at a sufficiently large number of locations, can lead to accurate construction of the phase-locked three-dimensional field. However, even with automation of the data acquisition by computer-controlled traversing, the total time for acquisition can be long for low speed water flows. We view the technique described herein, and extensions of it, to be useful as a diagnostic estimate, and a prelude to more detailed measurements.

In this investigation, the large-amplitude excitation of the cylinder provided, on the whole, reasonably repetitive flow patterns from cycle to cycle; minimal ensemble-averaging is required to obtain representative digitized images. This may not always be the case, particularly in downstream regions of the flow where the three-dimensional structure loses its original, highly coherent character. However, using the same technique as that described herein, it is straightforward, in concept, to ensemble-average a large number of successive images at the same phase. Currently a program is underway to ensemble-average the images in time-dependent flows using either a transducer signal or a highly coherent portion of an image as a phase reference. In doing so, consideration is being given to applying Fourier descriptors, allowing rapid averaging of line shape and orientation in Fourier space, followed by reconstruction of the averaged line and, thereby, image in physical space.

Acknowledgements

The authors gratefully acknowledge support of the Office of Naval Research and the National Science Foundation.

References

Griffin, O. M.; Ramberg, S. E. 1974: Vortex-street wakes of vibrating cylinders. J. Fluid Mech. 66, 553–576

Gumas, C.; Rockwell, D. 1985: The Fourier descriptor technique: a means of pattern recognition and description in fluid mechanics (to be submitted for publication)

Ho, C.-M.; Huerre, P. 1984: Perturbed free shear layer. Ann. Rev. Fluid Mech. 16, 365–424

Smith, C. R.; Paxson, R. D. 1983: A technique for evaluating of three-dimensional behavior in turbulent boundary layers using computer-augmented hydrogen-bubble-wire flow visualization. Exp. Fluids 1, 33–49

Smith, C. R.; Paxson, R. D. 1985: Computer augmented hydrogen bubble-wire flow visualization of turbulent boundary layers. In: Flow Visualization III (ed. Yang, W. J.) pp. 185–189. Washington: Hemisphere

Staubli, T. 1983: Calculation of the vibration of an elastically mounted cylinder using experimental data from forced oscillation. J. Fluids Eng. 105, 225–229

Wygnanski, I.; Peterson, R. A. 1985: Coherent motion in excited free shear flows. AIAA Paper 85-0539

Received February 3, 1987

Technical notes

Speckle photography applied to the density field of a flame

J.-Z. Shu

Institute of Mechanics, Academia Sinica, Beijing, People's Republic of China

J.-Y. Li

Institute of Engineering Thermophysics, Academia Sinica, Beijing, People's Republic of China

1 Introduction

The measurement of density fields by means of speckle photography, first introduced by Köpf (1972), has found a number of applications, e.g. to combustion (Farrell & Hofeldt 1984), turbulent jet flow (Wernekinck et al. 1985), or natural convection (Wernekinck & Merzkirch 1986). With this method one measures, in a recording plane, the two components of the angle by which individual light rays are deflected in the test field. These values can be converted into respective components of the density gradient in the flow. The measurement of these quantities can be performed with higher accuracy than with a schlieren system or a shearing interferometer, and the number of data obtainable from one single speckle record is by orders of magnitude larger than taken from a schlieren photograph or a shearing interferogram.

The speckle technique has the disadvantage that the flow with varying density cannot be visualized in real time. An optical arrangement is described here in which the set-up for taking speckle records is combined with a shearing interferometer using a Wollaston prism (Merz-

