APPLICATION OF A POINT-DIFFRACTION INTERFEROMETER TO UNSTEADY SHOCK WAVE PHENOMENA

Daiju Numata[1,c], Kiyonobu Ohtani[2]

[1]Tohoku University, 6-6-01 Aramaki-Aza-Aoba, Aoba-ku, Sendai-shi, Miyagi-ken, 9808579, Japan
[2]Institute of Fluid Science, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai-shi, Miyagi-ken, 9808577, Japan

[c]Corresponding author: Tel.: +81227954075; Fax: +81227954075; Email: numata.daiju@aero.mech.tohoku.ac.jp

KEYWORDS:
Main subjects: unsteady shock wave phenomena, flow visualization
Fluid: high speed flows, flows with shocks
Visualization method(s): point-diffraction interferometer
Other keywords: interferometer

ABSTRACT: To clarify an effectiveness of a point-diffraction interferometer (PDI) as a method to visualize unsteady shock wave phenomena, we developed simple pinhole setup and tried to visualize a propagation process of a spherical shock wave induced by an AgN_3 explosion by using PDI method, and recorded visualization images sequentially by using a high-speed digital video camera (Shimadzu Hyper-Vision, HPV-1). A continuous cw green laser (COMPASS 315M-50, COHERENT Inc., wavelength: 532 nm, output power: 50 mw) was used as a light source. The frame interval and the exposure time of video recording were 2 μs and 500 ns, respectively. Firstly, we applied the PDI method to visualization of a heated solder as a test of our PDI setup. Fringe image of thermal convection around the heated solder was clearly visualized. Secondly, we applied the PDI method to visualization of the unsteady shock wave phenomena. We visualized spherical shock wave induced by an AgN_3 explosion by using the PDI. By using the PDI method, the density contours caused by the AgN_3 explosion were clearly visualized as a fringe pattern. Additionally, a process of a propagation of the spherical shock wave caused by the AgN_3 explosion was clarified.

1. Introduction.

Optical visualization techniques that can visualize density field are suitable and effective method to clarify unsteady fluid phenomena such as shock wave propagation in various media. It is one of the non-contact measurement techniques, and it is possible to know the flow phenomena without interfering with the flow field by using those. A shadowgraph method, a Schlieren method and an interferometer are typically used as an optical visualization method. The shadowgraph and the Schlieren method takes advantage of the change in refractive index caused by changes in density of the fluid due to the flow phenomenon, and represent the amount of the second and first derivative of the density field, respectively. Interferometer techniques are visualization techniques using interference of light, and we can obtain density field from analyzing the interferogram.

In these optical visualization techniques, interferometer has a possibility of the quantitative measurement of flow phenomena. There are various types of the interferometer methods. Especially, a Mach-Zehnder interferometer and a double-exposure holographic interferometer are typically used in visualization of the high-speed gas dynamic phenomena. Interferometer technique can be a powerful tool for quantitative measurement of the flow field, and it is useful for validation of theoretical models and CFD results if we can visualize the density field due to the unsteady fluid phenomena time-sequentially and quantitatively. An example of a time-resolved visualization by using interferometer for unsteady flow field, Kleine et al.[1, 2] visualized the time-resolved two-dimensional shock wave interaction phenomena by using the Mach-Zehnder interferometer. However, to construct the conventional interference system, it is necessary to adjust the optical axis of the interferometer precisely in the process of construction of the optical system, and optical elements with high accuracy must be prepared for taking high-quality images. Therefore, we need much time and costs to use interferometer for visualizing flow phenomena.

