

Sound Measurement Using Speckle Interferometry

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Digital speckle interferometry (**DSI**) has been applied to the measurement of acoustic waves in water. The passage of sound waves through water causes fluctuations in the refractive index which produce minute deflections of a collimated laser beam passing through the measurement volume. This results in a dynamic speckle pattern at the far side of the measurement volume which is recorded using a high resolution digital CCD camera. The sound wave intensity has been reconstructed using data of DSI measurements and results of numerical ray tracing of the probing laser beam through the flowfield.

1 Introduction

Speckle interferometry is a density sensitive line-of-sight flow visualization techniques which allows simultaneous quantitative measurements of deflection angles of the laser light passed through the flow [1]. Digital versions of PIV and speckle interferometry (SI) improve significantly the possibilities of the techniques [1, 2]. *Digital particle image velocimetry* (DPIV) has recently been applied to the study of an acoustical velocity field in a flowfield associated with acoustical streaming and vortex shedding in air under high intensity sound generation by loudspeaker [3]. A digital version of PIV provides rapid access to two-dimensional velocity fields by imaging the displacement of tracer particles in a flow field using high resolution digital cameras.

A closely related technique, *digital speckle interferometry* (DSI), can also be applied in a similar way to the study of the density field in an acoustical wave for quantitative diagnostics of the intensity of the wave. Digital data treatment is based on the direct computer aided correlation analysis of the temporal evolution of dynamic speckle patterns. For DPIV this allows the instantaneous quantitative derivation of a 2D map velocity field in the selected plane, and for double exposure DSI this allows the measurements of deflection angles and retardation of the light passing through the flow under study.

A single exposure method is used with line-of-sight optics. When the fluctuating speckle pattern is recorded over a prolonged period (as compared to the characteristic time of the acoustic field) then the speckle images are smeared. This results in a relatively large speckle size and low contrast. The speckle enlargement is correlated with the intensity of acoustical field under study and this intensity can be reconstructed through digital analysis of the specklegram obtained. The dynamic speckle patterns are recorded using a digital CCD camera with high resolution. The reconstruction of the sound wave intensity is based on these data and uses laser ray tracing simulation.

2 Experiments

2.1 Speckle technique

A laser speckle interferometry enables the direct non-intrusive measurements of density gradients for optically transparent media with a non-uniform refractive index distribution [1]. Figure (1) includes the general principles of laser probing of a test media. An expanded parallel beam of laser light is transmitted through the test section. The wavefront of the transmitted laser light is disturbed due to refraction of the beam on the density gradients. In speckle interferometry, the test object is placed in front (on the left side) of the ground glass, and it is imaged by means of a lens onto the plane of the ground glass. The ground glass is worked as speckle-field generator and in the space behind it the laser light consist of the smallest granules of light – speckles. The speckles are recorded by digital CCD camera of high resolution. The camera is focused onto a plane at distance L from the ground glass. In double exposure mode, (**DEM**), two speckle patterns are superimposed by recording two exposures on the same CCD matrices, like in **PIV**. By digital specklegram processing as it is described below, it is possible to determine two components of the speckle displacement at each specklegram interrogation point. These values can be easily converted into the components of the deflection angle of the light passed through the flow studied. In single exposure mode (**SEM**), a speckle pattern is recorded for a relatively long time as compared to that for **DEM**. During this time the speckles could be in a movement due to changes in the refractive field distribution in a test object. This results in a relatively large speckle size and a decreasing of the speckle contrast in the time-integrated speckle image. The speckle blurring and enlargement is correlated to the intensity of density fluctuations in a flow under study and can be reconstructed through the autocorrelation analysis of the specklegram, described below. Application of these principles to acoustical standing wave monitoring is illustrated by Figs. 2, 3.

2.2 Acoustical wave generation

The laser light is passed through the standing wave and is recorded during several acoustical circles. This results in a relatively large speckle size and low contrast in the regions, between the acoustical pressure nodes. Along the nodes the light is not deflected and the speckle pattern is not disturbed. Like measurements of turbulence structures, the mean square temporal variation of a deflection angle within a coherence interval is directly proportional to the variance of refractive index field [4].

For quantitative determination of the refractive index fluctuation, an experimental calibration of SESM has been performed using rotating ground glass. A linear calibration curve has been obtained.

