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Numerical analysis on the starting processes of the unsteady flow field in the Ludwieg tube with a quiet nozzle

Junmou Shen*, Jian Lin , Jian Gong, Ruiqu Li

China Academy of Aerospace Aerodynamics , CHINA

Abstract :The starting processes of the Ludwieg tube hypersonic quiet tunnel plays very important role in the achievem ent of the quiet flow in the test section, which could affect the confidence coefficient of the data in the hypersonic trans ition experimental investigations. Thus, numerical analysis on that processes could help to understanding the running m ode of the Ludwieg tube quiet tunnel and the propagation principle of the expansion wave series. To verify our computa tional method, the same parameter of the BAM6QT (the Boeing/AFOSR Mach-6 quiet tunnel at Purdue University) is u sed to compute, and it is agrees with our computational results.

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Key Words :Ludwieg tube, Numerical analysis, Hypersonic, Quiet nozzle

1. Introduction

Ludwieg tube is one type of the impulse tunnel, which is running based on the expansion waves in the shock tube. The quiet flow field for the investigations on the hypersonic transition is supplied by the highly polished nozzle with a bleeding slot, which is located in the subsonic section upstream of the throat of the nozzle. A fast-open valve is settled downstream of the test section and separates the high pressure test gas and the vacuum tank with low pressure. After the valve opens, the shock wave and the expansion wave come into being and run upstream and downstream respectively. The expansion wave travels up and do wn the tube, which creates a constant steady flow to the expansion nozzle with pressure and temperature determined by the one-dimensional unsteady expansi on process. In the drive tube upstream of the nozzle, the expansion wave series will reflect between the u pstream end of the drive tube and the throat, as highl ighted in Fig 1. The running time of the Ludwieg tube is generally defined as the time of the expansion wave periodic reflection in the drive tube, and if the wall boundary layer in the drive tube is slowly thicken, the effective running time could be several periods reflection processes of the expansion waves.

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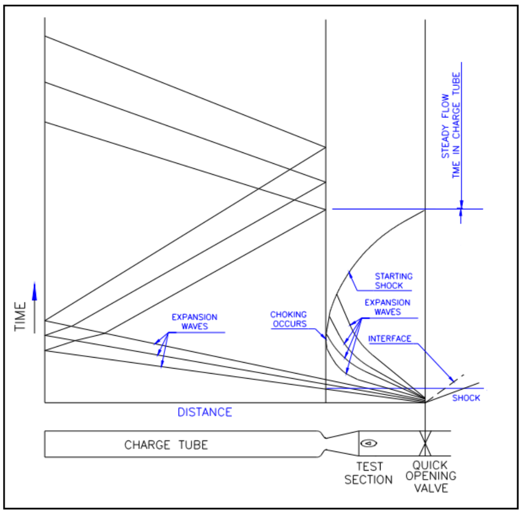
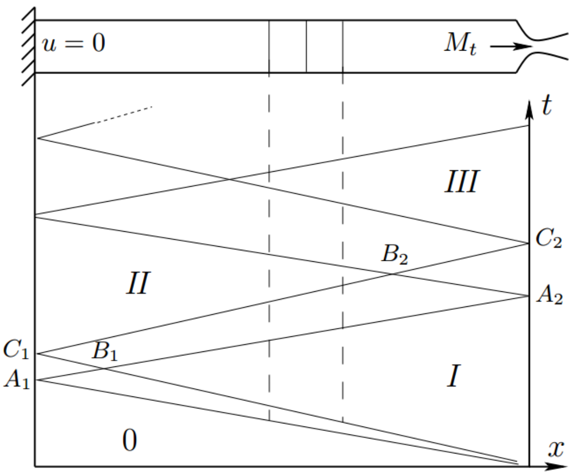
†Corresponding Author
Tel:+ 82-131-4132-1129,
E-mail: shenjunmou@163.com

Computational Fluid Dynamics (CFD) will be used to simulate the flow from the valve through the test section of the Ludwieg tube with quiet tunnel. Of course, the numerical analysis on the starting processes of the unsteady flow field in the Ludwieg tube with a quiet nozzle is a preliminary estimation and the relative investigation in details would be performed in the future.



(a)



(b)

Fig.1 Wind tunnel starting process[1]

2. Governing Equations and Numerical Methods

The Governing equations are the axisymmetric compressible Navier–Stokes equation, the continuous equation, the energy conservation equation and the state equation.

The system of governing equations are discretized by a cell centered finite volume method. We adopt Roe's flux difference splitting method[2] to evaluate inviscid numerical fluxes. The cell boundary values used to evaluate the numerical fluxes are obtained by 2rd order MUSCL approach[3]. The discretized governing equations are integrated in time by 3th-order Runge-Kutta method. The stepping-time is 5×10^{-5} .

