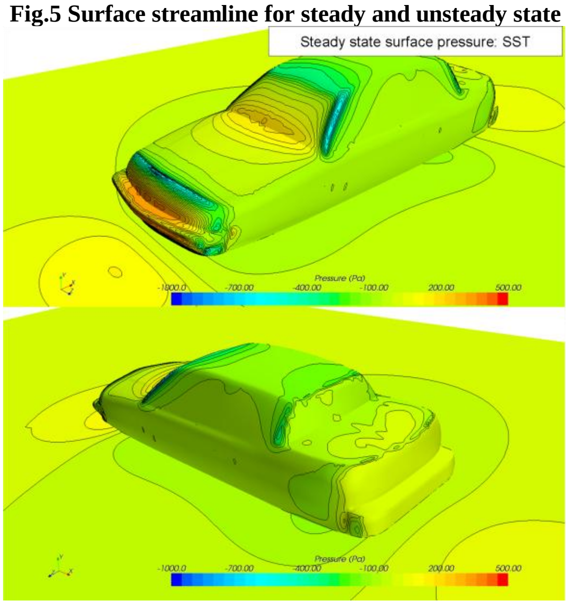


(a) steady state(RANS)

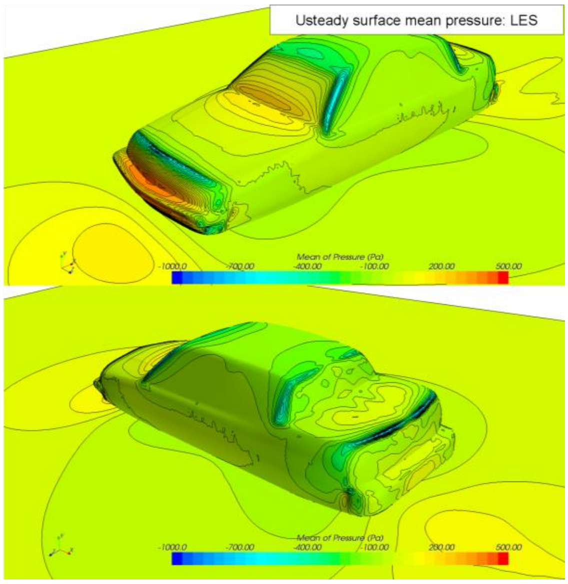


(b) unsteady state(LES)

Fig.5 Surface streamline for steady and unsteady state

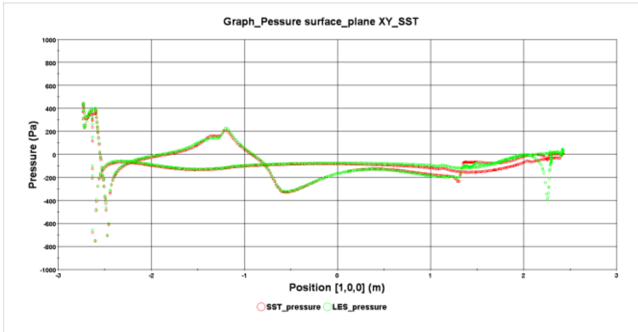


(a) Steady state(RANS)

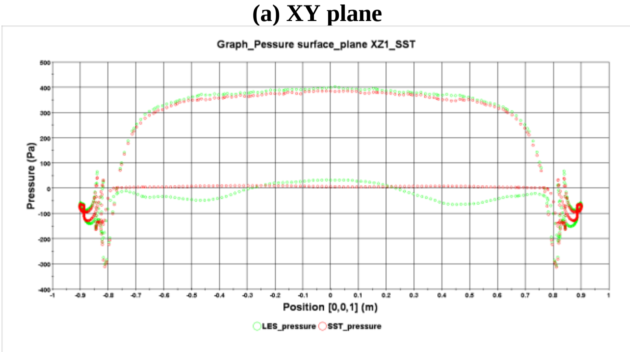


(b) unsteady state(LES)

