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Real-time color holographic interferometry devoted to 2D unsteady wake flows

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Abstract : A new optical technique based on real time holographic interferometry in true colors has been implemented around the transonic wind tunnel of the ONERA-Lille center to analyze 2D unsteady wake flows. Tests realized in color interferometry, real time and double exposure, use simultaneously three wavelengths of a continuous waves laser (argon and krypton mixed) and holograms are recorded on silver-halide single-layer panchromatic Slavich PFG03c plates. The very principle of real-time true color holographic interferometry uses three primary wavelengths (red, green and blue) to record, under no-flow conditions, the interference among the three measurement beams and the three reference beams simultaneously on a single reference hologram. After the holographic plate is developed, it is placed on the test setup again in the position it occupied during exposure and the hologram is illuminated again by the three reference beams and three measurement beams. A flat, uniform color can then be observed behind the hologram. So a horizontal, vertical, or even circular fringe pattern can be formed and the achromatic central fringe can be made out very clearly. The single color is used to determine the path difference zero on the interferograms. The flow studied was the unsteady flow downstream of a cylinder placed crosswise in the test section. A sequence of hundred interferograms was recorded on 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.

Keywords : Color Holography, Interferometry, High Speed Flow, Gas Density Field.

1. Introduction

Detailed analysis and characterization of complex, unsteady flows requires higher-performance metrics to measure quantities in a smaller space or shorter time, or both at once. This is why ONERA has spent some ten years starting with an existing system and developing an optical method based on differential interferometry with a Wollaston prism using a polarized white light source. The technique generates a sequence of interferograms in white light at an ultra-high speed from which the derivative of the mass density is measured in an aerodynamic flow to analyze the unsteady phenomena (Desse, 1990). The interferograms are analyzed nearly automatically by an image processing program specially designed for modeling the light intensity of the interference fringes as the path difference varies (Desse, 1997). This technique has the advantage of visualizing very small path differences and also the single central black or white fringe, representative of a null path difference (zero order).

Our latest work has thus led us to develop real-time true color holographic interferometry (Desse et al., 2002). This technique, whose capacity to analyze transparent or diffusive objects need no further demonstration, 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.

One of the two variants of color holographic interferometry is perfectly suitable for analyzing unsteady aerodynamic phenomenon (transparent objects) and for real time analysis of mechanical deformations (diffusive objects). The usual double-exposure method consists in recording the holograms of a transparent or diffusive object in two different states in succession, on the same photographic plate. This proven technique has yielded good results for several years, but it does have the disadvantage of not allowing the interferogram of the phenomenon being studied to be observed immediately and without interruption. Real-time holographic interferometry included time-average holographic interferometry, on the other hand, allows a direct observation through a reference hologram and makes it possible to take an ultra-high speed movie of the interferogram of a changing phenomenon (Surget, 1973). This was the method retained. Its feasibility has been demonstrated in the Franco-German Saint-Louis research institute (I.S.L.) and also in Onera's transonic wind tunnel at the Lille center. In the longer term, this metric tool should serve as a basis for a method of analyzing unsteady three-dimensional flows.

