Oscillatory Characteristics of a Pseudo-Shock Wave in a Rectangular Straight Duct*

Kazuyasu MATSUO**, Hiroaki MOCHIZUKI**,
Yoshiaki MIYAZATO** and Morito GOHYA***

The oscillatory characteristics of a pseudo-shock wave with a Mach number of 1.75 in a rectangular straight duct are experimentally investigated by static pressure measurements both on the duct axis and on the wall surface. The aspects of the pressure oscillation in the pseudo-shock region are analyzed from the treatment based on the intermittent characteristics, root-mean square, probability density function and cross correlation of the pressure signals. The correlation between the oscillatory characteristics and the flow mechanism of the pseudo-shock wave is also discussed in detail in the last section of the present paper.

Key Words: Compressible Flow, Boundary Layer, Internal Flow, Pseudo-Shock Wave, Pressure Oscillation, Intermittency

1. Introduction

It is well known that a normal shock wave in a duct interacts with a boundary layer on the wall surface and becomes a pseudo-shock wave⁽¹⁾⁻⁽⁹⁾. The location of the pseudo-shock wave in the duct is determined by the duct geometry and by the stagnation pressure ratio across the duct. However, even if these conditions are kept constant, the pseudo-shock wave oscillates around its mean position which causes extreme pressure oscillation⁽⁵⁾. Since such oscillation induces vibration of the duct or causes heavy sound noise to be emitted into the atmosphere, many studies have been performed so far to clarify the mechanism of the oscillation. In these investigations, it has been discussed that the oscillation may be due to the interaction of the pseudo-shock wave with disturbances propagating from its upstream or downstream flow regions⁽⁵⁾⁻⁽⁷⁾, or it may be due to the fluctuation of the boundary layer in the pseudo-shock region^{(8),(9)}. However, this problem is not yet settled, and there remain many unknown problems as to the cause and characteristics of the oscillation of the pseudo-shock wave.

In previous investigations, the oscillation was

studied by such methods as measuring wall pressure or visualizing flow with high-speed schlieren optical observation. The wall pressure increases monotonously from the beginning point to the final point in the pseudo-shock region. On the other hand, the time-mean static pressure distribution on the duct axis in this region shows extreme wavy variation⁽²⁾⁻⁽⁴⁾. In this respect, it may be considered that larger pressure oscillation is generated on the duct axis, rather than on the wall surface. In the present investigation, the oscillation of a λ -shaped pseudo-shock wave with a flow Mach number of 1.75 just upstream of the shock is studied in the test section with a rectangular cross section. The pressures are measured both on the wall surface and on the duct axis. The oscillatory characteristics of the pseudo-shock wave are examined in detail and the relationship between the mechanism of the pseudo-shock and its oscillation is also discussed.

2. Experimental Apparatus and Data Analysis

2.1 Test facility and instrumentation

The test facility is schematically shown in Fig. 1. High pressure dry air in a reservoir flows into the plenum chamber at the left end in Fig. 1, is accelerated to supersonic in the Laval nozzle, and then is discharged into the atmosphere through the test section, diffuser and the settling chamber. The length from the nozzle inlet to the throat is 78 mm, with a length of 122 mm from the throat to the nozzle exit, and the length of the test section is 528 mm. The widths of the

* Received 13th May 1992. Paper No. 91-0128 A

** Department of Energy Conversion Engineering, Graduate School of Engineering Sciences, Kyushu University, Kasuga, Fukuoka 816, Japan

*** IBM Japan, Ltd., Ichimiya, Yasu-cho, Yasu-gun, Shiga, Japan

nozzle and of the test section are constant at 32 mm. The height at the inlet of the test section is 25 mm, and both the upper and the lower walls of the test section are inclined at 0.4 deg to the center axis to stabilize the location of the pseudo-shock wave in the test section. Further, the side walls enclosed by the broken line are of optical glass to allow visualization of the flow by the schlieren optical method.

