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A Study on the Sound Noise Emission of Moving Vehicle by Using Proudman Model

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Abstract—***This paper aims at predicting the sound noise generated by a moving vehicle using the 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

Sound noise problem in a high speed vehicle is an important pollution near the highway resident environment. The tonal and broadband noises are harmful to the human's ear heath condition. The highway fence is an easy way to reduce the highway noise. The main noise sources of vehicle are tire-road interaction [1-4], power-train mechanical parts, and aerodynamics. The acoustic sound noise from the aerodynamic of solid body is defined as aero-acoustic noise [5-10]. Regarding the reduction of traffic vehicle noise, significant progress has been achieved with respect to the sound radiation of the power train of vehicles. As a result, the tire and aero-acoustic sources are more important than the engine and power-train mechanical source with the increasing vehicle speed and results in very complicated noise sources.

The tire-road interaction noise can be reduced by using flexible and soft pavement material for road surface [1,4]. It is well known that the pressure fluctuations on the front side window surface of a road vehicle are a major sound source for both the external and interior wind noises. The front side window aero-acoustic noise from A-pillar flow separation and reattachment was regarded as the main source of aerodynamic turbulent flow and rotating vortex [5-7]. The aero-acoustic sound noise is directly related to the aerodynamic of the vehicle body. Thus, it can be reduced by innovative vehicle design process. The wind tunnel facility for aerodynamic or aero-acoustic noise was equipped well to identify that. However, this study is not available in pre-design stage and it requires time scheduling and expensive cost. The computational fluid dynamics (CFD) and computational aero-acoustics (CAA) [11-18] are widely used for various engineering problems. The aerodynamic application is one of the engineering fields which the CFD and CAA have successfully adopted even though they're challenging in developing numerical method. The CFD and CAA can be selected and used in substitution of wind tunnel tests in pre-design process of developing new body shape for a vehicle. There are approximate broadband noise source (BNS) models for dipole and quadruple noise sources in CAA within combination of Reynolds Averaged Navier-Stokes (RANS) equations turbulent model. The steady and unsteady RANS equations are available. These dipole and quadruple models are attributed for surface and volumetric sound noise sources respectively and they can be used in vehicle design process successfully. In new vehicle design process, the aerodynamic characteristics and resulting aero-acoustic propagations are main design objective.

In this study, the characteristics and applicability of approximate broadband noise source of the Proudman model [13] is demonstrated by comparing the results with points sound pressure level (SPL, dB) obtained from the unsteady transient CAA analysis. The point pressure fluctuation was recorded and transformed to the spectral frequency domain to calculate the acoustic SPL to be used for reference value using the large eddy simulation (LES) simulation with the Smagorinsky-Subgrid Scale (S-SGS) sub grid scales model in unsteady CAA analysis. The commercial CFD code Star-CCM+ was used for CFD and CAA simulation in this study.

II. AERODYNAMIC NOISE: NUMERICAL METHOD, CFD AND CAA

In the frequency domain, the sound can be understood as the intensity of air pressure propagation. The time dependent frequency of air pressure fluctuation must be obtained from the unsteady transient simulation using LES, unsteady RANS (URANS), or detached eddy simulation (DES). Computational aero-acoustics (CAA) investigates the aerodynamic generation of sound by using numerical method. Sir James Light hill derived a theory for the estimation of the intensity of sound that radiates from a turbulent flow [11]. He established the theoretical background generally referred to when investigating aerodynamic noise and first introduced the concept of aero-acoustic analogy which consists of replacing the actual flow field responsible for generating noise with an equivalent system of noise sources. The noise sources act on a uniform stagnant fluid that is governed using standard acoustic propagation equations. The aerodynamic characterization of the sources then becomes the main issue in noise prediction. Before this, flow-generated noise studies

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were focused on the relation between the frequency of the fluid fluctuations and the emitted sound.

Thus, the CAA can be classified into two types, which are aero-acoustic analogy which models the propagation of sound waves by using integration techniques [11-18] and direct numerical simulation (DNS) for near-field propagation, according to the numerical method and process. Actually, DNS type aero-acoustic propagation can be simulated using unsteady 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. LES can use the central differencing in spatial discretization. In general, URANS is not guaranteed to account the broadband content arising from turbulent in vortex shedding. DES uses RANS only in the boundary layer. DES and LES perform similarly in terms of pressure spectra using bounded central differencing, where boundary layer structures do not directly affect the aero acoustics. When the hybrid BCD discretization scheme is used in DES, some key regions, such as an A-pillar or separated shear layers, suffer from numerical damping of the pressure fluctuations.

The integral method (IM) [11-18], which uses the aero-acoustic analogy, is fundamentally limited to near-field accuracy. It relies on the near-field flow data from CFD solution. The steady or unsteady strategies can be used according to the problems. For mid-to far-field noise prediction, the Ffowcs Williams-Hawkings (FW-H) acoustics integral formulation is the preferred strategy [16-18] to predict small amplitude acoustic pressure fluctuations at the locations of each receiver for the sound signal that is radiated from near-field flow.

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 Lighthill's acoustic analogy [11-13] 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, which are strictly applied to turbulence-generated flow-noise and can be attributed to the classical aero-acoustic categorization of dipoles [12] and quadruples [13-15] in shear and jet flows respectively. 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.

