SUBSONIC WAKE FLOWS ANALYSIS BY DIGITAL THREE-WAVELENGTHS HOLOGRAPHIC INTERFEROMETRY

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Abstract

In area of Fluids Mechanics, digital color holographic interferometry has been developed for analyzing unsteady wake flows. Based on Michelson interferometer, the optical setup uses three different lasers (red, green and blue lines) as luminous light source and it generates interferences micro fringes which are used as spatial carrier frequencies. One each channel, phase maps are computed for the reference and measurement interferograms respectively without flow and with flow. From phase difference maps, the evolution in time of instantaneous gas density field is obtained so that the mean flow deduced from instantaneous gas density maps covering one cycle of the vortex street. The case of the unsteady wake flow around a circular cylinder at Mach 0.45 is presented.

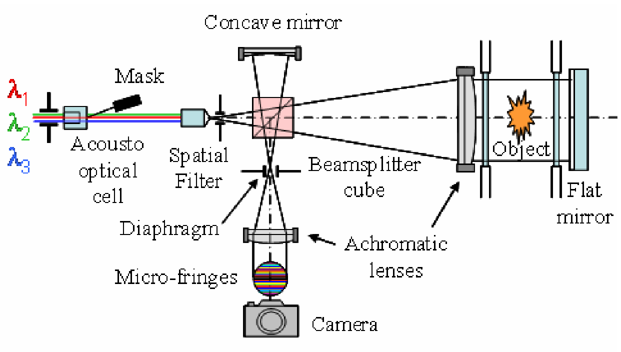
1 General Introduction

The fast development of technology, such as high resolution sensor, various DPSS lasers with a large coherence, data post processing and computation power give now opportunities to think and conceive new optical methods capable of simultaneous full field measurements with high spatial and temporal resolutions and giving absolute data. Digital holography with matrix sensor appeared in the last decade with cheap high resolution CCD or CMOS cameras and the increasing power of computers [1,2]. Image sensors have now size and spatial resolutions compatible with the needs for digital holographic recording. As regards to these considerations, ONERA and LAUM decided to join theirs respective skills acquired in the past in order to develop adaptable and new optical imaging methods, firstly having properties as full field imaging with high spatial and temporal resolutions, secondly giving absolute data after post processing and finally giving dynamic three dimensional measurements. These non-invasive optical methods are based on digital three wavelengths holographic interferometry [3] and theirs results can be directly compared to those obtained in color holographic interferometry using panchromatic plates [4]. An example is given here where the unsteady wake flow around a circular cylinder is analyzed at Mach 0.45. The frames recording is triggered from the phase of unsteady pressure signal of transducer implemented in the cylinder in order to cover one period of the vortex street. The maps of color interference fringes are deduced from red, green and blue phase difference maps. They are compared with those found by real-time color holographic interferometry using holographic plates. Finally, the interest by color using is shown as the variation in the background color due to the external disturbances can be quantified on every interferograms.

2 Application of digital color holographic interferometry to subsonic flows

2.1 Digital color holographic interferometer

Fig. 1 shows the optical setup implemented around the ONERA wind tunnel. Here, three different DPSS lasers having ten meters in coherence length are used as luminous light source. The assembly shown in Fig. 1 is very simple. It is like a conventional Michelson interferometer in which a beam splitter cube is inserted between the spatial filter and the test section. The spatial filter is placed at the focal point of the achromatic lens so that the test section is illuminated with a parallel light beam as in previous optical setups. 50% of the light is reflected from the concave spherical mirror to form the three reference beams and 50% of light passes through the test section to form the three measurement waves. The flat mirror placed just behind the test section returns the beams towards the beam splitter. 25% of light is focused on the diaphragm which is placed in front of the camera lens. So, 25% of the reference beam intensities are focused in the same diaphragm by the concave mirror. When the reference and measurement beams are strictly superimposed in the diaphragm, a uniform background color is obtained on the detector. When they are shifted in the diaphragm plane, interference fringes appear, and they will be used as spatial carrier frequencies before recording. This is achieved very simply by turning the concave mirror.



a) Digital optical bench

Fig. 1 Digital color holographic interferometer

2.2 Triggering and recording

As the framing rate is very slow compared to the frequency of the vortex street, a transducer has been implemented in the cylinder at an azimuth of 90° (perpendicular to the flow axis) in order to synchronize the interferograms recording with the signal of the unsteady pressure measurement. The cycle of the vortex street has been decomposed in eight different instants shifted by 76µs and at each instant, five interferograms have been recorded from several cycles to averaging the unsteady maps.