The wall static pressures are measured through pressure holes of 0.8 mm diameter in the center of the lower wall surface at 78 mm, 153 mm, 178 mm and 203 mm from the inlet of the test section, as shown by the letters A, B, C and D, respectively. Kulite differential transducers (Model XCQ-062) with a natural frequency of 500 kHz and Toyoda semiconductor transducers (Model PMS 5-1 H) with a natural frequency of 15 kHz are used for pressure measurement.

The static pressure distributions along the duct axis are measured by a through-tube inserted from the plenum chamber to the settling chamber, as shown in Fig. 1. The back pressure p_b in the settling chamber is nearly equal to the atmospheric pressure. The experiments are carried out in the case of the ratio $p_0/p_b=2.15$, where p_0 is the upstream plenum stagnation pressure. For this pressure ratio, the head of the pseudo-shock wave is positioned on time-average at 189 mm from the inlet of the test section along the duct axis and the flow Mach number just upstream of the head is 1.75.

The configuration of the through-tube is shown in Fig. 2. It consists of an inner tube and an outer tube. The inner tube with an outer diameter of 1.9 mm and an inner diameter of 1.7 mm is inserted into the outer tube with an outer diameter of 2.2 mm and an inner diameter of 2.0 mm, as shown in Fig. 2(a). The percentage of the cross-sectional area (3.80 mm²) of the outer tube to that of the test section at the inlet (800 mm²) is only 0.48%, so that the effect on the flow by inserting the through-tube into the duct is negligible. A 1.7-mm groove is slit in a section of the outer tube 150 mm to 650 mm downstream of the nozzle throat and a static pressure hole with a diameter of 0.5 mm

is drilled in the inner tube at the center of the slit. In the experiment, the outer tube is fixed and the inner tube is moved in the flow direction to measure the static pressures at various points along the duct axis. As shown in Fig. 2(b), the Kulite pressure transducer described above is inserted just after the pressure hole. The pressure signals from the transducers are input into a data recorder through amplifiers, and then analyzed by an NEC personal computer, Model PC-9801 VX, sampling each signal at 0.1 ms intervals through an A/D converter.

2.2 Data analysis

The measured static pressures were analyzed in the following manner. Let the time-mean pressure at the distance x from the inlet of the test section be $p_m(x)$ and its perturbation component be $p'(x, t)$; thus the static pressure $p(x, t)$ is given by

$$p(x, t) = p_m(x) + p'(x, t) \quad (1)$$

In terms of the sampling period Δt and the sampling data points N for $p(x, t)$, $p_m(x)$ may be obtained from the following equation.

$$p_m(x) = \frac{1}{N} \sum_{n=0}^{N-1} p(x, n\Delta t) \quad (2)$$

Also, the root-mean square $p_{rms}(x)$ in p can be defined as follows

$$p_{rms}(x) = \left\{ \frac{1}{N} \sum_{n=0}^{N-1} p'^2(x, n\Delta t) \right\}^{\frac{1}{2}} \quad (3)$$

Further, the probability density function pdf can be defined as

$$\text{pdf} = \lim_{\Delta p \rightarrow 0} \frac{\text{Prob}[p < p(t) < p + \Delta p]}{\Delta p} \approx \frac{m}{N\Delta p} \quad (4)$$

(a) Cross section of through-tube

(b) Arrangement of pressure hole and transducer in inner tube

Fig. 1 Schematic of experimental apparatus

where Δp is the divided pressure in the case of dividing the difference between the maximum and the minimum pressures in p into N equal pressures, and m is the number of data in Δp . Here, pdf means the probability that the value of the oscillating static pressure at a certain position is within a certain pressure range and it is thus possible to calculate the intermittency of pressure oscillation from the probability density distribution^{(10),(11)}. Further, in the present analysis, in order to clarify the relationship between the wall static pressure oscillations and those on the duct axis, the cross-correlation coefficient $R_{ij}(\tau)$ was calculated by the following equation:

$$R_{ij}(\tau) = \frac{\lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T p_i'(t) p_j'(t + \tau) dt}{\left(\lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T p_i'^2(t) dt \right)^{\frac{1}{2}} \left(\lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T p_j'^2(t) dt \right)^{\frac{1}{2}}} \quad (5)$$

where τ is the delay time, $T = N\Delta t$ the total sampling time of the data, and $p_i'(t)$ and $p_j'(t)$ fluctuation pressures at the reference point and the contrast point, respectively. In the present analysis, the location at $x = 178$ mm, which is the point of the foot of the front leg of the first shock, as will be described later, is selected as the reference point, and the cross-correlation coefficients of the pressure at this point with the axial static pressures, the pressures at the upstream wall point ($x = 153$ mm) and the downstream wall point ($x = 203$ mm) of the first shock are calculated. The sampling frequency of the data is 10 kHz and the number of data at each location is 4096 points.

