Numerical Investigation of a Pressure Wave Generated by a High-Speed Train Passing Through a Structure

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ABSTRACT A pressure wave generated by a high-speed train passing by a structure is numerically investigated. The compressible Navier-Stokes equations are solved with the FDM and the over-set grid technique is used for moving boundary. Computations are carried out for various structures and effect of shape of a structure on a generated pressure wave is discussed.

1 Introduction

The speed of the recent high-speed trains in operation is about 300km/h and that of the experimental Maglev train in Japan reaches 550km/h. They are still slower than the airplanes, however more severe aerodynamic and acoustic problems have been arising. A train runs on the ground where there are structures, people and an oncoming train while an airplane flies in the sky. Therefore, a high-speed train is likely to cause the environmental problems at relatively lower speed.

One of the most important environmental problems is the low frequency noise problem which is due to a pressure wave generated by interaction between a high-speed train and a structure near a railway. A typical example is a low frequency noise problem due to tunnel entry[1] illustrated in Fig. 1. The pressure increase in the tunnel induced by a train entering into a tunnel becomes a compression wave propagating down to the exit of the tunnel. The compression wave becomes a pulse wave which propagates outside the tunnel exit and causes the low frequency noise problem. Many researches have been done about this problem and the measures to suppress the low frequency noise have been established[1],[2].

The low frequency noise generated by tunnel entry of a train can be observed even at slower train speed such as 200km/h, since tunnel entry of a train strongly compresses the air inside a tunnel which forms a closed space. This phenomenon has not been observed or caused serious problems for the structures along a railway other than a tunnel. However, as the train speed increases, the low frequency noise is observed when a train passes by the other structures such as an over-bridge shown in Fig. 2 and a soundproofing panel.

In the present paper, the low frequency noise generated by interaction between a train and a structure is numerically investigated. An axisymmetric flow field where a high-speed train passes through a structure similar to an over-bridge is simulated by solving the compressible Euler equations with the Finite Difference Method. The zonal method in which a flow field is decomposed into several zones is used as the numerical technique for a moving boundary problem. The computational results illustrate the pressure wave generated by a train passing through a structure, and its directivity and the effect of geometry of a structure on it is discussed.

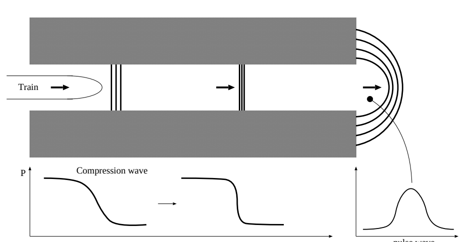

Figure 1: The low frequency noise from a tunnel

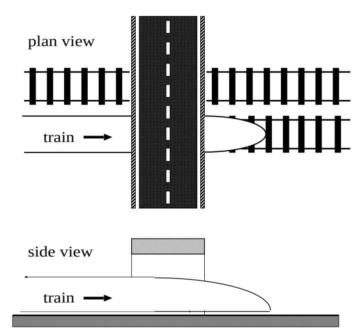

Figure 2: An over-bridge

2 Numerical Method

2.1 The computational flow field

In this study, the flow field where a train passes through a structure is modeled as shown in Fig. 3. The flow field is axisymmetric. The train is a cylinder with a paraboloid nose and tail and runs along the symmetry axis. The structure is modeled as a hollow cylinder.

Figure 4 shows the geometry of the computational flow field. At the beginning, the flow is at rest and the train impulsively starts to move at Mach number 0.41, i.e. about 500km/h. The non-reflective boundary condition is imposed at the outer boundary of the computational field to suppress the non-physical reflected waves.

The close-up view of the train and the structure is shown in Fig. 5. The diameter of the structure and the speed of sound are taken as the reference length and speed respectively. The diameter of the train is 0.35 and the blockage of the train to the tunnel is 0.12. The computations are carried out for the cases of 6 widths of the structure, $b = 0.5 \sim 6.0$.

