Emission of a Propagating Compression Wave from an Open End of a Tube*

(Experiment on Magnitude of Emitted Impulsive Wave)

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An experimental study is carried out on the emission of a propagating compression wave from an open end of a tube. A shock tube with a fast opening gate valve instead of a diaphragm is employed for producing compression waves of various strength. The magnitude of the impulsive wave emitted from an open end is compared with the results of aeroacoustic analysis presented in the previous reports. The directivity of the impulsive wave and its attenuation with distance are discussed. It has been shown that the magnitude of the emitted impulsive wave agrees well with the results of the aeroacoustic analysis, and the directivity of the impulsive wave is independent of the strength of the compression wave but depends on the length of the compression wave.

Key Words: Compressible Flow, Unsteady Flow, Compression Wave, Impulsive Wave, Acoustic Theory

1. Introduction

The phenomena of exhaust noise from an automotive engine and an impulsive wave generated from the exit of a train tunnel are becoming important problems with the increase in power of automotive engines and the advent of high-speed trains^{(1),(2)}. A feature of these sounds is that a compression wave with a gentle slope of pressure change rather than a pressure wave with a steep waveform or a shock wave is discharged into the surrounding area from the exit of a tube. The procedure of the open-end correction to determine the magnitude of an impulsive wave generated from an open end of a circular tube with an infinite baffle plate was described in the previous paper⁽³⁾. It was also shown that the magnitude of an impulsive wave is

proportional to the maximum time rate of pressure change at the open end. The time rate of pressure change at the open end and the relation between the length of the compression wavefront and the magnitude of an impulsive wave were discussed.

A number of experimental studies on the discharge of shock waves using a shock tube have been reported. The characteristics of attenuation with distance of an impulsive wave and the relation between the strength of a shock wave and the magnitude of an impulsive wave were determined experimentally⁽⁴⁾. Experimental studies using a baffle plate, silencer and liquid sheet at the open end were carried out to reduce the noise originated in an impulsive wave⁽⁵⁾⁻⁽⁷⁾.

The experimental studies dealt with the characteristics of an impulsive wave which occurs when a compression wave with a gentle waveform discharges into a surrounding area were little carried out. In this paper, the characteristics of an impulsive wave which occurs when a compression wave generated in a shock tube using a fast opening gate valve instead of a diaphragm discharges from the open end of a tube are investigated experimentally. The experimental

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Fig. 1 Experimental apparatus

results are discussed from the viewpoint of an aero-acoustic theory.

2. Experimental Apparatus and Procedures

The experimental apparatus consists of a high-pressure chamber (circular tube of 12 m length and 40 mm diameter), a fast opening gate valve⁽⁸⁾, a propagation tube for the compression wave (rectangular tube of 12.4 m length, 31 mm height, 19 mm width and 5.5 mm thickness) and a test section as shown in Fig. 1. The object of this experiment is to investigate the emission of a compression wave generated from the exit of a tunnel by the entry of a high-speed train. According to a one-dimensional analysis⁽⁹⁾, the magnitude of a compression wave is at most 1.6 kPa when a Shinkansen train in Japan enters a tunnel with a speed of 250 km/h. Since the shock tube using a diaphragm can hardly generate a weak compression wave such as this, a fast opening gate valve is used instead of the diaphragm in this study.

The plate of this valve is opened by high-pressure air in an actuating chamber as shown in Fig. 1. The opening time can be selected among the experimental conditions and the phenomenon of reappearance of the compression wave generated by the opening of the valve is clearly observed.

Air in the high-pressure chamber settled in pre-script pressure flows into the propagating tube for the compression wave after the opening of the valve, and a compression wave is generated in front of it. When the compression wave reaches the open end, an impulsive wave is emitted to the surrounding area. To simulate the ground of a tunnel exit, a wide flat plate is set at the open end of the propagating tube as shown in Fig. 1.

Measurements of a compression wave toward the open end are carried out 1.48 m upstream of the open end, in order to avoid the influences of an expansion wave which occurs due to the reflection of the compression wave at the open end. We call the compression wave at this point the 'initial compression wave' hereafter. Experiments are carried out under the condition of a pressure rise Δp^* of 2–8 kPa of the initial compression wave.

The measurements of an impulsive wave were carried out on the horizontal surface on which the axis of the tube lies (O-A in Fig. 1). To investigate the characteristics of attenuation with distance and directivity of an impulsive wave, pressure was measured at a distance from $r=5$ to 400 mm and angles from the axis of the tube of $\theta=0^\circ, 30^\circ, 60^\circ$ and 90° . The output signals from a pressure transducer (Kulite Co., Ltd., XCS-190-5) and a sound noise meter (Rion Co., Ltd., NA-51) are amplified by an amplifier and analyzed by a computer after passing through an A-D converter.

