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NOISE CONTROL FOR A BETTER ENVIRONMENT

Numerical study on the effect of transient wind conditions on the automotive aeroacoustic performance

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ABSTRACT

Real driving conditions of an automotive vehicle can generate time-varying and spatial modulating aeroacoustic characteristics, which is different from the result obtained by the aeroacoustic wind tunnel test and numerical simulation process with the well-controlled inflow condition. In this study, transient inflow toward a driving vehicle is focused on for exploring wind noise perturbation phenomena under actual atmospheric environments. The transient flow condition around a real driving vehicle is composed of random perturbations with turbulence intensities and lengths scales. The incoming flow fluctuations is applied to simulate the vehicle aeroacoustics, effects of major transient parameters including perturbed direction, spatial scale, and oscillating frequencies are considered. The LBM based numerical study can figure out the transient wind condition increases interior wind noise level in the high frequency range. Transient inflows strengthen major wind noise sources of A-pillar vortex and outside mirror rear wakes. Each effect can be analysed by comparing flow structures in the averaged domain and pressure fluctuation patterns in the frequency domain.

Keywords: Wind Noise, Transient Wind, On-road Turbulence
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1. INTRODUCTION

A driving vehicle on a paved road generates various kinds of noise induced by powertrain movements, impacts by road surface and tyres, and interactions between an exterior shape and air flow. Each noise phenomena has its own characteristics of tonality, frequency envelop, and source-transfer path relation. Relation between source and transfer path can divide two kinds of noise, structure-borne and air-borne. As a representative air-borne noise in a driving vehicle, wind noise can be defined as acoustic pressure transmission into a car interior area generated by complicated interaction between surfaces of a high-speed driving vehicle and atmospheric environment at rest or at quasi-rest. Vehicle wind noise can be quantified and reduced in the conventional development process of an automotive industry, especially by mimicking real driving condition on a proving ground and acoustic wind tunnel. But it is difficult to consider transient characteristics of the real driving condition as a quantitative inflow condition. It is because atmosphere always changes, pressure distribution on local ground area becomes temporally uneven, as a result, and air flows are perturbed with various temporal and spatial scales. The transient wind conditions can make a vehicle wind noise worse or more easily recognizable.

The transient flow around a driving vehicle, at first, was studied as one of the important factor of driving stability especially at high speed ranges. Aerodynamic load on a vehicle body can be exponentially increased as faster driving. As atmospheric conditions become more unsteady, large amount of aerodynamic loads make more perturbed forces on a vehicle, which severely threaten driving controllability and stability. Therefore, the characteristics of aerodynamic loads under unsteady airflow condition were studied and it was tried to imitate and analyse the unsteadiness in wind tunnel facilities[1-4]. Especially, the concepts of transient properties were established and investigated by developing multi-position air flow measurement system with high precision 3-D flow velocity sensors[5], measuring and analysing actual atmospheric turbulence characteristics on various environmental conditions[6-8,13-14]. Many studies tried to consider the transient flow condition in a vehicle wind noise performance. With the unsteady flow generator[8-9] or the real road test[10-12], transient inflow condition to a test vehicle can change interior noise characteristics in the sensitivity of yaw angle changes (a vehicle's angle of attack), temporal modulation tendencies, and frequency domain envelopes.

In this study, aeroacoustic characteristics under transient wind conditions including perturbed direction, spatial scale, and oscillating frequencies are investigated by the numerical study, which can show more detailed changes of fluid structures in comparison with the results of stationary inflow condition. Theories on the transient inflow conditions are based on intensive researches of on-road turbulence measurements and quantitative analysis[13-14]. The numerical method by the lattice Boltzmann method was established by previous studies on aerodynamic analysis under transient airflow conditions[15-16].

