

Density Field Measurement by Digital Laser Speckle Photography

by

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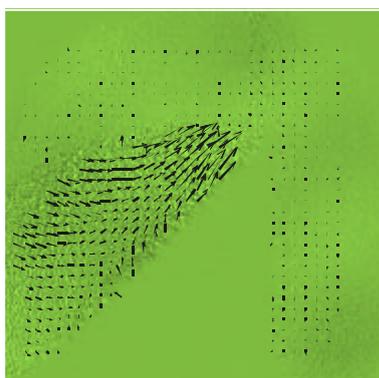
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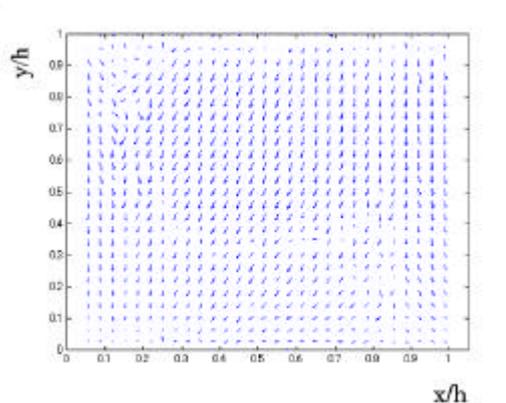
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ABSTRACT

Laser speckle photography is a well-established optical method which can be applied to quantitative measurements of density fields of fluid flows in wide dynamic range. In conventional technique of the method, density gradient vector map of a density field is reconstructed by optical Fourier transformation of a double-exposed laser speckle pattern recorded on a photographic film. This analogue method is extended to efficient digital method based on cross-correlation processing of separated images of the reference and the test. The digital technique, called digital laser speckle photography, improves laser speckle photography in the spatial resolution, in the dynamic range and in the efficiency of density field reconstruction. Practical setup of the method is very simple. Since only the light deflection is important for the density measurement in laser speckle photography, it is not required a long coherent light length for the laser source and then it has an advantage rather than the other optical method. The dynamic range and the accuracy of measurement are variable by a simple optical arrangement regulation. Both speckle patterns with and without a phase object placed at the test section are recorded by using a digital still camera or a CCD camera. The digital images of laser speckle pattern are acquired by PC, and the same algorithm with cross-correlation PIV can be applied to obtained the local density gradient vector. In this investigation, the method is applied to density field analyses in two different cases. The first case is density field analysis of Mach reflection of shock wave as a typical problem of compressible fluid flow, and the second is a thermal convection regulated by coupling with an acoustic standing wave induced in a horizontal closed duct. The results obtained are shown in fig.1.



(a) density gradient vector map of Mach reflection



(b) density gradient vector map of thermal convection current

Fig.1 Results of density gradient vector map by digital laser speckle photography.

1. INTRODUCTION

Laser speckle method such as laser speckle photography, laser speckle correlation, laser speckle interferometry or laser speckle tomography, has been established as an optical diagnosis for solid deformations and displacements, fluid motions, fluid density field, combustion field, and so on. Especially laser speckle photography is a well-established technique of two-dimensional measurements of instantaneous velocity field and density field of fluid flows by means of processing of double-exposed images of laser speckle pattern obtained by pulsed-laser-light-sheet illuminations of the flows. In conventional technique of this method, vector map of velocity or density gradient is reconstructed by an analogue technique based on point-by-point optical Fourier transformation of the double-exposed image recorded on a photographic film. That is corresponding to an auto-correlation technique. This process can be replaced by a digital processing technique of images captured by digital imaging devices. The digital method achieves the improvement in the spatial resolution, in the dynamic range and in the efficiency of vector map reconstruction.

This paper concentrates into density field measurements by this method. Although this method includes optical speckle noises in the image inherently, density field measurements by laser speckle photography are peculiar to its easiness of practical application in contrast to the other method. This method has an advantage with quantitative measurement of density, which has been shown by Wernekinck and Merzkirch [1], Erbeck and Merzkirch [2], Koepf [3], and Debrus [4]. Since only the light deflection is important in laser speckle photography, it is not required a long coherent length for the laser light source and then it has an advantage rather than the other optical method. The dynamic range and accuracy of measurement are variable by simple regulation of the optical arrangement. The information of density gradient is included implicitly in the speckle pattern. A correlation analysis in order to reconstruct a first derivative of density distribution can be applied. Therefore, the density gradient vector map is reconstructed by digital image processing, which corresponds to digital cross-correlation evaluation being used in digital PIV, of the laser speckle patterns recorded by a digital still camera or a CCD camera.