In contrast, a point-diffraction interferometer (PDI), which is suggested to Smartt et al.[3, 4], is a common-path interferometer. The PDI optical setup is a very simple configuration, and almost same setup as a conventional shadowgraph or a Schlieren optical system. The only difference between the PDI and the shadowgraph method (or the Schlieren method) is a “pinhole” structure on the focal point of the second collimator lens (or parabolic mirror). In the

PDI setup, a small pinhole made by the semi-transparent plate is put on the focal point of the second collimator lens, and is interfered with the light. In this setup, the pinhole acts as an "interferometer". Some aerodynamic phenomena, a dynamic stall[5] and flow structures around the airfoils[6, 7], were visualized by using the PDI. In these results, usability of the PDI for visualization of the flow phenomena is shown. However, the PDI method is mainly used for visualizing relatively slow phenomena or steady phenomena, and there is no result to apply the PDI method to a time-resolved visualization. In addition, the optical system for the PDI is a relatively simple optical system compared with other interferometer, however, design, configuration and the manufacturing accuracy of the pinhole is very important to obtain a good interferogram. To enhance the availability of the PDI and apply interferometer to the time-resolved visualization of the various fluid phenomena, it is important to construct the pinhole more simply.

In this study, to improve the versatility of the PDI, we proposed to the more easily production techniques of the pinhole by using a ND filter. Firstly, we made the pinhole from the ND filter and applied it to the PDI setup. Next step, we visualized a heated solder as a test of our PDI setup. Secondly, we applied this PDI method to visualization of the unsteady shock wave phenomena. We visualized spherical shock wave induced by an AgN_3 explosion by using the PDI method. Additionally, a process of a propagation of the spherical shock wave caused by the AgN_3 explosion was clarified.

2. Point-Diffraction Interferometer (PDI).

Figure 1 shows the principle of the point-diffraction interferometer[4]. In PDI setup, the small pinhole which is constructed on the semi-transparent plate is installed in part of a focal point of the second collimator lens. A converging light is diffracted when passing through the pinhole and spreading semi-spherically. This diffracted light acts as a reference beam and overlapped with the object beam, and we can get an interferogram on the film or the acceptance surface of the camera. In previous research, many researchers made pinholes on the photographic films for the PDI. For example, Kashitani et al. used high-resolution holographic films for a base plate of the pinhole part for the PDI[7]. On the other hand, to build a pinhole more easily and simply and save cost of making pinhole part, we used commercially available neutral density filter (ND filter) as a semi-transparent plate. In this study, PRO NDx series (Kenko Tokina Co., Ltd.) was used as a base of the pinhole plate. We removed a coating layer of the ND filter roundly by chemicals or focused laser beam, and used it as a pinhole for the PDI. This small hole on the ND filter acts as a pinhole having a thickness of coating layer of the original ND filter.

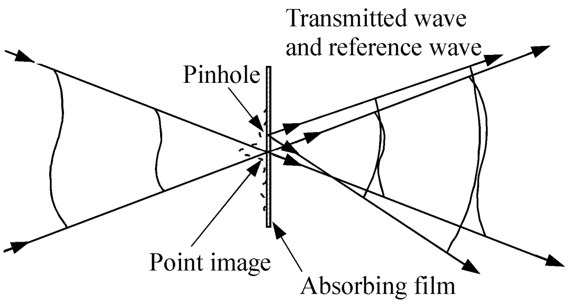


Fig. 1 Principle of the Point-Diffraction Interferometer (PDI)[4]

Interference fringes in visualized images by the PDI method were infinite interference fringes. Therefore, the relationship between the density change of the flow field and number of fringes in the interferogram ("order of interference") is represented as follows;

$$\rho - \rho_{ref} = \frac{\lambda}{KL}\varepsilon \tag{1}$$

where ρ, λ, K, L and ε are a density value of the flow field, a wavelength of the light source, a Gladstone-Dale constant, a width of the test section and the order of interference, respectively. A suffix *ref* means a "reference state". From equation (1), resolution of the interference fringes associated with the density change in the test section can be improved by using a light source which has shorter wavelength or enlarging the width of the test section.