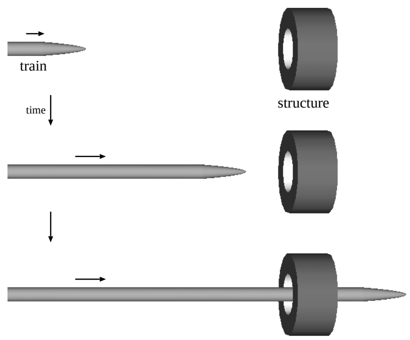

Figure 3: An axisimmetric flow field model where a train passes through a structure

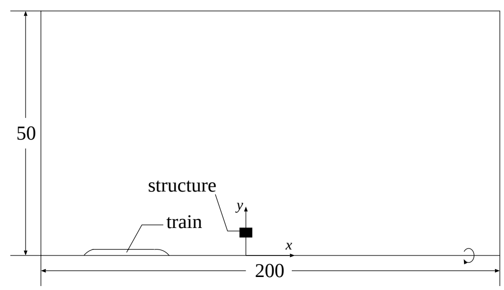

Figure 4: The computational flow field

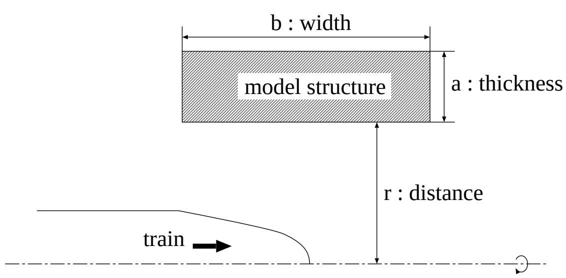

Figure 5: The close-up view of the flow field

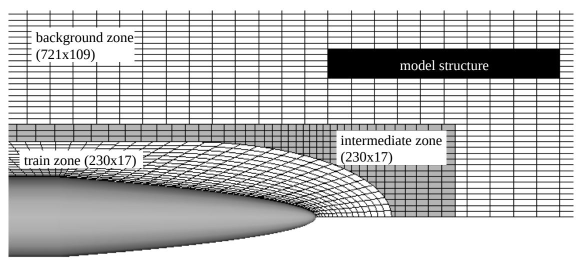

Figure 6: The zone geometry and the grid distributions

2.2 Basic equations

The basic equations are the axisymmetric compressible Euler equations written in the generalized coordinate,

$$\partial_t(y\hat{Q}) + \partial_\xi(y\hat{E}) + \partial_\eta(y\hat{F}) + y\hat{G} = 0,$$

where,

$$\hat{Q} = \frac{1}{J}\begin{bmatrix} \rho \\ \rho u \\ \rho v \\ e \end{bmatrix}, \quad \hat{E} = \frac{1}{J}\begin{bmatrix} \rho U \\ \rho u U + \xi_x p \\ \rho v U + \xi_y p \\ (e+p)U - \xi_t p \end{bmatrix}, \quad \hat{F} = \frac{1}{J}\begin{bmatrix} \rho V \\ \rho u V + \eta_x p \\ \rho v V + \eta_y p \\ (e+p)V - \eta_t p \end{bmatrix}, \quad \hat{G} = \frac{1}{J}\begin{bmatrix} 0 \\ 0 \\ p/y \\ 0 \end{bmatrix}.$$

The pressure is expressed by the equation of state for an ideal gas,

$$p = (\gamma - 1)\left\{e - \frac{1}{2}\rho(u^2 + v^2)\right\}.$$

The motion of the grid is expressed as,

$$\xi_x = y_\eta/J,\ \xi_y = -x_\eta/J,\ \eta_x = -y_\xi/J,\ \eta_y = x_\xi/J,$$

$$\begin{cases} \xi_t &= -\xi_x x_\tau - \xi_y y_\tau, \\ \eta_t &= -\eta_x x_\tau - \eta_y y_\tau, \end{cases}$$

where x_τ and y_τ are the speed of a grid. J is the transform Jacobian,

$$J = x_\xi y_\eta - y_\xi x_\eta.$$

U and V are the contravariant velocities,

$$\begin{cases} U &= \xi_t + \xi_x u + \xi_y v, \\ V &= \eta_t + \eta_x u + \eta_y v. \end{cases}$$

The effect of the viscosity is neglected in this study. The past studies show that the viscous effect on a pressure wave is small when a train nose enters a tunnel. However, care must be needed about a train tail where the flow is usually separated.

