NEW METHODS FOR THE PREDICTION OF THE MICRO-PRESSURE WAVE BY A HIGH-SPEED TRAIN ENTERING A TUNNEL

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Abstract

The compression wave generated by a high-speed train emerges from the exit portal of the tunnel, causing an impulsive noise called micro-pressure wave. In this study, we proposed new methods for the prediction of sonic-boom noise. First presented method is acoustic monopole analysis/Kirchhoff method. The compression wave by a train entering a tunnel is calculated by an approximate compact Green's function, and resultant noise at the tunnel exit is predicted by Linear Kirchhoff formulation. After Euler equations are first solved for the generation and propagation of the compression wave, the Kirchhoff formulation is also used for the prediction of acoustics at far field from the flow field data. The numerical prediction of compression waves and micro-pressure waves obtained by the present methods are compared with experimentally measured data. They show a reasonable agreement with each other. The proposed method in this study is shown to be a very useful tool to design the nose shape of a train and the geometry of a tunnel since it minimizes the pressure fluctuation in the tunnel and the corresponding booming noise.

1. Introduction

When a high-speed train enters a tunnel, compression waves are generated due to the abrupt change of cross sectional area. When the wave-front of the compression wave arrives at the exit of the tunnel, a pressure pulse is radiated out, which is stiff impulsive noise causing an important environmental problem. This pressure pulse (or "micro-pressure wave") often results in structural damage and much annoyance near the exit.. In this paper, new methods to predict the micro-pressure wave are proposed. First, CFD (Computational Fluid Dynamics) technique is combined with a Kirchhoff formulation. An Euler finite difference solver is first executed, from which the near-field flow data obtained. The data are then transferred to the linear Kirchhoff formulation to predict the far-field acoustics. Second, Howe's theory predicting the entry compression wave[1,2] is also combined with a Kirchhoff formulation. The propagation of pressure wave is numerically simulated by the method of characteristics, which is called acoustic monopole analysis. The proposed methods are compared with each other and validated with experimental data obtained in the Train Test Facility(T3F) at National Aerospace Laboratory (NLR) in the Netherlands.

2. Acoustic monopole analysis

Rayleigh's method for the approximate calculation of potential flow from the open end of semi-infinite flanged cylinder is used to obtain the analytical representation of the compression wave by train entering a tunnel.[1,2] This analytical method can consider the nose shape of train and arbitrary cross-section of tunnel. The nose shape is modeled as distribution of a monopole line sources. Equation (1) describes the generation of a compression wave during the passage of train nose into the tunnel before the onset of nonlinear steepening during the propagation along the track.

$$p \approx p(x,t) = \frac{\rho_0 U}{A} \int q(\vec{x}' + U[t], y', z') \frac{\partial \phi^*(\vec{x}')}{\partial x} d^3\vec{x}' \qquad (1)$$

where $q(x)$ represents the strength of monopole source; $\phi^*(x)$ describes the potential flow inside and outside the tunnel; $p(x,t)$ is pressure and ρ_0 and U is density and velocity of train, respectively. The propagating compression wave is numerically predicted using the methods of characteristics.[3]

3. CFD technique

For the numerical prediction of the compression wave and propagation wave, the unsteady, compressible and three-dimensional Euler equations are solved to analyze the flow field around the high-speed train. FDS technique is used for spatial discretization and MUSCL (Monotone Upstream-centered Scheme Conservation Laws) with van Albada flux limiter is used to achieve the third-order spatial accuracy.[4] Calculations of unsteady flow field around a moving body require a time accurate numerical integration. In the present study, Yoon's LU-SGS scheme, an implicit scheme, is chosen for efficient time marching.[5] The multiblock, patched and overlapping grid systems are used for computation.

4. Prediction of Micro-pressure wave

The Kirchhoff formulation is applied to predict the micro-pressure wave at the tunnel exit. The near-field flow data obtained by acoustic monopole analysis/method of characteristics or CFD are used as an input to Kirchhoff formulation.[6] The Kirchhoff formulation[7] is

$$p'(\vec{x},t) = \frac{1}{4\pi} \iint_S \left[\frac{\cos\theta}{r^2} p' - \frac{1}{r} \frac{\partial p'}{\partial n} + \frac{\cos\theta}{a_\infty r} \frac{\partial p'}{\partial \tau} \right] dS(\vec{y},\tau) \qquad (2)$$

where p' is the perturbed pressure; $(\vec{x},t)$ is the observer's location and time; $(\vec{y},\tau)$ is the source location and retarded time variables; θ is the angle between the normal vector $(\vec{n})$ on the surface and the radiation vector $(\vec{r})$; r is the distance between an observer and a source at the retarded time. Note that pressure and its derivatives are calculated at the retarded time, τ. The integration is performed at the control surface called Kirchhoff surface containing the flow field information. In the present study, the exit plane normal to the tunnel exit is considered as a control surface, and an image source of sound is imposed to consider the ground effect.