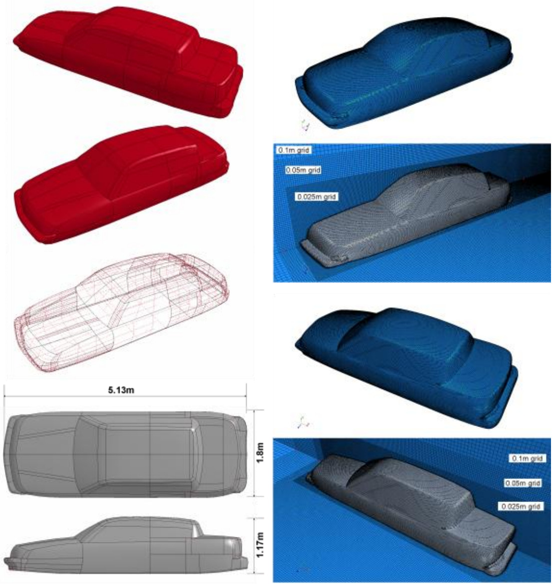

Fig.1 Geometry and grid definition of vehicle body

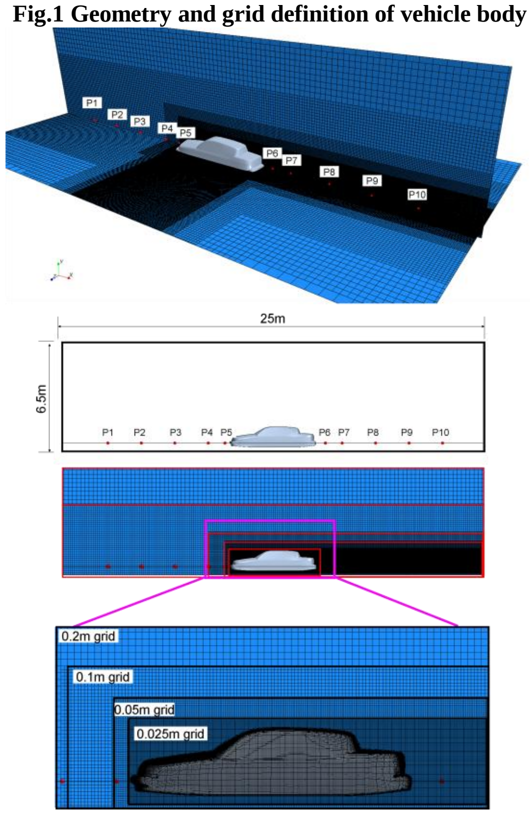

Fig.2 Grid definition of fluid domain

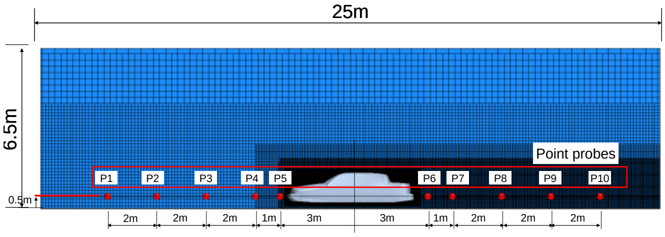

Fig.3 Point probes definition

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 the low Mach number problem. And

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the road ground surface interaction is also omitted in far-field propagation prediction because of the grid model complexity. Actually, the vortex shedding interaction to the road ground surface is not negligible but important in mid-to 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. An approximate BNS Proudman model [13] can be used for volumetric source term in steady state analysis which can drastically reduce the simulation cost within acceptable accuracy. The trial to use the Proudman model is worth of consideration for design of the vehicle and environmental quick solution. The characteristics and applicability of approximate broadband noise source Proudman model is demonstrated by comparing with SPL (dB) obtained from the unsteady transient CAA analysis. The point pressure fluctuation was recorded and transformed to the spectral frequency domain to evaluate the sound noise quantities in mid-field region.

III. GEOMETRY AND METHODOLOGY

To account the effects of vortex shedding interaction between road ground surfaces, the grid model should extend to mid-to far area. The effects of volumetric grid resolution for the Proudman BNS model are critical in mid-to far-field area. The preliminary parametric studies for grid resolutions were studies to determine the grid model. As a result, the geometry, grid models of vehicle and fluid domain are illustrated as in Fig.1 and Fig.2 illustrate for CFD and CAA. Fig.3 explains the locations of point probes in fluid domain to record the point pressure fluctuation. After recording the pressure history, the Fourier transform will be performed. As shown in Fig.1, 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 in Fig.2 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 18,160,000 and 18,540,000 respectively.

The effects of grid resolution of the Curle surface integral is not significant when the proper grid model is used, because it is not time dependent to the time or frequency domain but surface pressure distribution to calculate in an overall surface interest. However, the Proudman model needs higher quality volumetric grid to identify the broadband noise source in mid-to far-field. Thus in general, more numbers of grids and computational cost are needed to perform quadruple Proudman BNS model than dipole Curle surface BNS model. This is the reason why many CAA research works are interested in trying to adopt the integral method of Ffowcs Williams-Hawkings (FW-H) acoustics integral formulation for mid-to far-field problem. 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. The higher quality grid resolution must be used for quadrupole BNS model or unsteady CAA analysis. However, from the limitation of computation resource of this study, the limited numbers of grids were considered. More numbers of grid models for higher quality resolution will be adopted in the following studies.

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. To account the turbulent flow for the Proudman BNS model, which calculate the volumetric noise source term using aero-acoustic analogy, the shear stress transport (SST) turbulent model was selected for steady RANS solution. After obtaining steady state turbulent flow results in CFD, the quadrupole noise source was calculated using the Proudman BNS model.

IV. PROUDMAN BROADBAND NOISE SOURCE MODEL

The turbulent flow emitted from a solid vehicle body is often interest for generating far-field region. The Proudman's integral, based on acoustic analogy, can be used to approximate the location and intensity of noise source term in air volume to the total acoustic power from turbulent flow. In this paper, the Proudman model was used for quadruple sources of noise. This Lighthill Stress Tensor feature interrogates the flow field and compiles velocity derivatives which make up the Lighthill Stress Tensor. It is a scalar with vector components. By observing Lighthill results, it is possible to identify the location of flow-generated aero-acoustics sources. Lighthill's inhomogeneous wave equation governing the sound propagation is derived from conservation of mass and momentum:

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

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

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

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

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

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

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

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

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

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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 Proudman noise source model evaluates acoustic power per unit volume and the sound is from quadruples. Specifically, this model computes the acoustic power to evaluate the local contribution to the total acoustic power per unit volume from the turbulent flow. The Proudman model assumes isotropic turbulence. This model can be used for quadruple sources of noise, such as the areas around rear C-pillar or blunted body. Like the Curle model, 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. However, it is preferable for steady-state solutions.

The analytical result of Proudman [13] estimated the local acoustic power generated by unit volume of isotropic turbulence having no mean flow. Proudman considered the generation of noise by isotropic turbulence and using statistical models of various two-point moments, using the Lighthill analogy. In Proudman's high-Reynolds model for isotropic turbulence in near incompressible flow, Lilley [14] added the effects of retarded time in the evaluation of the two-point covariance of Lighthill's tensor (an effect previously neglected by Proudman), and obtained the following expression for acoustic power, AP per unit volume:

$$AP = \alpha\rho_0 \frac{u^3}{l}\frac{u^5}{a_0^5} \quad (9)$$

where, α : a constant related to the shape of the longitudinal velocity correlation; u : the root mean square of one of the velocity components; l : the longitudinal integral length scale of the velocity; ρ_0 : the far-field density ; a_0 : the far-field sound speed.

In Proudman's original derivation [13], α is approximately 13. In Proudman's paper, the terms of u and ε can be written as:

$$u = \sqrt{\left(\frac{2}{3}k\right)}, \quad \varepsilon = \frac{1.5u^3}{l} \quad (10)$$

In terms of the turbulence velocity scale and of the turbulence length scale, the local acoustic power due to the unit volume of isotropic turbulence (in W/m^3) becomes:

$$AP = \alpha_c \rho_0 \frac{U^3}{L}\frac{U^5}{a_0^5} \quad (11)$$

with: $U = \frac{L}{T}$, $\alpha_c = 0.629$, where ρ_0 : the far-field density; U : the turbulence velocity; L : the turbulence length scale; T : the turbulence time scale and a_0 is the far-field sound speed. The rescaled constant is based on Direct Numerical Simulation for isotropic turbulence done by Sarkar and Hussaini [15].