3. Experimental Results and Discussion

3.1 Optical observation and static pressure distribution

A typical schlieren photograph of the pseudo-shock wave in the test section and its sketch at the ratio $p_0/p_b = 2.15$ of the upstream plenum stagnation pressure p_0 to the downstream one p_b are shown in Fig. 3. The flow Mach number immediately upstream of the pseudo-shock wave is $M = 1.75$, the boundary layer thickness is $\delta = 4$ mm and the Reynolds number is $Re = 9.0 \times 10^6$ based on the length from the throat. The pseudo-shock wave is λ -shaped and its head is located at a distance 189 mm from the inlet of the test section.

The white regions just downstream of each shock show expansion regions where the flow is accelerated. Points A, B, C and D marked on the lower wall in Fig. 3(b) indicate the measuring points of the static pressures on the center of the lower wall, as shown in Fig. 1. Point E is located on the duct axis at the same cross section as that of point A. Points G, K, L and M

show the time-mean locations of the first, second, third and fourth shocks, respectively. Further, points F and H represent typical measuring points of the intermittency of pressure oscillation in the upstream and downstream regions of the first shock, respectively, which will be described in section 3.2. Furthermore, points I and J denote the measuring points in the expansion and compression regions between the first and the second shock waves, respectively, which will be described in section 3.3.

A distribution of the time-mean static pressure p_m on the duct axis measured by the through-tube is shown in Fig. 4 against the distance x from the inlet of the test section. Here, p_m is nondimensionalized by the plenum stagnation pressure p_0 . Also, $(x - x_s)/D$ in the abscissa denotes the distance measured from the mean position $x_s = 189$ mm of the first shock wave nondimensionalized by the equivalent tube diameter $D = 30$ mm at this position.

Points E, F, G and H marked on the abscissa correspond to the same symbols in Fig. 3(b), respectively, and will be explained in the following section. In the figure, the position $x = 177$ mm at which p_m abruptly increases is the farthest point in upstream movement of the first shock during the oscillation of the pseudo-shock wave. In addition, p_m gradually increases from the inlet of the test section to the location $x = 128$ mm due to a frictional effect which is similar to a supersonic Fanno flow⁽¹²⁾. The reason why the pressure gradient in $128 \text{ mm} < x < 177$ mm is a

(a) Schlieren photograph showing λ -shaped pseudo-shock wave

(b) Schematic sketch of Fig. (a)

Fig. 3 Schlieren photograph showing λ -shaped pseudo-shock wave and its schematic sketch

little larger than that in $x < 128$ mm may be considered to be due to the interaction between the first shock and the boundary layer on the through-tube. The effect of this gradient on the oscillations of the static pressures will be described later.

3.2 Static pressure oscillations on duct axis

Variation of the static pressure with time at points E, F, G and H on the duct axis shown in Fig. 4 are indicated in Figs. 5(a), (b), (c) and (d), respectively. The abscissa is time and the ordinate is the ratio p/p_0 of the local static pressure p to the plenum stagnation pressure p_0 . The ratio p_m/p_0 of the mean pressure p_m at each position to p_0 is represented by the arrow on the right ordinate in each figure. Since the measuring point E in Fig. 5(a) is located in a supersonic flow region far upstream from the time-mean position ($x_s = 189$ mm) of the first shock, the

Fig. 4 Time-mean static pressure distribution on duct axis

oscillation of the static pressure is negligible. The oscillation of the static pressure in Fig. 5(b) on the measuring point F located 9 mm upstream of x_s is significant. The point to which special attention should be paid is that the pressure becomes intermittently higher than the mean value p_m . This is due to the first shock wave intermittently passing through point F. The measuring point G in Fig. 5(c) is located exactly at x_s , so p/p_0 oscillates both to the larger side and to the smaller side from its mean value in nearly the same manner. The maximum amplitude in this case amounts to about 17 kPa (17% of the atmospheric pressure). The measuring point H in Fig. 5(d) is positioned 6 mm downstream of x_s , and it is identified that the pressure becomes intermittently lower than p_m due to the movement of the first shock.