2.3 The zonal method and the computational grid

The flow field where a train passes through a structure is a moving boundary problem and the zonal method is used in this study. In the zonal method, a flow field is decomposed into zones and each zone moves at the speed of a solid wall boundary inside the zone.

The flow field shown in Fig. 4 is decomposed into 3 zones, a train zone, a background zone and an intermediate zone. The zone geometry and the computational grid point distributions of each zone are shown in Fig. 6. The train zone moves at the same speed as the train over the background zone. The intermediate zone moves with the train zone to enhance the spatial accuracy of the flow around the train. The solid wall boundaries of the structure are imposed on the background zone. The number of the total grid points is approximately 86,000.

Each zone is solved each other with information at the interface region transferred between the zones. The Fortified Solution Algorithm (FSA)[3] is used for the information transfer algorithm. When the FSA is applied to the governing equations, the equations are written as,

$$\partial_t(y\hat{Q}) + \partial_\xi(y\hat{E}) + \partial_\eta(y\hat{F}) + y\hat{G} = |\chi|(\hat{Q}_f - \hat{Q}).$$

The right-hand side term is the fortifying term. The solution is fortified to be $\hat{Q}_f$ where the absolute value of χ is set to be sufficiently large. The solution obtained in the other zones is used for $\hat{Q}_f$. On the other hand, where χ is 0, the basic equations automatically go back to the original basic equations. The required implementation of this algorithm is just to add the source term to the right hand side and to set the χ parameter at the zone interface.

The physical data to be transferred between the zones is calculated with linear interpolation from the surrounding three points in the partner zone, since the grid points for each zone do not necessarily coincide in the overlap region, as often happens in the case of moving grid configurations. The conservation law is not maintained in the interpolating region. However, it is known that the linear interpolation does not cause serious problems particularly when there is no strong discontinuities such as a shock wave in the flow field.

2.4 Spatial and temporal discretisations

The convective terms are discretised with Roe's Flux Difference Splitting[4] and the higher order accuracy in space is obtained using the MUSCL[5]. The viscous terms are discretised with the central difference. The 2-stage Runge-Kutta method is used for the time integration scheme.

The detail of the numerical method is found in Ref.[6].

3 Computational Result

Figure 7 shows a series of the pressure contour plots when the train passes through the structure $b = 1$. At the beginning of the computation, pressure waves are generated around the train due to impulsive start as indicated in Fig. 7 at $t = -0.28$. These waves are not important and do not affect the phenomenon of our interest. When the train nose reaches at the structure at $t = 0.0$, the flow around the train interferes with the structure and the pressure field is affected. Then, pressure waves are generated due to the unsteadiness of the pressure field and they propagate around the structure. While the train body is passing through the structure, the flow field becomes steady state and no pressure waves are newly generated. When the train tail passes through the structure, the pressure waves are generated again. The similar behavior of the pressure waves is observed for the structures with different width.

Figure 8 shows the pressure histories at the point away from the structure in the lateral direction. For the narrowest structure, $b = 0.5$, a single pulse wave is observed. On the other hand, for the structure wider than $b = 0.5$, the oscillating pressure waves are found. This is caused by resonance of the pressure wave inside the structure and the frequency depends on the width of the

