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Visualization of turbulence anisotropy by single exposure speckle photography

N. Fomin, W. Merzkirch, D. Vitkin, H. Wintrich

Abstract A new technique based on single exposure speckle photography is described that allows to measure the degree of anisotropy of turbulence in a flow with fluctuating fluid density or temperature.

Since anisotropy is linked to shear in a flow, the method is also a means for discriminating regions of different shear rate.

1
Introduction

The suitability of speckle photography for experimentally studying flows with variable fluid density has been verified first by Köpf (1972) and Debrus et al. (1972). With this line-of-sight method one can produce, for a whole-field of view, quantitative data of the deflection angle of light deflected refractionally in the flow under study. Wernekinck et al. (1985) have shown that a measurement of the deflection angles can be realized even in turbulent flow with fluctuating fluid density. A great number of data values, usually several thousand values of the deflection angle, can be extracted from one specklegram. By means of statistical analysis of these data, Erbeck and Merzkirch (1988) have determined characteristic turbulent quantities under the assumption of homogeneous isotropic turbulence. The algorithm necessary for such an evaluation has been extended to the application to axisymmetric turbulence by Han (1993). For more details on the method and its application see the review article by Merzkirch (1995).

For the mentioned quantitative application it is necessary to record, on one photograph, two speckle patterns, one without flow, the second in the presence of the flow. It is required to take the recordings with a very short exposure time (< 1 μs) in order to freeze the turbulent structures. The deflection angles are determined from the displacement of speckles generated by the two exposures. The measurement is performed in an apparatus in which a pattern of Young's interference fringes is the form of the signal representing the displacement to be measured (Françon 1979).

In this note we describe a technique that allows to measure the degree of anisotropy of turbulence in a flow with fluctuating density or temperature. Different from the previous applications, only one exposure is taken with a relatively long exposure time (> 1 ms). The evaluation is performed in the same apparatus used for generating the Young's fringe patterns.

2
Experiments

Experiments are performed with an optical system that is basically the one described by Wernekinck and Merzkirch (1987). An expanded beam of light from a ruby laser operated without intensity modulation or CW laser is transmitted through the test flow, a turbulent butane/air flame. A ground glass plate serves as the speckle generating element. The speckle pattern is recorded on photographic film with an exposure time of the order of 1 ms. After photographic development the specklegram is interrogated, point by point, with a thin He/Ne laser beam in the apparatus sketched in Fig. 1.

The laser light is diffracted from the speckles, thus forming a halo that can be observed on a screen at some distance from the specklegram.

Since the specklegram is recorded with the exposure time being much longer than the time scale typical for the turbulent fluctuations, the images of the speckles are smeared, thus resulting in a relatively large speckle size and, consequently, in a small halo diameter. The halo generated from the single exposure specklegram is not modulated by Young's fringes. Usually, the visible halo is restricted to the zeroth diffraction order, and only in a few cases was it possible to observe the low intensity first diffraction order surrounding the zeroth order.

3
Analysis

Averaged speckles and observed halo both are of circular cross section if the turbulent fluctuations are uniformly distributed in a plane normal to the direction of light propagation, as it is given in isotropic turbulence. The halo diameter D, determined e.g. at the half of the intensity maximum, is inversely proportional to *the averaged* speckle diameter $\langle d \rangle$. With

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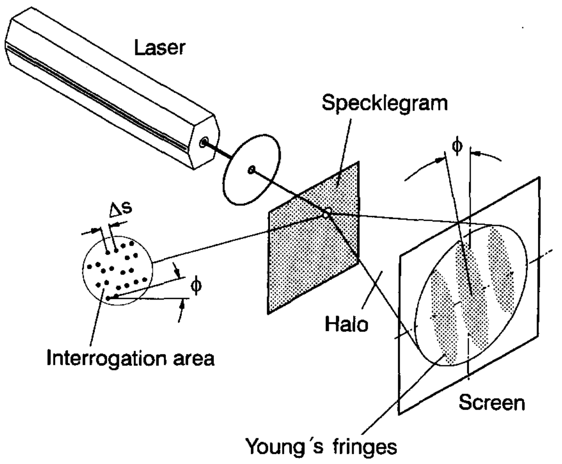