3. Experimental setup and experimental condition.

3.1 Spherical shock wave generation method.

In this research, an AgN_3 micro explosive (SHOWA KINZOKU KOGYO Co., Ltd., diameter d = 1.5 mm, length l = 1.5 mm, density ρ = 3.8 g/cm^3, 10.0 ± 0.1 mg/pellet) was used as a source of the spherical shock wave. The AgN_3 micro explosive was glued to the top of an optical fiber (Fujikura, Ltd., GC.600/750, core diameter d = 0.6 mm), and was put it onto the center of the test section. After that, the AgN_3 pellet was detonated by a pulsed Nd:YAG laser (OPTRON Technology, 13 mJ/pulse, duration time = 7 ns) via an optical fiber, and a spherical shock wave was generated and propagated it into the air.

3.2 Optical setup for the PDI.

Figure 2 shows the schematic of the optical setup for the PDI. A continuous cw green laser (COMPASS 315M-50, COHERENT Inc., wavelength = 532 nm, output power = 50 mW) was used as a light source. This laser light was expanded and adjusted to the parallel beam by using a beam expander and a parabolic mirror. The diameter and focal length of the parabolic mirror are 300 mm and 3,000 mm, respectively. Parallel beam incident the 2nd parabolic mirror, which has the same size and same focal length of the 1st parabolic mirror, after passing through the test section or flow phenomena, and is converged after that. Visualization images were recorded time-sequentially by using a high-speed digital video camera (Shimadzu Corporation, Hyper-Vision, HPV-1, maximum burst for continuous shooting = 104, maximum fps = 1,000,000 frame/sec, minimum exposure time = 250 ns, number of pixels = 312 pixels × 260 pixels). The AgN_3 micro explosive was put it onto the center of the test section which is already shown in section 3.1. We used a seizing signal of the pulsed Nd: YAG laser as a trigger signal source and synchronized flow phenomena and a camera recording timing. The frame interval and the exposure time of recorded images were 2 μs and 500 ns, respectively. In this study, we installed the pinhole in part of a focal point of the second collimator lens as shown in section 2.

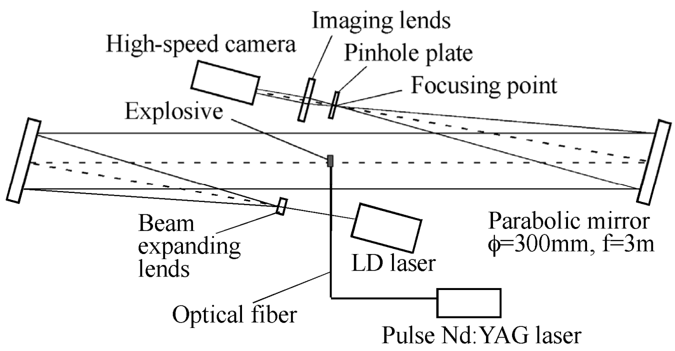
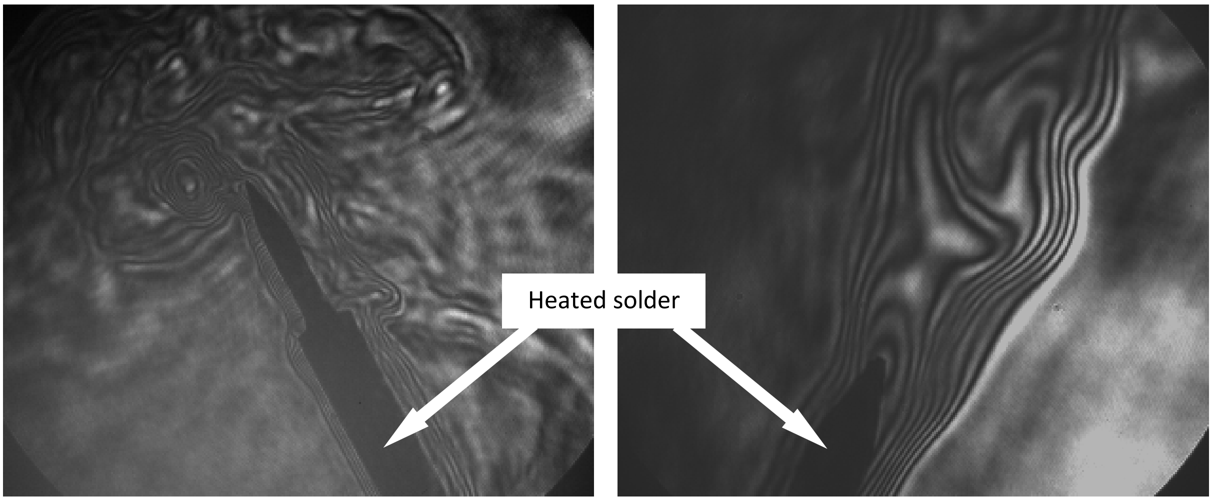