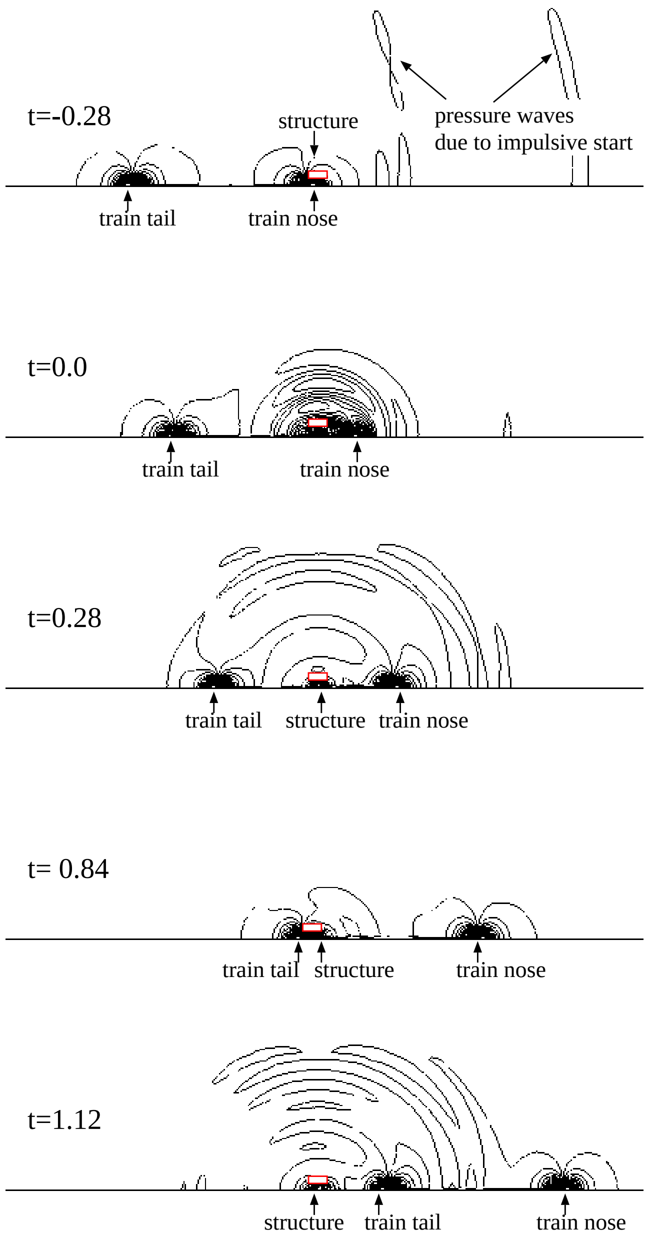

Figure 7: Pressure contour plots when the train passes through the structure (b=1)

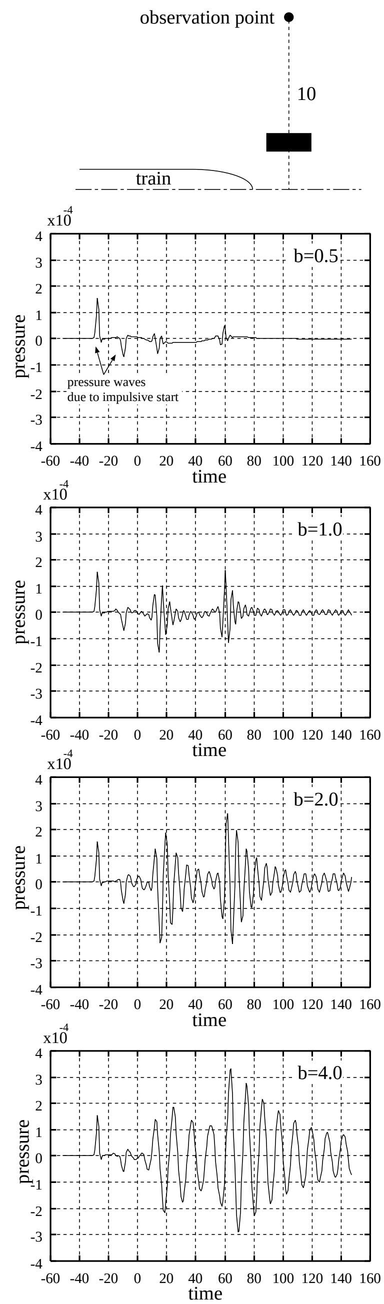

Figure 8: Pressure histories observed away from the structure in the lateral direction

structure.

The frequency of the pressure wave is plotted against the width of the structure in Fig. 9 and is compared with the theoretical resonance frequency inside the structure. For the structure wider than $b = 4$, the frequency of the emitted pressure wave corresponds to the resonance frequency. However, the frequency for the structure narrower than $b = 4$ is smaller than the resonance frequency. This is because the pressure wave generated by the train mainly contains low frequency component.