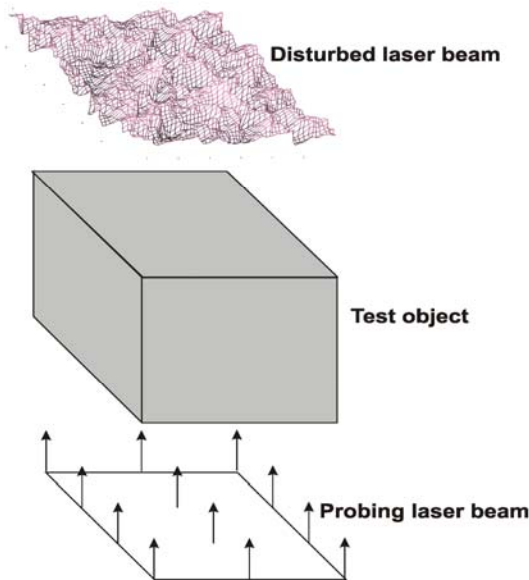


Figure 1: General principles of laser line-of-sight probing of refraction index field

The results of the reconstruction of the intensity in a standing acoustical wave are illustrated in Figs. 3, 4. The intensity is shown in arbitrary units. For the quantitative interpretation, numerical ray tracing of the probing laser beam through the acoustical field is under development, see below.

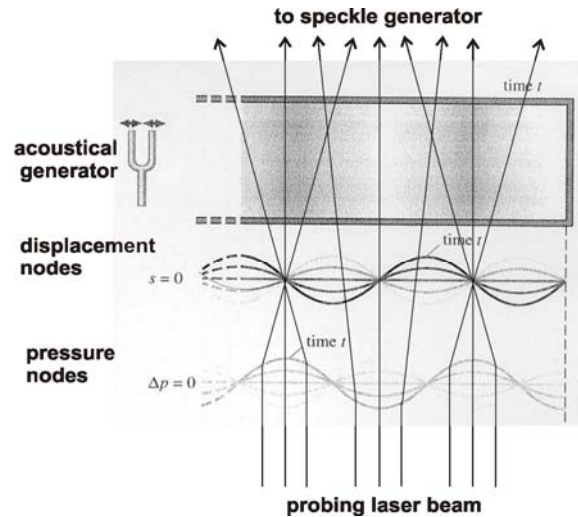


Figure 2: Monitoring of standing acoustical wave by single exposure speckle photography

2.3 The reconstruction procedure of a 3d acoustical field

The information obtained from line-of-sight optical measurements consists of the averaged data along the optical path. There are many approaches in determination of local parameters using such data. For acoustical flows the refractive index variations are caused by pressure fluctuations, see *e.g.* [5]. To analyse the possibilities of laser probing, a direct numerical simulation of laser tracing in the optical scheme has been performed. Under the assumption of geometrical optics the ray paths through the 3D field have been computed from the ray equation [6]. A numerical procedure of solving this ray equation allows the computation of the ray positions and the slope for a small increment in path length starting from the initial cross-section where the rays are parallel to the z-axis. At the exit cross-section the vector values of speckle shifts for different optical schemes have been calculated. The correlation functions of the density and deflection angle fields have been constructed and compared with experimental data.

