Holografic Interferometry used for Measurement of Temperature Field in Fluid

Vít Lédl, Tomáš Vít, Pavel Psota and Roman Doleček

Abstract—The presented paper shows the possibility of using holographic interferometry for measurement of temperature field in moving fluids. There are a few methods for identification of velocity fields in fluids, such us LDA, PIV, hot wire anemometry. It is very difficult to measure the temperature field in moving fluids. One of the often used methods is Constant Current Anemometry (CCA), which is a point temperature measurement method. Data are possibly acquired at frequencies up to 1000Hz. This frequency should be limiting factor for using of CCA in fluid when fast change of temperature occurs. This shortcoming of CCA measurements should be overcome by using of optical methods such as 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 also presented. The results from the holographic interferometry experiments will be compared with the temperature field achieved by methods CCA method.

Keywords—Holographic interferometry, pulsatile flow, temperature measurement, hot-wire anemometry

I. INTRODUCTION

THE well-known benefit of holographic interferometry is the differential character of the method, which means that imperfections in the beam paths do not influence the shape of the interference phase field. The main advantage of digital holographic interferometry (DHI) is its direct retrieval of the interference phase from the digital hologram [1]. 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.

$$\varphi_1(m,n) = \arctan\frac{\mathrm{Im}(h_1(m,n))}{\mathrm{Re}(h_1(m,n))}, \quad \varphi_2(m,n) = \arctan\frac{\mathrm{Im}(h_2(m,n))}{\mathrm{Re}(h_2(m,n))} \quad (1)$$

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For measurement of properties of a synthetic jet, DHI is very suitable, as it shows the temperature distribution in the area of interest. 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.
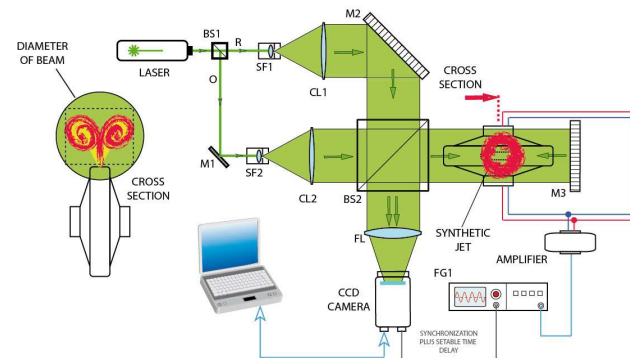

Fig. 1 setup for double sensitivity digital holographic interferometry (BS-beam splitter, SF-spatial filter, H -hologram, CL - collimating objective, M – mirror, FL-focusing lens, R-reference beam, O-object beam)

Previous experiments [2, 3] showed the usefulness of an interferometric setup based on a Twymann-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). There are many conditions that must be satisfied or else the functioning of the proposed setup is not feasible. Another problem is the frequency of the phenomenon. In our case of the frequency of the synthetic jet was 15 Hz. Because we required the high resolution in the measured area we were forced to use a 5Mpix camera cropped to 2048 x 2048 pixels. Those cameras are still quite slow. The maximum frame rate of AVT Stingray camera in this resolution is approximately 6 FPS. To have a good temporal resolution we would need at least 300 FPS for the 15 Hz frequency. In the periodic behavior of the synthetic jet operation we could presume the phenomenon as a quite coherent. Because of this presumption we could synchronize the camera capture with the certain chosen time within a period (we could make the capture in certain phase). As the frame rate of the camera is much slower than the frequency of the phenomenon it was necessary to ensure that the camera wait till the buffer is empty before

another capture is taken. The used camera does this automatically.

A 150-mW laser beam (Nd3+:YAG) is divided by a polarizing beam splitter BS1 equipped with λ/2 plates. After dividing, both beams are filtered by spatial filters SF and then collimated by collimating lenses CL. Apertures placed in front of the collimating objective ensure a final beam diameter of 50 mm. After collimation, beam O enters beam splitter BS2. One part of the beam is reflected by the beam splitter while the second part travels through the measured
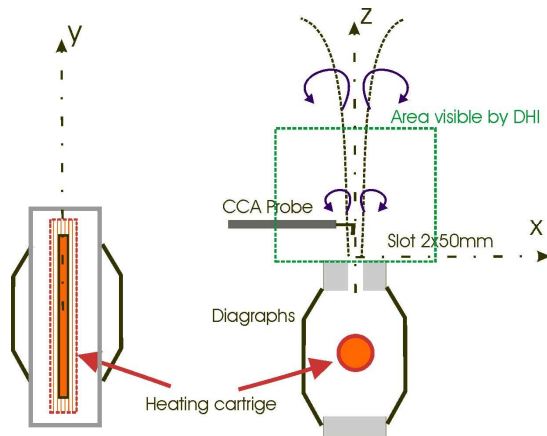

Fig. 2 A experimental device, system of coordinates and main dimensions for hot-wire anemometry and holographic interferometry

object and perpendicularly impinges on mirror M2, where it is reflected and goes through the measured object once more. This is the reason why the interferometer has double sensitivity. Then once again in beam splitter BS2 part of the light is reflected towards the CCD camera and the second part continues in the direction of collimating objective CL2. Beam tagged by R (the reference one) after collimation is reflected by mirror M2 towards the CCD camera and goes through beam splitter BS2; both beams impinge the CCD sensor from slightly different directions. The camera and the synthetic jet are synchronized. There is the possibility to set up the time delay of the capture relatively to zero. The wise selection of the delay time helps to distribute the samples equally over the whole period. 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.Our main concern in measuring the synthetic jet 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, which is a property 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 1 Kelvin [11].