2. Principle of real-time color holographic interferometry

The various holographic interferometry methods – double exposure (Surget, 1973), time-averaged (Helflinger et al., 1965), or real-time holography (Powell and Stetson, 1965, Stetson and Powell, 1965) – are the main scientific applications of holography. Until recent years, experiments in holographic interferometry were performed with a single laser, i.e., they were monochromatic. Most experiments found in the literature relate to transmission holograms and few experiments have been performed to date using holographic interferometry with reflected white light. It should be said that, in monochromatic mode, experiments in reflected white-light holography have little advantage over holographic interferometry in transmitted light. Recent publications mention the use of trichromatic differential interferometry (Desse, 1997) and holographic interferometry by reflection and all show that the essential advantage of color is that the achromatic fringe can be located in the observed field. This single white fringe determines the position of the optical path variation zeroes with certainty. When mechanical deformations are being observed, then, this fringe corresponds to the neutral line (locus of null deformations). The very principle of real-time true color holographic interferometry uses three primary wavelengths (red, green and blue) to record the interference among the three measurement beams and the three reference beams simultaneously on a single reference hologram. Under no-flow conditions, the undisturbed measurement waves ΣRM, ΣGM and ΣBM are recorded in the hologram by virtue of their interference with the three reference waves ΣRR, ΣGR and ΣBR. After the holographic plate H is developed, it is placed on the test setup again in the position it occupied during exposure. The difficulty here is resetting the three wavelengths simultaneously. Then the hologram is illuminated again by the three reference beams and three measurement beams, from which we get the three measurement beams ΣRM, ΣGM and ΣBM reconstructed by the hologram H simultaneously with the three coeval measurement waves transmitted by H, ΣRMC, ΣGMC and ΣBMC. The profiles of the ΣRM and ΣRMC, ΣGM and ΣGMC waves, and the ΣBM and ΣBMC waves are strictly identical to each other if no change has occurred between the two exposures and if the hologram gel has not contracted during development. So there will be three simultaneous interferences among the measurement waves constructed by the hologram and the coeval measurement waves. A flat, uniform color can then be observed behind the hologram. If a change in optical path is created in the test section, the three coeval waves will deform and adopt the profiles Σ'RMC, Σ'GMC and Σ'BMC while the waves reconstructed in the hologram, ΣRM, ΣGM and ΣBM, remain unchanged. Any color variations representing optical path variations will thus be visualized in real time behind the hologram (Fig. 1).

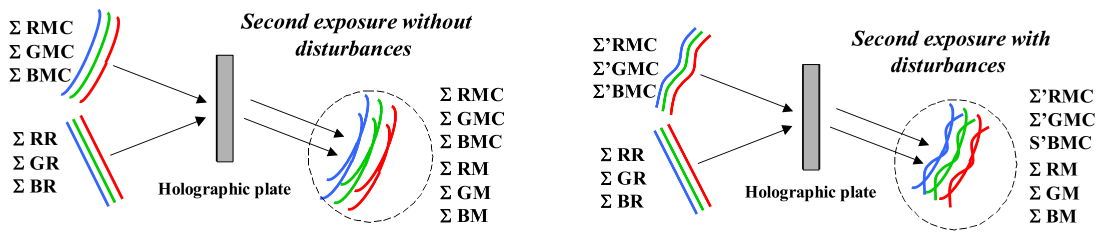


Fig.1. Interferences between diffracted waves and coeval waves.

3. Study of method feasibility

3.1 Problems to be solved

The following points have to be solved in order to use this method:
- A laser has to be found that will supply the three primary wavelengths forming as extensive as possible a base triangle (Desse, 1997).
- The laser has to be equipped with a Fabry-Perot etalon to increase the coherence length of the three lines selected.
- Parasitic lines have to be filtered out with an appropriate acousto-optical cell.
- A panchromatic holographic medium has to be found, and gel contraction controlled.
- A large light energy is needed to record the studied phenomena at ultra-high speed (the goal is 35,000 images per second with an exposure time of 750×10^{-9} s per shot).

Very high quality holographic images are needed.

3.2 Choice of laser and color base

The laser chosen is an Innova Spectrum 70 ionized gas laser (mixed argon and krypton) that produces approximately 10 visible lines with a total power of 4.7 W. The three wavelengths chosen for a triplet yielding the largest possible diagram in the representation of the CIE (Commission Internationale de l'Eclairage) colors. The three wavelengths retained are 647nm for the red line of krypton, 514nm, and 476nm for the green and blue lines of argon. All three exhibit a TEM00 mode. Laser adjustment and operation are discussed in extensive detail in Desse (2002). The laser is equipped with a specially designed Fabry-Perot etalon to simultaneously increase the coherence length of the blue line and the green line without annihilating the red line which has proper coherent length originally. The etalon is treated on both faces to get 66 % transmittance for the blue line, 63 % for the green line, and 61 % for the red line. This treatment increases the blue and green lines coherence length the two or three centimeters at a range of several tens of centimeters. This is sufficient because, in our study, the reference and measurement paths can be roughly equalized and the optical path variations to be measured are no greater than a few microns.