Next, for the range of $x = 171$ mm (18 mm upstream of x_s of the first shock wave) to $x = 255$ mm (66 mm downstream of x_s), maximum static pressure $p_{\max}$, mean value p_m and minimum pressure $p_{\min}$ on the duct axis and nondimensionalized by p_0 are shown in Fig. 6. The difference between $p_{\max}$ and $p_{\min}$ in Fig. 6 represents the amplitudes of static pressure oscillations. The symbols F, G, K, L and M in the figure are explained in Fig. 3. In the present experiment, the oscillating first shock wave moves farthest upstream to $x = 177$ mm. In the range between this position and the time-mean position G of the first shock wave, the pressure becomes intermittently higher than the mean value, as shown in Fig. 5(b). Therefore, in Fig. 6, the spacing between $p_{\max}/p_0$ and p_m/p_0 is larger than that between p_m/p_0 and $p_{\min}/p_0$ in the range of $177 \text{ mm} < x < 189$ mm. Further, in a region between point G and the farthest downstream position of $x = 198$ mm of the

Fig. 5 Pressure-time history showing static pressure oscillations on duct axis

first shock wave, the intermittent pressure oscillation appears in the side lower than the mean value, as shown in Fig. 5(d). In the same region in Fig. 6, the spacing between $p_{\max}/p_0$ and p_m/p_0 is smaller than that between p_m/p_0 and $p_{\min}/p_0$. In this way, the appearance of the intermittency in the static pressure oscillation differs in the upstream and the downstream regimes of the mean position of the first shock wave. The same phenomenon was confirmed in the upstream and the downstream regimes of a series of shock waves following the first shock wave.

As described above, it was clarified that the location of each shock in the pseudo-shock is closely related to static pressure oscillations. In order to elucidate this relationship in more detail, the root-mean squares p_{rms} of the static pressure oscillations on the duct axis were calculated. The results are indicated by white circles in Fig. 7. The abscissas in Fig. 7 are x and $(x-x_s)/D$ which are the same as those in Fig. 4, and p_{rms} of the ordinate is nondimensionalized by p_0 . The triangular marks in Fig. 7 indicate the experimental values at points A, B, C and D on the center line of the lower wall in Fig. 3(b). The letters E, F, G, H, K, L and M represent the same points as which are shown in Fig. 3 and described in relation to Figs. 3 to 6. In Fig. 7, since p_{rms} in the range of $x=78 \sim 128$ mm far upstream of the first shock wave is extremely small, it can be considered that the oscillation of the pseudo-shock wave hardly influences the flow in this range. p_{rms} gradually increases toward the downstream direction in the range of $x=128 \sim 177$ mm. This increase may be caused by the fact that the pressure signals by the oscillation of the pseudo-shock wave propagate upstream through the boundary layer on the through-tube. In the range of $x=177 \sim 204$ mm, p_{rms} abruptly increases and then decreases. This large variation results from the first shock oscillation.

Fig. 6 Maximum, mean and minimum values of static pressure oscillations along duct axis