Fig. 2 Optical setup for the PDI

4. Result and discussion.

4.1 Visualization tests of the PDI optical system using the ND filter pinhole.

Firstly, we conducted verification tests of the PDI setup which used the ND filter pinhole. We visualized a heated solder for evaluating our PDI setup. Figure 3 shows visualized images of the heated solder and rising warm air around a heated solder by using PDI method using ND filter pinhole. Figure 3 (a) shows an entire part of the heated solder, and Figure 3 (b) shows a zooming image of the top of the heated solder. In this case, we set the frame rate of the high-speed video camera 125 fps, and exposure time 1 ms. From Figure 3 (a) and (b), black and white fringe patterns around the heated solder was clearly visualized. Around the heated solder, fringe spacing of the recorded interferogram is narrower than other places. This means that a temperature gradient around the heated solder is larger than other parts. This fringe pattern and the tendency of the temperature gradient derived from the fringe pattern indicate that the visualization images using our PDI setup shows a typical thermal convection patterns around the heated solder. In addition, these images seem as same as the other interferogram visualized by other interferometer. These results indicate that the ND filter pinhole is well acting as a pinhole of the PDI interferometer.



(a) Entire image of the heated solder

(b) Zooming image of the top of the heated solder

Fig. 3 Visualization images of rising warm air around a solder by using the PDI method using ND filter pinhole