3.3 Optical filtering of the parasitic lines

The seven unused lines were at first filtered out by a birefringent plate system placed between analyzer and polarizer (Desse, 1997). The plate thickness was calculated to form a natural filter. This approach was then dropped because there was no way to adjust the color balance before and after the tests. The solution adopted is based on Acoustic Optic Tuning Filters (AOTF). By applying three different frequencies to the same crystal, three different wavelengths can be diffracted where the intensity of each wavelength is controlled by the amplitude of the separate frequencies. With this system, the balance of the three colors can be adjusted. Any residual divergence of the three beams can be compensated using a prismatic plate on the experimental setup.

3.4 Panchromatic holographic plates

Since the time Russian panchromatic plates came on the market a few years ago, progress has been made in true color holograms. The plates used are silver-coated single-film PFG 03C plates from the Slavich Company in Moscow. Their chemical treatment first includes a hardening of the gelatin, development, bleaching, a series of rinsings in alcohol, and slow drying. The hologram's spectral characteristics were analyzed by taking a double exposure holographic interferogram and placing a small mirror near the object to be analyzed, in order to make a spectral analysis of the reconstructed light waves. The spectrograms of the reconstructed waves in our very first validation tests showed that the three peaks corresponding to the reconstructed colors are slightly shifted by a few nanometers, which corresponds to the contraction of the gelatin thickness:

- 471 nm for the blue, or $\Delta\lambda = -5$ nm
- 511 nm for the green, or $\Delta\lambda = -3$ nm
- 640 nm for the red, or $\Delta\lambda = -7$ nm

These differences are reduced practically to zero in wind tunnel tests when the hologram is placed normal to the bisector of the angle formed by the measurement and reference beams.

In Fig. 2, we can see how are localized the interference fringes in transmission hologram at the recording for the three wavelengths (red, green and blue). Now, look at precisely the case of the hologram only recorded with the green line. At the restitution, if this hologram is illuminated in white light, it will diffract a green color if the gelatin thickness (Δe) is not modified by the chemical treatment of the hologram. A modification of the gelatin thickness will modify the interfringe in the gelatin. If $\Delta e < 0$, the hologram can diffract a blue color and if $\Delta e > 0$ the hologram can diffract a red color instead of a green color.

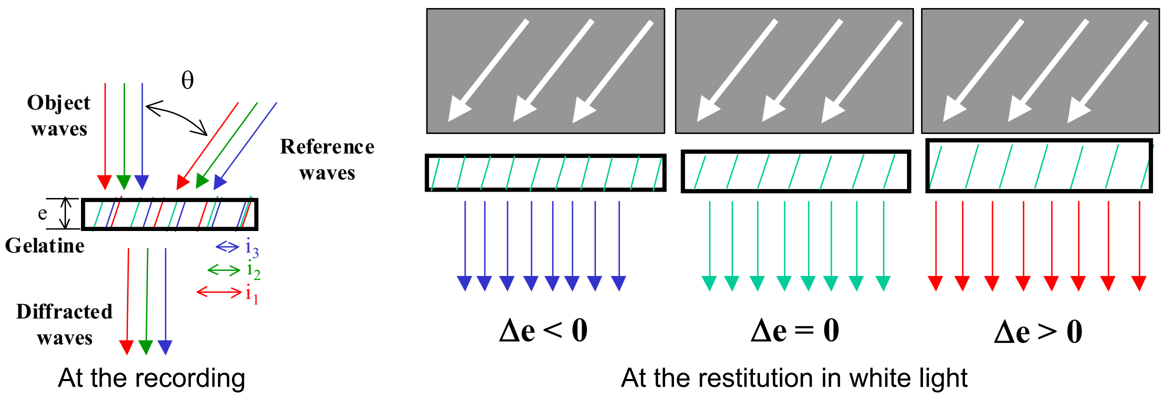


Fig. 2. Effect of the gelatin contraction of the diffracted waves.

4. Implementation of the technique in wind tunnel

The optical setup for testing the feasibility of the technique 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 Mach number can be varied from 0.3 to 1.1. The flow studied was the unsteady flow downstream of a cylinder of diameter D = 20 mm placed crosswise in the test section.

The optical setup is shown in Fig. 3. The Innova Spectrum laser emits the ten lines in the visible simultaneously. The beam power as it leaves the laser is 1.80 W when the etalon is flashed, and 1.20 W when it 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. The polarization of the three beams rotates 90° at the exit from the acousto-optic modulator, so that the polarization vectors lie parallel to the reflecting surfaces of the mirrors. This arrangement makes it possible to have beams of the same polarization interfere on the hologram. Beam splitter cube (S) splits the reference beams and three measurement beams. The three reference beams passe 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. In hologram plane, the measurement beam diameter is 40 mm. A diaphragm is placed in the focal plane just in front of the camera in order to be able to filter out any parasitic interference (Desse, 2002).