II. EXPERIMENTAL SETUP

A. Synthetic Jets

Synthetic Jets [4] are jets of fluid that are generated by pushing or pulling a fluid through an orifice by the interactions within the train of counter-rotating vortex pairs (in the presented 2D case).
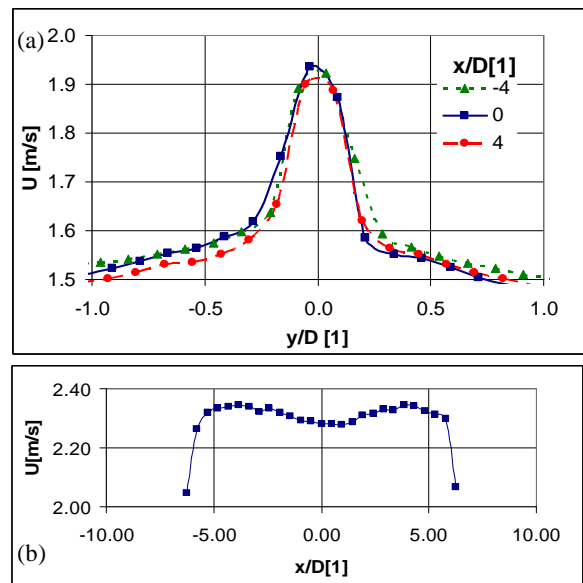

Fig. 3 Mean velocity in x (a) and y (b) direction. The velocity is acquired at z/D=1.2 (a) and z/D=8.5 (b). Mean velocity at z/D =1.2 seems to be smaller due to occurrence of the suction

These vortex pairs move with a velocity U that must be high enough to prevent interaction with suction in the orifice. Vortex pairs develop and dissipate and the SJ has the character of a free jet when it is far enough from the end of the orifice (see Fig.2). The time-mean mass flux of the flow in the orifice is zero, and so these devices are often called zero-net-mass-flux jets. Though the nozzle works with zero-net-mass flux, the momentum in the z-direction is non-zero. Synthetic jets have many promising applications such as control of primary flows [5] and are a valuable alternative for cooling/heating applications [6, 7].Based on the papers [8, 9], the oscillating character of the so-called synthetic impinging jet (SIJ) is used to enhance the heat transfer process. The SIJ combines the advantages of impinging jets and zero-net-mass-flux (synthetic) jets: the impinging jets achieve a high heat/mass transfer onto the exposed walls and the synthetic jets are generated by
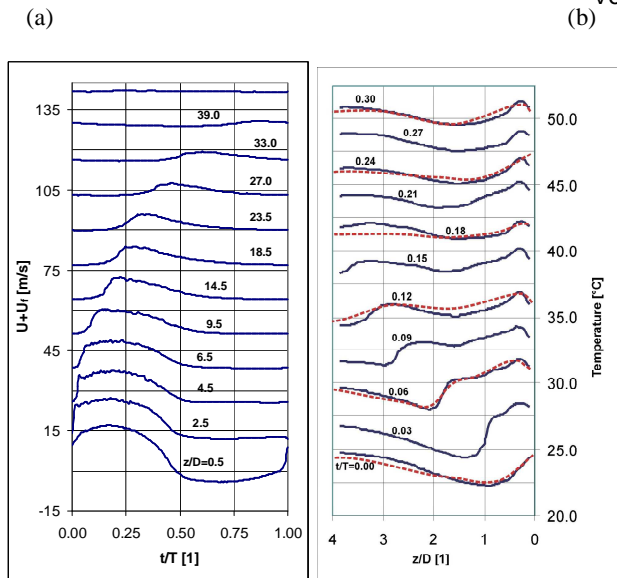
(a)   (b)

Fig. 4 Example of development of velocity in z direction in time (a). At z/D over 40 the jet has a character of continuous jet. Comparison of temperatures achieved by holography interferemetry (solid lines) and hot wire anemometry in CCA mode (doted lines) at y/D=0 (b). The results from DHI show the average temperature within the slot length. The HWA results are achieved at x/D=0.

relatively simple actuators – neither blowers nor fluid supply piping are needed. It is worth noting here that the oscillations cannot enhance impingement heat/mass transfer automatically; the effect can be sometimes increasing or sometimes decreasing (or negligible) – e.g. [10]. For a better understanding of the process, the temperature of the jet must be precisely measured.

