Investigations of Transonic Ludwig Tubes

Part 2 Starting Process in the Case of a Downstream Valve*

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Among many types of transonic wind tunnels, transonic Ludwig tube is the most suitable facility for very high Reynolds number transonic testing. However, its starting process is quite complicated and the flow mechanism is not yet understood. In the present paper, the starting process of a transonic Ludwig tube with a downstream quick-opening valve and a plenum exhaust system was experimentally investigated over a wide range of plenum chamber volumes and flow rates. The result shows that a steady and uniform flow in the test section is established when the mass flow rate through the porous wall of the test section becomes equal to that through the plenum exhaust system. Although this is the same as in the case of an upstream valve system, it has been also shown that the flow mechanism of both cases is quite different between the two.

Transonic Ludwig Tube, Starting Process, Downstream Valve

1. Introduction

In transonic Ludwig tubes,⁽¹⁾⁻⁽³⁾ the quick-opening valves which separate the driving gas and the gas to be driven can be located either upstream or downstream of the test section, but the flow mechanism of the starting process is quite different between the two cases. In the case of an upstream valve operation, a steady transonic flow is established in the propagating and the reflecting process of the compression waves, but in its starting process the compression waves generated at the valve pass through the test section and the starting load on a model in the test section is quite large. Furthermore, the flows are perturbed because of the upstream valve. On the other hand, in the case of a downstream valve operation which employs the exhausting valve together with the main valve, the flow is expected not to induce shock waves but there are many complicated problems such as to adjust the time of opening of both valves. In order to understand the difference in the flow characteristics of the two cases, it is necessary to make clear the starting process of the downstream valve operation and to compare it with that of an upstream valve operation. The mechanism of the starting process of the upstream valve operation was reported in the previous paper.⁽⁴⁾

In the present paper, the case of the downstream valve operation is experimentally

investigated by the pressure measurement and the optical observation by changing the volume ratio of the plenum chamber and the area ratio of the orifice. Based on the experimental results and by comparing them with those of the upstream valve system, the mechanism of the starting process of the Ludwig tube has been clarified.

2. Experimental apparatus

The Ludwig tube used in this work is shown schematically in Fig.1. The cross section and the length of supply tube are 70 mm square and about 12 m. The quadrantal circular nozzle and the test section of 280 mm long and with a cross section of 40 × 70 mm are located downstream of supply tube as shown in Fig.2. Upper and lower walls of the test section consist of porous plates, which have uniformly distributed holes of 3 mm diameter drilled normally to the plates. The porosity of the porous wall is 22 percent which is the same as that in Ref.(1) and the previous paper. The plenum flow through the porous wall is discharged into a vacuum tank via two suction pipes, and orifices are

Fig.1 Experimental apparatus and its measuring system

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installed in suction lines in order to control its flow rate. Hereafter, the quick-opening valve located downstream of the test section is denoted as the main valve and the quick-opening valves set in suction lines as the exhausting valve. These valves are operated by compressed air and they open at the same time. The opening times of the main valve and the exhausting valve are fixed at 10 ms and 6 ms respectively. The initial pressure ratio across the valves is kept constant at 15. Static pressure was measured using semiconductor pressure gauges mounted flush in the sidewall at various stations along the center line of the test section and in the tube. The measuring points I, II, III, IV and V correspond respectively to the locations upstream of the nozzle, the center of the test section, the exit of the test section, and upstream and downstream locations of the orifice. The flow in the test section was observed by a schlieren system and the moment when a photograph was taken was recorded. The plenum volume ratios α ($\equiv$ plenum chamber volume / test section volume) are 0.1, 1.5, and 13.5, and the orifice area ratios β (orifice area / suction pipe area) to control the plenum flow and hence the free stream Mach number are 0.04, 0.2, 0.3, 0.4 and 0.5. Air was used the working gas.

3. Experimental results

3.1 Pressure measurement

Typical pressure records at I, II and V are shown in Fig.3 by respective curves ①, ②, and ③, where the horizontal axis represents the time since the front of expansion waves generated at the valve has arrived at each point, and the vertical axis represents the absolute pressure. A wave diagram obtained from the pressure measurements is shown schematically in Fig.4, where the horizontal axis represents the distance along the tube measured from the valve location, and the vertical axis represents the time since the valve has started to open. Points a~d in Fig.4 correspond to the points a~d on ① and ② in Fig.3. During the opening time of the main valve (τ_0 in Fig.4), expansion and compression waves propagate upstream and downstream of the valve, respectively, and a flow is induced

