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Comparative analysis of surface pressure fluctuations of high-speed train running in open-field and tunnel using LES technique and wavenumber-frequency analysis

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ABSTRACT

The high-speed train interior noise induced by exterior flow field is one of critical issues for product developers to consider in a design state. The reliable numerical prediction of noise in a passenger cabin due to exterior flow requires decomposition of surface pressure fluctuations into the hydrodynamic (incompressible) and the acoustic (compressible) ones as well as the accurate computation of near aeroacoustic field, since the transmission characteristics of incompressible and compressible pressure waves through the wall panel of the cabin are quite different from each other. In this paper, the characteristics of surface pressure fluctuations of high-speed train are compared between two cases: one is that it cruises in an open-field and the other is that it is running in a tunnel. First, LES (Large Eddy Simulation) techniques were employed to predict exterior flow field including accurate near acoustic field around a high-speed train. Then, pressure fluctuations on the train surface are decomposed into incompressible and compressible ones using the wavenumber-frequency analysis. Lastly, the power levels due to each pressure field are estimated and compared. It is found that there is no significant difference in the power levels of incompressible surface pressure fluctuations between two cases. However, the decomposed compressible one in the tunnel case are about 7~10dB higher than that of the open-field case.

Keywords: High-speed train, EMU320, Wavenumber-frequency analysis, Wind noise
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1. INTRODUCTION

High-speed trains have been competitively developed around the world since the first line was launched in Japan in 1964. The competition is accelerated after the running speed of the French high-speed train TGV V150 exceeds 574.8km/h. Because it manifests the technological superiority over others, a lot of relevant researches are carried out between worldwide manufacturers to develop faster trains. However, as the running speed of high-speed trains increased, noise emissions also increased and especially the aerodynamic noise contributes more significantly than the tradition rolling noise.

Recently, several studies[1-5] were carried out on the aerodynamic noise of the high-speed trains. The common results are that the first bogie, the first pantograph, the first inter-coach space are main aerodynamic noise sources. However, these studies used simplified body model or only single part and focused only on external radiated noise.

The ultimate goal of this study is to develop the reliable systematic numerical methods for the prediction of the interior cabin noise of a high-speed train. In the present study as a first step for achieving the ultimate goal, the systematic numerical methodology is presented to obtain separated incompressible and compressible surface pressure field in the frequency-wavenumber domain. The proposed method is applied to the cases where the high speed train runs in an open field and a tunnel. The target train is the EMU 320 running at the speed of 300 km/s. First, LES (Large Eddy Simulation) techniques are employed to predict flow field including acoustic field around a high-speed train. Second, pressure fluctuations on the train surface are decomposed into incompressible and compressible ones using the wavenumber-frequency analysis. Lastly, averaged PSD (Power Spectral Density) levels of decomposed incompressible and compressible surface pressure are compared between two cases.

2. NUMERICAL METHOD AND TARGET MODEL

2.1 Large Eddy Simulation

In this section, the LES is briefly introduced. To predict the external flow including acoustic field around a train body running in an open field and a tunnel, LES with Smagorinski-Lilly model is used for solving the governing equations. LES compute only large eddies directly and hence low-pass spatial filter is applied to the conservation equations to formulate the unsteady governing equations for large scale motion. The three-dimensional compressible unsteady filtered Navier Stokes equations with the turbulent viscosity of the Smagorinski-Lilly model can be written in the form below:

$$\begin{aligned}
&\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho\bar{u}_i)=0\\
&\frac{\partial}{\partial t}(\rho\bar{u}_i)+\frac{\partial}{\partial x_j}\left(\rho\bar{u}_i\bar{u}_j\right)=\frac{\partial}{\partial x_i}\left(\sigma_{ij}\right)-\frac{\partial\bar{p}}{\partial x_i}-\frac{\partial\tau_{ij}}{\partial x_j}\\
&\frac{\partial\rho\bar{h}_s}{\partial t}+\frac{\partial\rho\bar{u}_i\bar{h}_s}{\partial x_i}-\frac{\partial\bar{p}}{\partial t}-\bar{u}_j\frac{\partial\bar{p}}{\partial x_i}-\frac{\partial}{\partial x_i}\left(\lambda\frac{\partial\bar{T}}{\partial x_i}\right)=-\frac{\partial}{\partial x_j}\left[\rho\left(\overline{u_i h_s}-\bar{u}_i\bar{h}_s\right)\right]
\end{aligned}\tag{1}$$

$$\mu_t=\rho L_s^2\,|\bar{S}|\ where\ |\bar{S}|=\sqrt{2\bar{S}_{ij}\bar{S}_{ij}}\tag{2}$$