5. Results

To validate the prediction method, the entry compression waves obtained by analytical theory and direct Euler computation are compared with the experimental data in figure 1(a) and 1(b). The train speed is (a) 300km/hr and (b) 350km/hr. The measured[6] and predicted results

show a good agreement with each other. For the prediction of acoustic monopole analysis, the maximum amplitude of pressure wave has a difference with the measured data but the gradient of the compression wave, playing an important role to generate the micro-pressure wave, approximately corresponds to the measured data. An accurate prediction of compression wave is very important in the prediction of micro-pressure wave because its strength is proportional to the gradient of the compression wave. In the viewpoint of the computing time, the acoustic monopole method can remarkably reduce the time consumption compared with the Euler simulation. To obtain the entry compression waveform like figure 7(a) and 7(b), it takes 67.2×10^3 seconds for three-dimensional Euler calculation, whereas the acoustic monopole analysis requires 1.61×10^3 seconds. Therefore, for an engineering aspect, a combined acoustic monopole analysis/Kirchhoff formulation is also a useful tool in preliminary design.
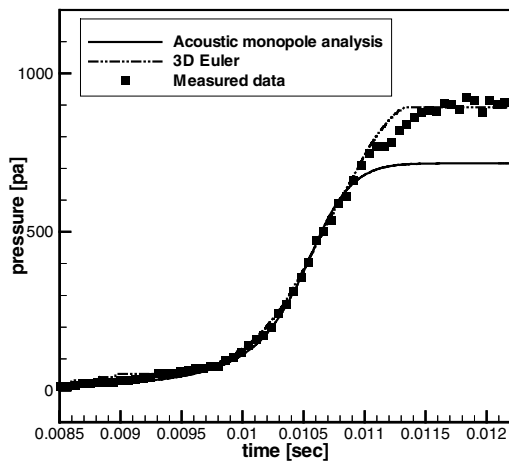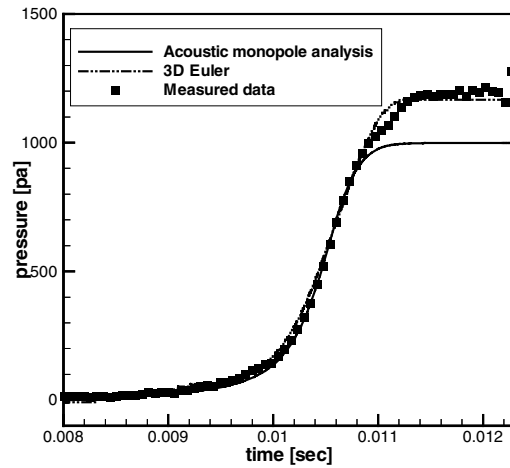

Fig. 1(a)   **Fig. 1(b)**
Fig.1 Entry compression wave for train speed of (a) 300km/hr and (b) 350km/hr

The flow-field data obtained by the acoustic monopole analysis and CFD is transferred to linear Kirchhoff formulation to predict the micro-pressure wave at the exit of tunnel. Figure 2(a) and 2(b) show the comparison of calculated results with experimental data at the speed of 300 and 350km/hr. The predicted micro-pressure wave shows a satisfactory agreement in both amplitude and waveform. Therefore, the proposed prediction method, a combined acoustic monopole analysis/Kirchhoff method and CFD/Kirchhoff method, works very well in predicting the micro-pressure wave as well as the aerodynamic interaction between the train and the tunnel.

Conclusions

New methods (combined acoustic monopole analysis/Kirchhoff method, CFD/Kirchhoff method) are attempted in predicting the compression wave and the micro-pressure wave generated by high-speed train entering the tunnel. The near-field flow data are obtained by acoustic monopole analysis where the train is modeled by monopole source and three-dimensional Euler solver. The data are transferred to the linear Kirchhoff formulation to predict acoustic far-field. The results are compared with the measured data. The agreement was found to be good in both compression wave and micro-pressure wave. This study can be

a very useful tool to design the nose shape of train and the geometry of tunnel to minimize the pressure fluctuation and the booming noise.
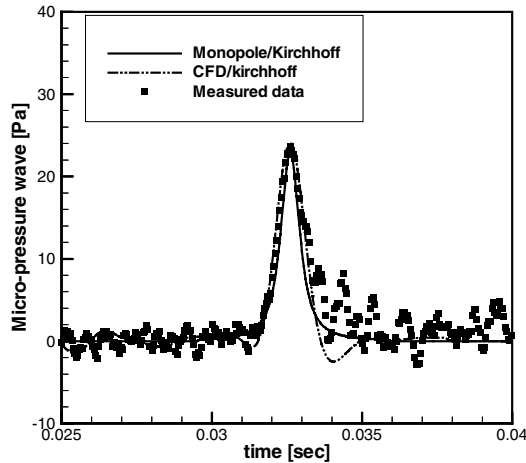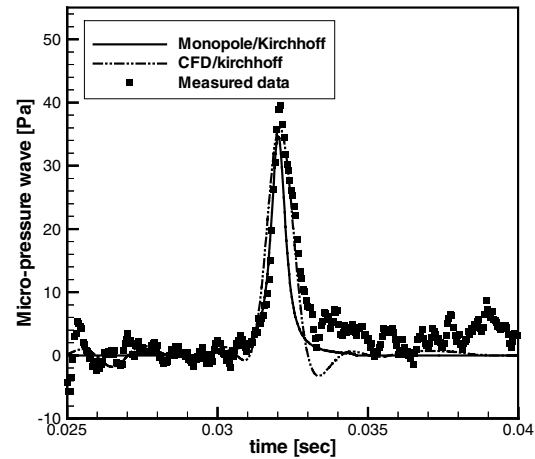

Fig. 2(a)   **Fig. 2(b)**

Fig.2 Micro-pressure wave for train speed of (a) 300km/hr and (b) 350km/hr

Acknowledgements

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