Behavior of a Weak Shock Wave Propagating through a Gas with Density Gradient in a Duct*

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When a high-speed train such as the Shinkansen enters a long tunnel, a pressure wave is generated at the nose of the train causing a sonic boom at the tunnel exit. This noise, which can be very disturbing to nearby residents, is strongly dependent on the speed of the train. Hence, a bottleneck has developed in the quest for increased rail capacity through the use of even faster trains. In order to reduce sonic boom, the authors have proposed passing the pressure or weak shock wave through a density gradient field perpendicular to the axis of a tunnel and located at its exit. In this report, the behavior of a weak shock wave passing through such density gradient fields is examined by means of both computer simulation and experiment.

Key Words: Shock Wave, Pressure Wave, Sonic Boom, Numerical Analysis, Experiment, Density Gradient, Tunnel, High-Speed Train, TVD Scheme

1. Introduction

When the Sanyo-Shinkansen was constructed, the sonic boom which is often caused at the exit of a long tunnel became a serious problem. The noise (sonic boom) is strongly dependent on the tunnel length, the blockage ratio of train to tunnel cross-sectional areas, and the train speed⁽¹⁾. TGV (in France) and ICE (in Germany) travel at much faster speeds than the Shinkansen, but they do not cause such noise because of their small blockage ratios⁽²⁾. Setoguchi et al.⁽³⁾ investigated the characteristics of discharged sonic booms from a tube caused by a weak shock wave. Kage et al.⁽⁴⁾ studied the relationship between shock wave intensity and various conditions of a train and a tunnel. Funabashi et al.⁽⁵⁾ reported on the results of

numerical simulations which were carried out to predict the weak shock wave formation driven by a leaky piston in a long tube. Ozawa et al. of RTRI (Railway Technical Research Institute of Japan) investigated the characteristics of the noise and concluded that it is directly caused by a pressure wave which is generated at the nose of a train. They classified the effects of booming into two types⁽¹⁾. The first type, which is strongly dependent on the maximum pressure of the sound, is audible. The second type, which is dependent on the pressure rise rate, causes vibrations of doors, windows, etc., which, in turn, results in noise. They have developed several methods to reduce such effects and adapted them to the long tunnels of the Shinkansen. These methods include constructing hoods at the entrances of tunnels⁽⁶⁾, opening the doors of the side branches in tunnels⁽⁷⁾, and increasing the sharpness of the noses of the Shinkansen train⁽⁸⁾. Recently, railway transportation has been experiencing a demand for increased capacity. High-speed transportation is one of the ways to meet this demand, but first, the noise problem must be overcome.

One of the simpler methods would be the

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construction of wider tunnels or narrower trains, but such methods are impractical for a line currently in operation. The authors have proposed a method to alleviate such noises. The pressure wave propagation direction is turned toward the bottom wall of a tunnel by passing the wave through a density gradient field placed near the exit. It can direct the weak shock wave or pressure wave in the vicinity of the bottom wall. In this report, the pressure wave is treated as a weak shock wave and its behavior as it passes through such a field is investigated utilizing both numerical simulations and experiment. Finally, the distance necessary to efficiently direct the waves is discussed.

2. Governing Equation of Computer Simulation

The behavior of weak shock waves traveling through a density gradient field in a duct was investigated utilizing a two-dimensional numerical simulation⁽⁹⁾. The equation will be expressed as the non-steady compressible inviscid equation of gas dynamics (i.e., the Euler equation expressed in vector form with conservative vector components). A TVD⁽¹⁰⁾ scheme was applied to accurately capture the shock wave behavior. Fractional operators⁽¹¹⁾, which can retain the second-order accuracy necessary to perform a two-dimensional simulation were employed. The CFL condition employed is 0.9.

3. Experimental Apparatus

The model duct of 6.2 m long has a rectangular cross section of 50 mm high, 40 mm wide. One end is closed and the other end is open. The duct is comprised of three sections. The first 1.6 m of the closed end is a driving section made of steel. The next 3.6 m is used as a driven section and is made of acrylic plates, 10 mm thick. These two sections are designed to generate a two-dimensional flow field which is

Fig. 1 Apparatus of control section

adopted by the numerical simulation in the previous section. A thin diaphragm is inserted between them. The driving section, which generates the shock waves, is pressurized up to 150 kPa with air. The last 0.9 m of the duct is used as a control section and is shown in Fig. 1. Shutters ① and ⑦ isolate the gas in the control section. A septum ④ separates the gas into two layers, i.e., the upper and lower layers. From the point of view of the gravitational effect, a gas of smaller density is introduced to the upper layer. Helium is used here as the light gas and air is used as the heavy gas. The theoretical sound velocity ratio of the gases from the top to the bottom wall is about 3.0.