In order to verify the practicability of digital laser speckle photography based on cross-correlation evaluation in density field measurements, the method is applied to two types of fluid flow. An interaction of a propagating shock wave with an object is a typical phenomenon in compressible fluid flows, and it induces complicated wave configuration and density field. Mach reflection of shock wave on a wedge placed in a shock tube is a well-investigated phenomenon both experimentally and numerically. In the cases of low Mach number, detailed quantitative measurements are required because disagreements between experimental and theoretical results still remain. Speckle method has been applied to density field measurements of Mach reflection by the authors (Hirahara et al. 1997), but the technique is improved in this investigation. As the second application, the density field of a thermal convection is measured with this method. Heat transfer by natural convection generated in a both-end-closed duct with rectangular cross-section is one of the fundamental engineering problems. The convection is induced by the upward inverse gradient of temperature in the horizontal duct. The patterns of convection currents are characterized by Rayleigh number. While cellular convection or roll type convection is generated at low Rayleigh number, the convection turns into unsteady and turbulent state as Rayleigh number increases. When an acoustic standing wave is superimposed on an unsteady thermal convection generating at high Rayleigh number in the duct, the unsteady convection is regulated into a range of steady, two-dimensional roll type structure characterized by $1/4$ wavelength of the sound. The velocity fields of the coupling convection currents have been investigated by using PIV method (Kawahashi et al., 1999). The temperature distribution obtained by the coupling is important information to understand the effect of sound field on the thermal convection. Therefore, density field measurements of the coupling convection currents by digital laser speckle photography are carried out instead of the direct temperature measurement.

2. EXPERIMENTAL METHOD and RESULTS

2.1 Basic arrangement for density field measurement

Figure 2 shows the optical set up of the speckle photography for density field measurements. Nd:YAG laser is employed for pulsed illumination in the experiment. The test section, an achromatic lens with focal length f , and a ground glass were placed $2f$ apart each other. Therefore, the image of test section is focused on the ground

glass. The laser speckle is generated by the light scattered from the ground glass. Camera image is defocused by L apart from the focused plane (the ground glass). Speckle photograph is taken by a digital still camera with 1.4M pixels or a CCD camera with 1M pixels. Speckle size on the camera image plane, which is determined by F-number of lens and size of aperture, was adjusted with an aperture in front of camera lens. Since the observation window area is 80×80 mm or 50×50 mm, the space resolution of the present measurement is order of 0.1mm/pixels.

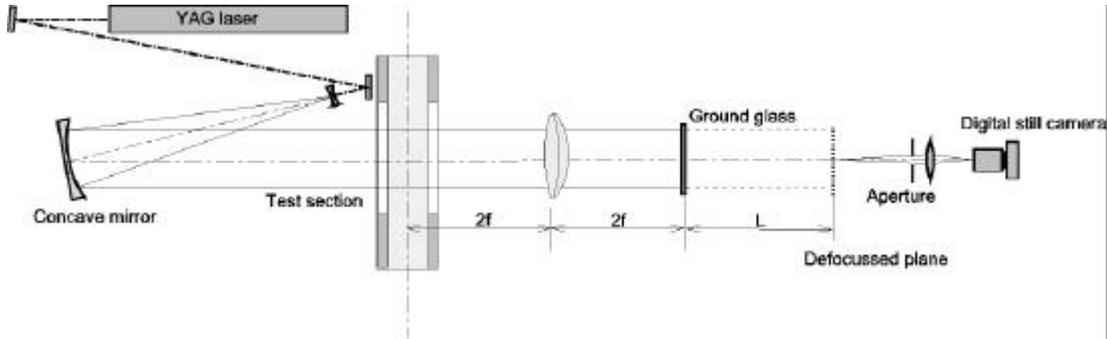


Fig.1 Schematic of optical set up of laser speckle photography.

Object beam passing through the test section may be deflected by the angle (ϵ_x, ϵ_y) , where x and y are the horizontal and the vertical coordinates. (ϵ_x, ϵ_y) is related to the density gradient for the respective direction with the following equation.

$$\mathbf{e}_i = K \int \frac{\partial \mathbf{r}}{\partial i} dz, \quad i = x, y \quad (3)$$

where K is the Gladstone-Dale constant, ρ the fluid density, z the width along the optical path of the test section. ϵ_x and ϵ_y are calculated by the correlation evaluation for the obtained speckle patterns. The reference image is taken before the respective test runs. (ϵ_x, ϵ_y) are calculated with the displacement of speckle pattern from the reference and flow images. Then, a simple relation, $\epsilon_i = \delta i / L$ gives a deflection angle of speckle over the image plane, where δi is speckle displacement in the recorded plane and it is calculated by cross-correlation analysis of Kaga's method (Kaga et al. [7]). The accuracy of the measurement depends on that of speckle displacement, δi . If the accuracy of δi is held in sub-pixels, the accuracy of this measurement should be kept in two or three digits at least. It may not be high accuracy, however, the dynamic range of the measurement can be varied in a wide range by choosing a suitable defocus length L . This is the most advantage of this measurement. Normally in the case of measurement of small density gradient field, L becomes very long. In that case, an optical guide is necessary to use in order to avoid the effect of density fluctuation of ambient air that causes error.