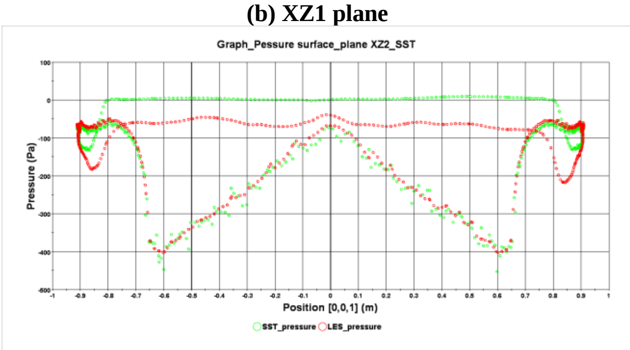
Fig.6 Surface pressure (mean pressure) for steady and unsteady state



(a) XY plane



(b) XZ1 plane



(c) XZ2 plane

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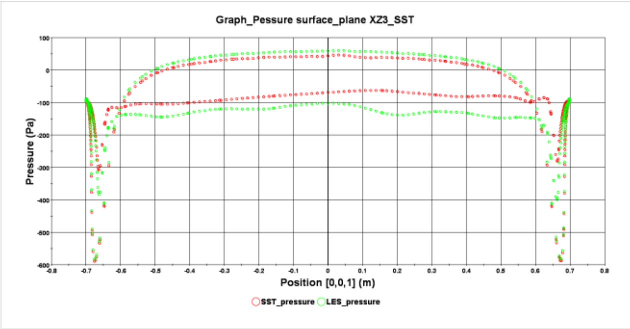


(d) XZ3 plane

Fig.7 Sectional pressure distributions for steady and unsteady state

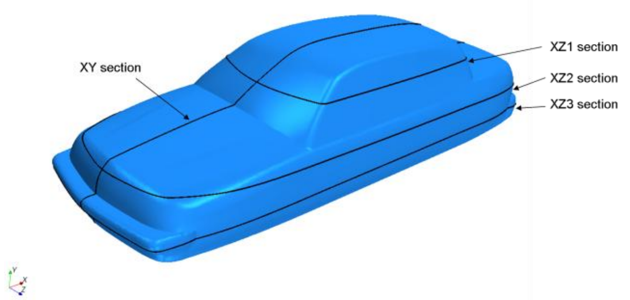


Fig.8 Sections definition

Thus, there are dipole and quadruple noise source in surface and volume, and they are highly related each other. However, it is commonly known that the volumetric quadruple noise source is little effect to the total intense level of sound noise in the low Mach number problem. But it may have an amount of influences which can not be ignored. Fig.3 and Fig.4 show the volumetric and surface Vorticity results for steady and unsteady state respectively. The noise source has the broadband frequency spectrum range for sound pressure level (SPL).

Fig.5 and Fig.6 illustrate the surface streamline and pressure for steady and unsteady state respectively. The mean pressure was used to identify the pressure for unsteady LES simulation. As shown in Fig.5, and Fig.6, there are little differences between two different states. The color of streamline in Fig.5 means the surface wall shear stress. According to the results of Fig.5, the wall shear stress of unsteady LES simulation is slightly higher than steady SST RANS simulation but not significant.

The sectional quantities of pressure, Vorticity, and wall shear stress can be evaluated in sections. Fig.7 shows the sectional pressure evaluation among them in sections which were defined in Fig.8. The pressure and mean pressure were used for steady and unsteady state respectively in Fig.7, and the results of pressure in steady RANS SST turbulent and unsteady LES simulation were similar, There are little differences also like wall shear stress in Fig.5.