The equivalent diameter of a rectangular tube is $D=23.6$ mm. Nondimensional quantities of position and time are defined using the equivalent diameter.

3. Experimental Results and Discussion

3.1 Initial compression wave

An example of the pressure waveform of an initial compression wave is shown in Fig. 2. The abscissa and ordinate denote the time t and gauge pressure Δp . The pressure rise Δp^* of an initial compression wave is 4 kPa in the case of Fig. 2. The pressure decreases suddenly at point d as the head of an expansion wave is generated due to the reflection of a compression wave at the open end. We define the

Fig. 2 An example of pressure waveform of initial compression wave

Fig. 3 Relation between pressure rise and length of initial compression wave

length of an initial compression wave as $L = a_1 t_1$, where a_1 is the speed of sound in atmosphere and t_1 is as defined in Fig. 2 using the maximum slope of the wavefront of an initial compression wave. The wavefront of an initial compression wave generated in our experiments is expressed as the following equation for $\Delta p^* = 2 - 8$ kPa.

$$\frac{\Delta p}{\Delta p^*} = \frac{2}{\pi} \tan^{-1} \left(1.2 \frac{a_1 t}{L} \right) \quad (1)$$

In the case of Fig. 2, the values on the right side of Eq. (1) are $t_1 = 1.2$ ms, $a_1 = 340$ m/s and $L = 408$ mm. The broken line in Fig. 2 represents the waveform of a compression wave which was determined by Eq. (1) and agrees well with the solid line showing the waveform obtained in our experiment.

The relation between Δp^* and L of an initial compression wave is shown in Fig. 3. It is found that the length L of the compression wave decreases with increasing Δp^* .

We define a nondimensional quantity ζ as the ratio of maximum time rate of pressure change at the open end to that an initial compression wave. The domain of L which is necessary for the open-end

Fig. 4 Relation between ζ and L/D

correction can be determined using the relation between ζ and L of an initial compression wavefront. Differentiating Eq. (1) with respect to t , the maximum time rate of pressure change of the initial compression waveform is given by

$$\left(\frac{\partial \Delta p}{\partial t} \right)_{i, \max} = \frac{2.4 a_1 \Delta p^*}{\pi L} \quad (2)$$

On the other hand, substituting p in Eq. (1) into Eq. (7) of Ref. 3 and then differentiating with respect to t , we obtain the following equation as the maximum time rate of pressure change at the open end:

$$\left(\frac{\partial \Delta p}{\partial t} \right)_{e, \max} = \frac{2 a_1 \Delta p^*}{\pi \Delta l} \tan^{-1} \left(\frac{1.2 \Delta l}{L} \right), \quad (3)$$

where Δl is the open-end correction length. Combining Eq. (2) and Eq. (3) yields

$$\begin{aligned} \zeta &\equiv \left(\frac{\partial \Delta p}{\partial t} \right)_{e, \max} / \left(\frac{\partial \Delta p}{\partial t} \right)_{i, \max} \\ &= \frac{L}{1.2 \Delta l} \tan^{-1} \left(\frac{1.2 \Delta l}{L} \right), \end{aligned} \quad (4)$$

where the values of open-end correction length Δl are $0.425D$ and $0.3D^{(10)}$ with and without an infinite baffle plate at the open end of a circular duct, respectively. Substituting these values of Δl into Eq. (4), the relation between ζ and L/D is shown by the solid lines in Fig. 4. The asymptotic value of ζ when L/D tends to a large value is unity. The experimental data show the values of ζ determined from the wavefront of an initial compression wave. Figure 4 shows that the values of ζ for the present experiments are nearly equal to unity. Therefore, it is not necessary to perform an open-end correction in our experiments.

3.2 Waveform of impulsive wave

Figure 5 shows the experimental waveform of an impulsive wave at a distance $r/D = 3.4$ on the axis of the tube, under the condition of an initial compression wave $\Delta p^* = 4$ kPa. The magnitude of the impulsive wave is 26.4 kPa and is small compared with the pressure rise of an initial compression wave $\Delta p^* = 4$ kPa.

Fig. 5 Waveform of impulsive wave ($r/D=3.4$, $\theta=0^\circ$, $\Delta p^*=4$ kPa)

According to the aeroacoustic theory⁽¹¹⁾, in our experimental conditions, the pressure change $\Delta p(r, t)$ at the far-field is given as follows.

$$\Delta p(r, t) = \frac{S}{\pi r a_1} \left(\frac{\partial \Delta p}{\partial t} \right)_i \quad (5)$$

Here, S is the cross-sectional area at the tube exit, which is equal to 589 mm^2 . The broken line in Fig. 5 shows the time rate of the pressure change of an initial compression wave. The peak value of this waveform is 23.1 Pa , which is slightly smaller than the experimental value of 26.4 Pa , but the shapes of the waveforms are similar.