2.2 Mach reflection measurement

Figure 3 shows a shock tube that is used in the present experiment. N_2 gas is used as a test gas. The cross-sectional area at the test section is 80×80 mm and the size of observation window is also 80×80 mm. The initial pressure in the driven tube is fixed at 500 Torr. That is required to increase the deflection angle in order to carry out a capable measurement in moderate density.

Figure 4 (a) and (b) show the speckle patterns of the reference and the object. These images are 800×800 pixels in size. The object speckle pattern is generated by the density field of Mach reflection of shock waves over a wedge. In this experiment, shock Mach number is controlled at $Ms=1.4$. Speckle pattern in these images is random function in space. Subtracting between these images, we can obtain the intensity difference, which indicates the modulation of the speckle pattern. Moderate speckle size, 3 to 5 pixels, is chosen for the measurement in the present experiment. The components of density gradient vectors are determined with speckle displacements δx and δy at any instance from obtained speckle photograph. The subtracted image, that is speckle correlation pattern, gives us the effective area of the measurement and shock pattern simultaneously. The

subtracted image is superimposed in the density gradient vector map in order to position these vectors. Figure 5 shows the experimental results of density gradient in the case of $Ms=1.4$ and wedge angle $\theta=20^\circ$. Corresponding initial density is 0.848 kg/m^3 . The size of interrogation spot in this processing is 16×16 pixels and the spot is shifted by 8 pixels overlap. Approximately, 1200 vectors are obtained for each run of experiment. Effective vectors are obtained inside the region bounded by reflected shock and Mach shock. Along the incident shock wave and Mach shock wave, where the density is discontinuous, effective data are not obtained from the correlation analysis. Deflected light by shock wave results in a low correlation near the shock wave. These obstructive factors may be removed by introducing a spatial filtering technique in the optical set-up.

Density gradient vectors are converging upon the wedge apex and triple point. A density gradient across the slipstream is also measured. In the region, which is bounded by Mach shock wave and slipstream, the density is not uniform. There is a density gradient towards Mach shock wave.

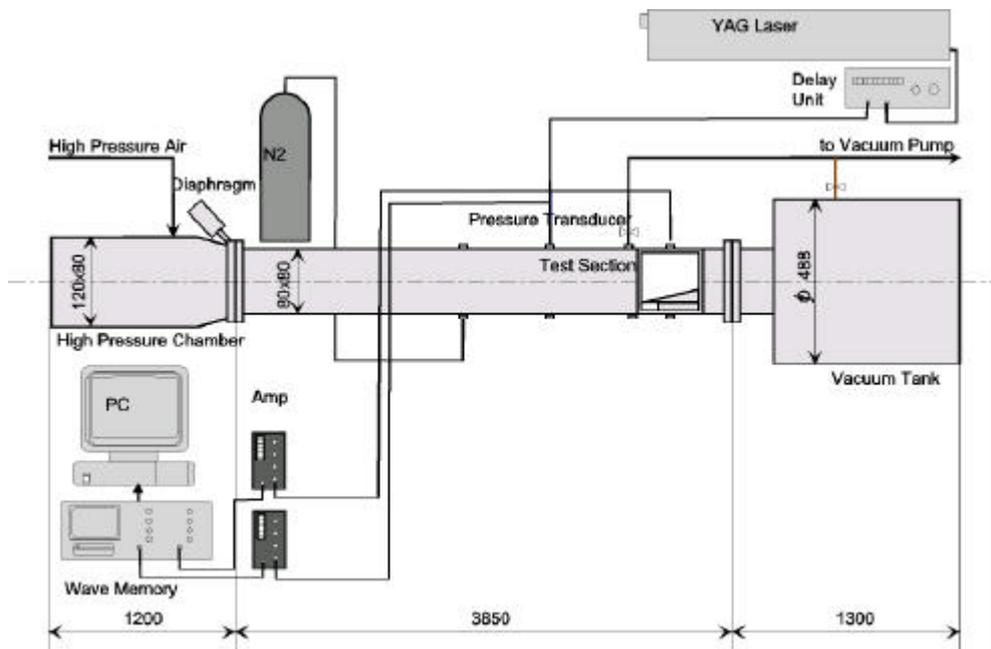
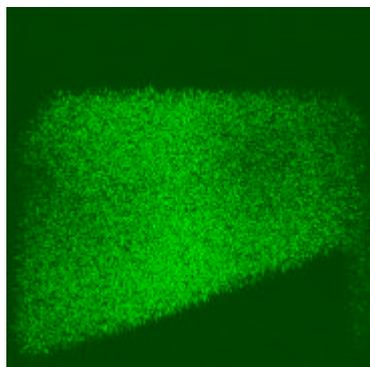
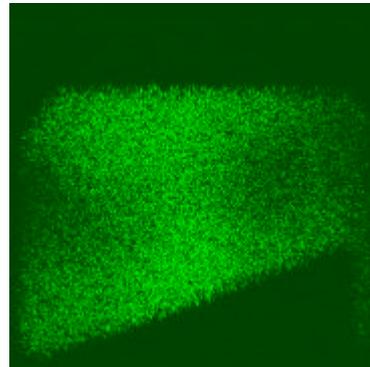