The total acoustic power per unit volume can be reported in dimensional units (W/m^3) and in dB:

$$AP(dB) = 10\log\left(\frac{AP}{P_{ref}}\right) \quad (12)$$

Where P_{ref} is the reference acoustic power. $P_{ref} = 1.0E^{-12}(W/m^3)$

V. NOISE SOURCE OF HIGH SPEED VEHICLE

The noise source of aero-acoustic is based on aerodynamic flow. Flow separation and induced turbulent flow is the source of flow fluctuation which can be visible in vortex shedding. The strong flow impinging will make higher noise emission. There are several noise sources which produce the Vorticity in boundary layer near the body. The vortex shedding or emitted air flow makes the Vorticity, flow, and pressure fluctuation. The intensity of pressure fluctuation is SPL for human ear. Thus, the higher pressure of flow produces higher noise. The Vorticity of air flow will be distributed into the air and contains the sound energy in frequency spectra as low frequency tonal noise and high frequency broadband noise.

The vortex shedding impinging produces secondary Vorticity from the road ground surface. Thus, the existence of road surface can be not ignorable but must be considered in mid-field region. Flow is generally divided into different groups depending on the properties of the fluid particles in the flow as lamina or turbulent. There is also a transitional flow, which describes the case when laminar flow is becoming turbulent but is not yet fully turbulent. Both laminar and turbulent flows are generally unsteady, meaning that the velocity at a given point in space varies with time. A flow is steady if there is no change in the velocity field through time. Therefore, it is not possible to have a steady turbulent flow. The noise source is directly related in pressure fluctuation in time domain, and it means the unsteadiness fundamentally.

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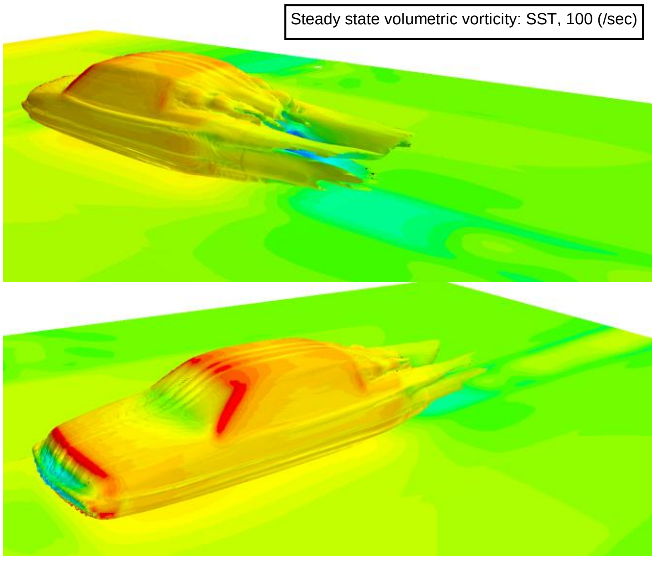
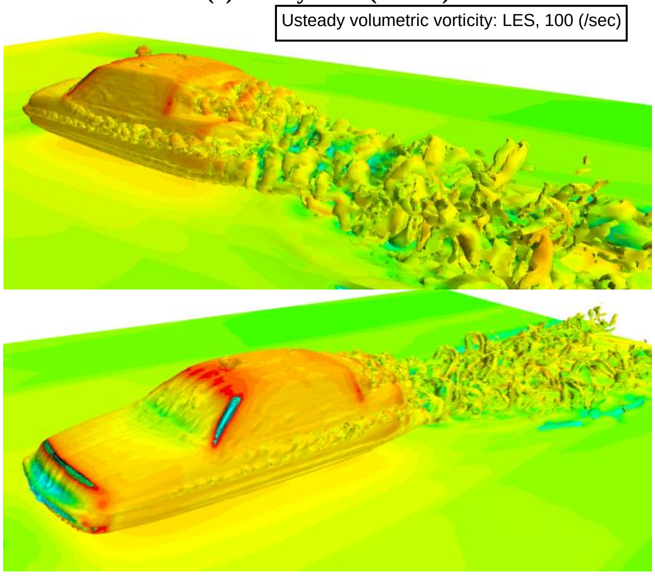
The steady noise source can be highly different from unsteady noise source because of unsteadiness.



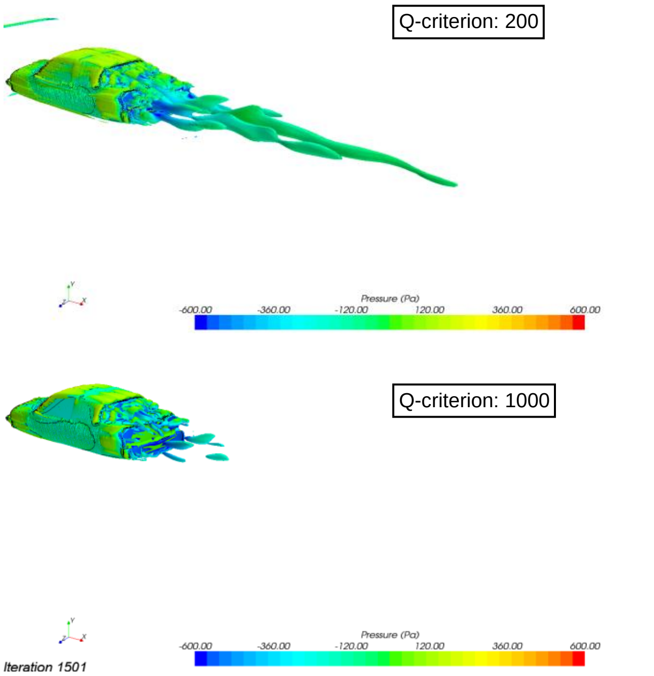
(a) Steady state (RANS)



