Digital laser diagnostics of the very fast 3D flows

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1 Introduction

Recent progress in digital images acquisition and computer-assisted images analysis opens new possibilities for the fast complex flows detailed diagnostics, based on the laser flow probing and obtained various (*i.e.* interferometric) images evaluation. Since the time of the first use of lasers for flow diagnostics, there are a number of laser sheet and line-of-sight techniques available for the very fast gas and plasma flows, see [1-3]. Among them are digital particle image velocimetry (**DPIV**) and digital speckle photography (**DSP**). While **PIV** uses laser sheet illumination, **SP** is line-of-sight technique and reconstruction of local parameters in 3D flows is a difficult mathematical task.

For the very fast flows with velocity gradients, the **PIV** techniques have problems with laser illumination, particle seeding and particles accelerations. For such flows, new **PIV** methods, based on single exposure technique and on the recordings of virtual particles, speckles, are discussed and examples of flowfield reconstructed are presented.

For the line-of-sight techniques, there are many approaches in determination of local parameters. The turbulent and reactive flows are the very complicated case for such reconstruction of local parameters, and statistical description of the flow field is one of the possible approaches, available for these cases. Turbulence affects the propagation of a probing laser beam through the medium under investigation by the way of the variations in the refractive index. These variations in different flowfields can be caused by concentration fluctuations in a mixing zone of components with different refractive indexes. For one-component flows the refractive index variations are caused by density fluctuations, or, in the case when the pressure variations are small, by temperature fluctuations. For the reactive flows like combustion or explosions, the variation of the refractive index are caused by both the density and species concentration fields.

The present paper discusses briefly mathematical procedures of 3D averaged field reconstruction based on the Radon integral transform and turbulence field reconstruction based on a novel Erbeck - Merzkirch integral transform connected with statistical optical data treatment and numerical flowfield simulation. Examples of the very fast 3D flowfield reconstructions using **DSP** with numerical simulation of optical ray tracing and computer-assisted tomography (**CAT**) are given below as well.

2 Experiments

The principles for measuring the light deflection angles by the SP are shown in Fig. 1. An interferometric pattern produced due to multiple interference in the diffuse laser light behind a ground glass is recorded. A random optical grating is produced by the ground glass, working as laser speckle pattern generator. The application of this optical methods for analyzing turbulent reactive flows has a number of advantages due to the very high spatial and temporal resolution of the technique. In this case, an instantaneous value of a local refraction angle measured can be considered as a sum of time-averaged and *rms* fluctuation values. Using digital recordings, a great amount of optical data can be directly accumulated in a **PC** memory. Statistical analysis of these data allows reconstructing both averaged and fluctuation components of the flowfield, as it is briefly described bellow.

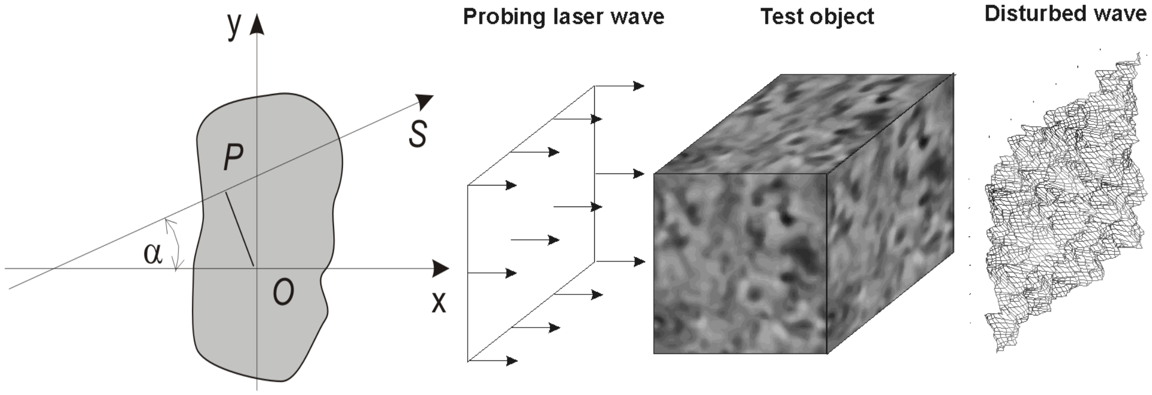

Fig. 1. *Geometry of the Radon transform (left) and general principles of light wavefront distortion under laser line-of sight probing of 3D phase object.*

3 Reconstruction of the local parameters in 3D flows

The general way to obtain interior flow information is to use multidirectional, line-of-sight measurements and to reconstruct the 3D data using computerized tomography. 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, see [4,5] for details.

In the 3D imaging, the computer assisted tomography (**CAT**) approach uses data of many projectional line-of-sight measurements which are available for quasi-stationary objects. Even for such objects the CAT-reconstruction of fine interior structures is a difficult mathematical task which is referred as inverse (ill-posed) problem. In these cases advanced diagnostics and digital recordings allow to improve data acquisition and to extract more detailed parameters of flow studied. Both large scale vortices and small scale vorticity affect the propagation of probing laser beam through the media under study and should be taken into account under the line-of-sight optical data treatment.

Several mathematical algorithms are available for reconstructing the 3D field from the information recorded in the various projections with the convolution back projection method being the most widely used. In the present paper an iteration technique has been adopted for the calculation of the Radon integral. This approach has been refined to accommodate information about the sought distribution as the first approximation. 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.

