Application of High-Speed Camera to 4D-CT Density Measurement of Unsteady Shock-Vortex Flow Discharged from Two Inclined and Cylindrical Holes

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Abstract
Laser Interferometric Computed Tomography (LICT) measurement is practically useful method to measure quantitatively supersonic unsteady flow field, and three-dimensional (3D) density distribution is obtained. In our previous study, the 3D flow fields have been observed by LICT measurement. However, it is still difficult to measure 3D density distribution of the different times in CT reconstruction technique (4D-CT). In this study, to realize the novel 4D-CT measurements, high-speed camera is applied to our LICT measurement. This is because successive images at sufficiently short intervals can be obtained by high-speed camera.

Key words
Laser Interferometry Computed Tomography (LICT), Shock-Vortex Flow, High-Speed Camera, 4D-CT, Algebraic Reconstruction Technique (ART)

1. Introduction
The supersonic unsteady flow fields have been commonly observed by qualitative and two-dimensional (2D) visualization methods, such as shadowgraph, schlieren, and quantitatively by 2D interferometric images. On the other hand, computed tomography (CT) methods have been recently applied to the investigation of three-dimensional (3D) flow fields. Subsonic and transonic free jets were studied by interferometric holography [1], and also supersonic jets were studied by Soller et al. [2]. These flow fields were however steady, so supersonic unsteady flow fields including shock waves and vortices have not been observed by experimental method. Laser interferometric computed tomography (LICT) is a useful visualization method to observe various 3D unsteady phenomena. In our previous study, the flow field including shock waves discharged from two parallel and cylindrical nozzles [3-6] and the flow fields were successfully reconstructed by filtered back projection (FBP) method and algebraic reconstruction technique (ART). The LICT measurement is a combination of Mach-Zehnder finite-fringe interferometry and multidirectional observation CT technique, where N₂ pulse laser is used as a light source. However, it was difficult to compare the 3D density distribution of the different delay times in our LICT measurement and CT reconstruction technique.

In this study, to realize the temporal 4D-CT measurements, a high-speed camera and continuous argon ion laser are applied to have novel LICT measurement. This is because continuous framing images can be obtained by high-speed camera. 3D flow fields are reconstructed from these framing images with different directional angles. In this paper, 3D unsteady supersonic flow field including shock waves discharged from two inclined and cylindrical holes has been investigated by high-speed framing LICT method and the CT reconstruction technique using ART.

2. Experimental Apparatus

2.1 Diaphragmless shock tube
A diaphragmless shock tube is used in LICT experiment to produce the shock waves with good reproducibility. Figure 1 shows layout of the experimental apparatus. Optical system consists of a high-speed camera, a Mach-Zehnder interferometer, an argon ion laser as a light source. The cross section of the low-pressure tube is 40mm×40mm square and the length of the low pressure tube is 3.1 meters. The driver gas is high-pressure helium and the test gas is low-pressure nitrogen. The incident Mach number Mᵢ is calculated from the distance between two pressure transducers as shown in Fig. 1 and pressure signals. In this experiment, incident Mach number of shock wave was fixed to 2.4.

Fig.1 Layout of experimental apparatus

2.2 Rotation model
The layout of the rotating plug is illustrated in Figs.2 and 3. Shock wave generated by the diaphragmless shock tube passes through a rotating plug set at the end of the tube, and the shock-vortex flow is discharged into the test section from two inclined and cylindrical φ3mm holes. Figure 3 shows coordinate system of the rotating plug. The x and y coordinates rotate with rotating plug around the z-axis, while light axis s is fixed with the shock tube, where rotation angle "θ" is defined as the angle between x-axis and s-axis. In order to obtain the multi-directional data, we had 36 shots and changed the rotation angle for each shot. The rotation angle is set from 0 degree to 175 degree at 5 degree intervals.
2.3 Mach-Zehnder observation system

Observation system consists of a Mach-Zehnder interferometer, an argon ion laser (H800AMAFF7, AUTEX, max 1.1W) as a light source, and a high-speed camera (ULTRA cam HS-106E, nac Image Technology Co., Ltd). The specifications of this camera are shown in Table 1. The projection data of the flow field are obtained as the interferometric finite-fringe images by the high-speed camera, and each series images are obtained at fixed rotation angle of rotating plug in each shot of experiment.

