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Disappearance of holographic and interference fringes accompanies optical diagnostics of a supersonic bow shock flow

Grigory Toker[a,*], Nikolay Korneev[b]

[a]Autonomous University of State Morelos (UAEM), CIICAp, FCQeI, Av. Universidad No. 1001, Z., Mexico
[b]National Institute for Astrophysics, Optics, and Electronics (INAOE), P.O. 51 & 216, Z.P. 72000, Puebla, Mexico

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Abstract

Preliminary results of optical diagnostics of bow shocks in a supersonic wind tunnel by applying dual-hologram shear interferometry technique are discussed. A strong refraction effect of the probing beam penetrating a region in the vicinity of a bow shock over a blunt nose cone model has been discovered. On a signal hologram the effect leads to the disappearance of holographic fringes in a narrow region attached to the shock wave front. A reconstructed interferogram in this region manifests the absence of an interference pattern.

Computer simulations were performed for a part of the probing beam penetrating the area of high-density steep gradients of compressed air attached to the central part of the shock front of a bow shock. The compressed area was modeled as a hyperbolic cap. The bow shock was assumed axisymmetric. The simulations made it possible to evaluate angles of deflections and found conformity with reconstructed interferograms (shadowgraphs).

It is concluded that in the above-indicated region of bow shocks probing light is deviated refractively into some angles, which could be large enough for light rays to be blocked out and never arrive at the detector (photo film). In the case when interferometric fringes disappear, the effect of strong refraction makes it impossible to measure air density gradients in some critical region.

Keywords: Dual hologram shearing interferometry; Supersonic wind tunnel; Bow shocks; Strong refraction effect; Blocking of refracted rays

1. Introduction

Modern experimental studies of supersonic and hypersonic compressible flows require more detailed data than before, mainly for the purposes of validation, verification and calibration of CFD calculations. As to non-intrusive tools developed for subsonic incompressible flows, such as particle image velocimetry (PIV) and laser doppler anemometry, they are not suitable for high-speed compressible flows. Hot wire, hot film techniques and Pitot tube surveys introduce strong disturbances, especially when the probes are submerged in a flow field in proximity to areas with discontinuities such as shock flows.

Non-intrusive optical diagnostic techniques have remained one of the main tools for extracting detailed information in this region of compressible flows. Quantitative data can be obtained by Schlieren [1], classic interferometry [2], reference beam [3] and shearing holographic techniques [4].

*Corresponding author.
E-mail address: toker@buzon.uaem.mx (G. Toker).

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It is well known that supersonic and hypersonic wind tunnel facilities during a run effectively generate acoustic disturbances. Unfortunately, reference beam classic and holographic interference schemes demonstrate a low mechanical stability and are not tolerant even to a low level of acoustical disturbances. Classic shearing schemes are more stable [5], but in general possess the majority of some shortcomings inherent to reference beam systems. During about three decades a dozen of acoustically tolerant optical schemes have been suggested. Unfortunately, these schemes possess of different shortcomings (corresponding references might be found in [6]).

The main disadvantages of such schemes are as follows: (i) inability to record finite width fringe interferograms; (ii) necessity to use an expensive pulsed laser system for very short exposure times; (iii) necessity to use high-quality optics, since the obtained interferograms are not compensated for aberrations and (iv) low acoustic stability because of remarkably spatially separated reference and object beams.

Ref. [6] suggests shearing dual hologram technique, based on using a highly mechanical stable diffraction interferometer suggested in [7]. The diffraction interference scheme with large-aperture Schlieren mirrors is well suited to various gas dynamic and high-power facilities. The advantages are the following: (i) simplicity of the optical scheme; secondly, (ii) a high spatial resolution which is comparable with resolution of Schlieren systems and (iii) a high mechanical stability comparable with stability of Schlieren systems. Tolerance to strong acoustical disturbances, which always accompany a wind tunnel run, is high enough for recording signal holograms by using a continuous wave laser system. Utilizing a phase grating with low spatial frequencies (10–30 lines/mm) makes it possible to use a series of standard photo films with resolving limits ~100 lines/mm.