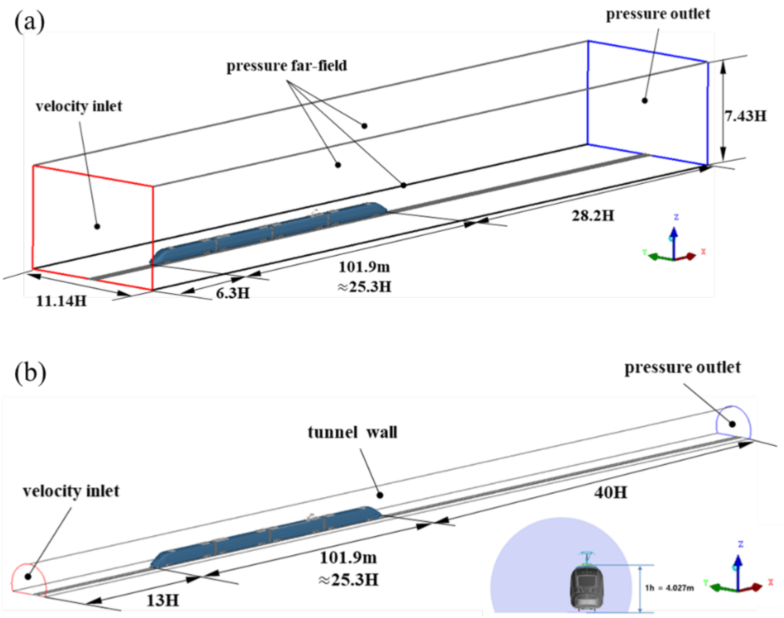

Fig. 1 – Computational domain of (a)open field and (b)tunnel cases. (1H: height of train)

Table 1 – Details on boundary setting for open field(O) and tunnel cases(T).

Case	Boundary	Setting	Remarks
O, T	Inlet boundary	Velocity inlet	83.33m/s(300km/h), non-reflecting
O, T	Outlet boundary	Pressure outlet	101325Pa, non-reflecting
O	Side and upper boundary	Pressure far field	101325Pa, Ma=0.24
T	Tunnel wall	Moving wall	83.33m/s
O, T	Ground boundary	Moving wall	83.33m/s
O, T	EMU wall	No-slip wall	
O, T	Rail wall	Moving wall	83.33m/s

2.2 Target models and details on simulation

The entire computational domains for each case with dimensions and the target train with zoomed parts are shown in Figs. 1 and 2, respectively. The applied boundary conditions are summarized in Table 1. The target train model is EMU-320 (Electric Multiple Unit-320) which is under development as a next Korean high-speed train base on the HEMU-430X high speed design unveiled in 2012. It consists of eight coaches. However, for simplicity but with out losing the main aeroacoustic source mechanism, only four coaches (TC, M'1, M'3, TC2 – car) are considered in the current study. The overall side-view of the EUM-320 are shown in the upper part of Fig. 2. The detailed geometries of the pantograph, HVAC, bogie and inter-coach which are considered to be important aerodynaimc noise sources are present in the middle and lower parts of Fig. 2. shows the target model and its modeled parts. The modelled train consists of eight bogies, two pantographs and six HVAC systems. Inter-coach spaces of EMU320 are fully shielded by outer-windshields. The front pantograph is lowered down and the rear one is rised up during the operation of train.

The computational mesh is composed of about 590, 625-milion cells made using Fluent Meshing. Tetrahedral cells are used together with 5 layers of prismatic elements near the wall surface.