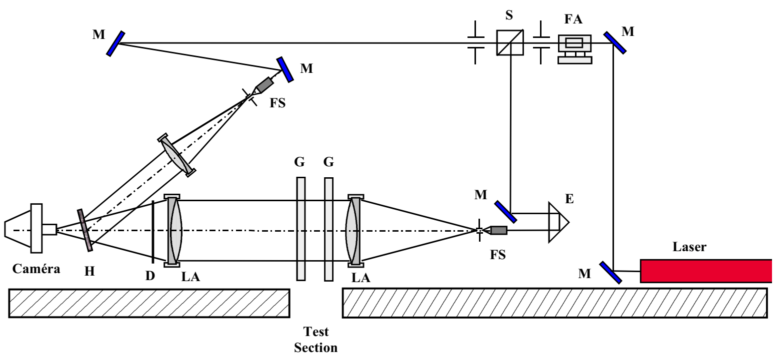


Fig. 3. Optical setup implemented around the wind tunnel.

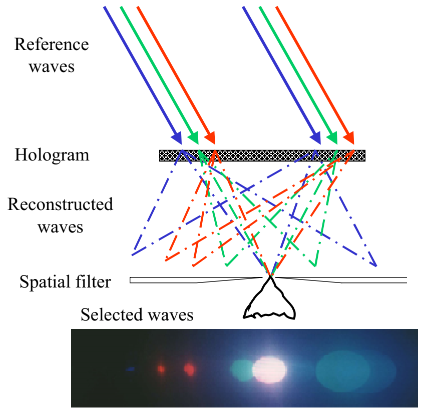
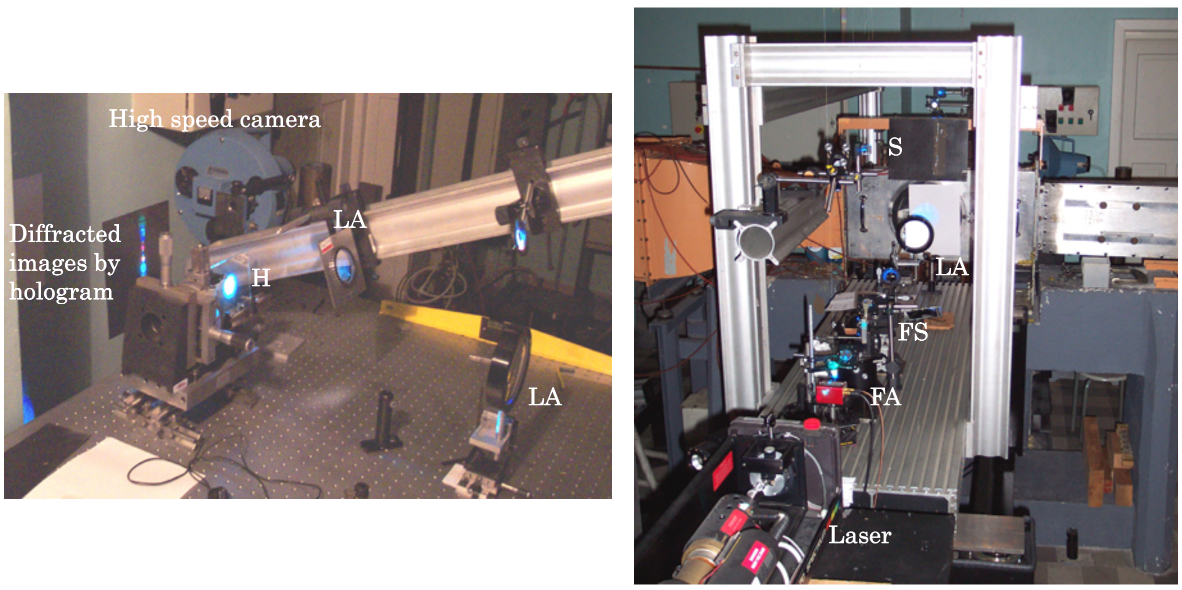


Fig. 4. Parasitic images in focal plane.