Experimental applications of the proposed technique are accompanied by some problems, which will be demonstrated below on examples of interference diagnostics of a supersonic bow shock. The main difficulties arise due to effects of refraction in the area attached to the front of a bow shock, which is characterized by a strong degree of compression and gradients. Strong steep air density gradients lead to remarkable refraction of a signal wave in this region and deflection of rays from their straightforward propagations. Some rays cannot arrive at a plane of registration, i.e. at the plane of a photo film, due to large arms of the receiver section of the optical scheme and remarkable deflections. Other problems arise due to a high level of flow fluctuations in some regions of a flow field, owing to excessive lateral shift, and may dramatically affect the contrast of the interference fringes. Both effects lead to disappearance of the interference pattern: in the first case holographic fringes also disappear, whereas in the second case the contrast of interference fringes dramatically drops.

2. Optical scheme

A supersonic wind tunnel with the test section $40 \times 50\,\mathrm{cm}^2$ was used to produce supersonic flow fields to be studied. An axisymmetric cylindrical model with blunted nose (diameter 40 mm, half-cone angle 30°) at zero angle of attack served to generate the shock wave flow field variations. Tests were run at Mach numbers $M = 1.6$–2.5. In each experiment, stagnation and static pressures were determined.

Shearing holograms were recorded by applying a holographic diffraction shearing interferometer [6] shown in Fig. 1.

The optical information carried by a test-collimated beam is received by the second Schlieren mirror (10) and refocused to the receiver section. A lens (12) is used to collimate the spherical beam and to illuminate a phase grating (13). The grating is located in the plane, which is optically conjugated to a bow shock over the model, i.e., the flow field under study is sharply focused by a collimator (10, 12) on the grating (13). A collimator (15, 17) images the phase grating on a photo film (18). A lens (15) refocuses the collimated beams of diffraction orders in the plane of a two-pinhole diaphragm (16) in order to select only the first orders. Zero and higher diffraction orders are blocked out.

The photo film (18) is thus exposed to the two non-shifted replicas of the probing wave (plus and minus first diffraction orders) and after that it is processed. Spatial frequencies of holograms were in the interval

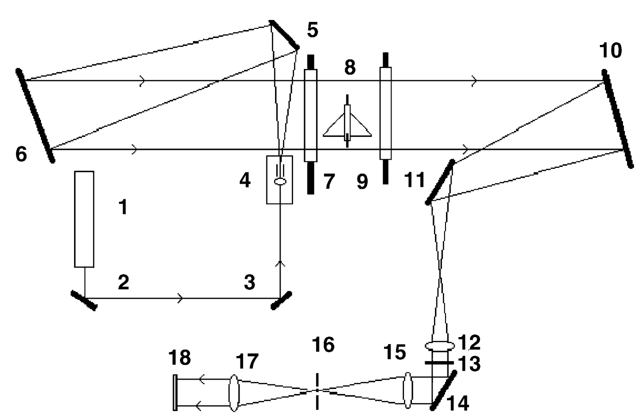

Fig. 1. Scheme of a diffraction lateral shearing holographic interferometer for wind tunnel testing and other wide-aperture facility diagnostics: (1) argon-ion laser; (2, 3, 5, 11, 14) flat mirrors; (4) spatial filter; (6, 10) spherical Schlieren mirrors (diameter 320 mm); (7, 9) viewing windows; (8) model; (12) collimating objective lens; (13) phase grating ($40\,\mathrm{mm}^{-1}$); (15, 17) collimators; (16) two-pinhole diaphragm and (18) photo film.

$45/180\,\mathrm{mm}^{-1}$. As long as the grating and the holograms exist in optically conjugated planes, their spatial frequencies do not depend on the wavelength λ.