2. NUMERICAL METHODS

2.1 Aerodynamic and aeroacoustic simulation

Numerical simulation is performed to explore aeroacoustic phenomena generated by aerodynamic behaviour of a driving vehicle. The lattice Boltzmann method (LBM) is applied to simulate 3-D unsteady compressible aerodynamics and aeoracoustics, which is known to high efficiency in parallel computing with hundreds million scale mesh size and high accuracy in the unsteady aerodynamic and aeroacoustic computation[17]. LBM, developed in the view point of mesoscopic particle physics, is based on the Lattice-Boltzmann equation approximated by the Bhatnagar-Gross-Krook(BGK) form as follows[18-19]:

$$f_i(\bar{x}+\bar{c}_i\Delta t, t+\Delta t) - f_i(\bar{x},t) = -\frac{\Delta t}{\tau}\left[f_i(\bar{x},t) - f_i^{eq}(\bar{x},t)\right] \qquad (1)$$

where f_i is the distribution function of particles at position *x*, and velocity c_i in direction *i* and at time *t*. The left side of equation 1 means the particle advection, while the right side represents the relaxation of the particles to the equilibrium state f_i^{eq}. The relation between relaxation time τ and kinematic viscosity v is written as $\tau = (v+0.5)/T$.

The commercial CFD/CAA software based on LBM, PowerFLOW, is applied to simulate a road vehicle aeroacoustics under the transient inflow condition. Especially, pre-determined simulation parameter setup[20], derived by the validation study with aeroacoustic wind tunnel experiments, is used to guarantee numerical accuracy and physical correlation for the unsteady simulation immersing in the transient upstream condition. In this study, the numerical setup for wind noise of a compact sedan includes 10 variable resolution (VR) regions, 264M voxels with minimum voxel size of 1.0mm, 5.83e-06 sec for l time step, and total simulation time of 3.0 sec.

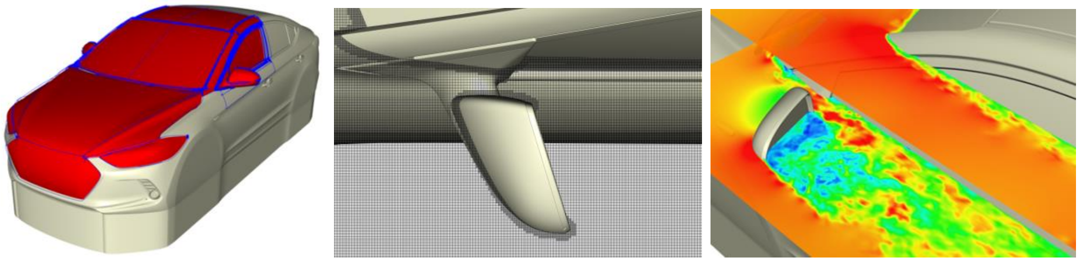


Figure 1. LBM simulation setup: [left] VRs - VR 9 (blue) and VR10(red); [center] cube voxel distributions; [right] simulation result for instantaneous flow (velocity magnitude)

2.2 Transient inflow condition

Atmospheric turbulent flow has complicated characteristics of time varying and spatial modulating, which has difficulty to solidify any quantitative properties. Stochastic approach can help simplifying and defining temporal and spatial changing phenomena. In this study, turbulence intensity, spatial length scale and spectrum parameters are changed as transient upstream properties, which are based on previous studies[6-7,13-14]. Turbulence intensity (I) and length scale (L_x) are defined as:

$$I = \sqrt{\frac{1}{3}\left(I_x^2 + I_y^2 + I_z^2\right)} \qquad where \quad I_x = \frac{\sigma(V_x(t))}{V_{ref}}$$

$$L_x = V_{ref}\frac{\int_0^{T_0} R_{uu}d\tau}{R_{uu}(0)}$$

where I_x, I_y, I_z are turbulence intensity of each direction of *x*, *y* and *z* axis respectively, $\sigma(\cdot)$ is standard deviation, V_{ref} is driving speed (characteristic velocity), R_{uu} is time autocorrelation of the *x*-velocity as a function of lag time (τ) in units of velocity squared, and T_0 is the lag time of the first zero crossing.

Figure 2 depicts transient inflow conditions in the time and frequency domain. Transient simulation of this study considers 8% of the turbulence intensity in 3-D directions, which can be similar as strong traffic condition according to the study in the German highway study[8]. Length scales *x*, *y* and *z* directions are 6.4m, 1.4m and 1.8m, these values are determined for length scale enough to cover a whole car and to minimize the effect of road turbulence eddies' size to the vehicle. These upstream setup parameters can be categorized as freeway traffic with a few road side obstacles condition in the study in the Australia[13-14] as shown in figure 3.