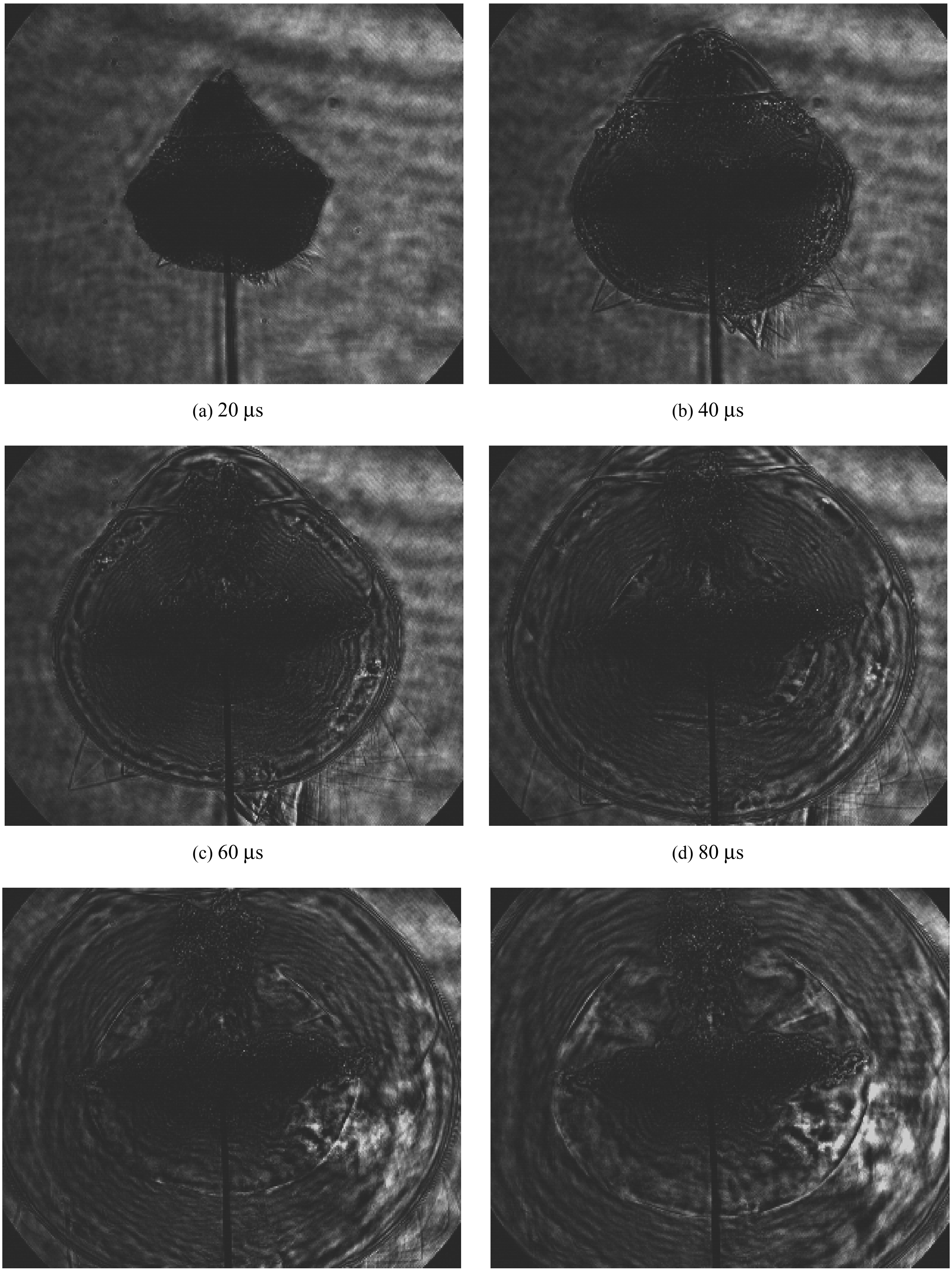
4.2 Visualization of the spherical shock wave induced by an AgN_3 explosion by using PDI.

Figure 4 shows visualization results of the spherical shock wave induced by an AgN_3 explosion by using the PDI method. The time interval of these images is 20 µs. Figure 4 (a) is a picture of after 20 µs from ignition timing of the AgN_3. These visualization results show that we can clearly visualize the spherical shock wave by using the PDI method using the ND filter pinhole. In Fig. 4 (a), all of fringes concentrate in the narrow region because there is a large density gradient around the center of the ignition point. In addition, the spatial resolution of the high-speed video camera is not enough, so we cannot see the fringe patterns clearly in Fig. 4 (a). In Fig. 4 (b), the diameter of the spherical shock wave expands more widely compared with the case of Fig. 4 (a), so that we can see the fringe patterns inside the spherical shock wave. In addition, there is a cell structure at the top of the spherical shock wave, and this structure is a typical feature of the AgN_3 induced spherical shock wave. After that, spherical shock wave expands and propagates passing through the test section. At the inside of the spherical shock wave, a secondary shock wave can be seen. In addition, we can clearly see many fringes around the center of the spherical shock wave.

Compared this PDI images to past results visualized by double exposure holographic interferometer technique using a pulsed ruby laser light source[8], the density distribution behind the expanding shock wave are qualitatively identical. Therefore, our PDI optical system by using the ND filter pinhole is effective to visualize and measure the spherical shock wave time-sequentially due to the explosion of the AgN_3 micro explosive.

Figure 5 shows the time-resolved visualization of the reflected-spherical shock waves from an inner surface of a half acrylic pipe. The spherical shock wave passes through from the left side to the right side of each image, and reflected from the inner surface of the half acrylic pipe (Fig. 5 (b)). In Fig. 5 (d), reflected shock wave converged on the focal point of the half acrylic pipe, and density field of the flow field around the focal point is clearly visualized by the PDI. After that, the focused shock wave expanded again from the convergent point.