Figure 10 compares the maximum amplitude of the pressure waves against the width of the structure. The result shows that the amplitude of the pressure wave increases as the structure becomes wider as is also seen in Fig. 7. However, the amplitude saturates at about $b = 6$. This indicates that the structure wider than a certain value, $b = 6$ in this particular case, has the same effect as a tunnel on the interaction with the flow around the train.

The directivity of the emitted pressure wave is presented in Fig. 11. The strong pressure fluctuation is observed in the lateral direction to the structure, i.e. $\theta = 90$ [deg] for all the cases.

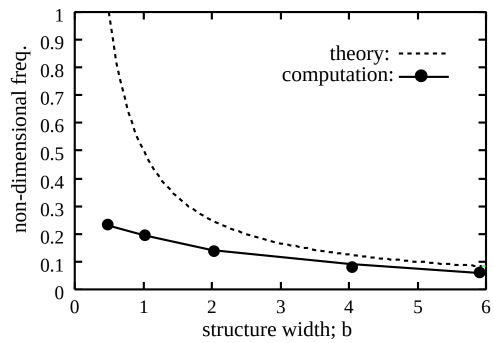

Figure 9: The non-dimensional frequency of the pressure wave compared with the resonance frequency.

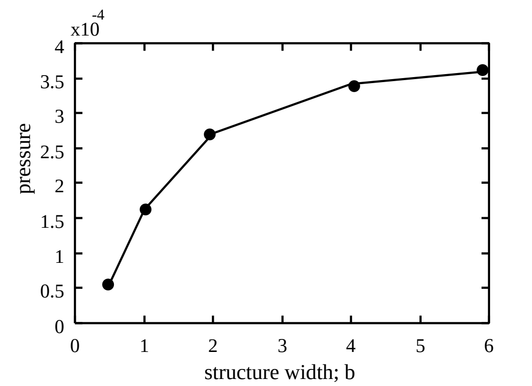

Figure 10: The amplitude of the pressure wave at the observation point

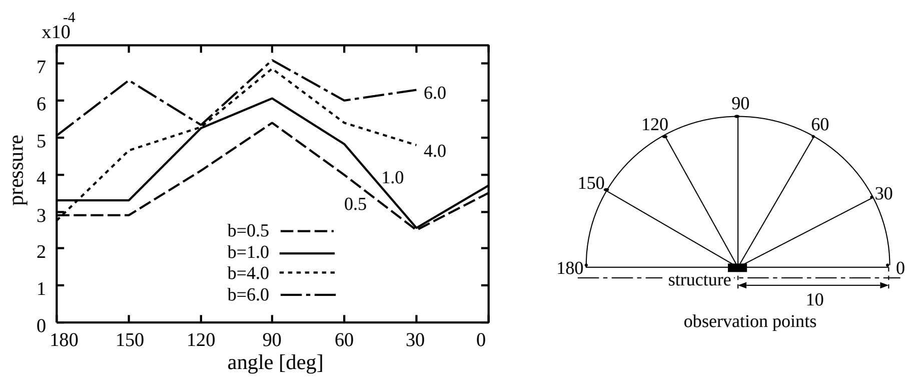

Figure 11: The directivity of the pressure wave

4 Summary

The axisymmetric flow field where a high-speed train passes through a model structure is studied with numerical simulation of the compressible Euler equations. The computations are carried out for the structures with the various widths and the effect of shape of the structure on the pressure wave is investigated.

The computational result shows the pressure waves are generated by the interaction between the flow field around the train and the structure when the train nose and tail pass through the structure. The oscillating pressure wave is observed for a wide structure, since the pressure wave gets in resonance inside the structure. The frequency of the pressure wave corresponds to the resonance frequency for the structure wider than a certain width, while the frequency for a narrow structure is smaller than the resonance frequency. The directivity of the pressure wave is in the lateral direction. The amplitude of the pressure wave increases as the structure becomes wider, but the amplitude saturates at a certain width.

In this study, the flow field is axisymmetric and inviscid and the structure is modeled as a hollow cylinder. In the future work, the viscous computation is to be carried out and the three-dimensional flow field where a train passes by more general shapes of the structure is to be investigated.

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