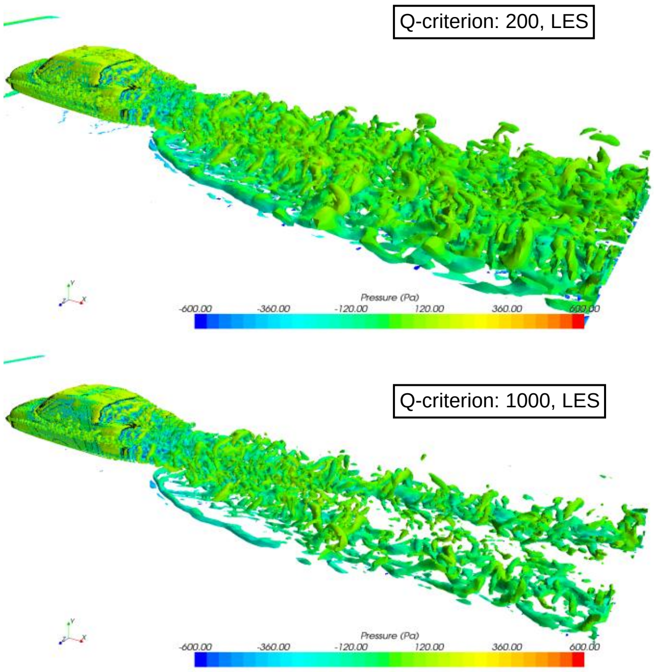
(b) unsteady state(LES)

Fig.4 Volumetric Vorticity for steady and unsteady state: 100(/sec)

From Fig4, Fig.5, the turbulent flow can be recognized by using Vorticity or Q-criterion to visualize the vortex. 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). As a result of this, 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. 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 represent the velocity field of flow.



(a) steady state(RANS)



(b) unsteady state(LES)

Fig.5 Q-criterion for steady and unsteady state: 200, 1000

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. From Fig.4, and Fig.5, even though same values for steady state, the iso-surface of Q-criterion and Vorticity in steady state are highly different from unsteady LES solution in rear vehicle or wake which related far-field. From those results, the large scale of vortex shedding is expected in unsteady flow rather than steady, and also similar pattern in sound noise propagation.

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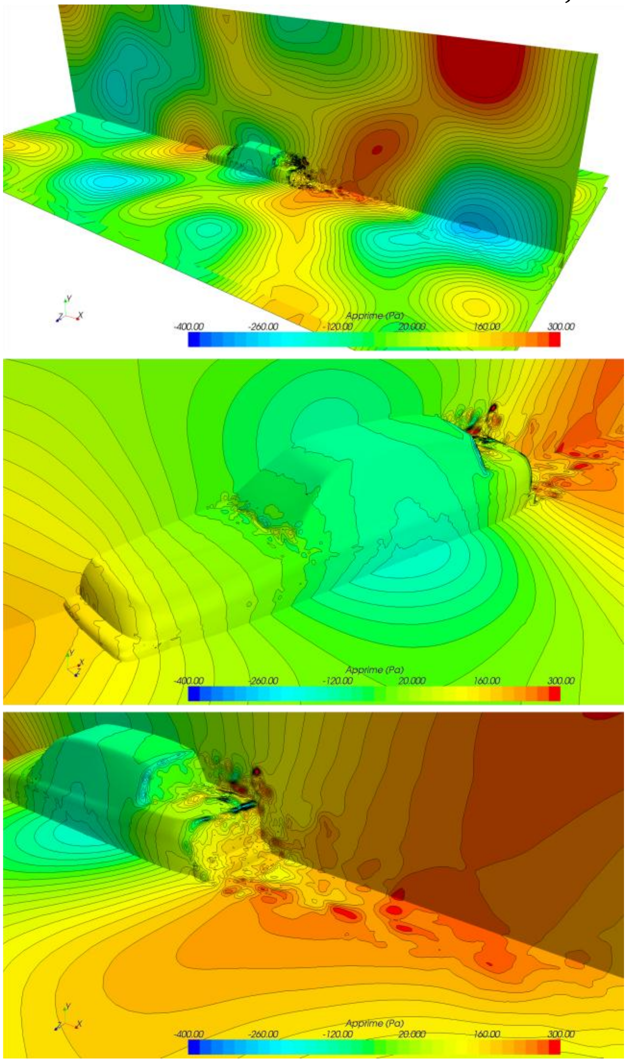
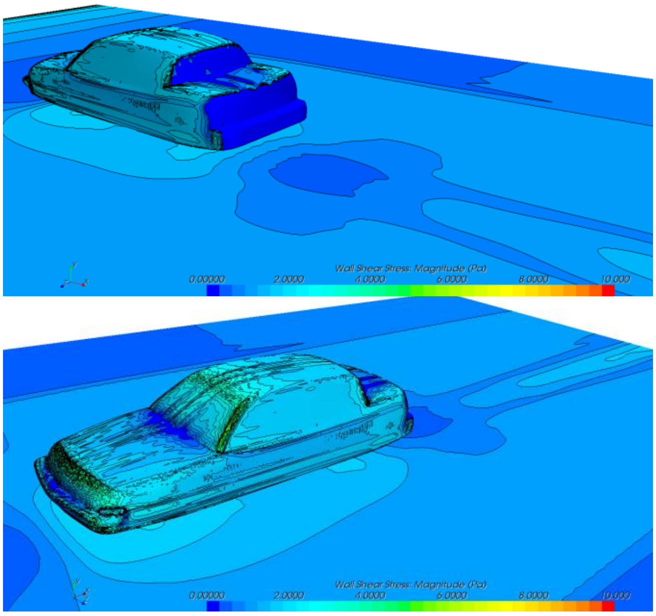


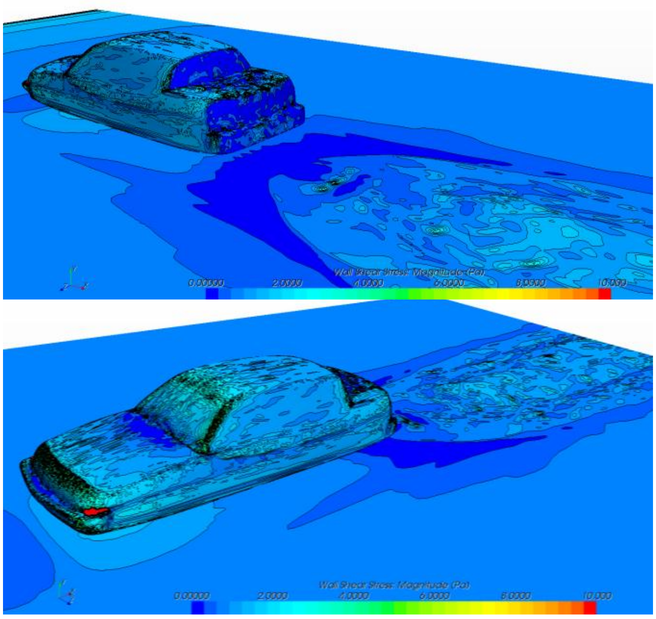
Fig.6 Unsteady pressure fluctuation: LES

Fig.6 illustrates the turbulent fluctuation and acoustical fluctuation in the near and far field respectively. There are higher unsteady turbulent fluctuations at the bottom of the front windshield and rear vehicle than the side window or A-pillar. And the acoustical fluctuation has large spherical volume than small turbulent fluctuation.