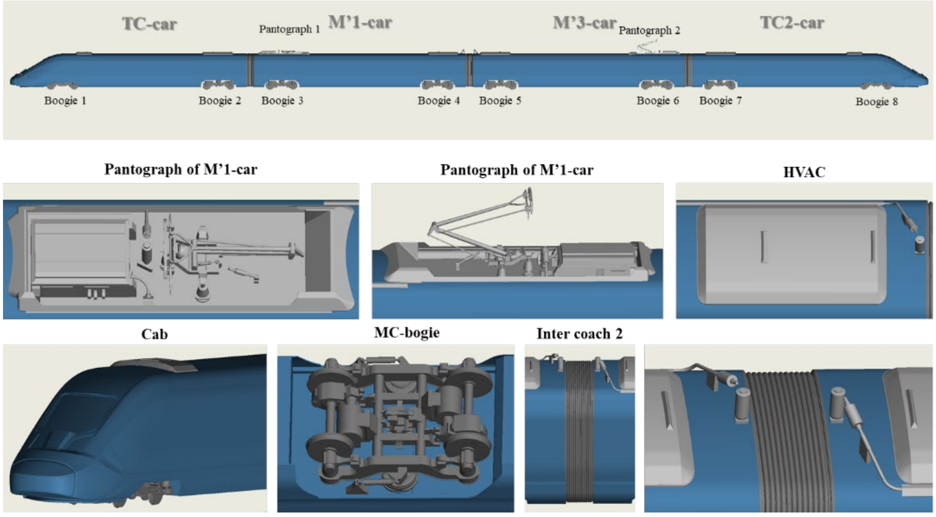

Fig. 2 – Target model(EMU320) and its details.

3. UNSTEADY FLOW RESULTS

Fig. 3 shows the instantaneous iso-contours of velocity magnitudes at the centered cross-sectional plane in both cases. It can be seen that significant velocity reduction is induced under the body and also shown that the strong separated flows cover the downstream coaches behind the TC-car. Fig. 4 shows the iso-contours of static pressure. It can be identified that the main aerodynamic sources are the bogies, pantographs and HVAC systems on the roof. However, there seems to be no noticeable difference between two cases except that the acoustic pressure wave generated from the trained is reflected off the tunnel wall in the tunnel cases.

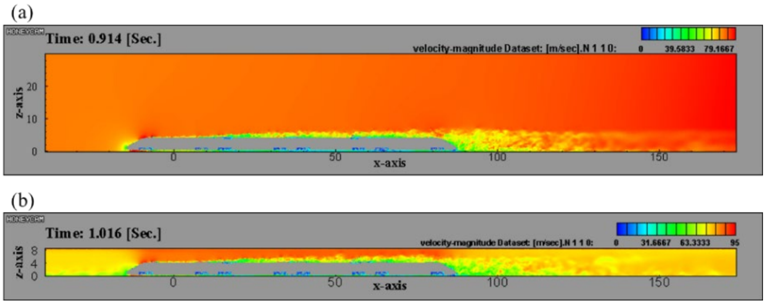

Fig. 3 – Instantaneous velocity magnitude contour of (a)open field and (b)tunnel case.

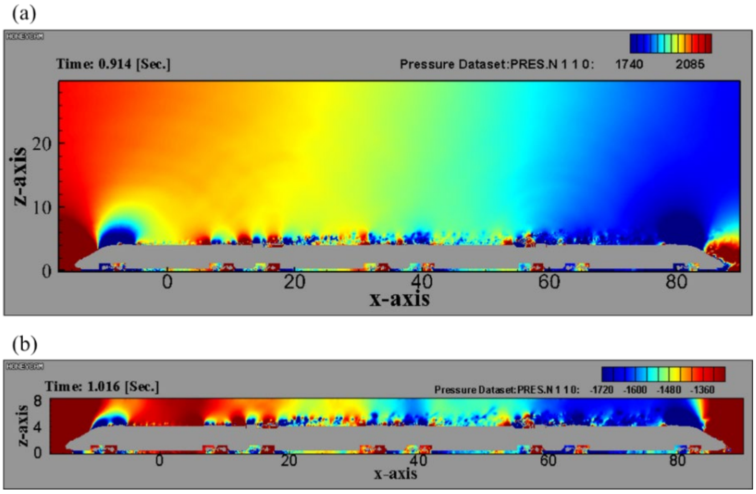

Fig. 4 – Instantaneous pressure field of (a)open field and (b)tunnel case.

4. ANALYSIS OF SURFACE PRESSURE FLUCTUATIONS

4.1 Wavenumber-frequency analysis of surface pressure

The phase speed $v_p = \omega / k$ can be used to decompose the surface pressure fluctuations into the incompressible and compressible components. The former convects at the mean flow velocity U and the latter does at the vector sum of mean flow velocity and the sound speed c. The wavenumber-frequency diagram of surface pressure fluctuation can be obtained from the Fourier transform of the surface pressure in the space-time domains. Three-dimensional discrete Fourier transform equation to obtain the three-dimensional modified periodogram can be written in the following form[6,7].