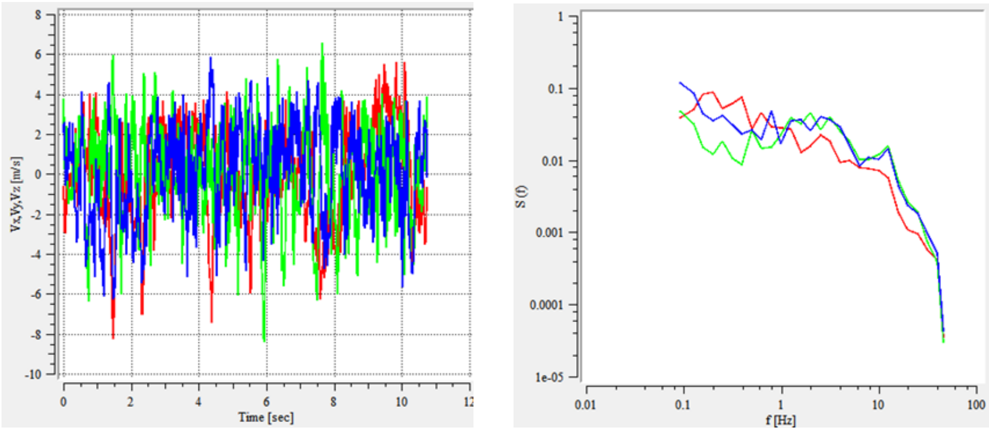


Figure 2. Transient inflow conditions: (left) temporal behaviour of x-,y-, and z- velocity, (right) frequency characteristics expressed by power spectral density (red: x-velocity, green: y-velocity, blue: z-velocity)

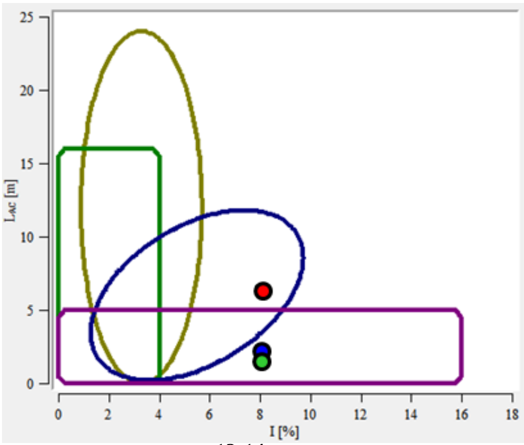


Figure 3. On-road turbulence classification[13-14]: dots represent turbulence intensity and length scale of this study; Red-, green-, and blue-dot indicate x-, y-, and z- velocity respectively. Lined areas categorize specific on-road conditions; olive-, green-, blue-, and violet-coloured area mean smooth terrain, city canyon, road side obstacles, and freeway traffic situation, respectively.

3. RESULTS AND ANALYSIS

3.1 Comparison of steady and transient inflow condition

Computational aeroacoustic study provides spectral contributions of perturbed pressures and velocities, which can become important wind noise sources. Figure 4 shows instantaneous velocity field in the uniform and transient inflow conditions. It is not easy to capture differences in the complicated vortex structures, but it could be found that the mirror wake structures are broken down to smaller and more complicated eddies in the transient case. Averaged flow structures in Figure 5 can make us estimate overall flow characteristics. Air flow behaviours passing vehicle's surfaces remain pressure distribution patterns, which can indicate the importance of A-pillar vortex and outside rear wake as the most crucial wind noise source and determine overall size or strength of wind noise sources. Comparison of static pressure distribution (Figure 5) informs that transient flows can increase A-pillar vortex affecting area along the A-pillar and change outside mirror wake region.