Fig.3 Experimental set-up of Mach reflection over wedge placed in shock tube.



(4-a) reference image



(4-b) object image

Fig.4 Laser speckle patterns and density gradient vector map of Mach reflection of shock wave.

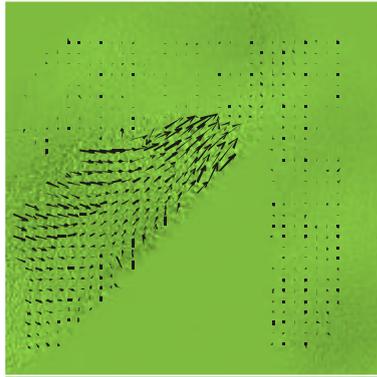


Fig. 5 Density gradient vector map in density field of Mach reflection over wedge.

2.3 Thermal convection measurement

Schematic of the experimental apparatus used is shown in fig.6. The duct is closed at one end, and the air-column in the duct is driven by a sound source placed at the other end. The cross-section of these ducts is rectangular, and the sidewall and the floor are made from glass of 10 mm thickness. The upper wall of the ducts is copper plate of 10 mm thickness for cooling uniformly. The length, the width and the height of each duct cavity are 900×100×25mm, respectively. A driver unit of horn speaker is utilized as the sound source. Pressure amplitude and histories at the closed end are measured by a pressure transducer. Thermal convection in the duct arises by cooling the upper wall with water at temperature 0°C. After acoustic standing wave is superimposed on the thermal convection, the density field of the coupling convection is measured by digital laser speckle photography. At the same condition, qualitative visualization by schlieren method and quantitative velocity field measurement by using PIV system with double-pulsed Nd:YAG laser are carried out in order to compare with the result of density field measurement. For velocity measurement, a longitudinal section at the half width of the duct seeded with fine particles (Expancel, $d:20\mu\text{m}$, $\rho: 40\text{Kg/m}^3$) is illuminated with pulsed-laser-light-sheet.

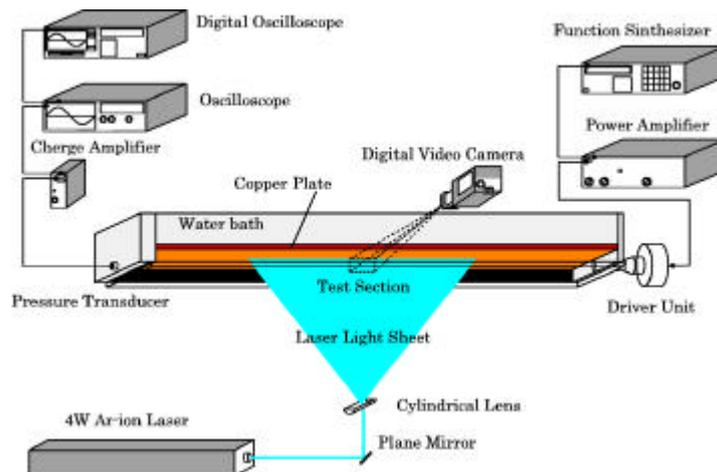


Fig.6 Experimental set-up for density and velocity field measurements of thermal convection current coupling with acoustic standing wave.