V. CURLE SURFACE SOUND PRESSURE LEVEL

The unsteady fluctuating surface pressure with the solid boundaries act on the fluid can be represented by the Cule surface integral. The model analyses the far field noise emitted by turbulent boundary layer flow over a solid body at low Mach number. The model can be enabled for steady and unsteady cases with Reynolds-Averaged Navier-Strokes (RANS) models which can provide turbulence time scale, turbulence length scale, and wall shear stress necessary to compute the mean-square time derivative of the source surface pressure. The resulting Curle surface integral is shown in Fig.9 and Fig.10. Fig.10 illustrates the sectional SPL (dB) of Curle surface integral at 4 sections (XY, XZ1, XZ2 and XZ3) which is defined in Fig.8. As shown in Fig. 9 and Fig.10, the Curle surface SPLs (dB) in BCP1 to BCP7 are approximately, 90dB, 20dB, 80dB, 70dB, 70dB, 60dB.. Their body surface distributions are highly related with the surface Vorticity results in Fig.4. But there are in-direct relationships with the surface pressure of Fig.6. Because the time derivative of the source surface pressure is necessary in Curle surface integral. In Fig.6, the surface pressure on the bottom of the front windshield is close to zero value and mainly positive, not negative. And the surface Vorticity, wall shear stress, and Curle SPL approach to zero. The contribution of the bottom of front windshield to surface quantities is not important but negligible. However, these results are steady state or averaged values. The average or mean pressure values of unsteady LES in Fig.6 are similar to the steady state results, which were obtained using SST-RANS turbulent model. In Fig6, when comparing the unsteady LES results to the steady state, the surface pressure of front of vehicle are similar but not rear vehicle. There are higher negative mean pressures at the edges of the roof and trunk, and also the rear surfaces.

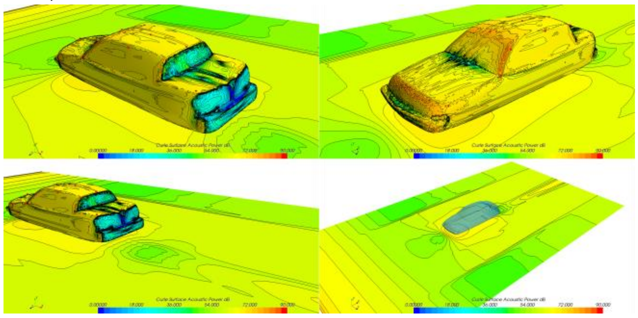
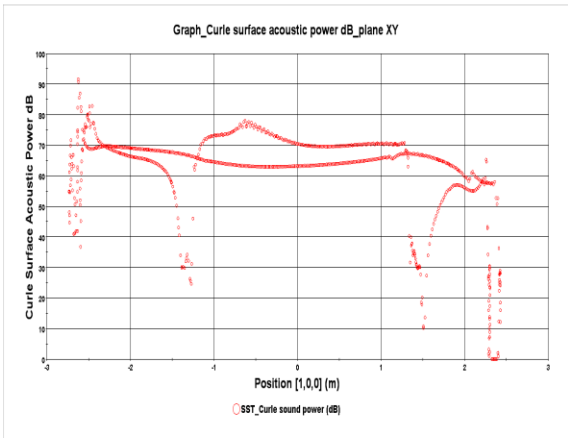


Fig.9 Surface Curle SPL (dB)



(a) XY plane

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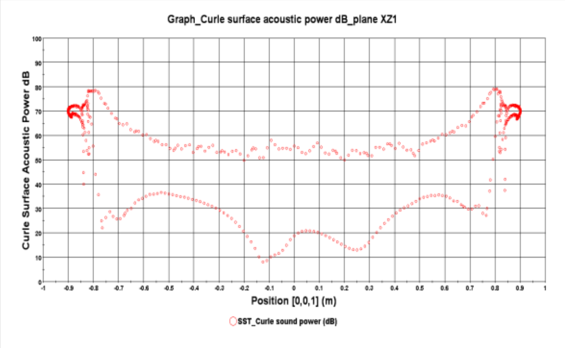
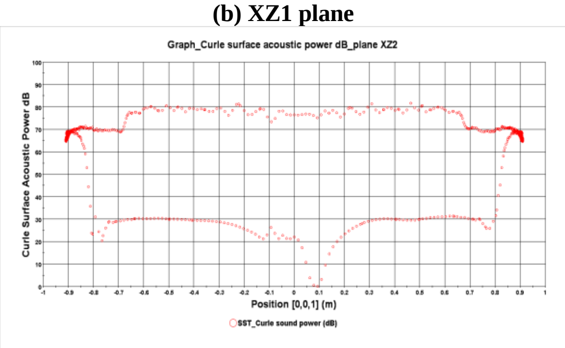
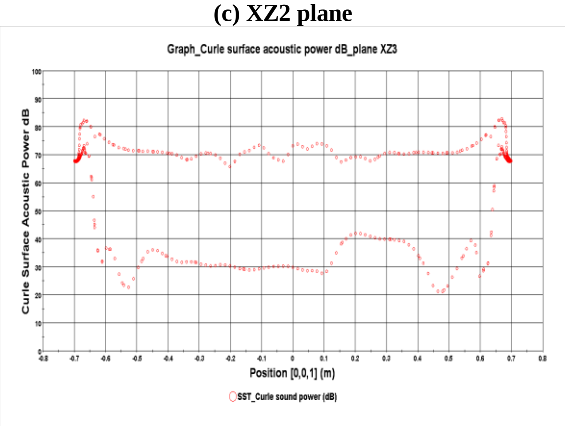