Although the lower gas is air, the displacement process was carried out for 20~30 seconds because helium easily leaks into the lower layer through crevices (made for removal of ④) in both sidewalls. During the displacement process, ten times the volume of gas in the layers are discharged into each layer from valves ②, and the displaced gases are exhausted from holes ⑧. Subsequently, ④ is removed and the two gases begin to diffuse. Several seconds later, the desired density gradient is formed (the duration is previously calibrated by means of hot wire ⑥ which is used as a gas sensor) and ① and ⑦ are opened at the same time. Immediately after this, the diaphragm is broken by a needle and a shock wave propagates into the control section. When the shock wave arrives there, the density gradient may not be constant throughout the control section. Accordingly, the results obtained here cannot be quantitatively compared with the numerical simulations, which are solved under the ideal conditions explained above, but it can be used as one of the qualitative verifications of the simulation. Pressure histories are measured by the transducers which are type 132 A of PCB whose natural frequency is 250 kHz. The measurement points are indicated by a distance x from the entrance shutter ①. There are ten points on both the top and bottom walls that face each other having the same x . They are placed at $x = -3.5$ cm, 17 cm and at 10-cm increments thereafter.

4. Result and Discussion

4.1 Propagation process

Figure 2 shows examples of simulated propagation processes of a shock wave. The grid numbers for the x and y directions are 400 and 20, respectively. The grid unit sizes of both directions are equal. Hereafter, distances in the numerical simulation will be expressed by grid numbers and they are denoted by x_g and y_g . $y_g = 0$ and 19 are set at the bottom and top walls of a duct, respectively. $x_g = 0$ is the point where the density gradient starts (see Fig. 2(a)).

The density in front of this field ($x_g < 0$) is set to ρ_0 (uniform), which corresponds to the density of air at room temperature and pressure. The densities at the bottom ($y_g = 0$) and the top ($y_g = 19$) walls at $x_g \geq 0$ are denoted by ρ_0 and ρ_t , and in this figure, they are set equal to ρ_0 and $\rho_0/6.25$, respectively. This implies that the sound velocity at $y_g = 19$ is 2.5 times faster than that at $y_g = 0$. The density changes linearly from the bottom to the top wall.

The recorded intensity values of pressure waves (which are defined by the ratio p_i/p_0 , where p_i is the recorded wave pressure and p_0 is the ambient pres-

sure) that caused a sonic boom in actual Shinkansen tunnels are approximately 1.01. However, I_s (shock wave intensity which is also defined as p_i/p_0) of the numerical simulation is set to 1.05 for comparison with experimental results. When I_s is smaller than 1.05, the reproducibility of the experiments becomes difficult. Elapsed time is denoted by τ . The unit of the ratio of τ to grid size is sec/m. At $\tau = 0$, a shock wave is set at $x_g = -40$ (see Fig. 2(b)) as an initial condition. At $\tau = 0.08$ (Fig. 2(c)), the shock wave has flattened and it approaches $x_g = 0$ where the density gradient begins. It is known that the numerical dissipation makes a shock wave thicker, and in this case, the shock wave spreads to 5 grids. Therefore, the relative sharpness (thickness) of a shock wave in comparison with a duct (tunnel) height is dependent on the total grid number for height employed by numerical simulation, that is, a fine grid for height relatively makes the shock wave sharper (thinner). At $\tau = 0.16$ (Fig. 2(d)), the shock wave thickness gradually becomes larger, and the shock wave changes to a pressure wave near the top wall. The peak pressure of the pressure wave at the top wall becomes lower than the initial shock wave pressure, and dp/dx_g , which can be converted to dp/dt measured at one point, decreases. (The wave is no longer a shock wave, but it is called a shock wave in this report for convenience.) Along the bottom wall, the pressure becomes higher ($\Delta p = 6.3$ kPa, where Δp is defined as pressure difference between any point and ambient) than the incident one ($\Delta p_i = 5$ kPa) and dp/dx_g is greater than that near the top (Fig. 2(d)). The finite amount of dp/dx_g at the bottom wall is caused by a numerical dissipation mentioned previously. The pressure wave in the vicinity of the bottom wall is actually a shock wave which is stronger than the incident one. The velocity map (Fig. 2(e)) reveals the reason why such a different deformation of a shock wave occurs. It should be mentioned that in this figure the grid for the x direction is plotted every other point. The velocity vectors become directed toward the low-speed region where ρ is high. The gas in this region is compressed and the pressure is increased further. As a result, the shock wave speeds at both the bottom and top walls are different from the theoretical speeds of a normal shock wave. The propagation speed in the vicinity of the top wall is lower than the theoretical speed, and the speed along the bottom wall is higher than the theoretical speed. However, the shock wave propagates faster at the top wall than it does at the bottom wall, and it inclines like an oblique shock wave. The angle of the wave propagation direction at $\tau = 0.16$ is about 37° to the duct axis (where the wave front is defined as 5% of