3.3 Relation between maximum time rate of pressure change of initial compression waveform and magnitude of impulsive wave

The magnitude of an impulsive wave is obtained as the maximum value of Eq. (5) in a case in which the open-end correction is unnecessary such as the present experiment. Namely,

$$\Delta p_{\max}(r) = \frac{S}{\pi r a_1} \left(\frac{\partial \Delta p}{\partial t} \right)_{i, \max} \quad (6)$$

After both sides of Eq. (5) are divided by the pressure rise Δp^* of an initial compression wave, the following equation is obtained.

$$\frac{\Delta p_{\max}(r)}{\Delta p^*} = \frac{S}{\pi r \sqrt{\kappa} D} \left\{ \frac{\partial (\Delta p / \Delta p^*)}{\partial t'} \right\}_{i, \max} \quad (7)$$

Here, κ is the specific heat ratio and t' is the non-dimensional time defined as $t' = t / (\sqrt{\kappa} D / a_1)$. When a compression wave discharges from the open end with an infinite baffle plate, $\Delta p_{\max}$ of Eq. (7) should be doubled, as follows.

$$\frac{\Delta p_{\max}(r)}{\Delta p^*} = \frac{2S}{\pi r \sqrt{\kappa} D} \left\{ \frac{\partial (\Delta p / \Delta p^*)}{\partial t'} \right\}_{i, \max} \quad (8)$$

The relation between nondimensional magnitude $\Delta p_{\max} / \Delta p^*$ and the maximum time rate of pressure change of an initial compression wave measured at a nondimensional distance $r/D=3.4$ far from the exit

Fig. 6 Relation between magnitude of impulsive wave and maximum time rate of pressure change of initial compression wave

portion is shown in Fig. 6. The experimental results for the various angles and the numerical results obtained using Eqs. (7) and (8) are shown. The maximum magnitude of an impulsive wave is obtained at $\theta=0^\circ$ and decreases with increasing θ . This indicates the existence of directivity of an impulsive wave. The experimental values are greater than the corresponding values on the solid line showing the numerical result of Eq. (7), while they are smaller than the corresponding values on the dotted line showing the numerical result of Eq. (8). This is due to the influence of tube thickness such as a baffle plate at the open end.

3.4 Attenuation of magnitude of impulsive wave with distance

Figure 7 shows the attenuation of magnitude of an impulsive wave on the axis ($\theta=0^\circ$). Circles represent the experimental data and the experimental condition indicated by point A corresponds to that of point A in Fig. 6. According to the acoustic theory, the reduction rates of sound level from the rectangular plane source with lengths b and c ($b > c$) are 6 dB, 3 dB and 0 by doubling of the distance in the regions of $r > 0.318b$, $0.318b > r > 0.318c$ and $0.318c > r$, respectively⁽¹²⁾. The dot-dashed lines of Fig. 7 indicate the boundary of these regions. These can be rewritten as $r=0.835D$ and $0.256D$ under the condition of the present experiment with consideration of the influences of the ground effect due to a horizontal plate located at the surface of the propagation tube. If the nondimensional distance of experimental point A is used as reference nondimensional distance r_{ref}/D , the magnitude of an impulsive wave at the other positions of the far-field are given by

$$\Delta p_{\max}(r) = \frac{r_{\text{ref}}}{r} \Delta p_{\max}(r_{\text{ref}}). \quad (9)$$

Fig. 7 Attenuation of magnitude of impulsive wave with distance

(a) $L/D=17.6$

(b) $L/D=9.53$

Fig. 8 Isobars of magnitude of impulsive wave

The straight line through point A obtained using Eq. (9) agrees well with the experimental results up to a distance $r/D > 0.835$ in Fig. 7. Therefore, it can be considered that the region of $r/D > 1$ is the far-field. The solid line at the region $0.256 < r/D < 0.835$ is written from the condition of $r/D = 0.835$. The gradient of this line is -3 dB/dd .

3.5 Directivity of impulsive wave

Figures 8(a) and (b) show the isobars of an emitted impulsive wave on the x - y plane of Fig. 1. The nondimensional lengths of the initial compression waves are $L/D = 17.6$ and 9.53 . If an impulsive wave does not have directivity, Fig. 8 is written by half-

circles with their center corresponding to the open end. Although the isobars in Fig. 8(a) has the form of a half-circle and the directivity is not remarkable, the shape of the isobars in Fig. 8(b) is similar to a half-ellipse. The directivity of an impulsive wave appears markedly in the direction of axis with decreasing length of an initial compression wave. The influence of distance from the open end on the directivity of an impulsive wave can be neglected because of the similarity of the isobars in Figs. 8(a) and (b).