Therefore, maximum pressure oscillation occurs at the mean position (corresponding to point G of $x_s=189$ mm) of the first shock. Likewise, p_{rms} shows the peak values at points K, L and M corresponding to the mean positions of the second, the third and the fourth shocks. Furthermore, in the downstream region from $x=270$ mm, p_{rms} settles at a nearly constant value of $p_{rms}/p_0=0.51 \times 10^{-2}$. According to the schlieren observation of the pseudo-shock wave and the analysis of the probability density function which will be described later, this region corresponds to a subsonic regime in the pseudo-shock wave, and thus no shock waves exists in this region. The pressure oscillations in this regime may be due to the mixing-diffusion effect between the high-speed flow in the central portion of the duct and low-speed flow in the neighborhood of the wall. Also, p_{rms} at points A and B on the lower wall are consistent with those on the duct axis. Further, the pressure oscillation at point C agrees well with that on the duct axis because point C exists in the oscillatory region of the front leg of the first shock wave. On the other hand, p_{rms} on point D is about half that on the duct axis, so it can be identified that the flow near the duct axis oscillates considerably more than in the neighborhood of the wall. This means that the boundary layer thickness on the through-tube is considerably thinner than that on the wall, and the pressures measured with the through-tube can be regarded as those in the flow without the through-tube. Also, since the pressure oscillations of the pseudo-shock measured by the through-tube clearly show the intermittency, as described before, it can be considered that the effect of the boundary layer on the through-tube on the oscillation of the pseudo-shock is

Fig. 7 Distribution of root-mean square of static pressure oscillations along duct axis

negligible. Here, in the present study, the position of each shock comprising the pseudo-shock wave is decided by the peak point of the root-mean-square values p_{rms}/p_0 in Fig. 7. It is confirmed that these positions agree well with the mean positions of each shock measured from the schlieren optical observation.

Next, the probability density functions pdf of the static pressure oscillations at points E, F, G and H in Fig. 3 are shown in Fig. 8 against the ratio $(p - p_m)/p_0$ of the difference $p - p_m$ between the static pressures p at each position and their mean values p_m to the plenum stagnation pressure p_0 . Each pdf is normalized so that the area enclosed by the abscissa and the curve denoting pdf becomes equal to unity. Further, the solid lines in Fig. 8 indicate normalized probability distributions (Gaussians) and white circles are experimental values. The ratio p_{rms}/p_0 of root-mean square p_{rms} to p_0 is also shown in Fig. 8. In Fig. 8, when the experimental peak value exists in the left side from the peak in the Gaussian, it means that the pressure becomes intermittently higher than the arithmetic mean value, and when it is in the right side, the pressure becomes intermittently lower.

The oscillation mean at position E far upstream of the pseudo-shock wave is extremely small, as indicated in Fig. 5(a), and the pdf agrees well with the Gaussian line, as shown in Fig. 8(a). Also, in Fig. 8(b), the experimental peak value exists on the left side from the peak in the Gaussian and it almost agrees with the Gaussian line in Fig. 8(c). Further, it

Fig. 8 Probability density function of static pressure oscillations on duct axis

exists on the right side in Fig. 8(d). From these results, it is said that the appearance of the probability density function of oscillation in the upstream region of the mean position of the first shock wave obviously differs from that in the downstream region. This is due to the fact that the pressure in the upstream region of the first shock varies from a lower to higher value when the first shock passes through the position toward the upstream direction, and the pressure in the downstream region varies reversely for shock movement toward the downstream direction, and these movements of the first shock occur intermittently, as described in Fig. 5.

3.3 Relationship between static pressure oscillations at wall and duct axis

As mentioned in section 3.2, the static pressure oscillations on the duct axis in the pseudo-shock wave are closely related with the mean positions of each shock forming the pseudo-shock wave. To clarify in more detail the mechanism of the pseudo-shock and its oscillation, the static pressure oscillation at point C ($x = 173$ mm, see Fig. 3) located at the foot of the front leg of the first shock was compared with those at point G ($x = 189$ mm, mean position of the first shock), point I ($x = 198$ mm, a point in the expansion region downstream of the first shock), and point J ($x = 207$ mm, a point in the compression region downstream of the first shock). The pressure variations with time at these points are shown in Figs. 9(a), (b) and (c). The ordinate in Fig. 9 is nondimensionalized by p_0 . The two pressure signals in each figure were simultaneously measured, but all signals in Figs. 9(a), (b) and (c) were not measured simultaneously. Figure 10 shows the cross-correlation coefficients $R_{ij}(\tau)$ between the pressure oscillation at point C and those at points G, I and J. At first, as shown by the dotted lines in Fig. 9(a), the two signals oscillate with almost the same phase. This state can be confirmed from the fact that the correlation coefficient has a positive peak value of 0.85, as shown in Fig. 10(a). Therefore, it can be said that the central portion of the first shock oscillates with the bifurcated one. On the other hand, signals C and I, as shown by the dotted lines in Fig. 9(b), are different in phase by 180 deg, and the pressure at point I decreases when the pressure at point C increases, and vice versa. This result can be understood from the fact that in Fig. 3(b), when the first shock moves upstream, although the pressure at point C increases, point I moves to the relatively downstream position in the expansion region. Also, this phenomenon can be checked by seeing that the correlation coefficient has the negative peak value of -0.65 in Fig. 10(b). Moreover, in Fig. 9(c), it is seen that the pressure signal at point J

