Holographic interferometry as a tool for visualization of temperature fields in fluids

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Abstract Measurement of temperature field in moving fluids is connected with many difficulties. Usage of point temperature measurement methods, such as Constant Current Anemometry (CCA), is limited to frequencies up to 3kHz. This frequency should be the limiting factor for using the CCA in fluid when fast change of temperature occurs. This shortcoming of CCA measurements should be overcome by using of optical methods such as digital holographic interferometry. It is necessary to employ a special holographic setup with double sensitivity instead of the commonly used Mach-Zehnder type of holographic interferometer in order to attain the parameters sufficient for the studied case. This setup is not light efficient like the Mach-Zehnder type but has double sensitivity. The special technique of acquiring and phase averaging of results from holographic interferometry is presented.

1 Introduction

Digital holographic interferometry (DHI) is used for measurement of temperature field of air generated by heated pulsed jets in presented study. For measurement of properties of a pulsatile jet, DHI is very suitable, as it can show entire 2D or 3D temperature distribution. For measurement of transparent objects "phase objects", a Mach-Zehnder holographic interferometer setup is usually used. Unfortunately, the phase change is quite small in this type of measurement, thus the sensitivity of the usual interferometer is not sufficient. Previous experiments [1, 2] showed the usefulness of an interferometric setup based on a Twymann-

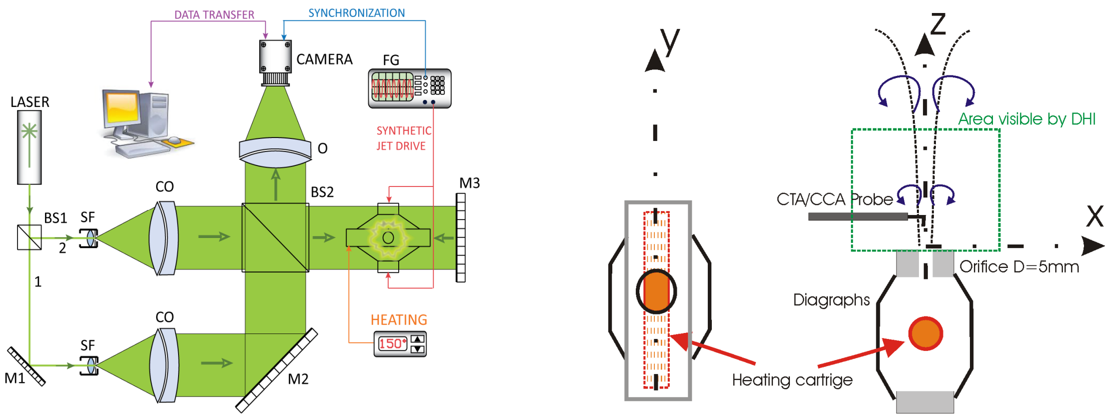

Fig.1 (a) Setup for digital holographic interferometry with double sensitivity (BS-beam splitter, M-mirror, SF spatial filter, CO-collimating objective, O-focusing objective, FG-function generator), (b) A experimental device, system of coordinates and main dimensions for hot-wire anemometry and holographic interferometry

Green interferometer. In this setup the light travels through the phase object twice, which brings the double sensitivity of the setup. However, the setup is more complicated to adjust and is not so light-efficient; energy is lost mainly in the beam splitter BS2 (Fig.1).

Process of capturing and evaluation of temperature field by means of holographic interferometry is shown at Fig.2. If two holograms are captured and the phase is extracted from both of them the interference phase modulo 2π is obtained by subtracting those phase fields:

$$\phi_1(m,n) = \arctan\frac{\mathrm{Im}(h_1(m,n))}{\mathrm{Re}(h_1(m,n))}, \qquad \phi_2(m,n) = \arctan\frac{\mathrm{Im}(h_2(m,n))}{\mathrm{Re}(h_2(m,n))} \tag{1}$$

For every phase ten holograms is captured. The phase calculated from those holograms is averaged. The digital hologram sequence is evaluated by semi-automatic software. Before the experiment can begin, the first hologram has to be recorded which then serves as a reference state (in our case it was a picture of the measured area under the heated surface without the impinging jet). The phase difference obtained by comparison of the reference hologram and the measured holograms is dependent on the refractive index *n* field distribution.