3. Computational Domain and Initial Conditions

The computational domain consists of high pressure (a charge tube, a contoured nozzle with bleed slot, the test section) and low pressure part. Namely, this domain is split into two parts: high pressure part and low pressure part. See Fig.2.

Firstly, to verify our computational method, the same parameter of the Boeing/AFOSR Mach-6 quiet tunnel (BAM6QT) at Purdue University is used to compute. The BAM6QT at Purdue University is a blowdown facility which is designed as a Ludwieg tube. The 37.4 long charge tube and its diameter of 444.5mm. The exit Mach number of 6 and the exit diameter of 240mm.

Secondly, we design a new Ludwieg tube quiet tunnel. The regions include the drive tube with the length of 40m and its diameter of 0.6 m, the nozzle with the length of 4.425 m, the exit Mach number of 6 and the exit diameter of 0.4 m, the bleeding slot with its gap width of 3.7 mm, the test section with the length of 6 m and the diameter of 0.4 m and the diffusion section with the length of 4 m and the same diameter as the test section. The size of the Ludwieg tube is close to the BAM6QT in Purdue University. The initial pressure is 1 MPa and the initial temperature is 450K. The fast-open valve in the diffusion section is simplified as one diaphragm so that the opening of the valve could be assumed as an instant operation. See Fig.2. The minimum grid size is10^{-4} m in each grid direction, and the total grid points are 17,1200 points.

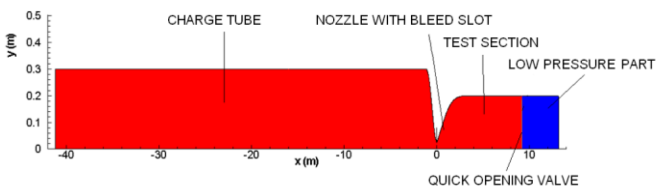


Fig.2 Computational grid system

4. Computational Results

The test results of BAM6QT at Purdue University could be inquired. Figure 3 shows the stepwise change of pressure as measured at the contraction wall [4]. When the quick opening valve starts, an expansion wave travels upstream through the test section into the charge tube. There it reflects forth and back and changes the state of the air each time it passes. From the theory of expansion wave spread speed and Figure 3, the flow condition in the test section to change approximately 200ms when the waves reaches the nozzle. Figure 4 shows a pressure trace computed and recorded during unsteady flow with initial pressure of 145psia. When the running time was t=0.8s, the nozzle exit Mach achieved the design demand. It is agree with the test results of BAM6QT.

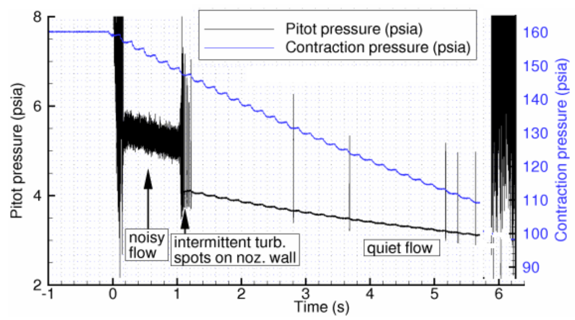


Fig. 3 Sample of contraction pressure in BAM6QT

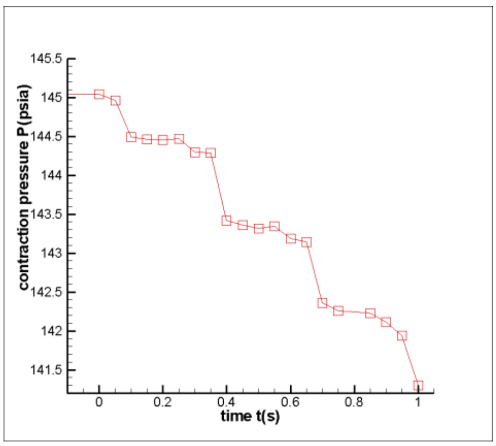


Fig. 4 Sample evaluation (x=-1m)

When the computational method is verified, the calculation of the new design Ludwieg tube quiet tunnel was underway. The Figure 2 shows the new design . The nozzle exit Mach number versus time was shown in Figure 5. The running time from 0s to 0.2s, expansion waves could pass through the nozzle into the charge tube. At this point, expansion waves will reflect at nozzle expansion part, and a shock wave system forms, which resulted in the exit Mach number magnified momentarily. Figure 6 shows the pressure versus time along the axis center line for difference location. The initial pressure P4 is 1 MPa, P is local static pressure. At the running time t=0s, when the quick opening valve just opens, the expension waves will start to upstream and lower the pressure gradually. The flow condition in the test section to change approximately 200ms, which is equal to time of the expansion wave periodic reflection. When the running time t is 0.85s, the nozzle exit Mach number achieve design demand, see Figure 7. At this same time, the streamlines superimposed with Mach number contours for flow is shown in Figure 8.