The mathematical procedure of tomographic reconstruction in turbulent flows was verified using numerical simulation with a "phantom" distribution of the refractive index. For each possible propagation direction in the flow simulation, the deflection angles of the light rays, **ε (α, p),** were determined from the refractive index distribution **n(x,y,z).** An estimated measurement error was added randomly. This added noise simulates the influence of low length scale vorticity as well as random experimental errors.

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

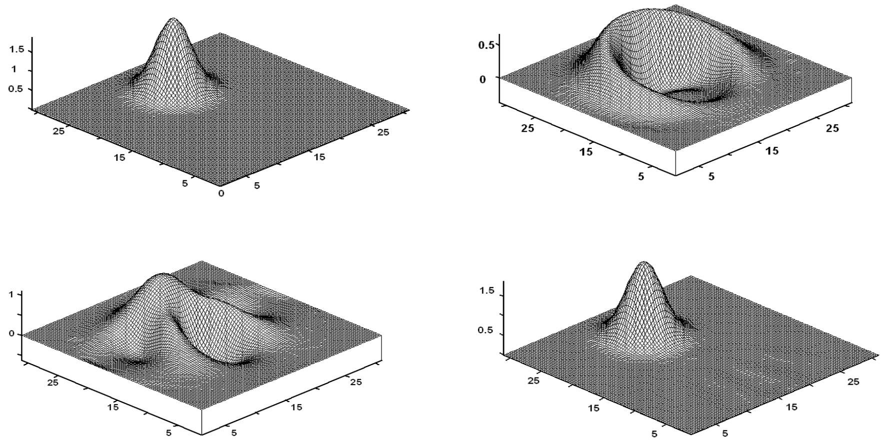

Fig. 2. *The simulation results for 2, 4, and 12 – projectional speckle tomography: reconstructed temperature profile in one horizontal section of a single non-axisymmetrical jet combustor. On the upper right corner- phantom distribution; others – reconstructed distributions using Radon integral transform*

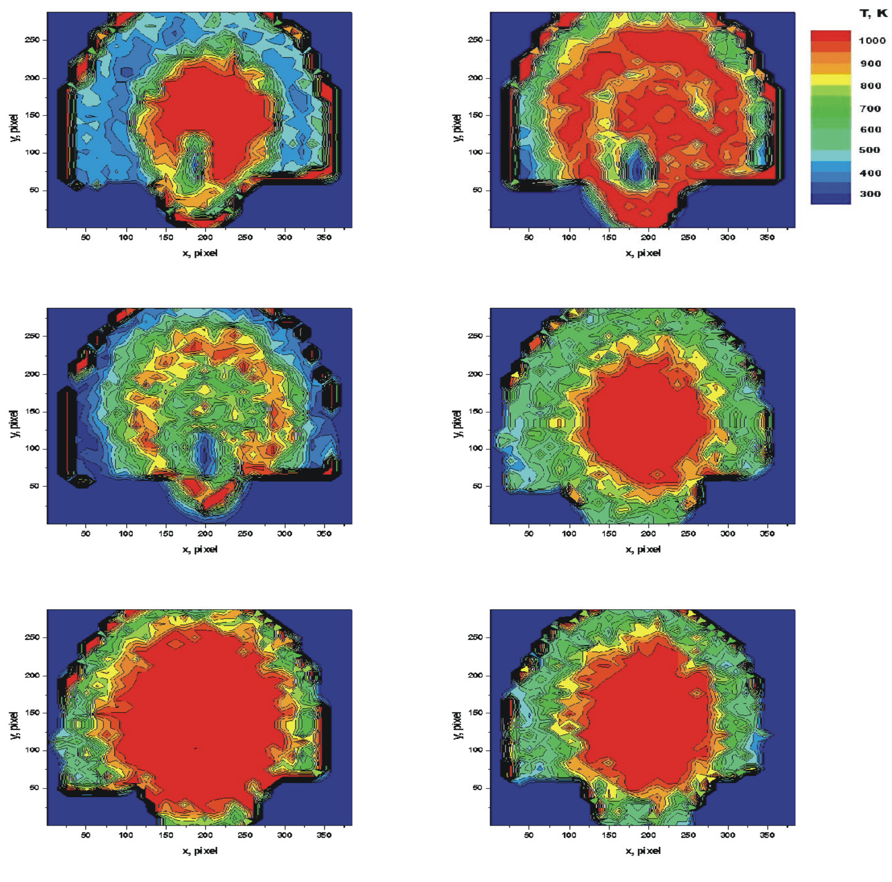

Fig. 3. *Instantaneous temperature fields in different cross-sections of 3D- combustion zone, reconstructed by using Radon integral transform and two-projectional speckle photography data...*

4 Correlation data analysis and reconstruction of statistical flow parameters

Correlation analysis of speckle photography data allows reconstructing statistical function of the deflection angles of the probing laser light, transmitted through the flowfield. Erbeck and Merzkirch has received a connection between density and deflection angle correlation functions, see [6,7] for details :

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

For the case of isotropic turbulence, this equation can be inverted with respect to correlation functions denoted by the symbols || and $\perp$:

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

Using these relations, local statistical functions are reconstructed for a number of complex flowfields including shock and acoustic waves, combustion zones, *etc*., and will be presented in the paper.

Conclusions

New **DPIV** and **DSP** methods are used for the very fast flow diagnostics. Velocity and pressure fields in MHz range acoustical wave are reconstructed [8]. Both macro and micro spatial structures of the turbulent scalar (density) field in compressible reactive flows are visualized and quantitatively characterized with the applied digital interferometric techniques. The macro structures are reconstructed using CAT with Radon integral transform. The microscale turbulence structures are determined by using the 3-D density correlation functions evaluated with Erbeck-Merzkirch integral transforms.

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