Fig. 1. Interrogation of specklegram with a thin He/Ne laser beam and formation of halo

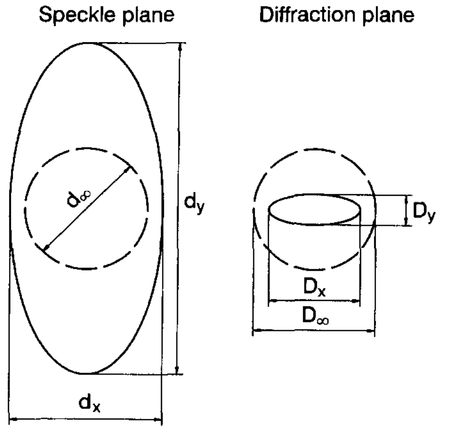

Fig. 2. Averaged speckle form and diffraction halo cross section for undisturbed (dashed) and disturbed (solid) specklegram regions

$\Delta d = \sqrt{(\Delta d_x)^2 + (\Delta d_y)^2}$

$\Delta d_x = d_x - d_\infty$

$\Delta d_y = d_y - d_\infty$

anisotropic turbulence, the speckles become *in the average* elongated in the preferential direction of the turbulent fluctuations, and the halo then has an elliptic cross section, with the longer axis of length D being normal to the direction of the speckle elongation (Fomin et al. 1992). The *averaged* deviation of the speckle from circular form is expressed by a quantity $\langle \Delta d \rangle$ (Fig. 2).

If several elongated speckles, all of them being deformed in the same direction, are present in an interrogation area, the extension D of the resulting halo is given by

$$\sqrt{\frac{\langle (\Delta d)^2 \rangle}{\langle (d_\infty)^2 \rangle}} = C_1 \left(\frac{D_\infty}{D} - 1 \right) \tag{1}$$

where C_1 is a constant, $\langle d_\infty \rangle$ is the averaged diameter of speckles in the fluid without flow, and D_∞ is the halo diameter for the speckles of size $\langle d_\infty \rangle$. The average $\langle\ \rangle$ is taken over all speckles inside the interrogation area.

With respect to the "undisturbed" speckle of diameter d_∞ the speckles might be deformed by the turbulent density fluctuations in two orthogonal directions x and y, but by different amounts, Δd_x and Δd_y (Fig. 2).

The lengths of the two axes, D_x and D_y, of the resulting elliptic halo cross-section are given by

$$\sqrt{\frac{\langle (\Delta d_x)^2 \rangle}{\langle (d_\infty)^2 \rangle}} = C_1 \left(\frac{D_\infty}{D_y} - 1 \right) \tag{2}$$

$$\sqrt{\frac{\langle (\Delta d_y)^2 \rangle}{\langle (d_\infty)^2 \rangle}} = C_1 \left(\frac{D_\infty}{D_x} - 1 \right) \tag{3}$$

A quantity A describing the deviation of the halo cross-section from circular form can be defined as the ratio

$$A = \sqrt{\frac{\langle (\Delta d_x)^2 \rangle}{\langle (\Delta d_y)^2 \rangle}} = \left(\frac{D_\infty}{D_x} - 1 \right) \Bigg/ \left(\frac{D_\infty}{D_y} - 1 \right) \simeq \frac{D_y}{D_x} \tag{4}$$

where $(D_x - D_y) \ll D_\infty$ has been assumed in the last relationship.

The averaged speckle elongation, expressed by Δd, is related to the average of the square of light deflection angle fluctuations, $\Delta\Theta$, by

$$\langle \Delta d^2 \rangle = L_1^2 \langle \Delta\Theta^2 \rangle \tag{5}$$

In the system used for the present studies (Wernekinck and Merzkirch 1987), L_1 is the "defocusing" distance between the ground glass and the plane imaged onto the photographic plate.