First, a micro-fringe image is recorded without the flow in order to constitute reference interferogram. Then, the wind tunnel is running and several interferograms are recorded at a phase of the unsteady pressure of the vortex street. Two micro fringes images recorded with and without the flow constitute reference and object interferograms.

The three Fourier transforms are calculated from each image in order to reconstruct the phase maps. An example of reference and measurement spectra is given in Fig. 2 for the green line. One can see that the spectrum only exhibits a spot representative to the green spatial carrier frequency. No parasitic frequencies due to the blue and red lines are found.

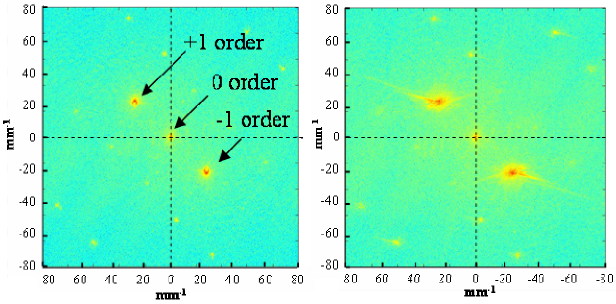


Fig. 2 Reference and object spectra

In obtain the phase maps, we have to filter Fourier spectra and to reconstruct the phase maps with the first order of hologram. One can note that the filtering window applied to Fourier spectra can be different for the reference and the measurement spectra. Then, the wrapped phase maps are obtained for the reference and measurement interferograms.

By subtracting the reference phase maps to the measurement phase maps on then three lines, the modulo2π phase difference maps are obtained. An example is given in Figure 3 for the red line. After unwrapping, the refractive index maps and the gas density field are computed assuming the Gladstone-Dale relation.

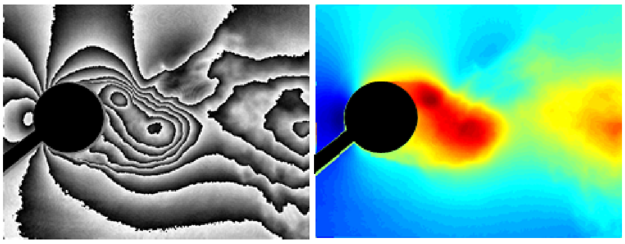


Fig.3 Wrapped and unwrapped phase difference maps

2.3 Results obtained at Mach 0.45

Knowing the phase difference $\Delta\phi$ and the wavelength λ, the optical path difference δ can be achieved according the relationship:

$$\delta = \frac{\lambda.\Delta\phi}{4\pi} \qquad (1)$$

As the optical system is with a double crossing of the test section, the optical path difference of the phenomenon is divided by a factor 2. If *e* is the width of the test section, the refractive index is deduced from the following relationship :

$$n-1 = \frac{\delta}{e} \qquad (2)$$

Finally, the Gladstone-Dale relationship allows to extract the gas density field :

$$\frac{\rho}{\rho_s} = \frac{\delta}{K.e} \qquad (3)$$

where ρ_s is the gas density under standard conditions (1 atmosphere, 273K) and K the Gladstone-Dale constant (296.10^{-6}).

