XXI ICTAM, 15-21 August 2004, Warsaw, Poland

3D VORTICS STRUCTURE MONITORING IN TURBULENT FLOWS BY DIGITAL SPECKLE PHOTOGRAPHY

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Summary 3D vortices structure in complex turbulent flows is reconstructed using computerized speckle tomography. Digital speckle photography (**DSP**) is used for the instantaneous quantitative derivation of a 2D map of deflection angles of the light passing through the flow under study. The macro structures are reconstructed using Radon integral transform and the microscale turbulence structures are determined by using Erbeck-Merzkirch integral transforms.

INTRODUCTION

Digital speckle photography (**DSP**) based on the computer aided acquisition and evaluation of time evolution of dynamic speckle patterns recorded by digital CCD cameras allows the instantaneous quantitative derivation of a 2D map of deflection angles and retardation of the light passing through the flow under study. Even for 3D flows, recent advances in digital optical data storage and analysis make it possible to extract quantitative data from line-of-sight flow visualization techniques [1,2]. Among the most important advantages of **DSP** are its high spatial resolution and the possibility to collect a great amount of experimental information from a single speckle-patterns record. In principle, the resolution can be as high as the diffraction limit of line-of-sight measurements (about 0.2-0.3 *mm)* [2]. For 2D flows the maps of the deflection angles so obtained can be easily transformed into 2D density (temperature) gradient maps using simple calculations and without any calibration. In addition, precise digital multi-projection measurements allow the reconstructing of a 3D vortices structure using computerized tomography approach as below.

SPECKLEGRAM RECORDINGS

The first step of digital specklegram processing is similar to PIV and is performed by evaluation of statistical functions (cross-correlation or structural functions) of the recorded dynamic speckle fields. The record of the whole field is scanned by moving a $N \cdot M$ pixels window across the field. The pattern of the window in a frame 1 taken from the first exposure specklegram is cross-correlated with the pattern of the respective window at the same position in a frame 2 from the second exposure specklegram. Finally, the speckles displacement attributed to the area covered by the window is found from determining the maximum peak of the correlation in quasi-real time operation, see [2,3].

TOMOGRAPHIC RECONSTRUCTION

The general way to obtain interior flow information is to use multidirectional, line- of- sight measurements and reconstruct the 3D data using computer assisted tomography (**CAT**). For a given test object, the quality of the tomographic reconstruction depends on the number of projections taken, the covered total angular range of viewing directions, and the amount of information available from each projection. The integral Radon transformation can be used for data obtained from either laminar or turbulent flow, but an exact determination of the interior flow parameter distributions would need an infinite number of projections. Because of the finite number of projection measurements

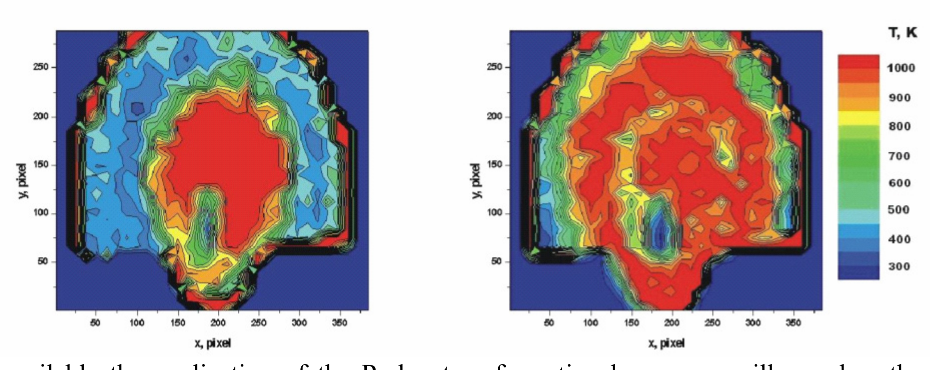

Fig. 1. Instantaneous temperature maps reconstructed by **CAT** with Radon integral equation using two-projectional **DSP**

available the application of the Radon transformation becomes an ill-posed mathematical problem. In practice this means that a small inaccuracy in the experimental data can lead to significantly large errors in the final flow parameter determination. The high data density is particularly advantageous for analyzing complex 3D turbulent flows. In the present paper an iteration technique has been adopted for the calculation of the Radon integral. The noise in the experimental data has been smoothed by a cubic spline technique. This smoothing procedure improves the reconstruction quality, but removes the low-scale variation of the refractive index distribution from the reconstructed field. For direct recording of the light ray deflection angles, as in **DSP**, the integral Radon transformation simplifies and the optical disturbance (refractive index distribution) can be predicted from the transformation

$$F(x,y) = n(x,y) - n_\infty = -\frac{n_\infty}{2\pi^2}\int_0^\pi d\alpha \int_{-\infty}^{\infty} \frac{\varepsilon(\alpha,p)}{p-p_0}dp \qquad (1)$$

Fig. 1 shows an example of quasi-real time reconstructing the local parameters in an open turbulent flame from data taken in two directions from digital speckle record.

SMALL SCALE VORTICITY EVALUATION

Using the relation between deflection angle and fluid density,

$$\varepsilon_q(p,q) = \mathrm{K}\int_0^L \frac{\partial\rho(p,q,s)}{\partial q}ds \qquad (2)$$

Erbeck and Merzkirch [4] has received a connection between density and deflection angle correlation functions

$$R_{\varepsilon q}(\xi,\eta) = -\mathrm{K}^2\int_0^L\int_0^L \frac{\partial^2}{\partial\eta^2}R_\rho(\xi,\eta,\zeta)\,dz'dz'' \qquad (3)$$

For the case of isotropic turbulence, this equation can be inverted with respect to density correlation functions:

$$R_\rho(r) = \frac{1}{\pi\ L\mathrm{K}^2}\int_r^\infty \frac{1}{\sqrt{\tau^2 - r^2}}\left\{\int_0^\tau R_\varepsilon(\tau^*)d\tau^*\right\}d\tau \qquad (4)$$

Using these data, both macro- and micro-scales of turbulence can be determined. Thus, the Erbeck-Merzkirch integral transform is an effective tool for local turbulence parameter determination using digital line-of-sight data. Both macro and micro spatial structures of the turbulent scalar (density) field in compressible flow can be visualized and quantitatively characterized with the applied multi-projectional **DSP** technique. It should be noted that the inversion of this functions to the original one, $R_\rho(r)$, is ill posed mathematical problem and care must be taken performing such calculations. As we can see, the inversion integrals are Abel type integrals, therefore the great experience of solving this equation may be used. The quality of this reconstruction for a small-scale vorticity is rather good with grids of about 200^2.

CONCLUSIONS

Both macro and micro spatial structures of the turbulent scalar (density) field in compressible flow can be visualized and quantitatively characterized with the applied speckle tomography techniques. The macro structures are reconstructed using Radon integral transform. The microscale turbulence structures are determined by using the 3-D density correlation functions evaluated with Erbeck-Merzkirch integral transforms. With "high density" speckle photography data the precision of the turbulence microscale determination using this integral transform for the isotropic turbulence is rather higher. For non-isotropic turbulence the evaluation would require a more correct conversion using multi-angular probing and convolution of Radon and Erbeck-Merzkirch integral transforms.

ACKNOWLEDGEMENTS. The research described in this publication was supported by the Belarusian Fund of Basic Research (grant N T02P-043) and by INTAS (INTAS Project N 00- 0135 ”Novel PIV system for fluid mechanics measurements”, project coordinator Dr. J. Kompenhans).

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