In these visualization experiments, the difference between our PDI setup and shadowgraph (or Schlieren) setup is only to install the ND filter pinhole on the focal point of the second collimator lens or not. Therefore, the setup for our PDI is very simple and easy to construct. These results indicate that the PDI method by using the ND filter pinhole is possible to obtain a time-resolved interference fringe images easier than those of other interferometer like Mach-Zehnder interferometer.

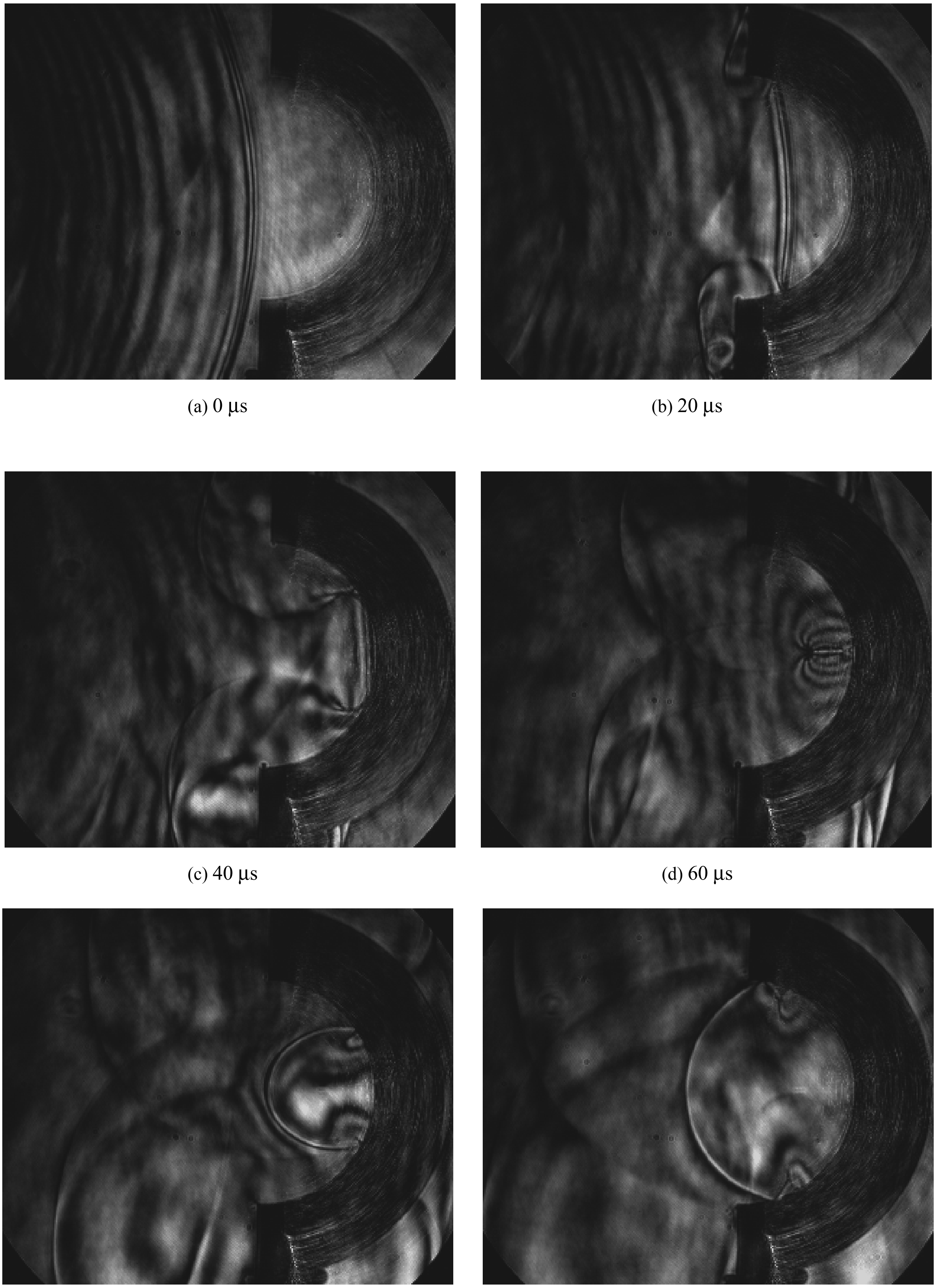


(a) 20 μs (b) 40 μs

(c) 60 μs (d) 80 μs

(e) 100 μs (f) 120 μs

Fig. 3 Time-resolved visualization of the spherical shock waves induced by an AgN_3 explosion



(a) 0 μs

(b) 20 μs

(c) 40 μs

(d) 60 μs

(e) 80 μs

(f) 100 μs

Fig. 4 Time-resolved visualization of the reflected-spherical shock waves from an inside of the half acrylic pipe

5. Conclusion.

To clarify an effectiveness of a point-diffraction interferometer (PDI) as a method to visualize unsteady shock wave phenomena, we developed simple pinhole setup by using the ND filter and tried to visualize a propagation process of the spherical shock wave induced by an AgN_3 explosion by using the PDI method, and recorded visualization images sequentially by using a high-speed digital video camera. Firstly, we applied the PDI method to visualization of the heated solder as a test of our PDI setup. Fringe image of thermal convection around the heated solder was clearly visualized. Secondly, we applied the PDI method to visualization of the unsteady shock wave phenomena. We visualized spherical shock wave induced by an AgN_3 explosion by using the PDI. By using the PDI method, the density contours caused by the AgN_3 explosion were clearly visualized as a fringe pattern, and we successfully get time-resolved visualization images of the spherical shock wave. Additionally, a process of the propagation of the spherical shock wave caused by the AgN_3 explosion was clarified.

