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RECENT IMPROVEMENTS IN COLOR INTERFEROMETRY

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Abstract

At the Lille center of the ONERA the fine characterization of complex flows has been a specificity known for more than twenty year, starting with an existing system, developing an optical method based on differential interferometry using Wollaston prism and a white polarized light source. A new schlieren interferometer has been build to analyze the unsteady flows and a lot of studies have been conducted where the unsteady pressure measurements have been simultaneously recorded with high speed visualizations. Several applications are presented in two-dimensional and axisymmetric flows and in a gaseous mixture where the two gases interface is submitted to acceleration. Another application concerns the evaluation of the skin friction coefficient from the color interference fringes obtained under white light by a fin oil film on a flat plate. Moreover, the quasi-automatic exploitation of color interferograms is based on the modeling of interference fringes versus the optical path difference, so that each pixel can be replaced by a value of refractive index. Finally, as differential interferometry produces the first derivative of the refractive index, real-time color holographic interferometry (RCHI) has been developed to obtain the refractive index itself. In this technique, the light source is made of three wavelengths (one red, one green and one blue) from a mixed gas (argon and krypton) laser. High resolution panchromatic holograms are recorded by transmission. The method has been successfully applied in the ONERA wind tunnel to analyze the two dimensional wake flow around a circular cylinder at Mach 0.4. High speed interferograms of the unsteady flow have been obtained at a framing rate of 35,000 frames per second with an exposure time of 750 nanosecond per frame. As recent improvements, one proposes to extend this method for the analysis of the three dimensional flows. In order to make that, the specific setup has been defined in a single sight direction, the aim being to reproduce the same optical setup along several sight directions, each shifted by a given angle. Contrary to the optical setup developed for the analysis of 2D flows, in the one proposed for 3D flows, reflection holograms are used. In the case of reflection holograms, the diffraction efficiency of plates is strongly influenced by the variations in the gelatin thickness produced during the holograms treatment. Solutions are proposed to control the gelatin shrinkage and tests are presented for two different types of holograms: Russian plates (Slavich) and French plates (Gentet). Finally, high speed interferograms obtained in a one sight direction are presented.

Keyword: *High speed interferometry, color holography, panchromatic hologram, unsteady flow*

1. Introduction

The ONERA-Lille center spends a great deal to develop quantitative and non intrusive optical methods which allow to instantaneously record a property on the flow in a large field. For the observation of high speed unsteady 2D or axisymmetric flows, different techniques have already been developed such as high speed schlieren or shadowgraph. Through them one can reach not only qualitative but also quantitative information such as propagation velocity of shock waves or vortical structures. But previous methods do not work when quantitative information is required about the gas density field. In this case interferometry be used. The problem of the analysis of monochromatic light interferograms lies in the identification of the fringes and their shift across flow discontinuities. When the density gradients are relatively weak the differential interferometry in polarized light is very well adapted. It produces colored interferograms, the analysis of which yields the density field after calibration of the whole set-up [1]. A first extension of this technique was made to the high speed visualization of varying flows and some applications are presented in two-dimensional and axisymmetric flows, in hypersonic flows and in a gaseous mixture [2],[3] and [4]. Moreover, another application concerns the evaluation of the skin friction coefficient from the color interference fringes obtained under white light by a fin oil film on a flat plate [5]. Finally, as differential interferometry produces the first derivative of the refractive index, real-time color holographic interferometry (RCHI) has been developed to obtain the refractive index itself [6]. In this technique, the light source is made of three wavelengths (one red, one green and one blue) from a mixed gas (argon and krypton) laser. High resolution panchromatic holograms are recorded by transmission. The method has been successfully applied in the ONERA wind tunnel to analyze the two dimensional wake flow around a circular cylinder at Mach 0.4. Currently, our work aims at extending this method for the analysis of the three dimensional flows. In order to make that, the specific setup has been defined in a single sight direction, the aim being to reproduce the same optical setup along several sight directions, each shifted by a given angle. Contrary to the optical setup developed for the analysis of 2D flows, in the one proposed for 3D flows, reflection holograms are used and the diffraction efficiency of plates is strongly influenced by the variations in the gelatin thickness due to the holograms treatment.

