INTERFEROMETRIC CT MEASUREMENT OF 3D INTERACTING FLOW FIELD WITH DISCHARGED SHOCK WAVES

Kazuo Maeno[1], Yoshihiro Koga[2], and Masanori Ota[2]

[1]*Faculty of Engineering, Chiba University*
[2]*Graduate student, Graduate School of Science and Technology, Chiba University*
1-33, Yayoi, Inage, Chiba 263-8522, Japan Email address : maeno@faculty.chiba-u.jp

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The purpose of this paper is to develop interferometric CT (Computed Tomography) technique to observe high-speed and three-dimensional (3-D) flow field that includes unsteady shock waves, and to clarify 3-D flow phenomena induced by the shock waves. In our previous study, 3-D complex flows discharged from square open end and a pair of circular open ends were studied by interferometric CT method[1],[2]. The shock Mach number at the exits of the open ends were both higher and lower than 2.0. As the results, various phenomena of 3-D flow field were clarified by the imaging techniques such as pseudo-color images, pseudo-schlieren images by pseudo-schlieren technique, 3-D isopycnic images, etc. In this paper, together with these processed data, computational fluid dynamics (CFD) simulation is also applied to our 3-D flow fields to clarify the experimental results. The CFD results can represent not only density but also another properties - pressure, temperature, velocity, etc - in the flow fields. Detailed discussion has been performed on experimental results of 3-D flow field discharged from a pair of circular open ends for incident shock Mach number of 2.0 by taking these properties into consideration. We applied a novel presentation method for flow field, which is named as “distribution combined schlieren image: DCSI” to our CT and CFD results to demonstrate the 3-D features of complex flow field with unsteady shock waves.

Experimental Apparatus:

We use a diaphragmless shock tube to produce a shock wave with good reproducibility. Figure 1 shows a schematic diagram of our experimental apparatus and CT observation system. The observation system consists of a CCD camera, a Mach-Zehnder interferometer, a pulsed nitrogen laser, a delay/pulse generator, and a personal computer. The shock wave is generated in the low-pressure tube of 3.1 meters in length, and its inner cross section is 40 mmx 40 mm square. A rotation duct model is installed at the end of the low-pressure tube. The duct is open to the low-pressure test section. Figure 2 illustrates the coordinate system of the rotation model with a pair of circular open ends and a finite-fringe interferogram taken by CCD camera, where zs is a frontal position of the primary shock wave, D is a diameter of circular open end, and zs/D is the normalized frontal position of the primary shock wave. The Mach number of the incident shock wave Mi is calculated by pressure jump across the shock wave. In this paper, Mi is fixed to 2.0. To obtain 3-D image of the flow field, we need the multidirectional projection data for a reproducible flow. A set of experiments are performed for several rotation angles at a combination of fixed initial driver/driven gas pressure conditions. The experiment is performed for 19 rotation angles between 0 degree and 90 degrees at five-degree intervals with fixed light path, considering the symmetric nature of the flow. The 3-D density distribution is recon- structed from a set of projection data for the same Mi and zs. The CT reconstruction algorithm is the convolution back- projection method by Shepp and Logan type filter function [3].

Numerical Simulation:

The CFD simulation for inviscid and compressible flow has been carried out on the 3-D flow field behind the shock waves discharged from a pair of circular open ends. The basic equations are the Euler equation system for compressible and inviscid flow assumed as perfect gas ($\gamma = 1.4$). The equation system is solved with a Harten-Yee type second-order upwind TVD scheme using finite difference method. The third-order Runge-Kutta method is applied to time integration.

Results and Discussion:

Experimental CT results and CFD results are illustrated in Fig. 3. Pseudo-shlieren images at y-z cross section are shown in Fig. 3. In pseudo-schlieren image, various phenomena of flow field induced by shock wave are exhibited clearly. Primary shock wave (PSW), secondary shock wave (SSW), contact surface (CS), transmitted shock wave (TSW), two vortices and shock-shock interaction are identified. In x-y cross section the shape of vortex ring, PSW on x-y plane can be observed. We find two vortex rings ejected from a pair of circular open ends. In the image CT results and CFD results agree well. So we have succeeded to identify various phenomena of the high-speed flow by using interferometric CT measurement.