Fig.7 and Fig.8 show the comparative demonstrations for surface wall shear stress and pressure. The mean pressure was selected for the unsteady LES case. The surface wall shear stress can explain the flow separation or turbulent flow in boundary layer. The overall results of wall shear are similar, both of steady and unsteady cases except the road ground surface. The interacting flow of vortex shedding to the road ground surface makes the turbulent on the road surface. There are considerable quantities on the road ground surface for potential noise source. When the steady BNS models are used, those effects can be ignorable. In general far-field CAA case, the mid field area is usually not considered, but only near field of vehicle body is the main interest. Thus, if the road surface under the vehicle is omitted, the importance noise source also can be ignored.



(a) Steady state(RANS)



(b) Unsteady state (LES)

Fig.7 Wall shear stress for steady and unsteady state

As explained before, Fig.8 shows the surface pressure in steady and unsteady case. To take into account the similar meaning of steady state, the mean pressure is considered for unsteady state. Thick contour lines are located on A-pillar and the rear vehicle on specially rear trunk edge in unsteady case. The high negative suction pressure is caused by higher flow velocity. That surface area can be dipole noise source, which is more important in the low Mach number problem and they produce strong rotating vortex to vehicle wake and vortex shedding interaction.

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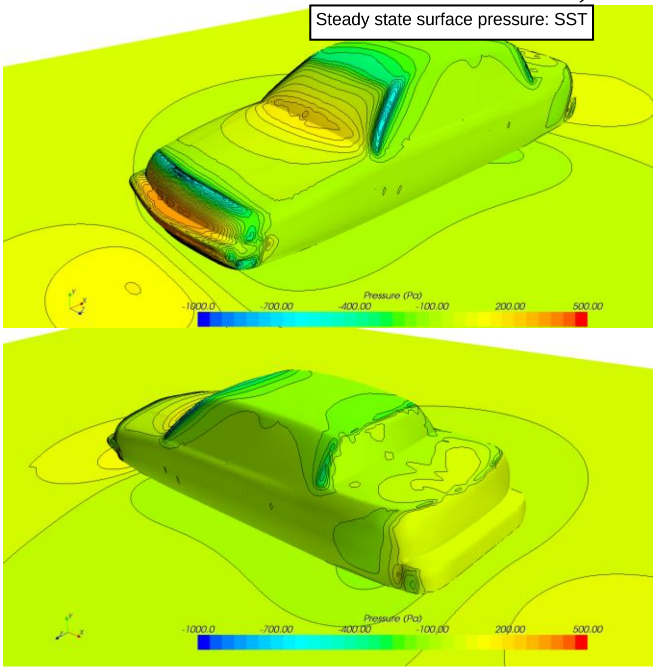
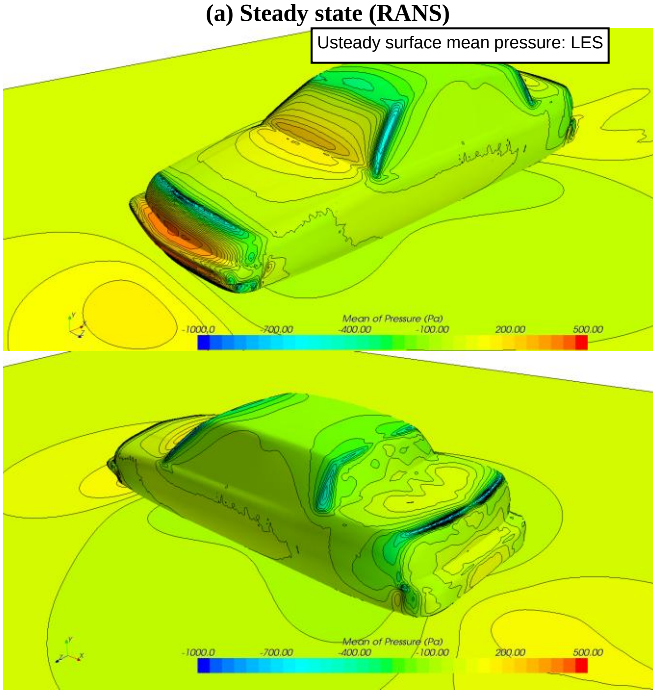


(a) Steady state (RANS)



(b) Unsteady state (LES)

Fig.8 Surface pressure for steady and unsteady state (mean pressure)

VI. VOLUMETRIC PROUDMAN NOISE SOURCE

The turbulent flow of steady state has constant velocity field. Thus, the vortex of steady state does not contain the pressure fluctuation. To analyze the SPL in frequency spectra, the unsteady DNS or similar numerical technique should be used. In this study, the RANS SST-turbulent model and LES with Smagorinsky-Subgrid Scale (S-SGS) sub grid scales were used in steady and unsteady simulation respectively. As long as the volumetric sound energy can be contained in volumetric vortex, the sound noise analysis can be understood as to find the vortex. However, the vortex is difficult to define clearly. In this study, the Vorticity is selected in visualizing the vortex rather than Q-criterion because the Vorticity is more clear and direct in velocity field. The level of intensity of Vorticity is not certain but trial. The SPL of volumetric Proudman is valuated in comparison with Vorticity.

When considering the acoustic fluctuation which is time derivative of pressure, there are many potential small parts of Vorticity which contain the sound energy in broadband frequency region. The SPL is distributed along the low to high frequency spectra. Even though low speed, cruising vehicle produces vortex flow around the body into the air. There are more aerodynamic Vorticity, if the turbulent flow, which is caused by the flow separation in higher speed, exists. Among the Vorticity, the higher pressure fluctuating particles can be emitted from the vehicle body to high frequency. And there are complex vortical structures impinging in local and global pressure fluctuations on the body part and road ground surface either which feed the acoustic high frequency turbulence-structure interaction. The buffeting noise, due to the open sunroof or side window, can be caused by an unsteady shear flow which was result in the periodic convection of large-scale vortices over the cavities. The time varying vortex shedding on the vehicle body also can produce a low frequency sound noise. The trailing edge noises can occur 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 vortical structures into fine turbulent structures. 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 BNS model can calculate the approximate SPL in volumetric turbulent flow for quadruple. The Proudman model can be used for BNS. As long as the turbulent flow is accurate or acceptable, the converted volumetric SPL shows the sound noise information of location and intensity. Thus fundamentally, the applicability and accuracy of Proudman BNS model deeply can rely on the steady or unsteady RANS solution, not the aero-acoustic analogy itself. If the data for the Proudman model is close to that of time varying flow, the resulting information of sound noise by the Proudman BNS model can be more accurate.

