Realization of micro step pressure on the shock tube with active incomplete broken diaphragm

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Abstract. Aiming at the problem of difficulty to generate small amplitude step pressure to meet the requirement of dynamic pressure calibration in shock tube device, this paper studies the active incomplete broken diaphragm method and establishes the relevant theoretical formula. Simulation and experimental studies show that incomplete broken diaphragm can reduce the magnitude of shock step pressure to a certain extent, but the following vortex behind the diaphragm will affect the pressure distribution and the step pressure quality in the shock tube. A transition mechanism with linear variable inner diameter is designed to reduce the impact of vortex, and the simulation and experimental results show its effectiveness.

1. Dynamic pressure calibration with shock tube
Shock tube is the most commonly used dynamic pressure calibration equipment. It mainly evaluates the time-domain response of the pressure sensor through step excitation [1, 2]. The shock tube is composed by driven and driver section, which is separated by a diaphragm. Subject to the selection and control of the diaphragm, it is often difficult to produce a slight step pressure to calibrate the micro-pressure sensors.

2. Principle of micro step pressure generation
In order to generate more litter step pressure on shock tube, the method of active incomplete broken diaphragm is studied, which design a certain mechanical structure to make only partial diaphragm rupture.

The step pressure generated by the shock tube is determined by the incident shock Mach number ($M_a$) and the initial pressure in the driven section ($P_1$). In the case of a complete rupture, there is a well-established formula to establish the relationship between $M_a$, $P_1$, and the pressure in the driver section before the rupture ($P_4$) [3, 4]:

$$\frac{P_4}{P_1} = \frac{1}{\alpha} \left( \frac{2\gamma M_a^2}{\gamma - 1} - 1 \right) \left( \frac{1}{1 + \gamma} - \frac{1}{M_a^2} \right)^{2/\gamma(\gamma-1)}$$

(1)

Where $\gamma$ denotes the gas specific heat ratio. and $\alpha = (1 + \gamma) / (\gamma - 1)$.

When the diaphragm rupture area is smaller than the tube’s diameter, the shock wave goes through the process of a small-caliber tube firstly then the normal diameter like the under figure 1.

Figure 1 The wave at the changeable tube diameter
At the position of the diaphragm, the shock wave satisfies the Bernoulli equation [5];
\[ \frac{P_1}{\gamma} + \frac{V_1^2}{2g} = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + h \]  

Where the subscript 1 and 2 are for the small-caliber and normal diameter part. \( h \) denotes the energy loss for local expansion. The cross section satisfies the continuity equation and momentum equation and \( h \) can be calculated by the under expression:

\[ h = \frac{V_2^2 - V_1^2}{g} + \frac{V_1^2 - V_2^2}{2g} = \frac{V_2^2}{2g} (\frac{A_2}{A_1} - 1)^2 \]  

Combined with the above relations, for the case of the driver and driven section both full of air medium, the step pressure of the reflected shock can be calculated by the following equation:

\[ \Delta P = \frac{P_0 - V_1^2}{g} \left(1 - \frac{A_1^2}{A_2^2}\right) \left[\frac{7M_0^2 - 1 - 4M_0^2 - 1}{3(M_0^2 + 5)}\right] - 1 \]  

Where \( M_0 \) is the ideal Mach number for the complete rupture obtained from Equation (1). The specific relation between the step pressure ratio (compared with the step pressure for complete rupture) and the diaphragm broken scale can be gotten as figure 2. It can be found that the diaphragm breaking scale affects the energy loss directly, therefore the Mach number of shock wave diminishes accompanied with the scale, which leads to smaller step pressure.

**Figure 2** The relation between the diaphragm broken scale and the step pressure ratio

3. **Simulation analysis of shock tube**

The Fluent simulation software was used to simulate the pressure distribution in the shock tube. The established model was based on the continuous equation, momentum equation and energy equation. The shock tube model with incomplete broken diaphragm is showed at figure 3.