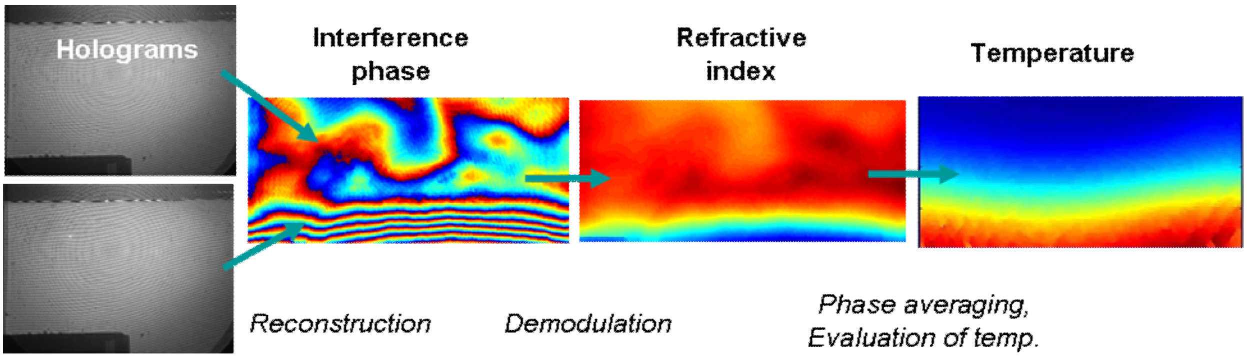

Fig.2 Steps for measurement of the temperature field by digital holographic interferometry

Our main concern in experiments is not the refractive index field distribution but the distribution of temperature. The value of this physical quantity is determined by the effect it has on the refractive index field. The key quantity is the density ρ of the gas. Its relation to refractive index *n* is given by the Gladston-Dale equation:

$$n - 1 = K\rho \tag{2}$$

where *K* is the Gladston-Dale constant and ρ is the density, which are the properties of the gas. If the supposed smallest detectable change in phase is better than fractions of π, the resolution of the measuring system is better than 0.2 Kelvin [3].

2 Experimental setup

Fig.1(b) shows the experimental setup and configuration used in this study. Synthetic Jet (SJ) actuator consists of a sealed cavity, which is equipped with an emitting orifice (diameter *D* = 5 mm) and a pair of electrodynamically actuating diaphragms running in opposite directions (diameter D_D was equal to 53 mm); originating from two ARN-100-10/4 loudspeakers of diameter 94 mm, with nominal electrical resistance 4 Ω. The orifice is oriented vertically upwards. The working fluid is air. The OMEGALUX CIR-10301/240V Cartridge Heater was equipped with K-type thermocouple and placed into the holder tube inside the actuator cavity. It is possible to control the temperature (T_c) of the heating cartage surface up to 200°C by a connected PID regulator during experiments. The uncertainty of the temperature of the wall was less than 0.2°C during single experiment.

The principle of SJ is well described in previous work of authors (see [4, 5]). The main parameters of used SJ are: the mean time orifice velocity $U_0 = \frac{1}{\tau}\int_0^{\tau_E} u_0(t)dt$, where τ is the time period, i.e. $\tau = 1/f$ and *f* is the frequency, τ_E is extrusion time ($\tau_E = T/2$ for the sinusoidal waveform or $\tau_E \neq T/2$ for the non-sinusoidal waveform), $u_0(t)$ means the periodical axial orifice velocity and non-dimensional temperature T^* is defined as: $T^*=(T-T_a)/(T_0-T_a)$, where T is a temperature of the fluid, T_a is a temperature of surrounding and T_0 is an average temperature at the nozzle.