(b) XZ1 plane



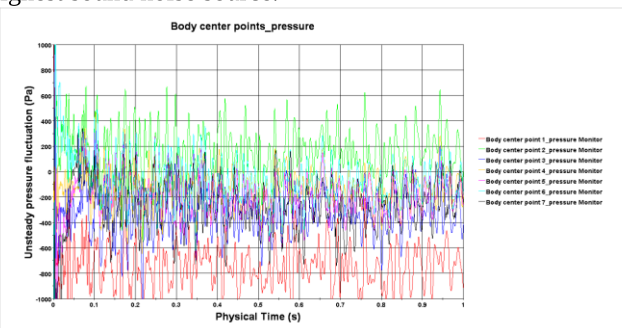
(c) XZ2 plane



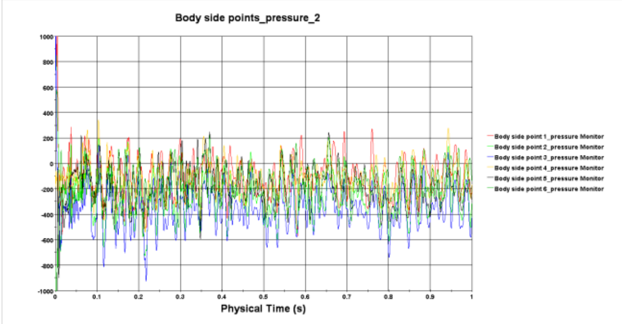
(d) XZ3 plane

Fig.10 Sectional Curle SPL (dB)

Thus, it can be expected that the unsteady pressure fluctuations will be higher in rear side than others. And similar and related results also can be seen in the surface Vorticity in Fig.4(b). It is interesting that many researches reported that the main sound noise sources are A-pillar area,but this is good agreement with the fact of the Curle surface integral in Fig.9 and Fig.10. The A-pillar area is the highest sound noise source.