2. Application of color interferometry to two-dimensional unsteady flows

The new optical set up is based on differential interferometry in polarized white light using one or two Wollaston prism and the principle is discuss in details by Desse [2]. In this example, the unsteady wake flow is analyzed around a circular cylinder 20 mm in diameter placed across the test section of ONERA's transonic tunnel. The two dimensional test section is 200 mm high and 42 mm wide. The cylinder is equipped with an unsteady pressure sensor. Tests are made for one value of the Mach number: 0.4. The camera used is a Dynafax model Cordin 350; its recording speed can vary from 200 to 35.000 frames per second. The maximum number of frames is 224 and the size of each recording is 10x8 mm², the pictures being taken on a 35 mm film. In this study, the exposure time is 1.5 µs and the time interval between two successive interferograms is 50 µs. Fig.1 shows some couple of high speed interferograms synchronized with the unsteady pressure recorded on the model and visualizing vertical and horizontal gradients.

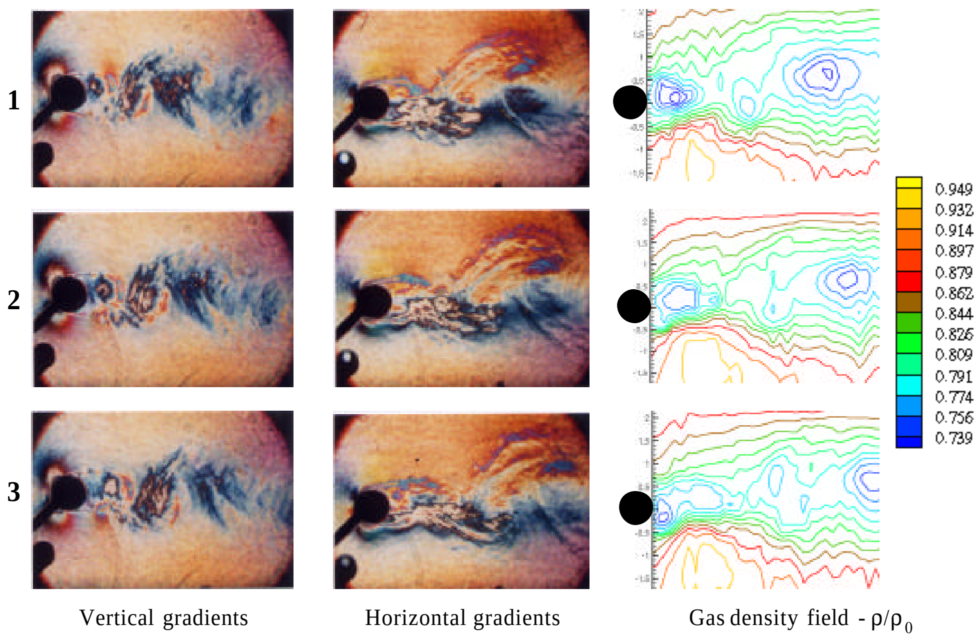


Fig.1. High speed interferograms and analysis – Δt = 50 µs

The analysis of the interferograms is conducted through the numerical model using, on the one hand, the spectrum of the light source located just behind the interferometer and, on the other hand, the filters of the video camera which is used to record the interference fringes from the interferometer. From the optical interference laws, the light intensity of the interference fringes can be computed versus the optical path difference. The experimental tint scale of the interferometer can be compared to the numerically calculated tints with the help of a color image processing board. As the test section width is known, the local refractive index can be obtained, which, according to the Gladstone-Dale relation, finally leads to the local gas density, provided a reference value is known on each line. The analysis of several interferograms showing horizontal gradients has allowed to reconstruct the gas density field and to obtain its evolution in time. The corresponding reconstruction of the gas density fields $\rho/\rho o$ analyzed just downstream of the cylinder is also given in Fig. 1, where ρ_o is the stagnation gas density. The gas density field shows the vortices as quasi-concentric rings where the gas density decreases towards the center. The ratio of the gas density decreases by about 20% in the middle of the first vortices. After, the vortices pass through a phase of dissipation where the gas density and the size of the vortex increase.