But the fundamental solution of steady RANS solution, which uses the turbulent model, can not be related to unsteady DNS, or similar. Even though URANS is used, the turbulent flow of vortex is highly different from the others. The reason of approximation of BNS model is not dependent to the theory but the turbulent flow prediction which obtained from the approximate CFD analysis.

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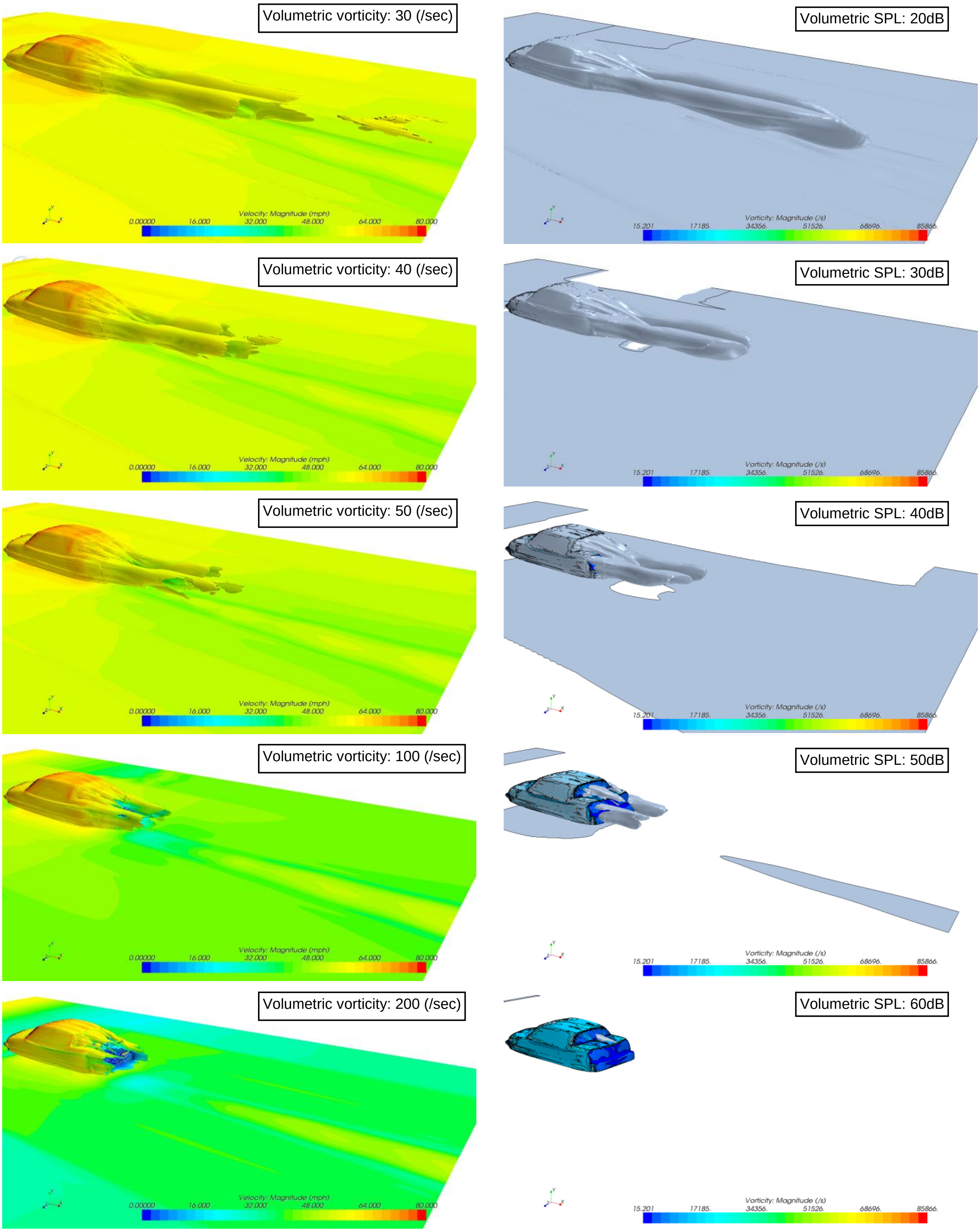

(a) Volumetric Vorticity

(b) Volumetric sound pressure level

Fig.9 Volumetric quadrupole noise source: Proudman model

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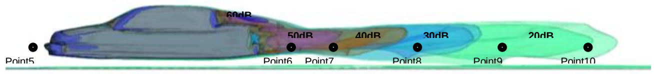

(a) Volumetric Vorticity

(b) Volumetric sound pressure level
Fig.10 Overlapped sound noise sources

Fig.9 shows the steady state Vorticity and volumetric SPL obtained from the Proudman BNS model in various Vorticity and SPLs. The predicted volumetric SPL means the volumetric area of equal noise intensity. The results of Fig.9 present the important information for sound noise source. The location of higher SPL is located near the rear vehicle in vortex wake and the shape of it is highly related to the volumetric Vorticity values. High to low Vorticity iso-surfaces demonstrate the sound noise sources which contain different SPL. As the values of Vorticity are decreasing, the area of it and related SPL also increase, and explains the characteristics of broadband distribution of sound noise. The sound noise is distributed on high frequency range. Thus, the Proudman BNS model can represent the upper bound of broadband sound noise quantities. In order to get consistency, the BNS model must be less dependent to the grid quality or resolution. The frequency for unsteady pressure fluctuation and SPL are highly dependent to the sound or acoustical wave length. To get accurate data of that in high frequency range, the more number of grids with smaller unit grid length must be used. But these requirements for unsteady simulation in enough time periods may be not available or possible in many of engineering and research capacity. In vehicle design process, the easy and quick solution is acceptable. The results of approximate Proudman show reasonable and acceptable information for near to far-field sound noise propagation. The results of the BNS model must be relied on the RANS turbulent model which the SST-turbulent model was used in this study to predict the near-wall instability of separation. The volumetric higher SPL is mainly near the vehicle which shows higher Vorticity or velocity field or turbulent flow from vehicle rear area. Fig.10 shows the comparative overlapped images for Vorticity and SPL. The properly choused Vorticity values are good agreement with volumetric SPL.

The steady state CFD solution can be said as the averaged mean flow without time varying fluctuation. The unsteady flow represents the time dependent characteristics. The flow vortex can be different according to the adopted numerical scheme for LES, URANS, or DES. Fig.11 presents the Vorticity iso-surface for steady and unsteady state respectively. LES with Smagorinsky-Subgrid Scale (S-SGS) sub grid scales were used for time dependent simulation for pressure fluctuation and acoustic. The bounded-central difference scheme was selected for convection term.