**Figure 3** The shock tube model with incomplete broken diaphragm

Take the case of the standard atmospheric pressure in the driven section and three times standard atmospheric pressure in the driver section as an example. The pressure profiles in three different stages of step pressure generation are showed in figure 4, which include the state before the diaphragm ruptures, the formation of the incident shock and the formation of the reflection shock. Compared with the complete broken diaphragm, we can find that broken diaphragm weakens the shock wave, but at the same time, the front of the shock wave is uneven, especially the reflected shock wave. This is due to the formation of a severe vortex at the root of the incomplete broken diaphragm. The propagation of the vortex affects the quality of the shock wave.

**Figure 4** The pressure distribution in the shock tube of incomplete diaphragm breaking

In order to reduce the influence of vortex, we designed a transitional mechanism with a linear variation of inner diameter. The shock tube model with transitional mechanism is showed at figure 5.
Figure 5 The shock tube model with the transition mechanism

Based on the above model, the generation of step pressure is simulated again. The pressure profiles in three different stages of step pressure generation are showed in figure 6. According to the simulation results, it can be found that the transition mechanism effectively reduces the vortex behind the diaphragm and makes the pressure at the front of the shock wave more uniform. The quality of incident and radiated shocks have been significantly increased.

Figure 6 The pressure distribution in the shock tube with the transition mechanism

4. Experiments and analysis

In order to further confirm the function of the incomplete broken diaphragm and the transitional mechanism and validate the validity of the theoretical analysis and simulation described above, relevant experiments were carried out on the new shock tube device of Changcheng Institute of Metrology & Measurement (CIMM) in Beijing. The total length of the new shock tube is 15 meters and the inside diameter is 60 mm, in which the driven section is 10m and the driver section is 5m. The transitional mechanism is like a smooth inner horn of 0.15 meters in length and constant in outer diameter. The inner diameter varies linearly from 40 mm to 60 mm. The transitional mechanism from three different perspectives are shown in figure 7.

Figure 7 Three views of the transition mechanism

Three kinds of experiments were performed, which include the normal broken diaphragm, incomplete broken diaphragm without transitional mechanism, incomplete broken diaphragm with transitional mechanism. Incomplete broken diaphragm without transitional mechanism was achieved by one steel ring, whose inner diameter is 40mm. All experiments were conducted with air and the initial pressure in the driven section was atmospheric pressure. And 0.07 mm thick aluminum diaphragms were used. One piezoelectric pressure sensor was used to measure the step shock pressure on the end face. The outputs of the pressure sensor with incomplete broken diaphragm are showed in figure 8 and figure 9.

Figure 8 Output of sensor without transitional mechanism

Figure 9 Output of sensor with transitional mechanism
It can be seen that in the case of incomplete broken diaphragm without transitional mechanism, the step pressure platform has some bumps, but the use of the transition mechanism significantly improves the quality of the step pressure but not change the magnitude, which is more in line with the requirements of dynamic pressure calibration.

Table 1 shows the theoretical, simulated and experimental step pressure amplitudes in the cases of complete broken diaphragm and incomplete broken diaphragm keeping the other conditions as uniform as possible. The diameter of the incomplete broken diaphragm is 40mm.

|                  | Amplitude with complete broken diaphragm | Amplitude with incomplete broken diaphragm | Amplitude ratio |
|------------------|----------------------------------------|------------------------------------------|-----------------|
| **Theory**       | 0.0712 MPa                             | 0.0612 MPa                               | 86.3%           |
| **Simulation**   | 0.0694 MPa                             | 0.0597 MPa                               | 86.1%           |
| **Experiment**   | 0.0705 MPa                             | 0.602 MPa                                | 85.4%           |

The table shows that with or without incomplete broken diaphragm, the experimental step pressure amplitude is close to both the theoretical and simulation results. And the amplitude attenuation rates caused by the incomplete broken diaphragm calculated by three ways are also very close, which are all about 0.86. This proves the validity of theoretical analysis and simulation calculation.

5. Conclusion

Theoretical, simulation and experimental studies show that incomplete broken diaphragm can effectively reduce the amplitude of shock step pressure, and the established theoretical formula can provide effective guidance to the relevant design. Through the simulation analysis and experimental research, it is also shown that the designed transitional mechanism can effectively reduce the influence of the vortex generated by the incomplete broken diaphragm on the shock step pressure waveforms.

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