These results show that our PDI method by using ND-filter pinhole is possible to obtain time-resolved interference fringe images easier than those of Mach-Zehnder interferometer. In the future, we will apply our PDI method to various unsteady fluid phenomena. In addition, we will combine this method and fast-responding pressure-sensitive paint (PSP) technique, and try to construct multi-dimensional composite measurement system to clarify the unsteady fluid phenomena particularly.

Acknowledgement.

We would like to express our sincere thanks to Mr. T. Ogawa at IFS, Tohoku University for his dedicated support to this study. This work was supported by KAKENHI 23760761.

References

1. H. Kleine et al., *Time-resolved Mach-Zehnder interferometry*, Proc. 29th Int. Cong. High-Speed Imaging & Photonics, #C02, 2010
2. H. Kleine et al., *Time-resolved Mach-Zehnder interferometry of shock waves*, Proc. 28th Int. Symp. on Shock Waves (ISSW2011), #2495, 2011
3. Smartt, R. N. et al. *Point-Diffraction Interferometer*, J. Opt. Soc. Am., 62, p.737, 1972
4. Smartt, R. N. et al. *Theory and Application of Point-Diffraction Interferometers*, Jpn. J. Appl. Phys., 14, Suppl. 14-1, pp.351-356, 1975
5. Chandrasekhara, M. S. et al., *Interferometric Investigations of Compressible Dynamic Stall over a Transiently Pitching Airfoil*, AIAA paper 93-0211, 1993
6. Masashi Kashitani et al., *Preliminary Study on Diaphragmless Shock Tube for Transonic Airfoil Testing with PDI*, AIAA 2010-744, 2010
7. Masashi Kashitani, et al. *Study on Effect of Operation Gas for Shock Tube Airfoil Frows with Point-Diffraction Interferometer*, J. of JSASS, 59, pp.34-41 (In Japanese), 2011
8. H. Kleine et al., *Simultaneous schlieren and interferometry flow visualization*, Proc. 24th Int. Cong. High-speed Photography & Photonics, pp.299-308, 2001