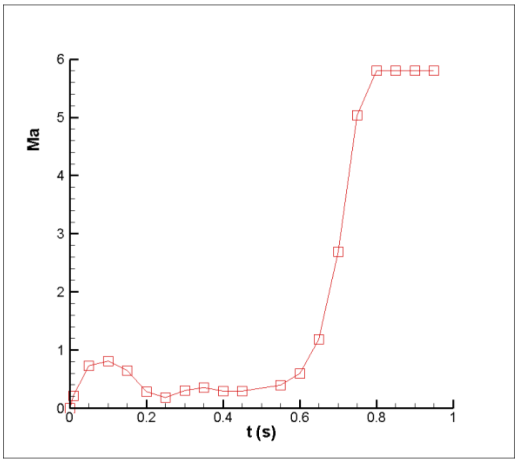


Fig.5 The nozzle exit Mach number

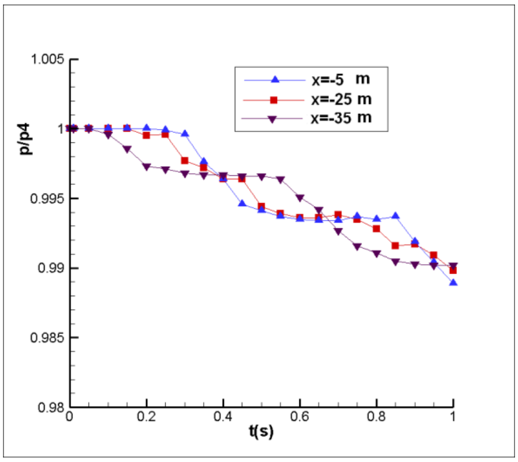


Fig.6 The pressure of the charge tube

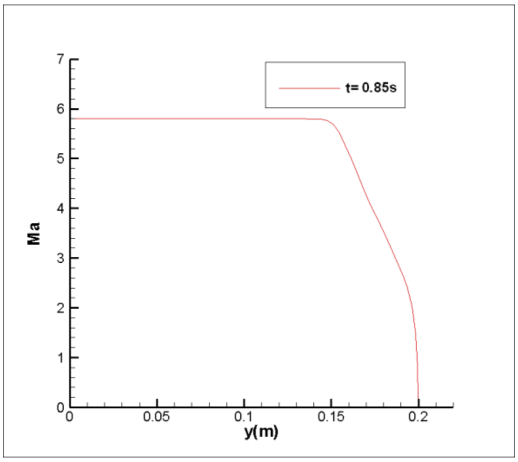


Fig.7 Mach number contours of the nozzle exit

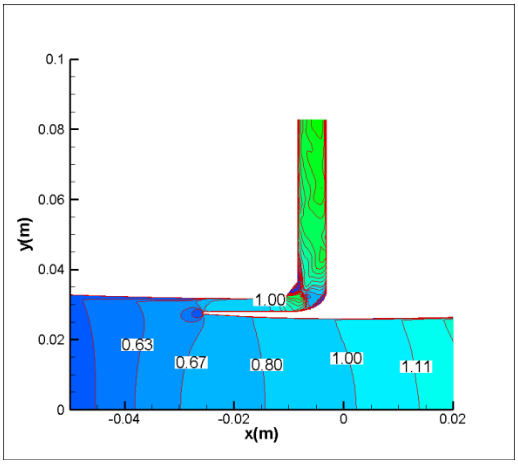


Fig.8 Mach number contours of the bleed slot

5. Conclusion

The study demonstrates the starting process of uns teady flow in Hypersonic Ludwieg tube quiet tunnel, which could preliminary describes the starting proce ss of a Ludwieg tube quiet tunnel. In the absence of t he computational study indicated the starting time to be approximately 0.85s. The quiet flow flied starting time of the BAM6QT at Purdue University is about 1 s[5]. The increase in starting process time is due to difference size and the viscous effects (normal shoc k-wave/boundary-layer imnteraction near the nozzle exit). The flow condition in the test section to chang e approximately 200ms, which is equal to tie of the e xpansion wave periodic reflection.

Acknowledgement

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Authors

Junmou Shen

Received his B.E. from Harb in Engineering University in 2011. Since 2011, he has g one on to postgraduate stu dies in China Academy of A erospace Aerodynamics.

He has forced on the desig n of nozzle, hypersonic bou ndary-layer transition, and t hermal environment test.