Gas density field are shown in Fig. 4 for the first six images of one cycle of the vortex street. Here, ρ_{io} is the stagnation gas density and one can see that the time evolution of the gas density fields shows that the gas density decreases to 73% of ρ_{io} in the vortex core. By averaging the unsteady gas density fields covering one cycle of the vortex street, the averaged field can be obtained

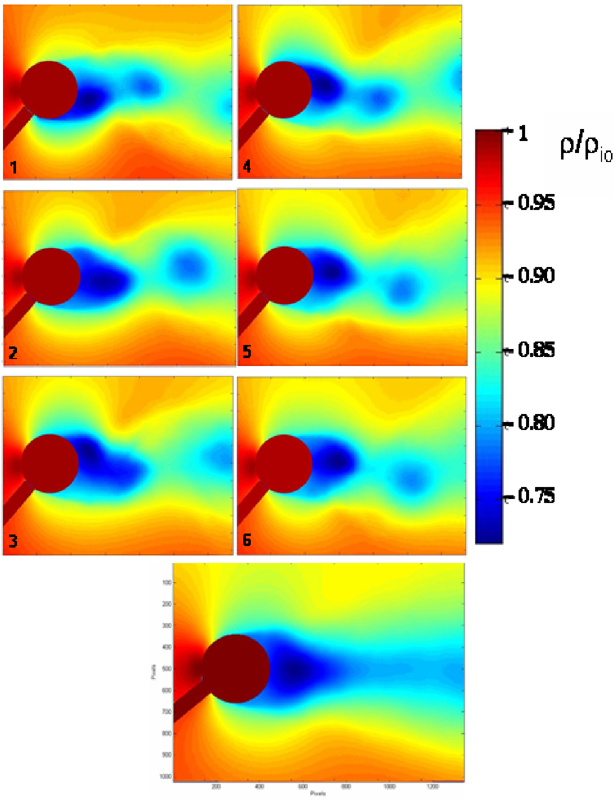


Fig.4 Evolution of instantaneous and averaged gas density fields – Δt = 87 µs

2.4 Comparison with image interferogram

If a comparison has to be made between an interferogram recorded with real-time holographic technique using holographic plate and digital hologram, the intensity of the interference fringes has to be computed on the three channels R, G, B from the phase maps according to the following relationship :

$$I_\lambda = A_\lambda.\cos(\Delta\phi_\lambda) \qquad (4)$$

As regards previous results obtained, silver-halide plate and digital holographic interferometry can be compared. Indeed, the technique of holographic interferometry in real time using panchromatic plates directly displays the color density variations of the flow. It's a light intensity information that is obtained. With digital holography, the three monochromatic intensity maps are superimposed to obtain a color map of the intensity of the interference fringes (Fig. 5).

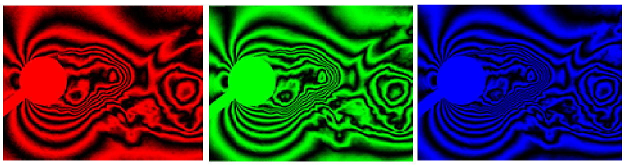


Fig.5 Intensity of interference fringes on each channel

This map can then be compared to that obtained using the reflection holographic plates. After locating an interferogram recorded at a phase very similar to that of digital interferogram, Fig. 6 shows that the correspondence is very good.