The experimental results represent the density distribution and density gradient calculated from 3-D density distribution. The CFD results represent not only the density but also another distributions - pressure, temperature, velocity, etc. Taking these CFD properties into consideration, a detailed discussion of experimental result can be produced. Thus, we propose a novel method for visualization - Distribution Combined Schlieren Image (DCSI). DCSI is a fusion of pseudo-color images and pseudo-schlieren image. Figure 4 shows DCSI of CT and CFD results. The left side is the CT DCSI and the right side is the CFD DCSI of density distribution at y-z cross section. In our interferometric CT measurement, we can obtain 3-D density distribution and density gradient. From these data DCSI of experimental CT results can be obtained. This is one of the advantages of our 3-D CT measurement. We can easily interpret our complex flow field (eg. where is compressed, expanded...) at sight in DCSI. This DCSI will be a powerful tool for displaying and studying complex and real3-D flow phenomena.

References

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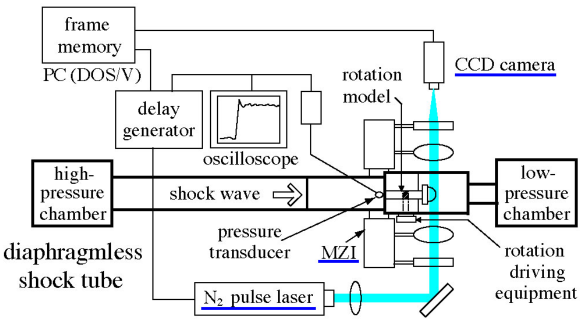


Fig. 1. Schematic diagram of experimental apparatus

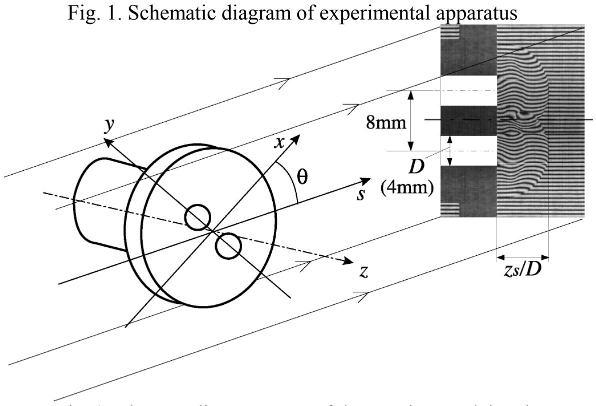


Fig. 2. The coordinate system of the rotation model and a finite-fringe interferogram taken by CCD camera.

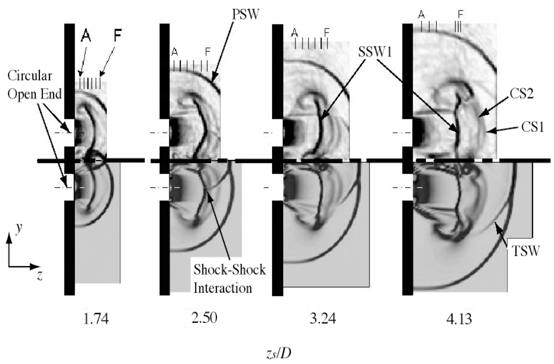
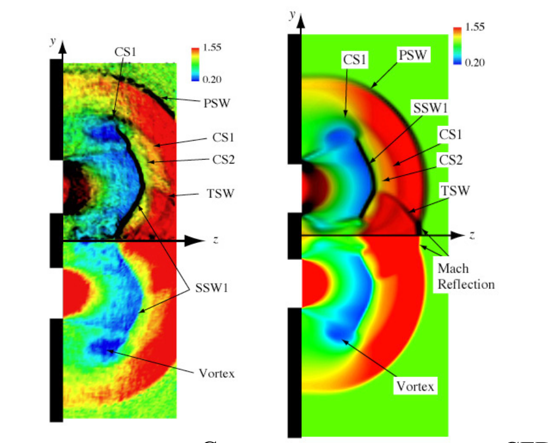


Fig. 3. Pseudo-schleren images at *y-z* cross section.



C CFD

Fig. 4. Distribution combined schlieren images at y-z cross section