As it has been shown by Weiner (1967), the mean square of the temporal fluctuations of the deflection angle is related to the mean square of the refractive index (n) variations by

$$\overline{\Delta\Theta^2} = \frac{2}{3} \frac{L}{L_c} \overline{\Delta n^2} \tag{6}$$

where L is the length of the optical path through the flow under study, and L_c is a correlation length of the turbulent density field, e.g. the turbulent integral scale. The upper bar refers to time averaging.

The averaging expressed by the symbol $\langle\ \rangle$ in Eq. (5) includes both time averaging (over the length of the speckle exposure time) and spatial averaging (over the interrogation area). Making use of Weiner's result (6) appears justified due to the assumption of ergodicity (Hinze 1975) and the assumption of locally homogeneous turbulence in flow areas equivalent to the interrogation area. The temporal mean is then equal to the ensemble average taken for the events in the interrogation area, and one has

$$\overline{\Delta n^2(r, t)} = \langle \Delta n^2(r, t) \rangle \tag{7}$$

where r designates a spatial position and t time, and

$$\Delta n = n - \bar{n} = n - \langle n \rangle \tag{8}$$

For isobaric flows the variation of the refraction index n is related to the variation of temperature by

$$\langle \Delta n^2 \rangle = C_2 \langle \Delta T^2 \rangle \tag{9}$$

with C_2 being constant.

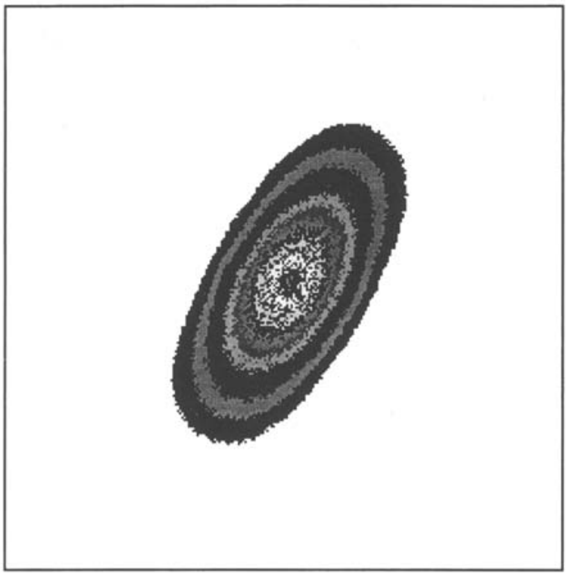

Fig. 3. Elliptic diffraction halo obtained with anisotropic turbulent flow. The different gray scales indicate intensity. Original is in colour

The mean square value of speckle elongation in the ith direction is then given by

$$\langle \Delta d_i^2 \rangle = C_3 \langle \Delta T_i^2 \rangle \tag{10}$$

where C_3 is constant.

Therefore, at a first approximation, the measured value of $(D_\infty/D-1)$ is proportional to the intensity of the temperature fluctuations

$$D_\infty/D-1 \sim \sqrt{\frac{\langle \Delta T^2 \rangle}{T_\infty^2}} \tag{11}$$

and the ratio $A=D_y/D_x$ is proportional to the anisotropy of the turbulent temperature field:

$$A=D_y/D_x \sim \sqrt{\frac{\langle \Delta T_x^2 \rangle}{\langle \Delta T_y^2 \rangle}} \tag{12}$$

4

Results and discussion

The cross section of a halo projected onto a screen in the device described in Sect. 2 is viewed by a CCD camera whose recording is digitized and then evaluated for determining the quantities D (or D_x, D_y) and A. A digitized pattern of an elliptic halo and its intensity distribution are shown in Fig. 3.