B. Hot wire anemometry experiments

Figure 2(a) shows a schematic view of the actuator cavity and the configuration tested in this study. The actuator consists of a cavity which is equipped with an emitting slot (length L was equal to 50mm; width s was equal to 2.0 mm; corresponding characteristic diameter D was equal to 4 mm) and a pair of electrodynamically actuating diaphragms running in opposite directions (diameter DD 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. The temperature of the cartridge heater (T_c) has varied between 50-200°C and controlled by a connected PID regulator during experiments. The uncertainty of the set temperature of the wall was less than 0.2°C. Results for T_c=50°C are presented in this paper to show the sensitivity of the DHI method. The input power of the loudspeakers was set to 4W, the frequency of the oscillations was set to f = 1/T = 15Hz.

The velocity field and the temperature field in the vicinity of slot were measured by a Dantec Stream Line system with two CTA modules and one CCA module. The temperature

field was simultaneously measured with holographic interferometry. Dantec 55P14 90°-wire probe operating in constant temperature mode was used to measure velocity magnitude; a

Dantec 55P31 resistance thermometer, 1 micron wire, operating in constant current mode was used to measure temperature. The sampling frequency and number of samples were 1 kHz and 4096, respectively.

The phase averaging of the velocity, temperature and heat transfer coefficient during one cycle was carried out by means of a decomposition of the quantity. For example, in the case
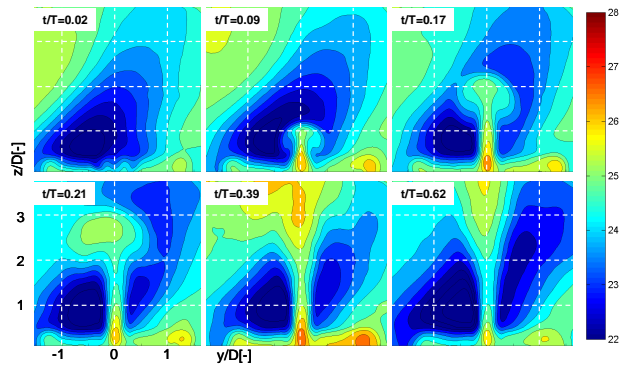

Fig. 5 Average temperature within the slot length. Snapshots at different t/T achieved by digital holographic interferometry. The development of the jet is clearly visible from figure

of the velocity decomposition, u = U + U_f + u', where U is the time-mean velocity, U_f is the periodic phase-locked component, and u' is the fluctuation component (represented by RMS velocity fluctuations). Taking into account the pulsating velocity character at the actuator orifice, positive (extrusion) and negative (suction) flow orientations were assumed and the velocities during the suction stroke were inverted to reflect the flow direction.

In order to determine the value of the temperature by CCA, the correction taking in the account the velocity has been carried out.

III. RESULTS

It is necessary to consider velocity and temperature field to be 2D in the x direction for correct measurements using the DHI. For this purpose, velocity profiles were measured in the x direction (y/D=0; z/D = 8.5) and in three sections in the y direction (x/D=-4, 0, 4; z/D=1.2). The results of the experiments are shown in Fig.3. The results show relatively good 2D character of velocity field. Deviation of velocity at y/D=0 and z/D = 8.5 is less then 2%.

Figure 4(a) illustrates the development of the fluid "puff" out of the actuator and the development of the cycle shape (which starts from being almost symmetrical in the orifice plane, z equal to 0). The figure also shows the increase of the phase shift of the maximum velocity during advection. The range of the actuator suction is approximately z/D equal to

2.5, further downstream only a positive orientation of the z velocity component exists during the actuation cycle. From this experiment the Reynolds number was established as Re≈1570.

Figure 4(b) shows the time development of the temperature measured by digital holographic interferometry (at y/D = 0). The results from CCA experiments (at y/D = 0 and x/D = 0) are shown for comparison

Figure 5 shows a temperature fields acquired by DHI. The pictures correspond to different time of the cycle t/T. The development of the 2D structure is clearly visible. It illustrates the development of the temperature field. The position and development of large coherent structures, which puff from the orifice, is evident.

IV. CONCLUSIONS

The presented paper compares two experimental methods: hot-wire anemometry and holographic interferometry from the point of view of measurement of an unsteady temperature field.

Digital holographic interferometry can record the whole (2D) temperature field at once with a frequency that is limited only by the parameters of the CCD camera used.

Unfortunately, the method integrates the phase change in the propagation direction of the ray on the entire path of the rays going through the measured area. This phenomenon can easily spoil the measurement as in each plane perpendicular to the direction of propagation the phase distribution can be different. Digital holographic interferometry is very sensitive to noise and needs a sophisticated procedure and software to evaluate the results. The presented results show possibility of implementing a phase averaging method into the evaluation software used. The next step it the development will be the full 3D digital holography. The needed algorithms are now the point of investigation. Hot-wire anemometry brings with it the possibility of simultaneous measurement of different quantities such as temperature and velocity or for example the heat transfer coefficient, or shear stress. The equipment is ready to acquire data with frequency of up to hundreds of kHz (kHz in the case of temperature measurement). However, two disadvantages are also evident: (1) The probe with its support disturbs the velocity and temperature field, (2) It needs correction when the temperature and velocity fields ale measured together and (3) It is necessary to traverse the probe at a number of points, which is time consuming and extremely demanding to sustain the equal conditions during the whole period of measurement.

ACKNOWLEDGMENT

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