3. Application of color interferometry to axisymmetric wake flows

The structure of a hot supersonic hot jet at Mach 1.8 injected into a coaxial supersonic flow at Mach 1.5 has been analyzed by differential interferometry because it is a non-intrusive technique particularly well suited to investigation of phenomena related to compressibility and high temperatures [3]. The unsteady character of the flow is taken into account by adapting the exposure time of the recordings to some characteristic time scale. The method is sufficiently sensitive to be able to make a quantitative analysis to reconstruct the local density field. This operation is possible from a single interferogram provided the flow is two-dimensional or axisymmetric. The interferograms recorded were analyzed assuming that the structure was axisymmetric.

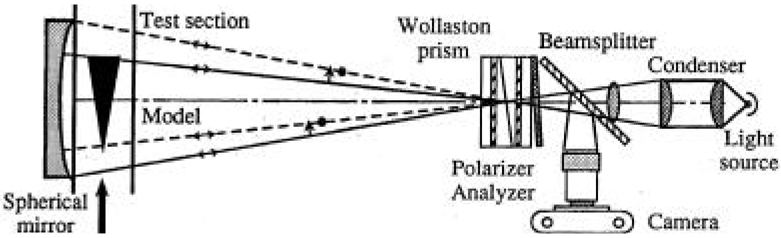
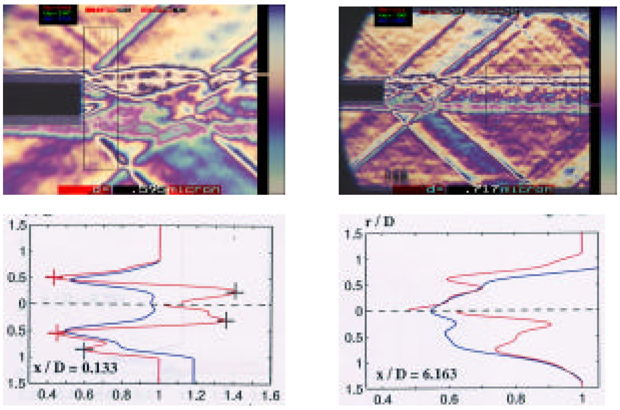


Fig.2. Experimental set up modified for axisymmetric flows

Fig. 2 shows the optical setup modified to analyzed the axisymmetric flow. The two waves issued from the Wollaston prism (4° pasting angle) cross the test section and are returned by a spherical mirror at the same location in the Wollaston prism. A beam splitter inserted in the optical axis returns the rays on the photographic camera. The technique was extended to the analysis of rapidly varying phenomena by substituting a flash source for the initial continuous light source. In our case, the fluid velocity in the jet was around 685 m/s. The interferogram exposure time therefore had to be very short. The exposure time of the flash source used, equal to 0.3 µs, corresponds to a fluid displacement of around 0.2 mm.



Axisymmetric Non-axisymmetric

Fig.3. Radial distribution of the gas density

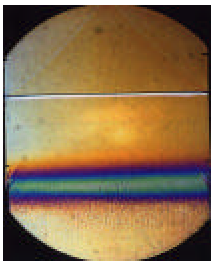
Fig. 3 shows two interferograms recorded for two different pressure ratios of 2.74 and 3.38 at the same temperature ratio of 1.67. The radial density distribution was determined by spectrum analysis of the colors in the upper and lower half-planes. If the flow is strictly axisymmetric, the two profiles should be identical. In Fig. 3 and for the axisymmetric case, the profiles of the optical thickness (blue line) and the gas density (red line) obtained near the nozzle exit section are relatively symmetric about the flow axis. In the non-axisymmetric case, the analysis made far downstream provides relatively contrasted density profiles which reflect the presence of local turbulences in the flow. Finally, the density profiles measured in the jet were superimposed on the flow image. They showed that, close to the jet exit, the density minima were always positioned on the boundary between the potential cone and the reflected shock wave while, further downstream, they are on the boundary separating the internal and external parts of the jet. This structure was observed in all the cases and indirectly validates the analysis method.