A software for use on a PC was developed that allowed to determine automatically the quantities D and A while the specklegram is interrogated with the He/Ne laser beam (see Fig. 1). RMS values of the temperature fluctuations and anisotropy of the temperature field can be determined with the aid of Eqs. (11) and (12). As an example illustrating the potentials of the method Figs. 4 and 5 show results taken with the turbulent butane/air flame for a field of view of 20×30 mm^2. The planar distributions of the RMS values (Fig. 4) and the values of A (Fig. 5) are presented in form of different gray scales, black representing the highest values in both cases. The figures depict the state of turbulence for the instant of time at which the specklegram was recorded. It is seen that the turbulence state, at this particular instant, is not symmetric with respect to the flow axis. Locations of higher turbulence intensity, expressed by the higher RMS values on the right side of Fig. 4, coincide with locations of high turbulence anisotropy, as seen in Fig. 5.

To summarize, single exposure speckle photography offers a means for quickly visualizing and determining the degree of

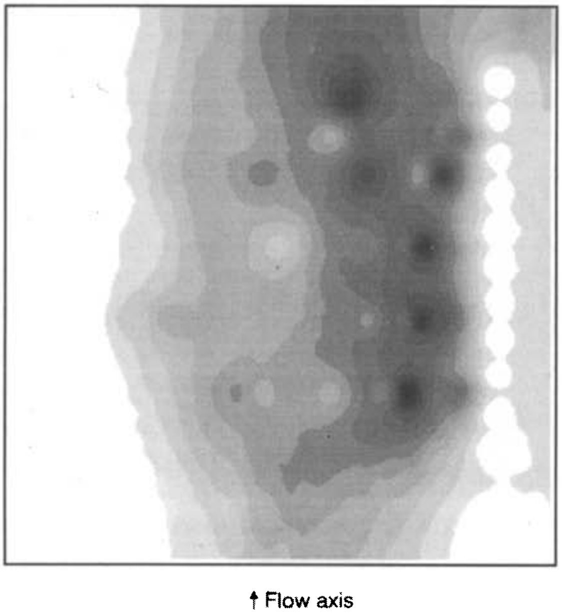

Fig. 4. RMS values of temperature fluctuations in turbulent flame, visualized by different gray scales (in arbitrary units, dark indicating the highest values)

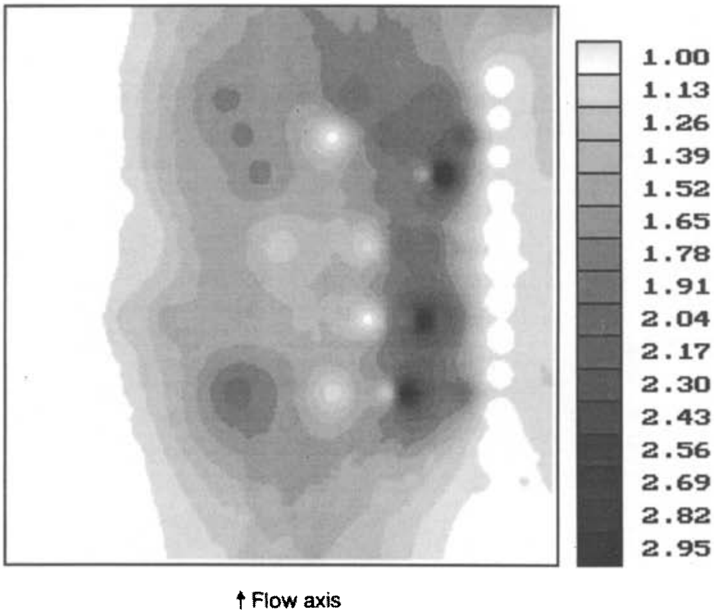

Fig. 5. Anisotropy of turbulence in flame expressed by ratio A (Eq. (12)). Gray scales indicate values of A

anisotropy of a turbulent temperature or density field. Since anisotropy is linked to shear in a flow, the method is also a means for discriminating regions of different turbulent shear rate.

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