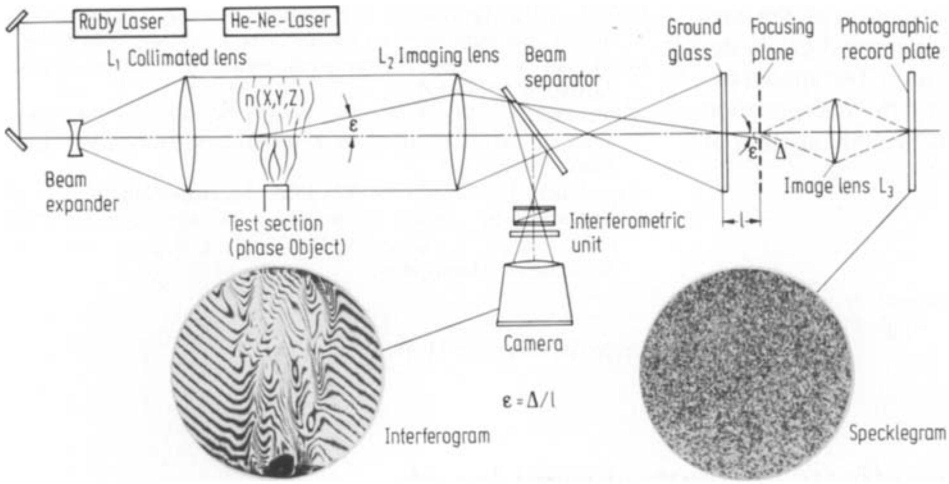

Fig. 1. Optical set-up for the simultaneous recording of a specklegram and a shearing interferogram of a transparent phase object (compressible flow)

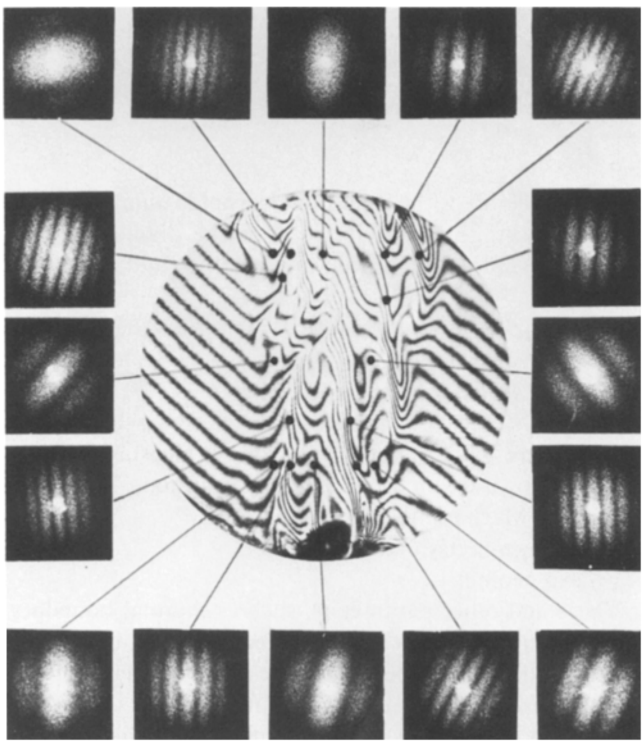

Fig. 2. Shearing interferogram of the Bunsen burner flame (center), and patterns of Young's fringes obtained by the point-by-point analysis of the specklegram at 16 different positions in the field of view

kirch 1964). The latter instrument allows for observing the flow in real time, and interferograms and specklegrams can be taken simultaneously. The system is applied to a fluctuating Bunsen burner flame.

2 Optical arrangement and experiments

The optical arrangement is shown in Fig. 1. A ruby laser serves as the light source. The expanded and then collimated laser beam passes through the test field. A vertical plane in the test field is focused by means of the imaging lens through the beam separator onto the ground glass. The beam separator provides that the major part of the available light is used for taking the specklegrams (in the horizontal arm). This set-up is designed according to the system described by Wernekinck and Merzkirch (1986). A plane at distance l from the ground glass is focused onto the photographic film. The ruby laser is pulsed twice, the first pulse without flow in the test section, the second pulse in the presence of the flow. Deflection of a light ray by an angle ε in the flow field results in a local displacement Δ of the speckle pattern, with $\Delta = \varepsilon \cdot l$. The two overlapping speckle patterns of the double exposure can be analyzed; e.g. with the point-by-point evaluation method that has been described extensively in the literature on speckle photography.

The other part of the light is directed by the beam separator into a Wollaston prism shearing interferometer. Interferograms can be recorded on photographic film. If the He-Ne laser is used instead of the ruby laser, an interferometric image of the flow can be observed in real time on a screen.