Directivity coefficient $R(\theta)$, which is defined as the ratio of $[\Delta p_{\max}(r)]_{\theta}$ to $[\Delta p_{\max}(r)]_{\theta=0}$ at the same distance from the exit, is given by

$$R(\theta) \equiv \frac{[\Delta p_{\max}(r)]_{\theta}}{[\Delta p_{\max}(r)]_{\theta=0}}, \quad (10)$$

where θ is the angle from the axis shown in Fig. 1. In the cases of a rectangular plane source and a circular plane source, $R(\theta)$ on the horizontal plane containing the center of the source is given by the following equations⁽¹³⁾.

$$R(\theta) = \frac{\sin \varphi}{\varphi} \quad \varphi = \frac{\pi c}{\lambda} \cos\left(\frac{\pi}{2} - \theta\right) \quad (11)$$

$$R(\theta) = \frac{2J_1(\varphi)}{\varphi} \quad \varphi = \frac{\pi D}{\lambda} \sin \theta, \quad (12)$$

where c is the width of a rectangular tube, D the diameter of a circular tube, λ the wavelength and J_1 the first-order Bessel function.

In the case that an initial compression wave of $L/D = 9.53$ is discharged from the rectangular open end, the relation between $R(\theta)$ and θ at a distance $r/D = 6.8$ is shown in Fig. 9(a). The solid lines show the numerical results obtained using Eq. (11) at $\lambda = 0.1L \sim 0.2L$. The experimental results agree with the numerical results for $\lambda = 0.16L$. Therefore, the directivity of an impulsive wave which is emitted from the open end of a rectangular tube can be determined from Eq. (11).

The directivity coefficient $R(\theta)$ of an impulsive wave is calculated by the TVD method in the case that an initial compression wave represented by Eq. (4) in Ref. (3) is discharged from a circular tube. Numerical and experimental results are shown in Fig. 9(b) at $r/D = 2.22$. The solid lines show the numerical results obtained using Eq. (12) at $\lambda = 2L$. It is found that the directivity coefficient $R(\theta)$ is independent of the pressure rise $\Delta p^*/p_1$; therefore, the same characteristics of directivity exist for different values of $\Delta p^*/p_1$. Furthermore, the directivity becomes marked with decreasing L/D , similar to the experimental results shown in Fig. 8. Although the directivity coefficient given by Eq. (12) in the case of $L/D = 0.7$ is estimated to be smaller than the numerical results obtained using the TVD method, these values

(a) Comparison between experimental results and Eq.(11)

(b) Comparison between numerical results obtained using TVD method and Eq.(12)

Fig. 9 Directivity of impulsive wave

are in agreement in the cases of $L/D=1.4$ and 2.8 . Therefore, the directivity of an impulsive wave which is generated when a compression wave of length L discharges from the open end of a circular tube can be determined from Eq.(12) assuming the λ as a multiple of L .

Hence, the magnitude of an impulsive wave at the position (r, θ) of the far-field can be expressed by the following equation which is obtained by combining Eqs.(9) and (10).

$$[\Delta p_{\max}(r)]_{\theta} = \frac{r_{\text{ref}}}{r} R(\theta) [\Delta p_{\max}(r_{\text{ref}})]_{\theta=0}, \quad (13)$$

where $[\Delta p_{\max}(r_{\text{ref}})]_{\theta=0}$ denotes the magnitude of an impulsive wave at a reference point on the axis.

4. Conclusions

The characteristics of an impulsive wave which is generated by the emission of a propagating compression wave from the open end of a rectangular tube are investigated experimentally. The conclusions are summarized as follows.

(1) The wavefront of a compression wave obtained using a fast opening gate valve in this study is expressed as Eq.(1). The open-end correction can be neglected in the case of $L/D > 4$, in the present experiment.

(2) The magnitude of an impulsive wave is small compared with the pressure rise of a compression wave. The experimental value of pressure change in the far-field agrees well with the numerical result obtained using Eq.(5).

(3) The magnitude of an impulsive wave is intermediate between the numerical values obtained using Eqs.(7) and (8). It is shown that the thickness of a propagation tube for a compression wave acts as a baffle plate at the open end.

(4) The attenuation with distance of an impulsive wave along the axis of a tube agrees with that of an acoustic wave emitted from a rectangular plane source as determined by the acoustic theory. The region $r/D > 1$ can be treated as the far-field. The changes in magnitude with the distance in the far-field agree with the numerical result obtained using Eq.(9).

(5) The directivity of an impulsive wave depends on the length L rather than the pressure rise of a compression wave and becomes more evident with decreasing r/D . The directivity of an impulsive wave can be determined using Eqs.(11) and (12) in the cases of a rectangular and a circular tube, respectively. The magnitude of an impulsive wave at any position of the far-field can be determined using Eq.(13).

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