That is, the hologram is first illuminated in the absence of flow and is then developed and placed back in exactly its original position. When the hologram is illuminated with the reference beam, nine diffraction images are seen. Of the nine, three coincide and focus exactly at a single point if the setup is perfectly achromatic. These three images correspond to the diffraction of the blue image by the blue beam, that of the green image by the green beam, and that of the red image by the red beam. As it can be seen in Fig.4, a spatial filter is then used to only select the three achromatic images. Figure 5 shows the two views of the optical set-up from each side of the test section.



Reception side

Emission side

Fig. 5. Optical set-up on each side of the test section.

At the level of the acousto-optic cell, the three light waves have practically the same power (of the order of 70mW per channel). The beam splitter cube distributes 85 % of this power to the reference path and 15 % to the measurement path. At the level of the hologram, we measure 250μW/cm² in the red and blue and 280μW/cm² in the green for the reference beam, while the measurement beam powers are 30μW/cm² in the red and 40μW/cm² in the green and blue. These proportions can be used to obtain a perfect balance among the powers of the three waves diffracted by the hologram when re-positioning it, and the three coeval waves. For reference, the hologram diffracts 70 μW/cm² in the red, 65μW/cm² in the green, and 90μW/cm² in the blue. The first exposure lasts 2s. The holograms are then subjected to treatments to harden the gel, 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.

5. Analysis of interferograms at Mach 0.37

Figure 6 gives a sequence of six interferograms of the flow around the cylinder at Mach 0.37. The time interval between each picture is 100 μs. 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. The results of this are shown in Fig. 7. The "○" 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.

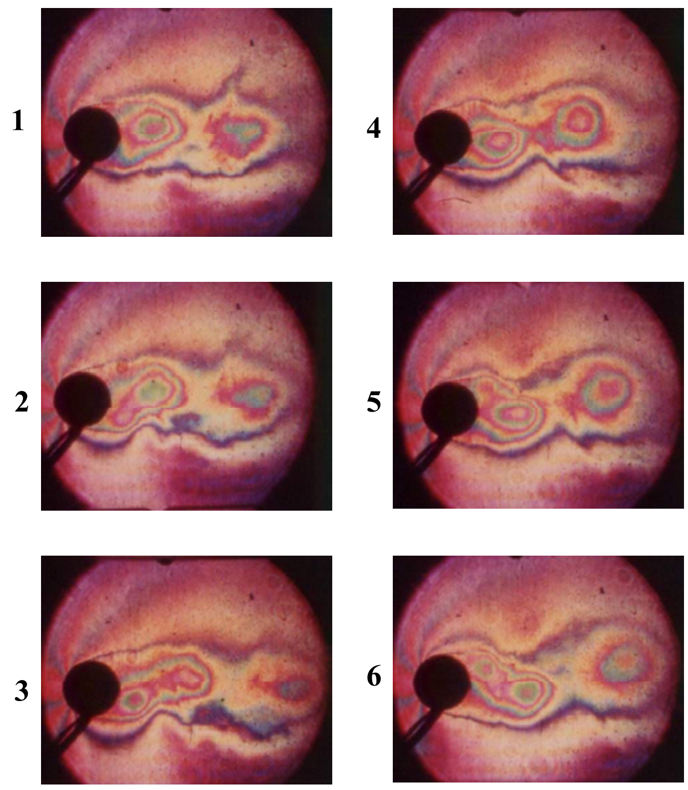


Fig. 6. High speed holographic interferograms – ΔT = 100μs.

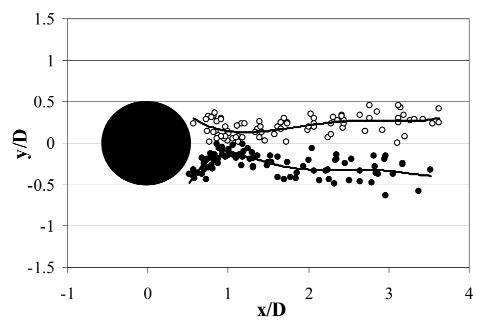


Fig. 7. Vortices trajectories.