4. Application of color interferometry to the gaseous mixture

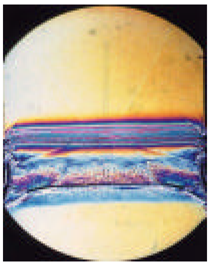
Differential interferometry has also been used to analyze the stability of the interface separating two fluids of highly different densities when it is impacted by an incoming shock wave. Tests were made at the Commissariat à l'Energie Atomique. For that, a shock tube has been built to visualize the evolution of these diffuse interfaces, the light gas being above the heavy one. The shock tube is vertical in order to keep the interface stable before the arrival of the shock wave. Several diagnostic techniques have been used: X-ray densitometry and differential interferometry. Concerning the X-ray technique, one can obtain the partial gas density profile of one of two gases from a careful calibration if the gases pair is air/xenon. In the case of SF6/air, both gases are transparent to X-rays and the radiography can not be used. Only differential interferometry can yield a measurement of SF6 repartition in air.

The optical setup requires two Wollaston prisms installed head to foot and two "Clairaut" achromatic lenses, 800 mm in focal length and 120 mm in diameter. The Wollaston prisms are pasted with an angle of 0.5°, which generates a shifting of 0.157 mm between the two interfering rays. The second lens near the high speed camera is located so that the middle of the test section is at its focus. So, if the camera objective is focused for infinity, the interference fringes and the test section central plane are focused on the film.

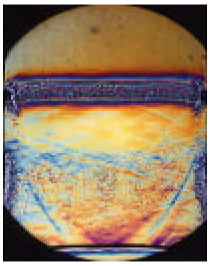
In the case of two gases mixture, the Gladstone-Dale relation can be extended if the Gladstone-Dale constants of each gas are known. Then, the analysis of interferogram yields the partial density profile of one of two gases across the interface. Fig. 4 shows three interferograms recorded at different times. In interferogram (a), the shock wave has already crossed the interface, has reflected from the tube end wall and is about to again impact on the modified interface. Picture (b) has been taken shortly after this second impact and the wave is seen to have been partly transmitted into SF6 and partly reflected into air. On picture (c) the transmitted wave can be seen close to the bottom of the picture while the reflected part has again reflected from the end wall and is about to impact on the interface. The SF6 partial density profiles have been obtained through the interface by averaging a dozen of interferograms. For the xenon/air gases pair, xenon partial density profiles have been compared to those obtained with the X-ray technique. The two techniques yield very similar results.



a) t = 1080 µs



b) t = 1340 µs



c) t = 1698 µs

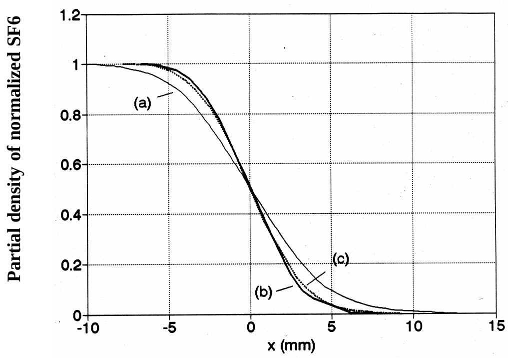


Fig. 4. Gas density profiles of SF6 - Interface: SF6 – Air , Ms = 1 .45

5. Real-time Color Holographic Interferometry (RCHI)

5.1 Application to 2D flows

Our latest work has thus led us to develop true color real-time holographic interferometry which combines the advantages of differential interferometry with those of monochromatic holographic interferometry. With this, not only small path differences but also large ones can be measured because the interference fringe diagram obtained is very broad and well-contrasted. Also, as opposed to monochromatic holographic interferometry that can provide only relative data, color holographic interferometry generates the achromatic fringe and also provides absolute data throughout the entire field of observation and its feasibility has been demonstrated in the Franco-German Saint-Louis research institute [6].

The optical setup shown in Fig.5 has been implemented around ONERA's wind tunnel at the Lille center. For reference, this wind tunnel is equipped with a 2D test section 200 mm high and 42 mm across. The flow studied was the unsteady flow downstream of a cylinder of diameter D = 20 mm placed crosswise in the test section. An argon and krypton mixed gas laser emits the ten lines in the visible simultaneously. The beam power as it leaves the laser is 1.20 W when the Fabry Perot etalon is tilted. The red, green, and blue lines we want are diffracted by an acousto-optic cell (FA) and the three patterns that are generated by three appropriate frequencies. Beam splitter cube (S) splits the reference beams and three measurement beams. The three reference beams pass over the test section, and they are expanded by a microscope objective lens and an achromatic lens (FS) then, an achromatic lens is used to illuminate the hologram with a parallel light beam of 60 mm in diameter. The three measurement beams are collimated the same way to form three parallel light beams between the two achromatic lenses (LA) and cross the test section. Hologram (H) is thus illuminated on the same side by the three parallel reference beams and the three convergent measurement waves. A diaphragm is placed in the focal plane just in front of the camera in order to filter out any parasitic interference. That is, the hologram is first illuminated in the absence of flow (2s) and is then developed and placed back in exactly its original position.