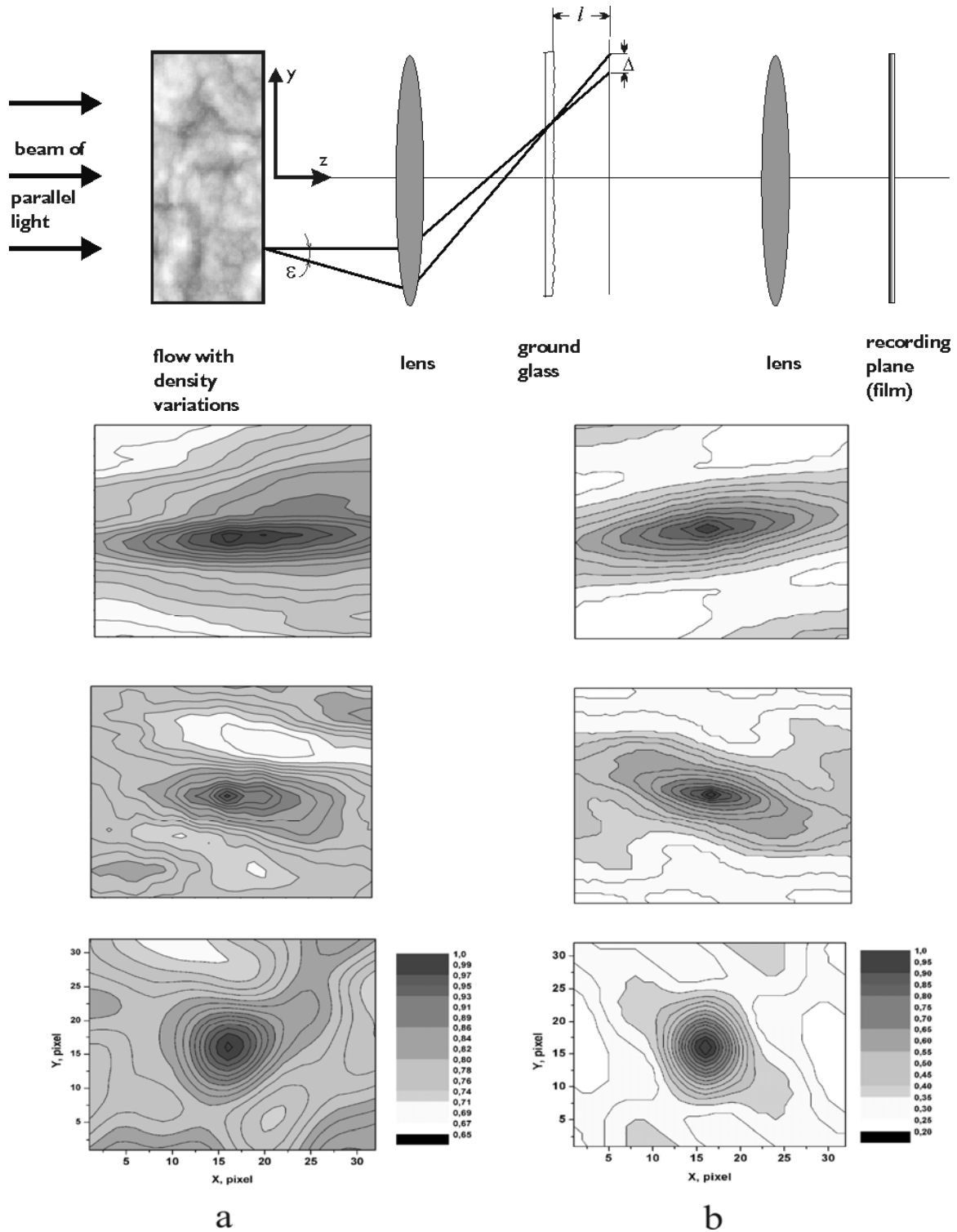


Figure 3: Optical configuration for single-exposure speckle photography (on the top) and results of evaluation of specklegram autocorrelation functions. Upper autocorrelations correspond to a relatively large image displacement during exposure time, lower functions - to smaller displacements. The autocorrelation functions in (a) are obtained by using FFTs, and corresponding images in (b) - are results of the direct evaluation of the autocorrelation functions subjected to a low-pass noise filtering.

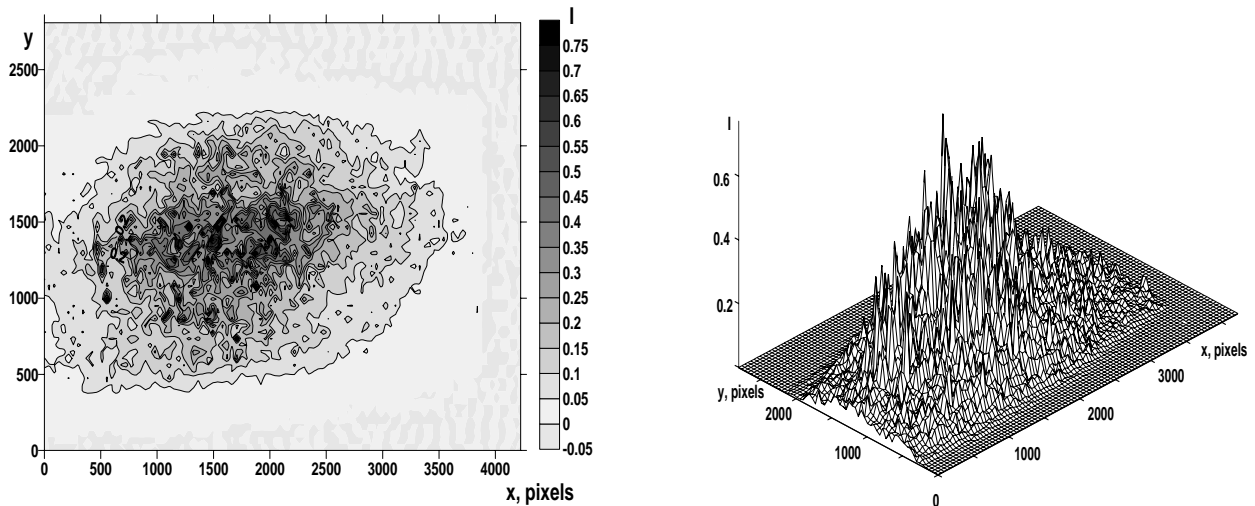


Figure 4: Reconstructed intensity of a standing acoustical wave in water (on the right) and its isolines in one of the cross-sections (on the left).

3 Conclusions

A spatial distribution of intensity of acoustical field in a standing wave has been reconstructed by using experimental data obtained by digital single-exposure laser speckle photography and numerical simulation of 3D ray tracing through the field under study. The evaluation procedure uses autocorrelation analysis of the specklegram obtained with FFT and low-pass noise filtering to check the statistical function of speckle intensity distributions. Thus, the line-of-sight **DSI** allows acoustical field monitoring in liquids without using particles for visualization. The evaluation procedure is fast enough and the technique can be realized in real-time operation mode.

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