Frequency domain analysis emphasises the differences due to upstream turbulences. Figures in Table 1 can compare the strength of pressure fluctuations in the frequency domain (in these figures, 1-octave band scales). We should focus on two important regions in the door side glass surface, one is A-pillar vortex area along the A-pillar, and the other is mirror wake region in the back of the outside rear view mirror. First of all, transient inflows increase the strength of A-pillar vortex, which is dramatically observed in the 500 *Hz*- and 1000 *Hz*-band results. In the mirror wake region, overall strengths of pressure fluctuations are similar between two cases, but the wake eddies' distribution pattern of the transient condition has much more complicated edges, which can be thought as the important cause of noise annoyance. The transient flow components around a driving vehicle stimulate turbulence cascading phenomena, as a result turbulent eddies become smaller and irregular.

Interior noise transmitted into a vehicle cabin space by various pressure fluctuations on the wind shield and door glass surfaces is calculated by one of vibroacoustic simulation methods, SEA (Stochastic Energy Analysis). Figure 6 compares interior transmitted noise level between uniform and transient cases, which shows that transient inflow strengthens aeroacoustic noise sources and generates more wind noise and its negative effect covers broad band frequency region, especially higher frequency bands.

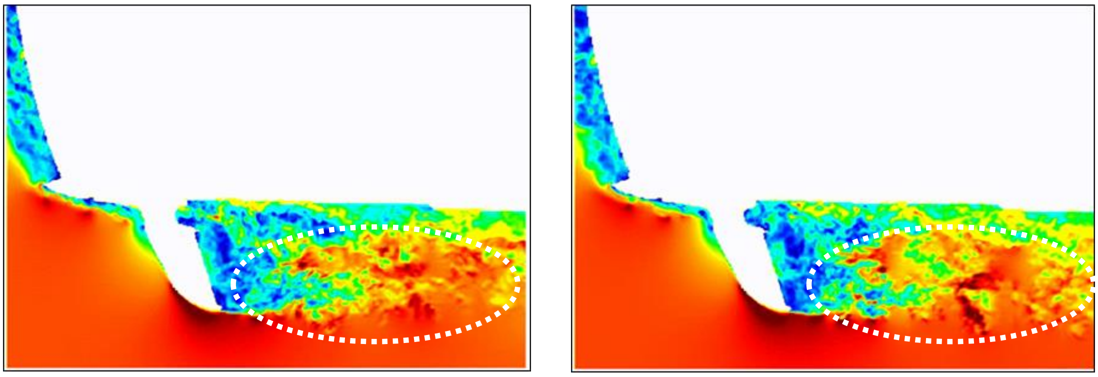


Figure 4. Instantaneous velocity magnitude field in the uniform(left) and transient(right) inflow conditions