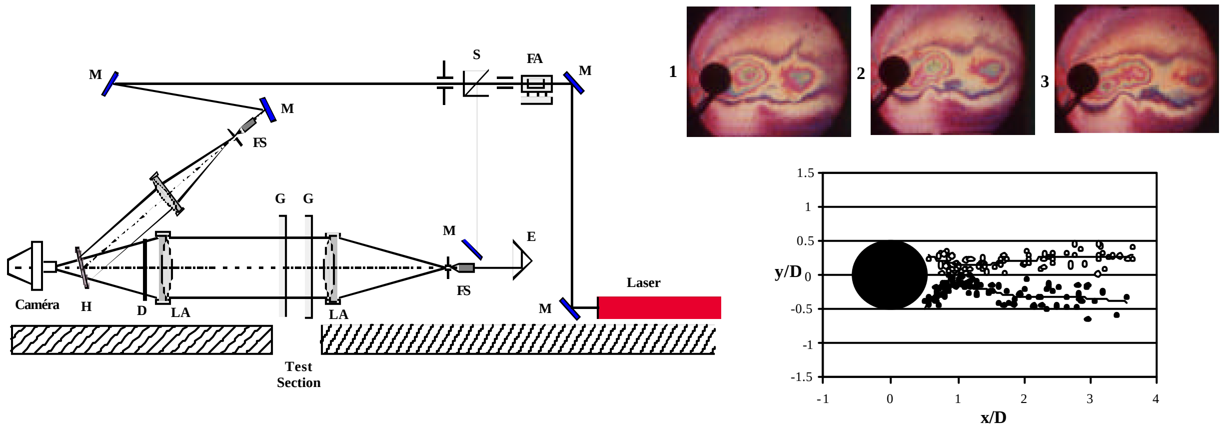


Fig. 5. Interferograms and results obtained with real-time color holographic interferometry setup

The holograms are then subjected to treatments to harden the gelatin, develop it, and bleach it. When the hologram is put back in place, the light power at the camera entrance is $1.5.10^{-3}$ Watt at the focal point, which is sufficient to record interferograms at an ultra-high rate of 35,000 frames per second with an exposure time of 750 nanoseconds per shot. Fig. 5 gives three successive interferograms shifted by 100µs of the flow around the cylinder at Mach 0.37. The vortex formation and dissipation phases can be seen very clearly, along with the fringe beat to either side of the cylinder. Several types of measurements were made by analyzing a sequence of some 100 interferograms. First, the vortex center defined by the center of the concentric rings was located in space for each interferogram, which made it possible to determine the mean paths for the vortices issuing from the upper and lower surfaces (fig.5). The "o" symbols represent the positions of the vortex centers from the upper surface, and the "•" symbols those of the lower surface. Remarkably, the two paths exhibit a horizontal symmetry about the x = 0 axis passing through the cylinder center. We may also point out that even at x/D = 4 downstream of the cylinder, the upper and lower vortex paths do not come together and line up. The gas density at the center of the vortices has been also measured in order to see how ρ/ρ_0 varies for the vortices emanating from the upper and lower surfaces. The trend curves plotted show the same variations.