Figure 2 demonstrates the application of this system to an unstable, fluctuating Bunsen burner flame. The central interferogram, taken in the finite fringe width mode, gives an overall-view of the flow at a particular instant of time. The simultaneously recorded specklegram has been evaluated with the point-by-point analysis. For each evaluated point one obtains a pattern of Young's interference fringes that provides information on the magnitude and direction of light deflection, at the respective position in the test field. The Young's fringes for 16 different positions are indicated in Fig. 2. It is obvious that the light deflection varies randomly in the flame, and it is also possible to relate the measurable light deflection angle to the local density gradient that follows from the fringe pattern in the central interferogram.

This experiment is another demonstration of the usefulness of speckle photography for measuring the light deflection in flows with fluctuating density. The simultaneously recorded interferogram facilitates the interpretation of the data field derived by the point-by-point analysis of the specklegram.

References

Farrell, P. V.; Hofeldt, D. L. 1984: Temperature measurement in gases using speckle photography. Appl. Opt. 23, 1055–1059

Köpf, U. 1972: Application of speckling for measuring the deflection of laser light by phase objects. Opt. Commun. 5, 347–350

Merzkirch, W. F. 1964: A simple schlieren interferometer system. AIAA J. 3, 1974–1976

Wernekinck, U.; Merzkirch, W.; Fomin, N. A. 1985: Measurement of light deflection in a turbulent density field. Exp. Fluids 3, 206–208

Wernekinck, U.; Merzkirch, W. 1986: Measurement of natural convection by speckle photography. In: Heat transfer 1986 (eds.: Tien, C. L.; Carey, V. P.; Ferrell, J. K.), pp. 531–535. Washington: Hemisphere

Received November 11, 1986

Inlet centerline turbulence effects on reattachment length in axisymmetric sudden-expansion flows

R. M. C. So

Mechanical and Aerospace Engineering, Arizona State University, Tempe, AZ 85287, USA

Abstract. The important parameters that affect the reattachment length in an axisymmetric sudden-expansion flow are examined. It is found that inlet centerline turbulence stands out as the most important; namely increased inlet centerline turbulence causes the reattachment length to decrease.

1 Introduction

Flow through sudden expansions can be found in many different engineering applications; such as combustors, pipe networks, heat exchangers and nuclear reactors. Because of their practical importance, sudden-expansion flows have been investigated by numerous researchers. Besides the loss in the flow, investigators are also interested in the behavior of the separating shear layer, its reattachment downstream and the formation and structure of the recirculation region immediately downstream of the sudden expansion. Since the recirculation region is used to anchor the flame, a knowledge of the reattachment length and the structure of the recirculation region is of particular interest to designers of dump combustors. In view of this, any empirical relation between the reattachment length and the important flow parameters will be most helpful. Therefore, the purpose of this note is to examine the dependence of the reattachment length on the various flow parameters of importance.

2 Effects of inlet centerline turbulence

Among the more important parameters that affect isothermal flows through an axisymmetric sudden expansion are:

(1) $Re = U_i d_1/\nu$, the inlet flow Reynolds number, where U_i is the average inlet velocity, d_1 is the diameter at the inlet to the sudden expansion and ν is the fluid kinematic viscosity,

(2) d_2/d_1, the expansion ratio, where d_2 is the diameter of the downstream tube,

(3) $H = (d_2 - d_1)/2$, the step height,

(4) inlet centerline turbulence level, characterized by u_0'/U_i, where u_0' is the centerline rms u measured at less than $H/2$ downstream of the sudden expansion,

(5) inlet Mach number,

(6) inlet geometry and

(7) exit geometry.

These and other parameters, such as thermal boundary conditions in the case of non-isothermal flows, have been investigated by a number of researchers. In order to eliminate the dependence of the reattachment length (x_L) on H, it is usually reported as x_L/H. A summary of these results is given in Table 1. In Table 1, x_L is determined either from the locus of zero mean U, the dividing streamline, the locations of the maximum heat and mass transfer or from flow visualization. The Table only shows turbulent flow results. Therefore, all x_L/H measurements at $Re < 2000$ are excluded. The different methods of determining x_L/H obviously would not give the same result under the same flow conditions and geometry. However, the differences among them are small (Moon and Rudinger 1977) and could not have accounted for the variations observed (Table 1).

These results show that x_L/H varies from 4.0–12 in a Re range of $2{,}000 - 2 \times 10^6$, an inlet Mach number range of $< 0.1 - 1.0$ and a d_2/d_1 range of 1.25–3.76. The inlet