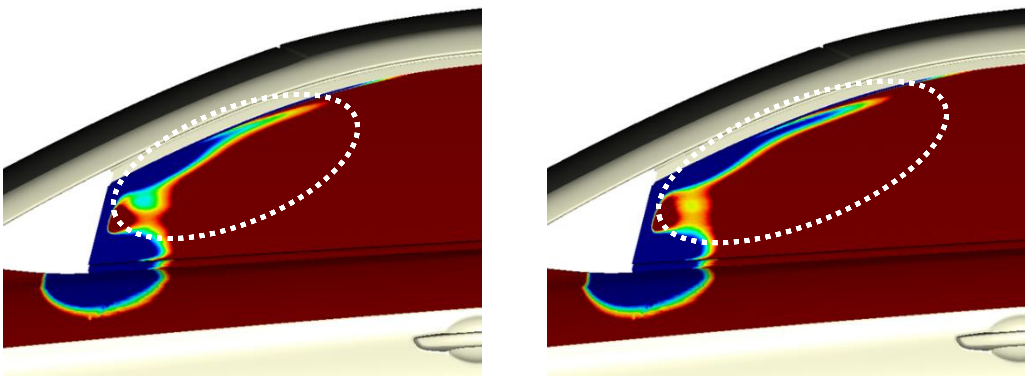
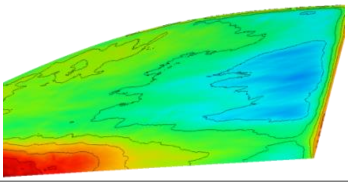
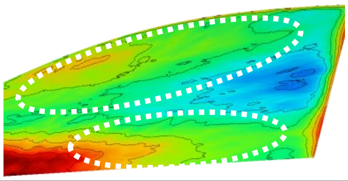
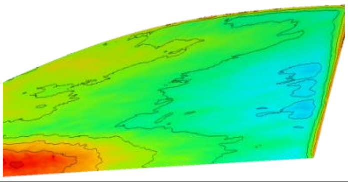
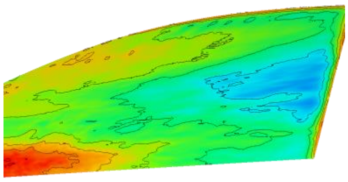
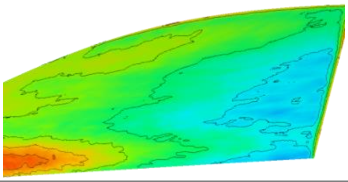
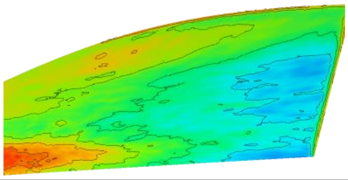
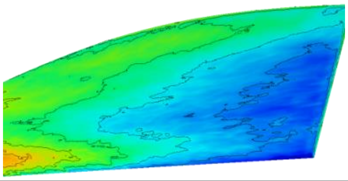
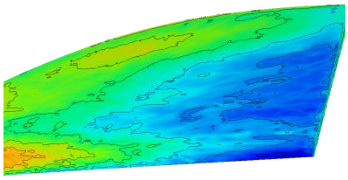
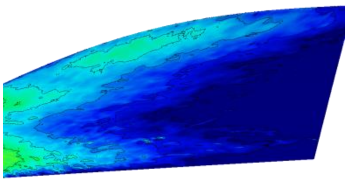
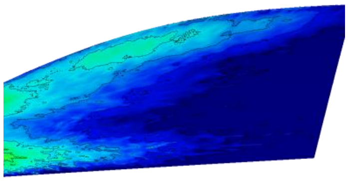


Figure 5. Averaged flow structure of static pressure in the uniform(left) and transient(right) inflow conditions

Table 1. Frequency analysis of pressure fluctuations on a door glass surface

	Uniform inflow	*Transient inflow*
125 Hz		
250 Hz		
500 Hz		
1000 Hz		
2000 Hz		

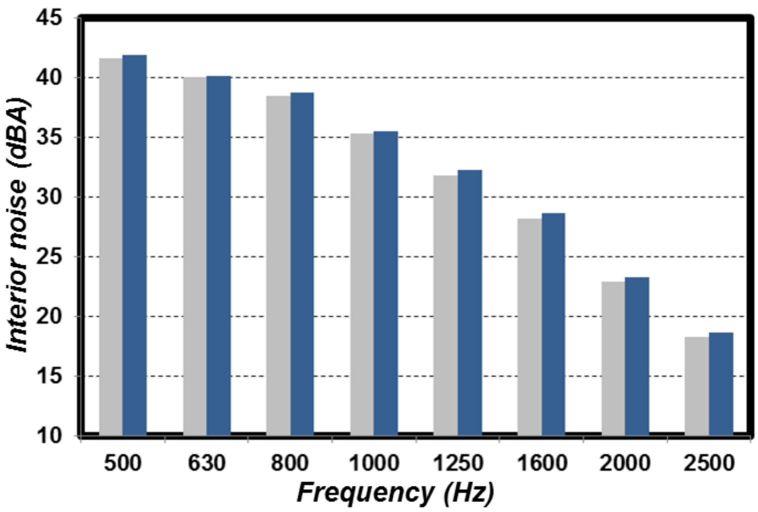


Figure 6. Interior noise level: uniform (grey) and transient (blue) inflow conditions

4. CONCLUSIONS

Turbulence on the road driving condition makes the total wind noise worse and annoying. But, the complicated characteristics of on-road turbulence cause difficulties in defining the quantitative analysis. Many researches are applying statistical properties to characterize the transient behaviour, mostly, which are turbulent intensity, length scale and frequency characteristics (especially, in the low frequency region). In this study, the effect of transient inflow condition is explored by numerical analysis based on LBM. It is found that the transient inflow condition makes A-pillar vortex more strengthen, eddy structures rear outside mirror more complicated, and interior noise level increased.

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