Fig. 9 Static pressure oscillations on both point C on wall and points G, I and J on duct axis

Fig. 10 Cross-correlation coefficient of static pressure oscillation between point C and points G, I and J

changes in nearly the same phase as that at point C, as shown by the dotted lines, and the peak value of the cross-correlation coefficient is about 0.5 in Fig. 10(c).

It was thus found that the static pressure oscillation at point C is closely related to those at points G, I and J on the duct axis. To clarify in more detail the relationship between the static pressure oscillations on the duct axis and on the wall, the peak value $R_{ij, pk}$ of the cross-correlation coefficients between the static pressure oscillation at point C and those at points on the duct axis are indicated against the distance x in Fig. 11. Figure 11 indicates the magnitude of pressure response at each position on the duct axis in the pseudo-shock region against the pressure variation at point C. As mentioned before, since measuring point C is positioned nearly at the foot of the front leg of the first shock and the foot almost coincides with the separation point of the boundary layer, Fig. 11 indicates the relationship between the pressure oscillation caused by the change of the separation point and those in the central region in the pseudo-shock wave, which results from a normal shock-boundary layer interaction.

Now, in Fig. 11, the peak $R_{ij, pk}$ of the cross-correlation coefficient in the range of $x=180\sim189$ mm is a considerably larger value of about 0.85. Therefore, this range exists in the region where the central normal part of the first shock wave oscillates backward and forward, and it is found that the central part of the shock oscillates with the front leg in almost the

Fig. 11 Variation in flow direction for peak values of cross-correlation coefficient

same phase. $R_{ij, pk}$ abruptly decreases in the range of $x=189\sim198$ mm and then abruptly increases in $x=198\sim207$ mm. This can be explained in the following way. As shown in Fig. 3, position H ($x=195$ mm) locates in the expansion region after the first shock in the time-mean flow. However, point H may be located for an instant in the compression region downstream of the first shock because the first shock oscillates within the range of $x=177\sim198$ mm within the present experiment. From the above consideration, it can be stated that $R_{ij, pk}$ decreases in the range of $x=189\sim198$ mm because the compression effect on the flow caused by the first shock gradually decreases along the distance. As a result, $R_{ij, pk}$ becomes minimum at point I ($x=198$ mm) corresponding to the farthest

downstream position of the first shock during its oscillation. Likewise, it can be said that $R_{ij, pk}$ increases in the region of $x=198\sim 207$ mm because the compression effect by the second shock becomes larger as x increases in this range. As is clearly shown in Fig. 11, the same pattern of variation in $R_{ij, pk}$ as mentioned above is repeated in the downstream region of the second shock. But, in this region, the absolute value of $R_{ij, pk}$ becomes smaller because the amplitude of oscillation of the second shock is smaller and its strength is weaker.

4. Conclusions

The oscillatory characteristics of the pseudo-shock wave with a flow Mach number of 1.75 in a test section with a rectangular cross section were studied by measuring both static pressure oscillations on the wall and on the duct axis by a through-tube. The results obtained are summarized as follows.

(1) The intermittency in pressure oscillations on the duct axis occurs on the side larger than the time-mean static pressure p_m in the upstream region of the time-mean position x_s of the first shock wave, and on a smaller side in the downstream region of x_s . The intermittent static pressure oscillation at x_s arises both on the larger side and on the smaller side than p_m in nearly the same manner. Such an intermittent oscillatory characteristic of the first shock was also confirmed from the distributions of the probability density function of the static pressure oscillations.