Fig. 2 Deformation process of shock wave ($I_s = 1.05$, $\rho_t/\rho_0 = 1/6.25$; simulation)

the difference between p_0 and the peak pressure of the pressure wave). dp/dx_g , which dominates the intensity of radiated sound noise⁽¹⁾, is greatly alleviated in this way in the upper half of the duct and it is focused in the vicinity of the bottom wall. Accordingly, some countermeasure at the bottom wall can decrease dp/dt and p at the exit of the tunnel. At $\tau \geq 0.16$, the angle becomes constant. The shock wave speed from top to bottom is almost constant (approximately 480 m/s when air is chosen as a medium), and the pressure profile does not change much. When τ is 0.32 (Fig. 2(f)), dp/dx_g at the top wall is almost the same as that at $\tau=0.16$ while that of the bottom wall is reduced. Furthermore, $\Delta p_{\max}$ is higher here than it was at $\tau=0.16$. At $\tau=0.53$, the values of dp/dx_g at the top wall and $\Delta p_{\max}$ at the bottom wall have both decreased (relative to their value at $\tau=0.32$).

Figure 3 shows the pressure histories of the top and the bottom walls measured at several x . The density gradient field starts at $x=0$ cm and ends at $x=90$ cm. A normal shock wave arrives at both walls of $x=-3.5$ cm without experiencing the density gradient effect. The two pressure records at the top and the

Fig. 3 Pressure histories on the top and bottom walls ($I_s=1.05$, helium and air for upper and lower layers, respectively; experiment)

bottom walls correspond to and overlap each other. The results show a delay prior to step up of about 20 μ s. This is due to the size of the pressure transducers. The pressure histories of the top wall exhibit very blunt waves as is shown by the numerical simulation. The shock wave of the bottom wall arrives much later than that at the top wall and it indicates the inclination of the shock wave. The initial part of the shock wave does not show sudden step up even at the bottom wall, and dp/dt is smaller than that at $x=-3.5$ cm. This phenomenon was also predicted by the numerical simulation. The peak pressure attained at $x=37$ cm is higher than that at $x=7$ cm. Theoretically, the peak pressure could go to infinity, but, in actual experiment, the finite size of the pressure transducer and the incompleteness of the density gradient among others make the peak pressure finite just like the peak pressure simulated by computer. When the shock wave arrives at $x=67$ cm, the difference between arrival times at the top and the bottom walls is almost the same as that at $x=7$ cm. It also means that the inclination angle of the shock wave does not increase further similarly to the results shown by numerical simulation.

When the shock wave arrives at $x=94$ cm where the density gradient has ended, the peak pressure becomes very small but is still higher than the incident one. A second big wave appears behind the first wave, a phenomenon that also occurred in the numerical simulation (Fig. 2(g)). Such phenomenon was not observed by both numerical simulation and experiment when density gradient was not applied. Therefore, the second wave was thought to be generated by a reflection of the first wave at the bottom and top walls. However, such a reflected wave cannot be observed in pressure wave history by numerical simulation. Thus, the formation mechanism of the second wave cannot be clarified as yet.

4.2 Influence of shock wave intensity on pressure history

For the density gradient to be effective in breaking or alleviating the shock wave, its efficiency (i.e., the length of the field) must be taken into account. The issue is how well dp/dt at the top wall is reduced. Two factors can be used as its indexes. One of them is peak pressure at the bottom wall, which can reflect how the gas is directed. (This peak pressure will be absorbed by some suitable countermeasure devised on the bottom wall when this method is applied to an actual tunnel.) The other one is dp/dx_g at the top wall. (It will be radiated from an exit.)

Figure 4 shows the results along a duct. The peak pressure rise at the bottom wall, which is denoted by $\Delta p_{\max}$, is normalized by Δp_i and dp/dx_g is normalized

by $\Delta p_i/H_g$ (where H_g is the height of a duct defined in the same manner as x_g). They are plotted against a normalized distance x_g/H_g . The calculated values of I_s are 1.2, 1.1 and 1.05. ρ_b is set equal to ρ_0 , and the

Fig. 4 Influence of I_s on the peak pressure on bottom wall, and on the pressure gradient on top wall, along x_g ($\rho_i/\rho_0=1/6.25$; simulation)

Fig. 5 Influence of I_s on the peak pressure on bottom wall, and on the pressure gradient on top wall, along x (Helium and air for upper and lower layers, respectively; experiment)

magnitude of the density gradient is represented by ρ_i/ρ_0 and it is $1/6.25$ in this figure. dp/dx_g is calculated as a mean value of two points on the $p-x_g$ curve, that is, 10 and 90% of the pressure increment from p_0 to the peak pressure. This figure shows the results for $x_g/H_g = 0 \sim 15$. The three curves of $\Delta p_{\max}/\Delta p_i$ are similar and the three curves of $(dp/dx_g)/(\Delta p_i/H_g)$ also resemble each other. They oscillate along x_g/H_g but the amplitudes are different. The desired effect is rapidly established within $x_g/H_g < 2.0$. After this, they only fluctuate or oscillate slightly. Therefore, a density gradient field with a length-to-height ratio of 2 or less might be sufficient to decrease dp/dt in the vicinity of the top wall.