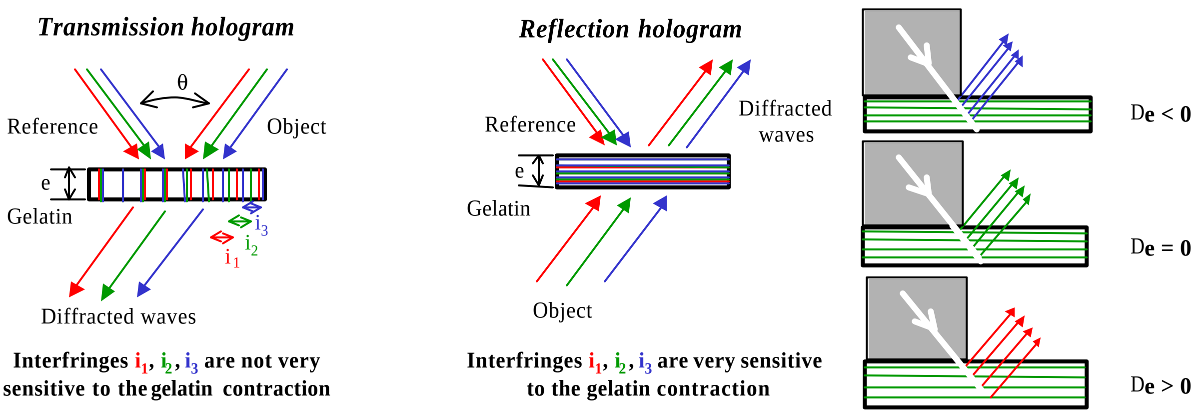
5.2 Application to 3D flows

Currently, our last work concerns the definition of real-time color holographic interferometry setup for analyzing the unsteady 3D flows. It is based on several crossings of the flow following different view angles. As the optical differences to measure are smaller in 3D flows than in the 2D case, it is preferable that each optical ray crosses the phenomena twice in order to increase the sensitivity. To simplify the setup, all the optical pieces are located on the same side of the wind tunnel, except the flat mirror which reflects the light rays back into the test section. Because of these considerations, the holograms will be reflection, not transmission holograms. In Fig.6, one can see how are the interference fringes inscribed into the gelatin thickness when the holographic image is recorded by transmission and reflection. In transmission, the interference fringes are put down perpendicular to the plate and a small variation in the gelatin thickness caused by the chemical treatment of the hologram does not modify the three inter fringe distances. On the other hand, in reflection, the interference fringes are recorded parallel to the plate surface and the inter fringe distance is very sensitive to a small variation of the gelatin thickness.

Fig. 6 presents the effects of the gelatin contraction when reflection holograms are recorded with a green wavelength. At restitution, a white light source (xenon source) illuminates three different holograms at the incidence that the reference wave had at recording. One can see that if the gelatin thickness is kept constant ($\Delta e=0$), the hologram only diffracts the wavelength of the recording, i.e. for the green hologram, the green wavelength contained in the xenon spectrum. If the gelatin thickness has decreased by 5% ($\Delta e<0$), the fringe spacing will be proportionally reduced and the diffracted wavelength will correspond to a blue line.

On the contrary, if the gelatin thickness increases by 20% (Δe>0), the hologram restituted in white light will diffract a wavelength close to red. For the diffracted color change not to be detected by a human eye, it is mandatory that the gelatin thickness be controlled with an accuracy of less than 0.2%. For the Agfa plates, typically 10 µm thick, this means changes in thickness of less than 20 nm. As the optical technique is based of the knowledge of the true colors diffracted by the hologram, variations of the gelatin thickness are a cause for strong errors in the data analysis. This gelatin shrinkage problem is crucial and has to be perfectly mastered.

Fig. 6. Problems raised by the gelatine contraction on the different waves



Now, ONERA is working on a setup to simultaneously record reflection holograms with the red, green and blue wavelengths and to restitute the holograms with a xenon light source, with the aims to first solve the problem of controlling the holographic plate gelatin. Two types of holograms have been tested: Russian plates from Slavich and French plates from Gentet. Concerning the first ones, a specific treatment proposed by Bjelkhagen [7] has allowed obtaining a gelatin contraction smaller than 20nm by mixing 2ml of glycerol in the last bath of ethanol (100% ethanol drying). We can mention that the treatment applied to the Russian plates includes about ten steps and it is very sensitive to the temperature and the PH solutions. About the French plates, we have also obtained basically no variation in the gelatin thickness by drying @50°C in oven before the exposition. The treatment of these plates is very easy because only two baths are used: developer and bleaching and the products are no carcinogenic. Fig. 7 shows the spectrum diffracted by Gentet plates when they are illuminated in white light and some interferograms obtained.