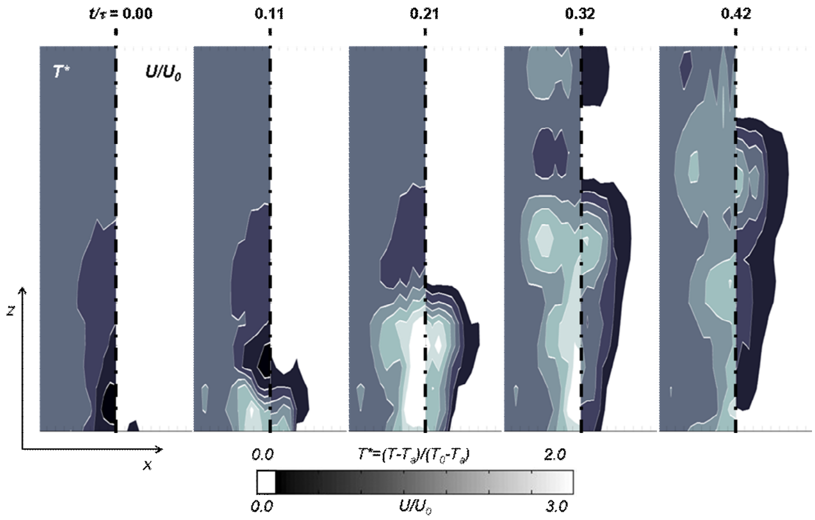

Fig.3 Velocity (right side) and temperature (left side) fields at plane y=0 at different times t/τ of the cycle measured by CTA/CCA. The velocity field on +x, +z quadrant was measured due to the symmetry of the setup.

3 Results

Fig.3 shows time development of the velocity (right side) and temperature (left side) fields in plane $y = 0$. Figure shows development of the single puff at frequency of oscillations $f = 15$ Hz. The development of velocity and temperature fields as well as motion of coherent structures is evident.

Fig.4 shows a comparison of 2D temperature fields acquired by DHI (left side of each picture) and CCA (right side of each picture). The pictures correspond to different time of the cycle t/τ. The development of the 2D structure is clearly visible. Fig.4 illustrates the ability of DHI to visualize 2D temperature field. The position and development of large coherent structures, which puff from the orifice, is evident. It must be noted that in 2D cases, DHI integrates the phase change along the entire path of the rays going through the measured area (through the *y* axes), and the results must be presented as the average temperature in the *y* direction. The Abel transformation could be used to partially solve this problem. More sufficient is the application of a tomographic approach [6].

4 Conclusion

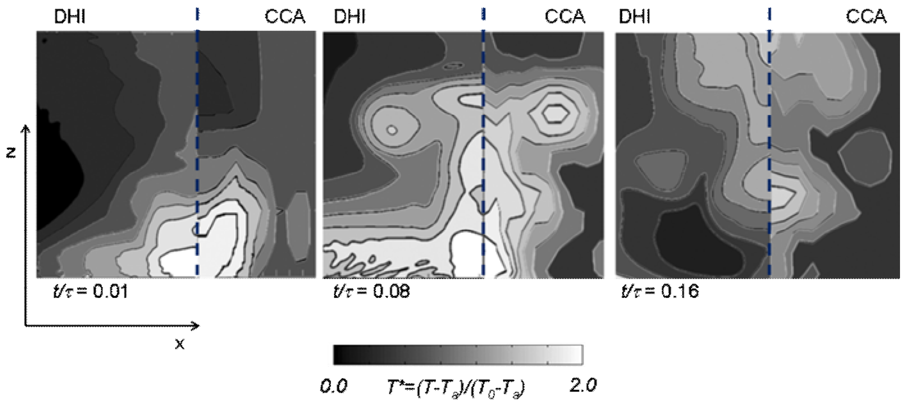

Fig.4. Temperature field above the jet. Images at different t/τ achieved by digital holographic interferometry and CCA. The development of the jet is clearly visible from figures. Results from DHI represents average temperature field in y direction. Results from CCA are achieved at y = 0.

Digital holographic interferometry is very sensitive to noise and needs a sophisticated procedure and software to evaluate the results. Also the usually not high enough framerate of the cameras could be limiting in many applications. Both of the problems are addressed by the presented method. Well synchronized camera capture time with the phase of observed phenomenon is the key in coherent phenomenon measurement. Such wisely done synchronization brings the benefit of fast developing phenomenon measurement (some frames might be skipped between the exposures of the camera). The series of the images having the same phase (meant in time of the phenomenon development) could be captured and later averaged. The presented results show strength of the implementation of phase averaging to DHI. The third great benefit of the method not researched in this paper is the possibility of obtaining the data suitable for topographic reconstruction.

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