$$S_{m.n} = S(m\Delta f, n\Delta k_x, o\Delta k_y) = \frac{\Delta x \Delta y}{N_t N_x N_y F_s} \left| \sum_{k=0}^{N_t-1} \sum_{l=0}^{N_x-1} \sum_{j=0}^{N_y-1} w_{klj} P_{klj} e^{-2i\pi\left(\frac{km}{N_t} - \frac{nl}{N_x} - \frac{oj}{N_y}\right)} \right|^2 \Bigg/ \frac{1}{N_t N_x N_y} \sum_{k=0}^{N_t-1} \sum_{l=0}^{N_x-1} \sum_{j=0}^{N_y-1} \left| w_{klj} \right|^2 \quad (3)$$

w_{kij}: hanning window

In the three dimensional periodograms, the incompressible and compressible parts can be separated by using the slanted Dirac cone which is written in the form,

$$\omega = c_0 \sqrt{k_x^2 + k_y^2} + k_x u_0 \quad (4)$$

The wavenumber-frequency analysis is conducted by applying Eq. (3) to the predicted total pressure field on the surfaces of the train. The sampling rate f_s and the frequency interval Δf are 5000Hz and 4.88Hz, respectively.

4.2 Results of wavenumber-frequency analysis

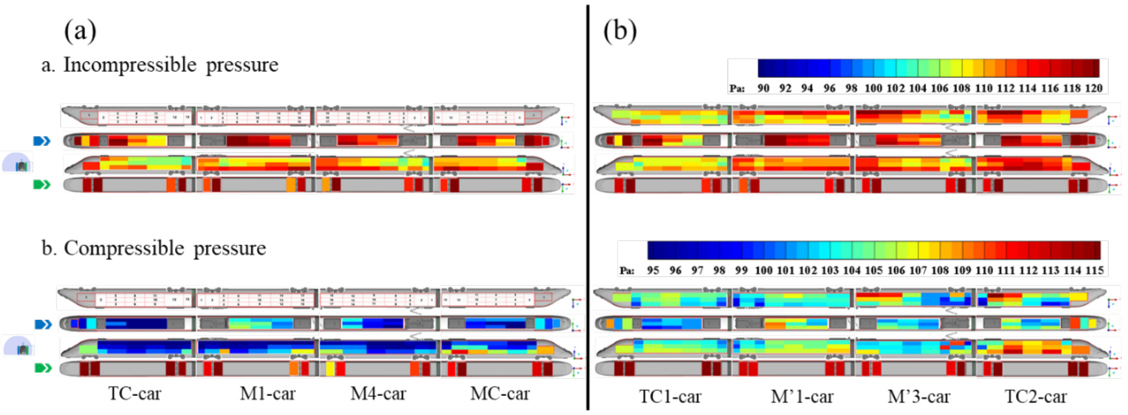

Fig. 5 – Averaged PDS levels of each incompressible and compressible surface pressure fluctuations: (a)open field case, (b)tunnel case.

In order to quantitatively analyse and compare characteristics of surface pressure fluctuations of a high-speed train between two case: cruising in the open field and in the tunnel, the averaged PSD levels of incompressible and compressible pressure fluctuations are shown on each sub-section of train surface in Figure 5. It can be found that there is no significant difference in the PSD levels of incompressible surface pressure fluctuations between two cases but the decomposed compressible ones for the tunnel case are about 7~10dB higher than that for the open-field case.

5. CONCLUSIONS

In this paper, the characteristics of fluctuating surface pressure on the high-speed train, EMU320 running at the speed 300km/h in an open field and a tunnel was investigated by using the high-accurate LES technique combined with wavenumber-frequency analysis. Exterior flow field including compressible acoustic components around the EUM320 is computed by using the LES with approximately 600 million of grid cells. The predicted flow field results shows the dominant aerodynamic source regions: pantographs, bogies, and HVAC systems. There is no noticeable difference between two cases in terms of total pressure distribution, except that the aerodynamic noise radiated from the above-described sources of the train running in the tunnel is confined inside the tunnel and thus behaves like waves in a pipe. In order to decompose surface pressure fluctuations into incompressible and compressible ones, the wavenumber-frequency analysis was performed on the surface pressure field on the train. The decomposed incompressible and compressible pressure fields between two cases are compared in terms of PSD levels. The predicted PSD levels of compressible pressure fluctuations in the case of a train cruising in the tunnel are approximately 7~10dB higher than that of a train running in an open field, while there is no significant difference between two cases in terms of incompressible pressure levels. .

A future study aims to incorporate the decomposed surface pressure fields for the prediction of interior cabin noise of the high-speed train. The result can be utilized to assess the relative contributions of the incompressible and compressible surface pressure fields to the interior noise and thus helps to develop an effective design of cabin structure for the reduction of interior noise.

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