from left to right. The expansion waves propagate in the supply tube through the nozzle throat until the accelerated flow in the test section is choked at the throat. After the tail of expansion waves has propagated upstream, the flow in the supply tube becomes steady and uniform. Some of expansion waves generated at the main valve propagate into the plenum chamber through the porous wall, and causes a flow from the plenum chamber to the test section. The expansion waves generated at the exhausting valve, on the other hand, propagate upstream of the orifice in the suction line, and after they have arrived at the porous wall due to interference with expansion waves generated by the main valve, the flow from the plenum chamber changes into a flow from the test section to the plenum chamber, and the flow in the test section becomes supersonic being accelerated by this plenum flow. Expansion waves generated at the exhausting valve pass through the orifice until the flow is choked there, and repeat reflections between the orifice and the porous wall. This reflecting process, however, is not shown in Fig.4. The pressure drop between a and b on curve ① in Fig.3 is caused by the expansion waves transmitted through the nozzle, and after this the pressure is constant until point c. The point c indicates the time when the front of the expansion waves reflected

Fig.2 Details of test section

Fig.3 Pressure-time records at measuring points I, II and V ($\alpha=1.5$, $\beta=0.4$)

Fig.4 Wave diagram in starting process

at the end of the supply tube arrives at the measuring point I, and a further drop of pressure is caused by the succeeding waves. The decrease of the pressure after point a of the curve ② is due to the expansion waves generated by the main valve at the beginning, but the further decrease is caused by expansion waves generated by both exhaust and main valves. According to the results of the optical observation which will be described later, the point b corresponds to the time when the flow at the measuring point II becomes supersonic. In this case, a starting shock wave which appears in the starting process of a conventional supersonic nozzle is not observed, and a supersonic flow is fully established instantaneously through test section. The pressure at point II continues to decrease after the point b due to the expansion waves in the reflecting process between the orifice and the porous wall, and becomes constant after the point c. The time of point c lags considerably behind the time when the tail of the expansion waves caused by the valve arrives at the measuring point II. Let the process between points a and c on curve ② in Fig.3 be defined as the starting process and the time or the length τ_s between the points a and c on the vertical line at the measuring point II in Fig.4 be the starting time. The flow mechanism of the starting process and the physical meaning of the point c will be discussed in detail later. The decrease of the pressure between points a and b on the curve ③ in Fig.3 is caused by the incident expansion waves induced by the exhaust valve opening, and its further decrease is caused by the combined effect of the reflected expansion waves from the orifice and the shock wave generated by the choking

at the orifice. The fluctuations in the pressure after the passage of a shock wave is caused by unsteady flow condition upstream of the orifice. The rise of the pressure at the point c is explained by the shock wave which returns to the orifice in consequence of the pressure rising in the vacuum tank. The pressure curves at points III and IV are qualitatively the same as that the measuring point II.

3.2 Optical observation

An example of schlieren photographs of the flow in the test section in the starting process is given in Fig.5 for the case when $\alpha=1.5$, $\beta=0.4$, where τ is the time since the front of the expansion waves generated at the valve arrives at the measuring point II. The direction of the flow is from left to right. The black and parallel bands indicate the porous walls and the upper and lower regions of them are the plenum chamber. In Fig.5(a) and (b), where τ is small, the flow is not fully accelerated and as a whole it is subsonic. In Fig.(c), the flow is transonic being accelerated by the increase of the plenum flow, and the pressure waves generated by the disturbances from the edges of the holes are observed. Fig.5(d) and (e) correspond to the flow after the starting process has terminated, where the shape of the pressure waves is uniform throughout the test section, and the flow uniformity is seen to be achieved. Fig.5(f) shows the state of the flow after the reflected expansion waves from the end of the supply tube have arrived, where the angle of pressure waves to the flow direction is larger than that of Fig.5-(e) showing that the flow is decelerated.

Figure 6 shows the variation of the Mach number in the test section (represented

Fig.5 Schlieren photographs showing flow in starting process ($\alpha=1.5$, $\beta=0.4$)

Fig.6 Variation of flow Mach number M_2 with time

by M_2) with time. The Mach number was determined from the static and the total pressure measurements at the point II. Figure 6(a) represents the case when α was varied under the condition of $\beta = 0.4$, and Fig. 6(b) represents the case when β was varied under the condition of $\alpha = 1.5$. In Figs. 6(a) and (b), the Mach number M_2 in the starting process increases gradually with time and approaches asymptotically the value of the steady condition. When the flow is choked at the nozzle throat, the flow in the test section will become supersonic if there is any outgoing flow through the porous wall. In the present case, however, an inflow to the test section from the plenum chamber through the porous wall is induced and it delays the expansion waves caused by the exhaust valve opening start to induce an outgoing flow. This is the reason why the time when the flow in the test section becomes supersonic and consequently the time when the value of the steady condition is approached delay considerably from the opening time. Thus the remarkable difference of the history of the Mach number between the upstream and downstream valve system can be explained by the histories of the flow through the porous wall in both cases. As to the effect of α , Fig. 6(a) shows that the rate of increase of the Mach number M_2 is reduced and the time when M_2 reaches a constant value delays with an increasing α . The increase of β which is shown in Fig. 6(b), renders the constant value of the Mach number M_2 larger and the time until it reaches the constant value larger. The effects of α and β on the time when the flow Mach number in the test section becomes constant will be discussed in detail later.