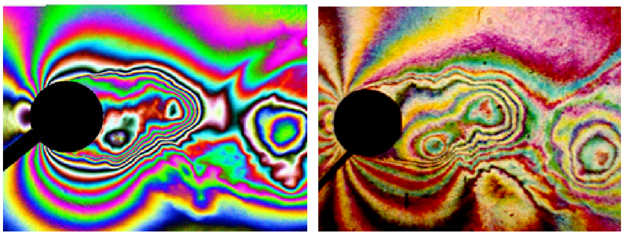


Fig. 6. Comparison between image and digital interferogram

So and in practical point of view, in image color holographic interferometry, a reflection panchromatic holographic plate (7,000 to 10,000 lines per mm in spatial resolution) has to be illuminated with a total energy of 600 µJ and the resetting of holographic plate is very sensitive and delicate. In digital technique, energy of 1µJ is sufficient to illuminate the sensor (155 lines per mm in resolution). The implementation is easy enough and the phase difference is entirely estimated with a computer. The coherence lengths of the three lasers must be more 2 meters in the two optical setups. In image holographic interferometry, about 220 successive frames of the phenomenon can be recorded at high framing rate (35,000 images per second with an exposure time of 750 ns for each). Each image has to be digitalized and processed. Also, it is important to obtain a reference hologram of about 50% diffraction efficiency for the three lines. In digital holographic interferometry, the framing rate is limited to 9 frames per second, full size and a synchronized triggering of interferograms recording has to be used to analyze unsteady phenomena.

2.4 Interest in color

The gas density measured to the cylinder nose is particular as the gas density is equal to the stagnation gas density though the position of the vortex street, that means the color found at this point has to be the same on each interferogram.

Here, the intensity of color interferences fringes is computed by imposing the white color ($\delta = 0$ µm) on each interferogram. Note this shifting is only made possible by the use of color in the experiments. Fig. 7 exhibits the evolution of interference fringes of the first six images shown in Fig. 4 and covering one cycle of the vortex street.

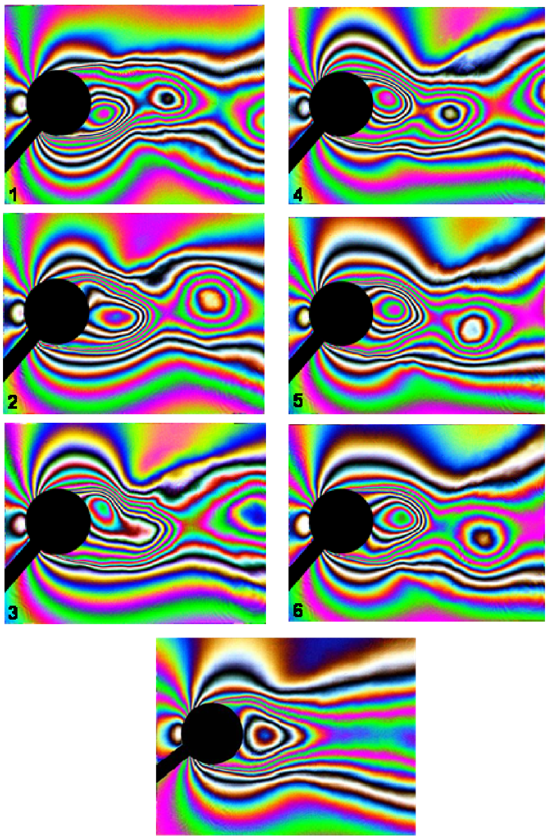


Fig. 7 *Evolution of instantaneous and averaged interference fringes – $\Delta t = 87$ µs*

3 Conclusion

The possibilities of image and digital color holographic interferometry have been demonstrated. Color holographic interferometry using panchromatic plates will continue to be used due to the high resolution of holographic plates. In near future, digital three-wavelength holographic interferometry seems the best candidate to characterize the future complex flows. Although CCD resolution and size are not as good as that of holographic plates, the digital approach is more accessible and versatile since the time for the hologram processing is greatly reduced and the processing is purely numerical. On the other hand, the value of using color has been demonstrated as the zero order fringe can be easily determined and the variation in the background color due to disturbances can be quantified. The limitations of the digital method seem to lie in the wide spectral sensitivity of the sensor which produces light diffusion in each monochromatic hologram. Work is currently in progress for removing the color diffusion using a segmentation approach. Success in this strategy will allow increasing the spatial resolution in the reconstructed object. Future work will focus on the extension of the proposed technique for analyzing 3D unsteady wake flows. At present, a specific setup of digital holographic interferometry has been defined in a single sight direction, and the aim will be to reproduce the same optical setup along several sight directions, each shifted by a given angle. It is obvious that the optical setup can be reproduced no more than three or four times. But the lack of sight directions should be compensated by high tomographic interferogram resolution for the reconstruction of the 3D gas density field.

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