Figure 5 shows experimental results which represent the influence of I_s on $\Delta p_{\max}/\Delta p_i$ measured on the bottom wall, and of $(dp/dt)/(\Delta p_i/\Delta t)$ measured on the top wall along x . x is normalized by H . dp/dt is calculated in the same manner as dp/dx_g and Δt is defined as the sound transit time from the top to the bottom wall through the mixture of gases in two layers. $(dp/dt)/(\Delta p_i/\Delta t)$ can be converted to $(dp/dx_g)/(\Delta p_i/H_g)$ by multiplying with the sound velocity. The maximum value of $\Delta p_{\max}/\Delta p_i$ is greater than the result of the numerical simulation, although the recorded pressure is averaged over the diaphragm of the pressure transducer. This is due to the numerical dissipation mentioned above. The peak pressures except for that of $I_s=1.20$, decrease slightly near $x/H=3$ and then gradually increase again. $\Delta p_{\max}/\Delta p_i$ is higher everywhere than it is at $x/H=0$ and $(dp/dt)/(\Delta p_i/\Delta t)$ is reduced drastically at all x/H greater than zero. The pattern of the shock wave does not change very much after $x/H=5.0$. A length from $x/H=0$ to 2 is sufficient to attain an effective density gradient field.

4.3 Influence of the magnitude of density gradient on pressure history

Figure 6 shows the effect of the magnitude of the density gradient on $\Delta p_{\max}/\Delta p_i$ and $(dp/dx_g)/(\Delta p_i/H_g)$ of the simulation at $I_s=1.05$. Density gradients (ρ_b/ρ_0) investigated in this figure are $1/6.25$, $1/3.00$ and $1/2.00$ for $\rho_b=\rho_0$. When the density gradient is small, the distance to the point where the bottom wall pressure reaches its maximum becomes slightly longer. The larger the density gradient is, the larger the effect will be. The experimental result was expected to be so similar to the simulation that the experiment was not performed.

4.4 Shock wave velocity in a density gradient field

It has been shown that the behavior of shock wave velocities (U_{sw}) in a density gradient field is complex. They do not follow the theoretical behavior.

Fig. 6 Influence of magnitude of density gradient on pressure gradient and peak pressure along x_g ($I_s = 1.05$; simulation)

Fig. 7 Shock wave velocity in a density gradient field

However, the mean velocity is found between the highest and the lowest theoretical velocity and it becomes almost constant after the shock wave travels a considerable distance in a density gradient field. The controlling factor of the velocity must be discussed. One of the characteristic velocities which has physical meaning and which can be compared with U_{sw} is the bulk mean velocity (U_{bulk}), which is the shock wave velocity in fully mixed gas. Figure 7 shows the relationship between the bulk mean shock wave velocity versus the measured or simulated velocity through a density gradient field. When U_{sw} can be expressed by

U_{bulk} , the marks should lie on the straight broken line whose slope is 45° . ρ_0/ρ_b , which expresses the result of the numerical simulation in this figure, means that the density at the top wall is ρ_0 and the density at the bottom wall is ρ_b , while ρ_t/ρ_0 is the same as defined previously. Experimental results are denoted by their gas mixtures, for instance, Air/CO₂. The condition of $\rho_0/\rho_b = 2/3$ is similar to the experimental condition of Air/CO₂. Most symbols lie on the broken line, which means that a fully developed shock wave velocity in a density gradient field can be approximately expressed by bulk mean velocity.

5. Conclusion

The behavior of a shock wave passing through a density gradient field in a duct was investigated. Some device at the bottom wall of such field is expected to be developed in order to alleviate sonic boom in the vicinity of a tunnel exit. The following conclusions were obtained.

(1) A shock wave front inclines, and its speeds in the vicinity of the top and the bottom walls become the same after traveling through a density gradient field at a distance 1~2 times the duct height. From the standpoint of both dp/dt at the top wall and $\Delta p_{max}/\Delta p_i$ at the bottom wall, the effective length of the density gradient field is also 1~2 times of duct height.

(2) A fully developed shock wave velocity in a density gradient field is almost the same as the bulk mean velocity.

This method can be used in conjunction with other methods proposed by RTRI which are devised to alleviate the generation of a strong pressure wave or alleviate the wave when it increases, because it also can alleviate a shock wave which has developed.

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