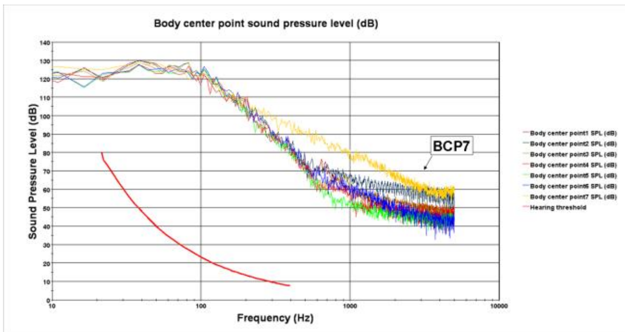


(a) Center points

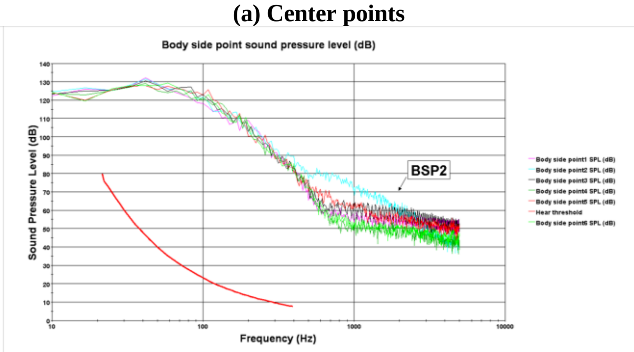


(b) Body side points

Fig.11 Point unsteady pressure fluctuation for center and side



(a) Center points



(b) Body side points

Fig.12 Point SPL (dB) spectrum

There are little contributions of road surface to the sound noise source in steady state Curle surface integral in vehicle rear area which the vortex shedding and its interaction to the road surface are significant. When using steady state SST-turbulent RANS simulation, the time dependent transient vortex shedding is not possible to get in fluid domain. These flow characteristics also can be seen in the surface Vorticity in Fig.4. In the unsteady state simulation, there is noticeable surface Vorticity on the road surface which could not be seen in steady state results.

Fig.11 and Fig.12 show the unsteady point pressure fluctuations and frequency spectrum of SPL (dB) from the unsteady LES simulation with the Smagorinsky-Subgrid Scale (S-SGS) sub grid scales model. To perform the simulation, the same grid model was adopted which was illustrated in Fig.1. The comprehensive descriptions about the unsteady LES simulation were omitted. In higher frequency range of 1K to 5K, the body center points of BCP2 and BCP7 are an approach to the 60dB SPLs. The others are between 40dB to 50dB. They are contrast to the steady state Curle surface integral results which is shown in Fig.9 and Fig.10and the SPLs of other body center points (BCP1, BCP3, BCP4, BCP5, BCP6) are approximately20dB below the Curle surface integral. The point SPLs (dB) of body side points approach to 40dB to 50dB are 10dB below the body center points. The BSP2 shows intensive sound noise source among body side points, and approximately 20dB below the steady state Curle surface integral. The comparative results of unsteady pressure fluctuations between body center and side points are a good match with the steady state Curle surface integral which is presented in Fig.9. Thus, the results of Curle surface integral for surface SPL are reasonable values for overall distributions of sound noise sources. Also, the surface quantities of Vorticity and wall shear stress, which are related with the turbulent flow, represent the aerodynamic or aero-acoustic noise source than surface pressure. The discrepancies of unsteady pressure fluctuation of near-field are approximately 20dB below than Curle surface integral in higher frequency spectral, that are mainly caused by the poor grid model, used in the studies. Thus in the future work, the finer grid model with more numbers of grid in near-field domain is necessary to compensate the SPL in higher frequency range.

VI. CONCLUSION

In this study, the steady and unsteady state CFD/CAA simulations were performed to get the aero-acoustic sound noise information of the high speed vehicle in near-field to study the accuracy and applicability of the Curle BNS model. The BNS model is convenient and easy to analyze the noise source information of location and intensity. There are many research works done to calculate them in reasonable approaches before. The mesh quality tests were done in these studies which were not shown in this paper. As long as there are little effects of grid quality on the value of Curle BNS model in turbulent boundary layer, the Curle surface SPL (dB) was converged to the specific values according to the turbulent flow quantities. Rather it might be attributed by the RANS turbulent model. In this study, the steady state SST-turbulent model was used to get accurate flow separation and reattachment. As comparing with unsteady transient LES simulation for near-field point pressure fluctuation and resulting SPL (dB) in frequency spectrum, there are similar SPL distributions in attached region or higher Vorticity and wall shear stress values. The higher separated flow region of bottom of front windshield and rear of vehicle trunk edge, which are close to zero value in Vorticity and wall shear stress, are higher unsteady pressure fluctuation and show significant SPL (dB) discrepancies. When evaluating unsteady SPL (dB) in near-field, there is little relationship on the Curle surface integral results in that region which show near to zero vorticity and wall shear stress. The overall values of Curle surface integral are 20dB higher than unsteady CAA from point pressure spectral. The discrepancies might come from the grid quality for LES simulation and the effects of large scale vortex shedding of the interaction to road surface could not be analyzed in steady state simulation. As a result, there will be higher discrepancies in the Curle surface integral on the road surface SPL and also, they will affect the far-field sound noise propagation. In the future work, a higher quality grid model should be used in the unsteady LES simulation to increase the SPL in higher frequency range, and the effects of road surface on the mid to far-field fluid domain will be studied.

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