3.3 Starting time

As described in the previous sections, the orifice area ratio and the plenum volume ratio affect remarkably the flow in the starting process and accordingly the starting time. The starting time is an important criterion for the performance of a transonic

Fig. 7 Relation between Mach number in test section and starting time

Ludwig tube. In Figure 7, the starting times τ_s obtained by the pressure measurement for $\alpha = 0.1, 1.5$ and 13.5 are shown and are compared with those in Ref. (1), where the horizontal axis represents the Mach number at the measuring point II. Because M_2 is determined only by β , as was stated previously, the horizontal axis is considered to represent β . The figure shows that τ_s increases with M_2 , or with β , for constant values of α . This result shows an opposite tendency to the case of the upstream valve. The values of τ_s which range from 40 ms to 60 ms, are about 4 to 6 times the valve opening time, and are about 2 times those of the upstream valve operation. Figure 8 shows the relation between the starting time τ_s and the plenum volume ratio α . As shown in the figure, the value of τ_s increases with α for a fixed value of β , and this result is in the same tendency as the case of the upstream valve operation.

4. Discussion

The experiments show that the orifice area and the plenum volume affect remarkably the starting process and the starting time. Hence, in this chapter, the flow mechanism in the starting process, i.e., the process through which a steady transonic flow is established will be discussed in relation to the mass flow rate entering the plenum chamber through the porous wall and that discharging through the orifice.

In Figure 9, the time variation of the flow rate of the mass entering the plenum chamber Δm_i and of that discharging from the plenum chamber Δm_o , are shown together with the time histories of the static pressure P_s , P_t , and the total pressure P_{0t} , at respective measuring points II, V and W. The variation of the Mach number M_2 is also shown in the figure. The horizontal axis in the figure represents the time since the incident expansion waves have arrived at the measuring point II. Let us take the case of $\alpha = 1.5$ and $\beta = 0.4$ which is shown by solid curves in the

Fig. 8 Relation between plenum volume ratio and starting time

figure as the standard case and two other cases of $\beta < 0.4$, $\alpha = 1.5$ and of $\alpha > 1.5$, $\beta = 0.4$ which are shown by broken and dotted curves as the reference cases in order to investigate the effects of the orifice area and the plenum volume. The points denoted by a, b', c', etc. in Figs.9(a)~(e) represent the time of the same event in each case. In standard case denoted by the solid line, the fall of pressure P_2 (Fig.9(a)) in its initial stage is caused by the expansion waves generated successively at the main valve, which act to increase the test section Mach number on one hand and to decrease it by inducing a flow from the plenum chamber through the porous wall which has changed from the entering to the outgoing one from the test section on the other hand. Further decrease of pressure P_2 is caused by the flow owing to the expansion waves generated at the exhausting valve. The first fall of the pressure in Fig.9(b) and (c) is caused by the expansion waves generated by opening the exhausting valve. They accelerate the flow in the suction pipe until the flow passing through the orifice is choked at the point c in Fig.(b). The point b in Fig.9(c) represents the time of passage of the shock wave generated by the choking at the orifice. The point c in Fig.(b) appears slightly earlier than the point b in Fig.9(c) because the measuring point V locates slightly downstream of the orifice. When the flow is choked at the orifice any change of the flow downstream should not influence the flow of the test section, and the test section Mach number should be steady. This is one of necessary conditions that the flow in the test section becomes steady. The test section Mach number M_2 in Fig.9(d) however keeps increasing due to the incident expansion waves generated by the valve opening. This means that the choking at the orifice is not enough condition to obtain a steady transonic flow. (This increase of M_2 is rather slow and it takes a long time before it becomes larger than unity or the flow becomes supersonic.) At a time when $M_2 > 1$, the flow at the exit of the test section is supersonic and so the flow downstream of the test section does not influence the flow in the test section. This is another necessary condition that the flow in the test section is steady. Thus if the conditions that the flow is choked both at the nozzle throat and at the orifice, and the flow at the exit of the test section becomes supersonic are satisfied, then a steady transonic flow is expected to be established in the reflecting process of the expansion waves between the porous wall and the orifice. This is shown in Fig.9 (c) where the value of M_2 increases with an increasing plenum flow and approaches asymptotically the value of the steady condition in the supersonic range. The time variation of Δm_i and Δm_o in this process is shown in Fig.9(e). At first the time variation of the outgoing flow from the plenum chamber through the porous wall (negative value of Δm_i) is induced by the incident expansion wave generated at the main valve. It reaches the maximum value and thereafter decreases and changes into an entering flow (positive value of Δm_i) because the incident expansion waves generated by the exhausting valve overcome the effect of the main valve. Δm_i