Table 1 Specifications of high-speed camera

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image sensor</td>
<td>ISIS-CCD Image sensor</td>
</tr>
<tr>
<td>Resolution</td>
<td>360 × 410pixel</td>
</tr>
<tr>
<td>Frame rate</td>
<td>700,000fps (max 1,250,000fps)</td>
</tr>
<tr>
<td>Continuous shooting</td>
<td>120images</td>
</tr>
<tr>
<td>Electronics shutter</td>
<td>200ms (min 100ns)</td>
</tr>
</tbody>
</table>

3. CT Measurement

3.1 Projection data

Each series of projection data are obtained by each shot of diaphragmless shock tube in LICT measurement. Therefore, it is important to keep high accuracy of image data for each reconstruction of the good quality CT image. To carry out this CT reconstruction with sufficiently high accuracy, the normalized frontal position $z_s/D$ of the primary shock wave is defined as shown in Fig.4, where parameter $D$ (=3mm) is diameter of a circular nozzle, and parameter $z_s$ is the frontal position of discharged primary shock wave measured as the axial position on the digitalized projection image. Based on the $z_s$ and Mach number, accuracy of each reconstruction is enhanced.

To obtain 3D digitalized reconstruction data of density distribution, each projection image has to be calculated by fringe-tracking method. Fringe tracking method is divided into three steps. First, fringes are tracked by tracking algorithm, secondly, the displacement $\Delta H$ of these fringes is calculated. Finally, integral quantity of density change is obtained according to the following expression,

$$
\int (\rho - \rho_0) ds = \frac{\Delta H}{H_0} \times \frac{\lambda}{K}
$$

(1)

where $\rho_0$ is initial density of test section, $H_0$ is averaged initial spacing distance of fringes, $\lambda$ is wavelength of the Ar-ion laser, and $K$ is Gradstone-Dale constant.

3.2 Reconstruction technique for CT

ART is used as the reconstruction technique for our CT reconstruction from the series of different projection data. ART is one of the robust and basic reconstruction techniques. Filtered Back Projection (FBP) method is generally used as CT reconstruction technique. The noise levels, however, of reconstructed CT image are lower in our case of ART than those of FBP. Therefore, ART is useful reconstruction technique especially in our experiment of the reconstruction using high-speed framing projection data.

4. Distribution Combined Schlieren Images (DCSI)

The reconstructed experimental CT images can be presented as the sliced pseudo-color images, and these images represent density distribution. However, it is hard to identify the locations of discontinuous line or surface in these pseudo-color images. On the other hand, pseudo-schliren technique is also useful to identify these positions. Figure 5 shows pseudo-Schliren image, pseudo-color image and Distribution Combined Schliren Images (DCSI), which was originally developed in our research.
Our DCSI is a combination of pseudo-Schlieren image and pseudo-color image, therefore, this novel expression method shows not only density distribution but also the locations of discontinuous line and surface clearly. This method was suggested by Ota et al. [7], and it became much easier to understand the structure of shock waves and flow field.

5. Results and Discussion

In this section the experimental 4D-CT images reconstructed by ART are presented by the sliced 2D-DCSI images with different temporal cases and different sliced locations. Experimental conditions are set as follows. The incident Mach number $M_i$ is 2.4 and diameter of two inclined and cylindrical nozzle $D$ is 3mm.