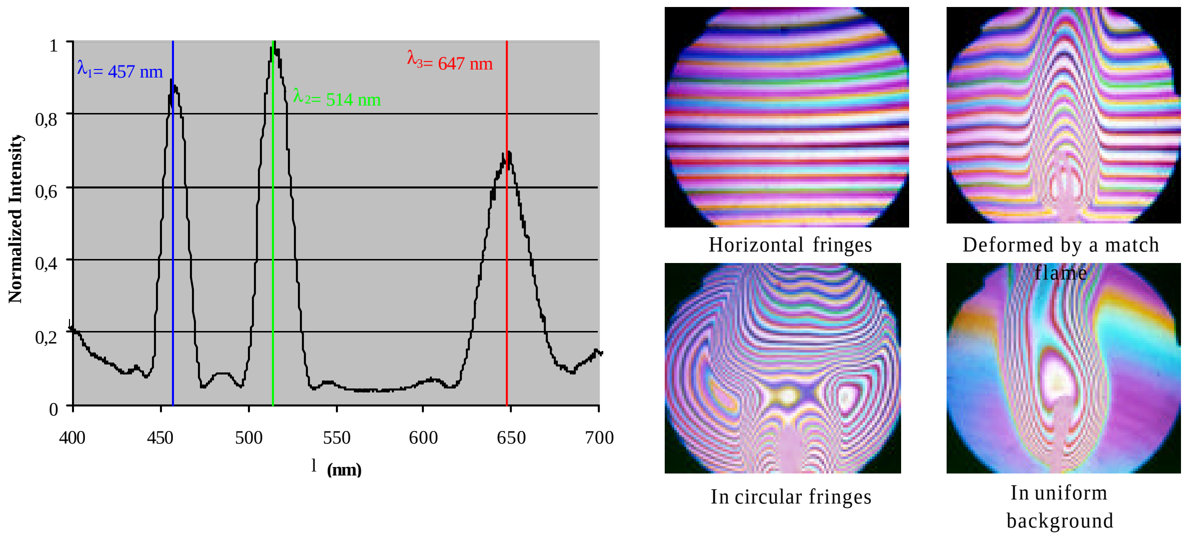


Fig. 7. White light diffracted by the Gentet hologram and interferograms obtained

On the graph of Fig.7 we can see that the three different gratings inscribed in the hologram gelatin diffract very well the three different wavelengths (blue, green and red) of the emitted laser source. In fact, the response of the hologram shows that the bell curves are centered on the three laser rays. In these conditions, there is basically no difference in the gelatin thickness before and after the chemical treatment of the plates. Moreover, if the power of the three reference and measurement wavelengths are the same, it is possible to obtain very well luminous and contrasted fringes. Fig. 7 exhibits four interferograms of color interference fringes. The first one recorded in narrowed fringes shows the white fringe and the others ones, the deformation of fringes produced by a small match in narrowed fringes, in circular fringes and when the background tint is uniform. Similar results have been obtained with the Slavich plates.

The problem of the gelatin contraction being solved, next tests will consist to include the two types of holograms in “Denisyuk” optical set up and in a separated reference optical set up.

6. Conclusion

It has been shown that the high speed two-dimensional flows can be analyzed by differential interferometry using Wollaston prism and a polarized white light source. Described applications show the large capability of the technique to measure the variation of the refractive index in axisymmetric flows, hypersonic flows and also in gaseous mixtures. Another application, not presented here, concerns the evaluation of the skin friction coefficient from the color interference fringes obtained under white light by a fin oil film on a flat plate. Moreover, the quasi-automatic exploitation of color interferograms is based on the modeling of interference fringes versus the optical path difference, so that each pixel can be replaced by a value of refractive index.

As differential interferometry produces the first derivative of the refractive index, the real-time color holographic interferometry has been developed to obtain absolute measurements of the gas density. By using three different wavelengths, a white central fringe representing the zero order is obtained on the interferogram. An application is given in two-dimensional flow represented by the unsteady flow around a circular cylinder at Mach 0.37.

Concerning the analysis of the 3D flows, reflection holograms have to use and the problems raised by the chemical treatment which induces shrinkage of the gelatin have been mastered to increase the diffraction efficiency and the true colors restitution. Examples are presented.

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