increases with a decrease of the plenum pressure due to the reflection of the expansion waves repeated between the orifice and the porous wall. The time variations of the outgoing flow rate from the plenum chamber through the orifice Δm_o , on the other hand, increases with time due to the expansion waves generated at the exhausting valve and reaches the maximum value at the choking point c. After the choking point c, Δm_o decreases with time because the total pressure upstream of the orifice (Fig.(b)) falls due to the reflecting expansion waves between the orifice and the porous wall. After the process described above, Δm_i and Δm_o become equal at the point a. Because the difference between Δm_i and Δm_o corresponds to the flow rate discharged from the plenum chamber, an equilibrium condition is established in the enclosed system after their values have become equal. The final point of the starting process defined in section 3.1 corresponds to the point a where the condition of $\Delta m_i = \Delta m_o$ is established. As to the effect of the orifice area ratio β , we can discuss about the differences between the solid and the broken lines in Fig.(a)~(e). The variation of each quantity in about 20 ms from its beginning in Fig.(a), (b) and (c) is caused mainly by the incident expansion waves generated by the main valve opening, hence the variation of Δm_i in its process is not affected by β and the solid line overlaps the broken one. Thereafter, in the case of the broken line, the pressure and accordingly the incoming mass flow rate in the plenum chamber decreases more slowly than the solid line case because the strength of the expansion waves generated at the exhausting valve decreases with a decreasing β . On the other hand, the effect of β on Δm_o is very large; the choking occurs earlier and the maximum flow rate at this time point c', is considerably smaller than that of the standard case point c, when β is decreased. After

Fig.9 Flow mechanism in starting process

the choking point c' , the decreasing ratio of Δm_0 is almost the same as that of the solid line. As the result, the point a' when Δm_i becomes equal to Δm_0 appears earlier than the point a , and the value of Δm_i at the point a' is smaller than that at the point a . After all, if the orifice area ratio β is reduced under the condition of fixed value of α , the mass of the gas discharged from the plenum chamber is smaller and the time when the equilibrium condition is established comes earlier, and the test section Mach number at the equilibrium condition is smaller. The relation of M_2 and τ_s in Fig. 7 is well explained by this rule. The effect of the plenum volume ratio α is examined by comparing the dotted-broken line with the solid one in Fig. (e). Because the change of Δm_i is affected mainly by the incident expansion waves generated at the main valve in its first period, the both lines overlap each other, but in the following period, the increasing rate of Δm_i denoted by the dotted-broken line becomes smaller than that of the solid line because the decreasing rate of the plenum pressure decreases with an increase of α due to reflections of the expansion waves. On the other hand, Δm_0 and therefore the choking point of the dotted-broken line which is denoted by the point c' almost coincide with that of the solid line because Δm_0 is mainly caused by the incident expansion waves generated at the exhaust valve before the flow chokes at the orifice. After the choking occurred, decreasing rate of Δm_0 of the dotted-broken line becomes smaller than that of the solid line due to the volume effect of the plenum chamber which causes a variation of the total pressure upstream of the orifice (Fig. (b)). As the result, the point a' when Δm_i becomes equal to Δm_0 appears later than the point a . Therefore if α is increased under the condition of constant β , the mass of gas discharged from the plenum chamber increases and the time when the equilibrium condition is established delays. The relation of α and τ_s in Fig. 8 is well explained by this rule.

5. Conclusions

The starting process in a transonic Ludwig tube with a downstream valve was investigated experimentally by varying the orifice area and the plenum chamber volume. The conclusions are summarized as follows.

(1) Based on the results of the pressure measurements, a wave diagram for the starting process was constructed, and the flow in this process was clarified by studying the wave diagram and the pressure history.

(2) In the starting process of the downstream valve system, a supersonic flow is fully established instantly through the test section, fairly long time after the flow has been choked at the nozzle throat, and this is considerably different from the case of the upstream valve system.

(3) The test section Mach number in the starting process increases gradually with time and approaches asymptotically the value the steady condition. This result is also quite different from the case of the upstream valve operation, but it is due to the difference of the flow mechanism or the flow histories at the porous wall in both cases.

(4) The starting time is about 4 ~ 6 times the main valve opening time, and is about 2 times the value in the upstream valve operation. By reducing the orifice area and the plenum volume, the starting time can be made shorter.

(5) The necessary conditions to establish a steady transonic flow have been studied by examining the difference between the ratios of the masses flowing into (Δm_i) and out of (Δm_0) the plenum chamber. Such a flow achieved in a slightly supersonic Mach number range when Δm_i has become equal to Δm_0 .

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