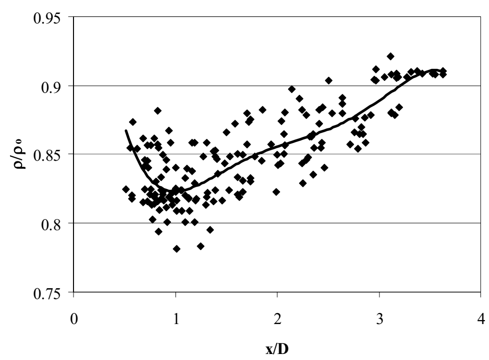


Fig. 8. Vortices gas density.

Lastly, the colors of each interferogram were analyzed using the Midi program, which models the light intensity and experimental interference fringe colors as a function of the path difference (Desse, 1997). The gas density measured under free stream conditions is the same as that measured at the outer flow of the wake (measured in the vicinity of the wind tunnel's upper and lower walls). Starting from a point external to the wake, we can work back to the gas density at the total point (at the cylinder nose) and also measure the gas density at the center of the vortices. The graph of Fig. 8 show how ρ/ρ_0 varies for the vortices emanating from the upper and lower surfaces. The trend curves plotted show the same variations. For $0.5 < x/D < 1$, the vortices are in a formation or agglomeration phase because the gas density decreases at their center. Then, when $x/D > 1$, the vortices enter a dissipation phase because the gas density increases again at their centers. The drop in gas density is large, reaching about 18 % ρ_0. A rather large dispersion may nonetheless be noticed in the data. This is due mainly to the unsteady character of the flow and to our evaluation of the vortex centers, which are not very easy to determine when the vortices are in the dissipation phase. Moreover, taking the hologram transfer function into account in the exact modeling of the interference fringes should greatly improve the modeled colors between the orders of interference, and thereby the measurement precision.

6. Conclusion

The data presented show the feasibility of real-time color holographic interferometry for analyzing aerodynamic flows (analysis of transparent objects). The holography stand has been designed and now operates. The problems of external vibrations have been solved, along with the problem of the monomode character of the blue line, at the cost of a major energy loss. This approach may not be usable for analyzing diffusive objects because it requires a great deal of light. A Diode-Pumped Solid-Sate (DPSS) type blue laser will certainly have to be used to replace the blue line of our Innova Spectrum 70 laser.

The wind tunnel data show that the field size is determined solely by the diameter of the "clairaut" lenses. Moreover, the spatial filter can be used to separate the diffracted images easily in the focal plane. In the optical arrangement, the acousto-optic cell yields good results and makes it possible to fix the reference hologram exposure time. It is also important to collimate the three reference beams on the hologram. In any case, this technique is subject to the use of the Russian holograms and the chemical treatments applied to them.

Many points can be improved, because this is the first time this technique has been implanted around a wind tunnel. Firstly, the rigidity of the setup can and must be further improved. As concerns the interferograms, comparative analysis of straight-fringe interferograms with interferograms using uniform background color modes would be useful for evaluating the precision of the two methods.

Our upcoming studies will concern the analysis of diffusive objects for purposes of quantifying mechanical deformations. An adequate optical setup will have to be created and this will be used to evaluate the new possibilities of real time color holographic interferometry for the analysis of diffusive objects.

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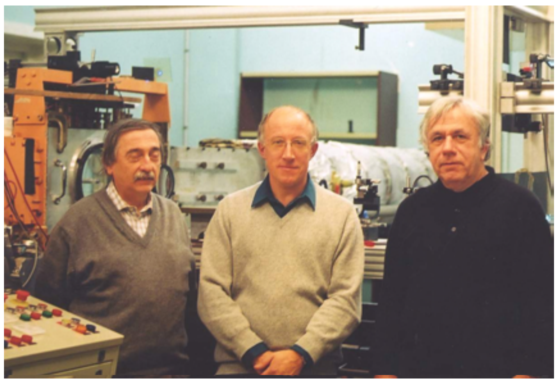
Author Profile



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Jean-Louis Tribillon : Doctor/engineer, famous specialist in color holography. He has a very large experience in color holography using pulsed lasers and he has recorded a lot of color interferograms known in the entire world. He works in the Direction des systèmes de Forces et de la prospective, Service Recherche Etude Amont.