(2) The distribution of the root-mean square p_{rms} of the static pressure oscillations along the duct axis changes in a wavy form and the peak locations agree with the time-mean positions of each shock forming the pseudo-shock wave. Furthermore, their peak values are smaller in the order of the first, the second and the third shocks. The p_{rms} for the subsonic region in the pseudo-shock wave is nearly constant and is about 0.5% of the stagnation pressure p_0 in the present experiment.

(3) The static pressure on the duct axis between the first and the second shocks oscillates in either the same phase or in one different from that at the foot of the front leg of the first shock, depending on the position of the measuring point relative to the time-mean shock position. Also, when the time-mean location of the foot of the front leg is selected as the reference point, the peak value of the cross-correlation coefficient of the static pressure oscillation between this point and those obtained along the duct axis is positive at the time-mean position of the first shock, and abruptly decreases to a negative value in

the expansion region just after the first shock. It then abruptly increases to a positive value in the compression region under the influence of the second shock wave. The phase of static pressure oscillations and the variation in the peak value of the cross-correlation coefficient mentioned above are physically explained by taking into consideration the flow structure consisting of expansion and compression regions between the first and the second shock waves.

References

- (1) Matsuo, K., On the Pseudo-Shock Waves, Flow (in Japanese), Vol. 6, No. 4(1987), p. 308.
- (2) Tamaki, T., Tomita, Y. and Yamane, R., A Study of Pseudo-Shock I. λ -Type Pseudo-Shock, Bull. JSME, Vol. 13, No. 55(1970), p. 51.
- (3) Tamaki, T., Tomita, Y. and Yamane, R., A Study of Pseudo-Shock II. x -Type Pseudo-Shock, Bull. JSME, Vol. 14, No. 74(1971), p. 807.
- (4) Om, D. and Childs, M. E., Multiple Transonic Shock-Wave/Turbulent Boundary Layer Interaction in a Circular Duct, AIAA J., Vol. 23, No. 10(1985), p. 1506.
- (5) Ikui, T., Matsuo, K., Nagai, M. and Honjo, M., Oscillation Phenomena of Pseudo-Shock Waves, Bull. JSME, Vol. 17, No. 112(1974), p. 1278.
- (6) Yamane, R., Kondo, E., Tomita, Y. and Sakae, N., Vibration of Pseudo-Shock in Straight Duct, I. Fluctuation of Static Pressure, Bull. JSME, Vol. 27, No. 229(1984), p. 1385.
- (7) Yamane, R., Takahashi, M. and Saito, H., Vibration of Pseudo-Shock in Straight Duct, II. Correlation of Static Pressure Fluctuation, Bull. JSME, Vol. 27, No. 229(1984), p. 1393.
- (8) Sugiyama, H., Takeda, H., Zhang, J., Okuda, K. and Yamagishi, H., Locations and Oscillation Phenomena of Pseudo-Shock Waves in a Straight Rectangular Duct, JSME Int. J., Ser. II, Vol. 31, No. 1(1988), p. 9.
- (9) Sugiyama, H., Takeda, H., Zhang, J., Sekiyama, M. and Yamagishi, H., Locations and Oscillation Phenomena of Pseudo-Shock Waves in a Straight Rectangular Duct (2nd Report, Spectral Analysis of Wall Pressure Fluctuation in Pseudo-Shock Waves), Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 53, No. 490, B(1987), p. 1666.
- (10) Spina, E. F. and Smith, A. J., Organized structure in a supersonic turbulent boundary layer, Princeton Univ. Rep., (1986), p. 31.
- (11) Dolling, D. S. and Or, C. T., Unsteadiness of the Shock Wave Structure in Attached and Separated Compression Ramp Flows, Experiments in Fluids, Vol. 3(1985), p. 24.
- (12) Ikui, T. and Matsuo, K., Compressible Gas Dynamics (in Japanese), (1987), p. 51. Rikougakusha.