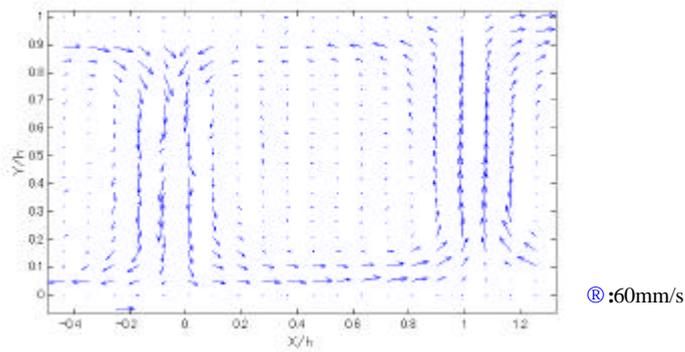
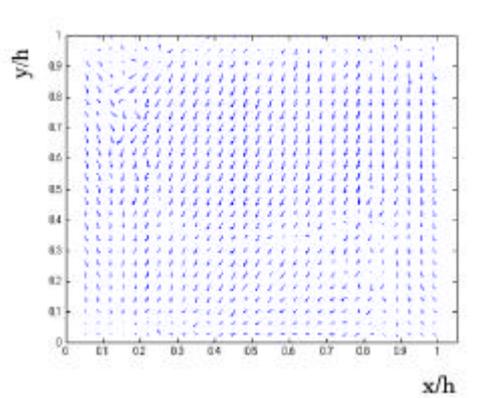
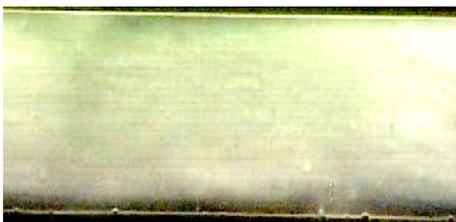


Fig.7 Velocity vector diagram of thermal convection current coupling with acoustic standing wave. ($Ra:2.6 \times 10^4$, $\bar{p}:1.5kPa$)



(a) density gradient vector map of thermal convection current generating within one roll cell.



(b-1) schlieren pattern with horizontal knife edge



(b-2) schlieren pattern with vertical knife edge

Fig.8 Density field measurements of thermal convection current coupling with acoustic standing wave.

Figure 7 shows a velocity vector map. The experimental conditions are as follows. The modes of standing wave are determined in condition that the 1/4 wavelength of sound is nearly equal to the duct height. The sound pressure amplitude (Δp) at closed end is 1.5 kPa, and the temperature difference (ΔT) between the floor and the upper wall of the duct is about 16K, corresponding to the range of Rayleigh number (Ra) 2.6×10^4 . Figure 8 shows a density gradient vector map of the coupling convection and schlieren pattern obtained at the same

experimental conditions. These figures show that the density gradient in the central part region of convection current is almost uniform, the vectors turn to the stagnation point of descendent current that is corresponding to the loop point of the standing wave, and the change of vector directions of both vertical and horizontal components agree with the schlieren patterns illustrating thermal boundary layer and start points of ascending or descending current.

3.CONCLUSION

1. Practical applications of digital laser speckle photography based on cross-correlation evaluation have been successfully carried out for different types of fluid flows.
2. Density gradient distribution in the vicinity of the triple point of Mach reflection was clarified quantitatively.
3. Density field of thermal convection coupling with acoustic standing wave was analyzed, and the aspect of temperature distribution in the convection current was estimated from the result.

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REFERENCES

- Wernekinck, U., Merzkirch, W.(1987), Speckle Photography of Spatially extended Refractive-Index Fields, Applied Optics, Vol.26, No.1, pp.31-32.
- Erbeck, R., Merzkirch,W. (1988), Speckle photographic measurement of turbulence in an air stream with fluctuating temperature, Exp. in Fluid, Vol.6, pp.89-93.
- Koepf, U. (1972), Application of Speckling for Measuring the Deflection of Laser Light by Phase Objects, Opt. Comm., Vol.5, pp.347-350
- Debrus, S., et al. (1972), Groundglass Differential Interferometer, Appl. Opt., Vol.11, pp.853-857.
- Hirahara, H., Kawahashi, M. (1997), Density Field Measurement of Mach Reflection of Shock Waves by Laser Speckle Method, Proc. SPIE, Voi.3172, pp.238-245.
- Kawahashi, M., Nishino, K. and Hirahara, H. (1999); PIV measurements of thermal convection currents transformed by finite amplitude acoustic standing wave, Proc. 3rd Int. Workshop on PIV-Santa Barbara, pp.439-443
- Kaga,A. et al. (1992), Application of a Fast Algorithm for Pattern Tracking on Airflow Measurements, Flow Visualisation VI, Proc. Sixth Int. Symp. on Flow Visualisation, Yokohama, pp.853-857.