The unsteady vortex shedding is impinging to the road ground surface in far away from the vehicle which can not be seen in steady state. Lower value of Vorticity iso-surface is not distinguishable but similar and combined very close. Thus, Vorticity iso-surfaces of 30 to 50 in an unsteady case are similar. But larger periodically rotating vortex shedding is prevailing. Compared with steady state, the sound energy can be largely distributed over the wider area of bounded road ground surface. Due to the complex vortex shedding phenomena in unsteady LES simulation, there might be wider SPL distribution along the broadband frequency range. From the result of Fig.11, if the SPL of Proudman is theoretically correct, the SPL of unsteady state can be predicted using the steady state Proudman model. Approximately, the steady SPL of 200-Vorticity value is 60dB from Fig.9 and Fig.10. Likewise, 100Vorticity value is 50dB, and 30-Vorticity value is 20. As long as the assumption is valid, similar SPL can be obtained from the unsteady simulation.

The unsteady pressure fluctuation has sound noise source energy. Usually, the intensity of acoustic fluctuation is recognized by SPL in frequency range. The Fourier transform is used to evaluate it from time domain by using recorded point pressure time history. The pressure fluctuation at each points are illustrated in Fig.12(a). The defined points are described in Fig.3. Five of them are the front of vehicle and the rest of them are behind. Thus, the characteristics of aerodynamic and resulting aero-acoustics are obtained, if the characteristics of recorded data investigated. The steady state results, which were illustrated in Fig.4 to Fig.11, can give approximate information of the unsteady acoustic characteristics. Far away from the vehicle, such as Point10, does not have higher value of Vorticity. Around Point10, only weak vortex shedding is emitted. And the points of the front vehicle are not surrounded by the vortex, but only free-stream air flow is passing through. Thus, the lower SPL of the front of the vehicle is expected than behind of it. When investigating the points pressure fluctuation in Fig.12(a), it is hard to classify or predict the acoustic quantities. The most of point pressure fluctuations are similar to see. After transforming the data of time to frequency range, those point data can be classified more clearly. Fig.13 represents the selected results for Point5, Point6 and Point10. The SPL at each point is similar in low frequency range up to 200 Hz. After that, the SPL started to branch. At the highest frequency of 5K Hz, the SPLs are 45dB, 25dB, 20dB for Point6, Point10 and Point5 respectively.

These obtained SPL for Point6 and Point10 are in approximate agreement with steady state results which were obtained from the Proudman BNS model, when investigating the compactly overlapped image of Fig.10. The steady state CFD solution can not make unsteady acoustic fluctuation exactly. But the overall SPL distributions are similar to the unsteady result in frequency range.

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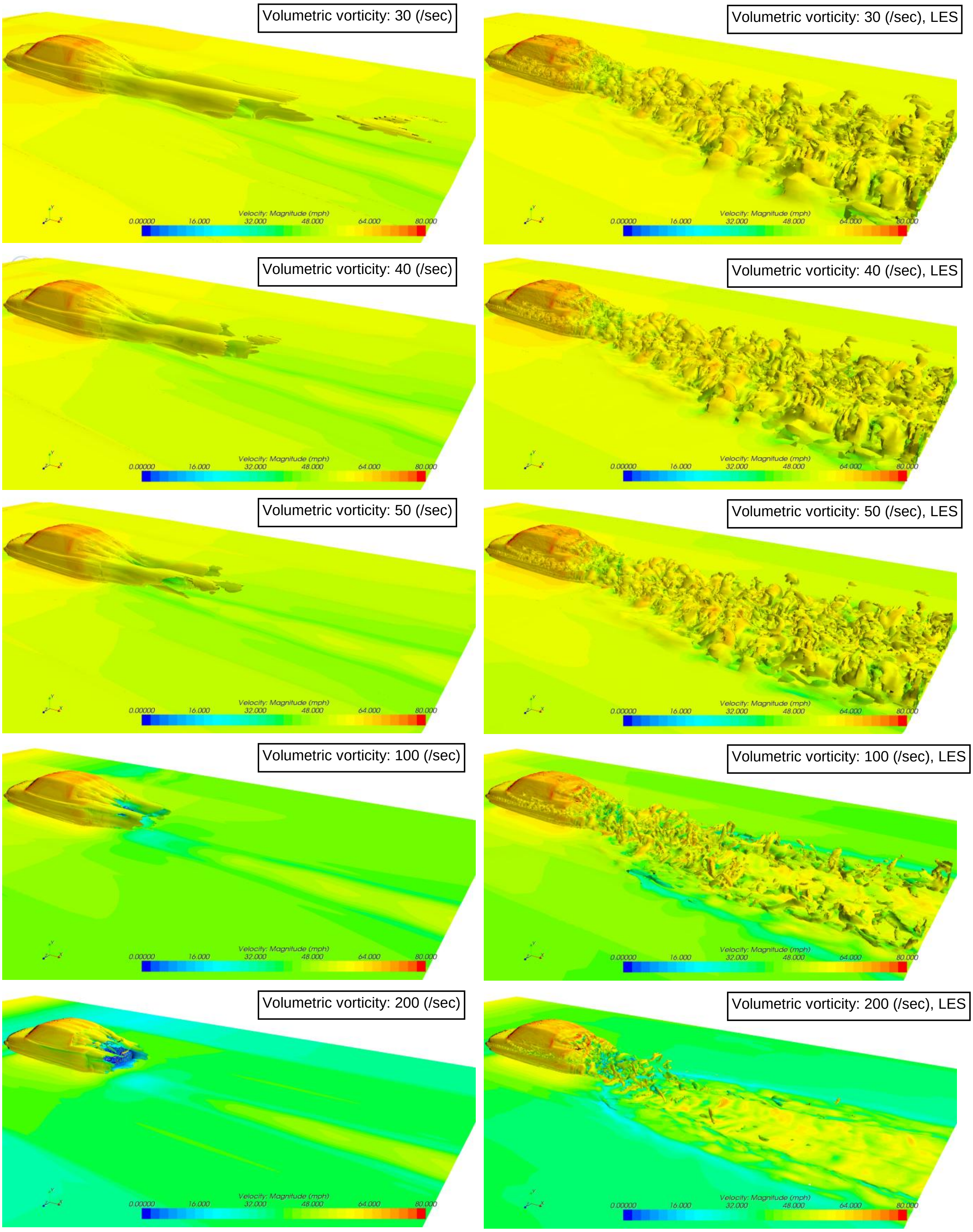