5.1 Result of the $y$-$z$ cross section

Figure 6 shows the DCSI images which are the vertical center line $y$-$z$ cross section of the different time cases discharging from the inclined and circular holes. Table 2 shows the normalized frontal positions of primary shock wave (PSW) $z_s$ and the delay time after the shock wave discharge at the exit of the holes. The $z_s$ is computed from the number of pixels of the image and the delay time is computed from frame rate of high-speed camera. Shock wave velocity gradually decreases as the relationally rabid change of the shock wave spreads out. However, Table 2 shows changing shock wave velocity. It is considered that continuous photographing interval of the camera was not constant. It is possible to obtain the temporal development of the shock wave phenomenon, because in Fig.6 images show several unsteady phenomena, for example, the primary shock wave (PSW), the secondary shock wave (SSW), the transmitted shock wave (TSW) and two vortices. In Case1, there are high density regions near the exit of opening ends. When it separates from an opening end, low density portion of vortex appears near the surface of a wall. Therefore, it is most likely that as for unsteady shock-vortex flow discharged from two inclined and cylindrical holes, vortices are formed from two holes near the surface of a wall. In Case2 and Case3, the vortex grows up leaving near the surface of a wall. In Case4 and Case5, the vortex grows up and covers the front of the jet hole of a shock wave, and the secondary shock wave is formed behind the domain of the compression wave. In Case2~Case5, the primary shock waves cross each other to form transmitted shock wave we judged because density is higher than other area. As time goes by, the domain of the transmitted shock wave becomes larger and the density decreases.
Table 2 Data of each case

<table>
<thead>
<tr>
<th>Case</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>z (mm)</td>
<td>3.29</td>
<td>4.74</td>
<td>5.36</td>
<td>6.67</td>
<td>7.33</td>
</tr>
<tr>
<td>t (μs)</td>
<td>5.7</td>
<td>8.6</td>
<td>10.0</td>
<td>12.9</td>
<td>14.3</td>
</tr>
</tbody>
</table>

5.2 Result of the x-y cross section

Figures 7, 8 and 9 show temporal evolution of density distributions captured in DCSIs in three different planes at z/D=0.95, 0.53 and 0.11, respectively. Each x-y cross-section is referred to as A, B and C, respectively, and is shown in the lower right of each figure in Case 5.

In Case 1 of Fig.7, shock wave has not reached cross-section A yet. In Case 2, two primary shock waves (PSW) have not interfered. In Case 3, the primary shock waves move ahead, and form the transmitted shock wave (TSW). Discontinuous surface in Case 4 and Case 5 is considered formation of a secondary shock wave.

In Case 1 of Fig.8, two primary shock waves have not interfered. In Case 2, the primary shock waves move ahead, and form the transmitted shock wave. In Case 3, a secondary shock wave is formed. In Case 4 and Case 5, two vortices emerge and Mach reflection (MR) can be seen on the x-axis.

In Case 1 of Fig.9, presence of a pair of vortices are confirmed, because cross-section C (z/D=0.11) is located close to the surface of the wall. Observation of the primary shock wave becomes difficult as time goes by, while it is still possible to observe Mach reflection because it is formed clearly.

Fig.7 Reconstructed 3D flow field of the different time cases by ART (x-y cross section A: 0.95)

Fig.8 Reconstructed 3D flow field of the different time cases by ART (x-y cross section B: 0.53)

Fig.9 Reconstructed 3D flow field of the different time cases by ART (x-y cross section C: 0.11)
6. Conclusion
To realize the temporal 4D-CT measurements, high-speed camera has been applied to LICT measurement in our experiment. The projection data of different time can be acquired from multi-directional series of images photographed by high-speed camera.

The 3D density fields of different time cases can be acquired from these projection data. DCSI shows several unsteady phenomena, for example, the primary shock wave, secondary shock wave, the transmitted shock wave and the vortex. It is possible to get temporal alteration of a shock wave phenomenon by comparing cross section of different time cases.

Nomenclature

- \( D \): diameter of two inclined cylindrical nozzles [m]
- \( H_0 \): averaged initial distance of fringes
- \( K \): Gladstone-dale constant
- \( M_i \): incident Mach number
- \( t \): delay time after shock wave discharging at the exit of the holes
- \( z_s \): frontal position of the primary shock wave [m]
- \( \Delta H \): displacement of fringes
- \( \lambda \): wavelength of laser [m]
- \( \rho \): density [kg/m\(^3\)]
- \( \rho_0 \): initial density distribution [kg/m\(^3\)]

References