(a) Steady state (RANS) **(b) Unsteady state (LES)**

Fig.11 Volumetric Vorticity for steady and unsteady state

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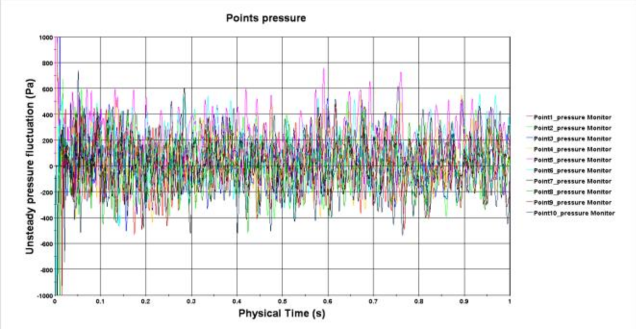
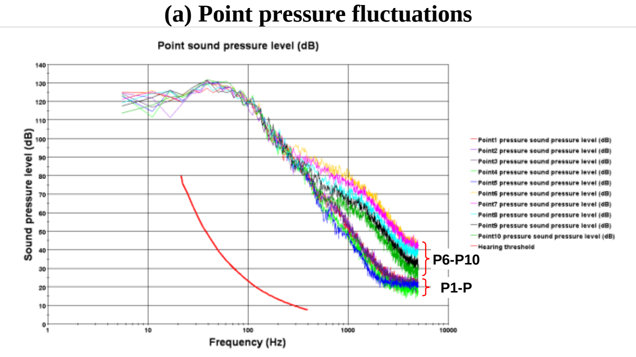
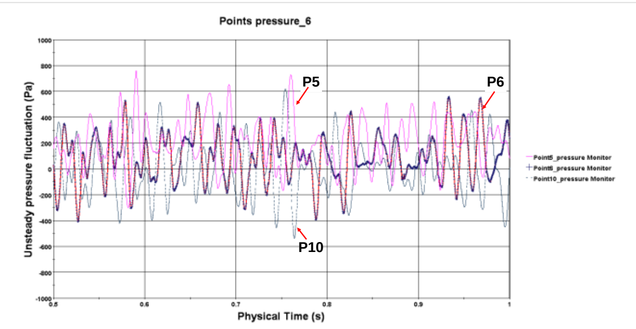


(a) Point pressure fluctuations

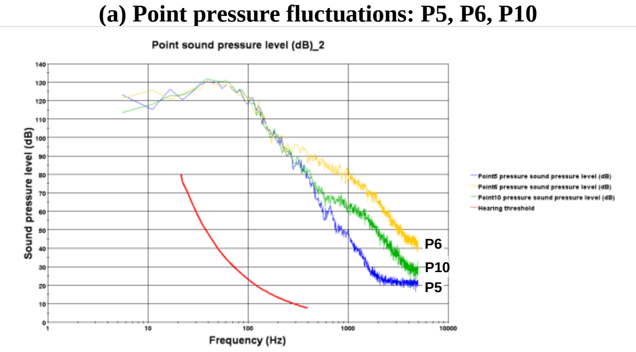


(b) Points sound pressure level (dB)

Fig.12 Point pressure fluctuation and corresponding sound pressure level (dB)



(a) Point pressure fluctuations: P5, P6, P10



(b) Points sound pressure level (dB): P5, P6, P10

Fig.13 Selected point pressure fluctuation and corresponding sound pressure level (dB)

As explained before, sound energy is contained in broadband range of frequency in turbulent flow or aerodynamic flow. The Proudman model uses the concept of aero-acoustic analogy, which consists of replacing the actual flow field responsible for generating noise with an equivalent system of volumetric noise sources. The noise sources act on a uniform stagnant fluid that is governed using standard acoustic propagation equations. The represented sound noise is idealized or maximum acoustic values that can be obtained in aero-acoustic field. The grid model in this study is not the dedicated model because of computing resource limitation. There are errors and mismatches between the SPL in steady and unsteady. But a finer quality grid model will increase the intensity of SPL in higher frequency range.

VII. CONCLUSION

In this study, the Proudman approximate broadband noise source model, which is easy and efficient, was adopted with the SST-turbulent model for steady state solution. LES simulation was performed for unsteady pressure fluctuation information. The Proudman SPL was coincident with steady state vortex which was identified by Vorticity rather than Q-criterion. It was expected that more numbers of grids for higher quality mesh can increase the Proudman result for SPL iso-surface. But the Proudman model is for broadband nature for higher frequency. It is rather highly dependent to the vortex flow or steady state CFD results. The accuracy and applicability of the Proudman BNS model might be more dependent to the RANS turbulent model.

Compared with steady state, the unsteady state pressure fluctuation for acoustic fluctuation was complex and difficult to classify in time domain. After transforming the pressure fluctuation into frequency range, the SPL was distributed along the frequency range. The SPL of points was broadband nature in frequency spectra. The SPL of point was converged to the similar value of Proudman in high frequency range.

As a result, the approximate Proudman model adequately predicted the actual unsteady acoustic characteristics. Even though different point locations, the low frequency tonal SPL were similar or equal in tonal sound. The higher turbulent, which is for higher frequency range sound noise, was branched from 200 Hz in current grid model. Aero-acoustic characteristics of the current study are highly and directly dependent to the CFD analysis in both of steady and unsteady solution. It is well known the frequency of air-fluid domain is dependent to the grid size. To get accurate aero-acoustic characteristic in high frequency range of broadband region, more numbers of grids for high quality fluid domain should be used, but it is not easy in many cases. There are possibilities of converging aero-acoustic SPL of unsteady state solution which was obtained by using LES to the steady state Proudman model. From the study, approximate and acceptable distribution of acoustic information for unsteady pressure fluctuation could be obtained by performing the Proudman BNS model. In a future study, a higher quality grid model will be used to validate the Proudman's broadband characteristics which can predict the unsteady value. By using the proper and adequate steady state RANS turbulent model, the results of the Proudman model will give accurate information for unsteady SPL in broadband higher frequency range.

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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] 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.

[12] N. Curle, "The Influence of Solid Boundaries upon Aerodynamic Sound", Proceedings of the Royal Society of London, series A, Mathematical and Physical Sciences, vol. 231, pp. 505-514, 1955.

[13] I. Proudman, "The Generation of Noise by Isotropic Turbulence", Proc. R. Soc. Lond. vol. **214**, pp. 119-132, 1952.

[14] G. M. Lilley, "The radiated noise from isotropic turbulence revisited", NASA Contract Report No. 93-75, NASA Langley Research Center, 1993.

[15] S. Sarkar, and M. Y. Hussaini, "Computation of the Sound Generated by Isotropic Turbulence", NASA Report 191543, ICASE Report No. 93-74, 1993.

[16] 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.

[17] 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.

[18] 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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