The spatial resolution of the technique is determined by coefficients of total magnification $M_t = 0.2$ and $0.475\times$ and the spatial frequency of a recorded shearing hologram f. The smallest detail, which might be seen in a reconstructed interferogram, is $3/(2f) = 8.3$–$33\,\mu$m. Taking into account the coefficient of magnification $0.2\times$ the resolution varies in limits 42–165 μm. The experimentally found value is worse than ~0.3 mm. This discrepancy may be explained by not enough high optical quality of the receiver section, when the smallest phase details of the flow field cannot be recorded on a signal hologram due to aberrations of the Schlieren mirror (10). For larger magnification, the experimentally found resolution is not better than 0.2 mm.

In Figs. 2 and 3, a series of reconstructed interferograms for Mach number $M = 1.6$ and 2.5, supplemented with correspondent shadowgraphs is presented. A shadowgraph can be easily reconstructed from a signal hologram only. Figs. 2(a)–(d) demonstrate the situation for the weakest degree of compression, where the only narrow <1 mm area attached to the top of the model has not holographic fringes. Regions with high steep density gradients and consequently remarkable refraction are clearly visible in the reconstructed shadow picture (shadowgraph) (see Figs. 2(a) and (c)). These regions are attached to a bow shock.

In Figs. 3(a) and (b) bow shocks at $M = 2.5$ can be observed. The regime with $M = 2.5$ maximizing compression downstream of a bow shock is characterized with further spreading of the region with disappearance of interference fringes. In the region between the top of the model and the central part of a bow shock, holographic fringes are not observed.

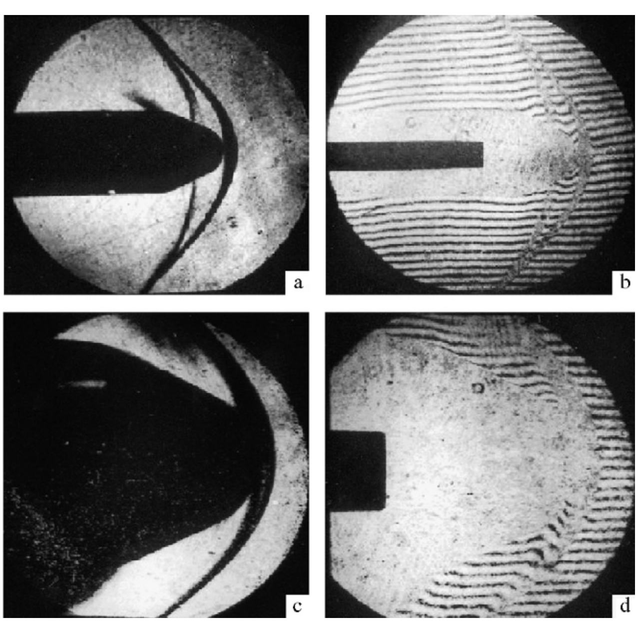

Fig. 2. Reconstructed shadowgraph (a, c) and shearing interferogram (b, d) at Mach number $M = 1.6$. Shears: 0.2 mm. Coefficient of magnification is $0.2\times$ (a, b) and $0.475\times$ (c, d).

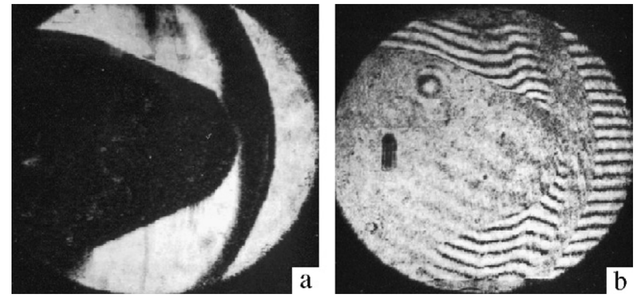

Fig. 3. Reconstructed shadowgraph (a) and shearing interferogram (b) at Mach number $M = 2.5$. Shears: $s = \Delta x = 0.2$ mm. Coefficient of magnification is $0.475\times$.

Flow field with mediate Mach number $M = 2.0$ and shears: (a) $s = \Delta y = 0.1$; (b) $s = \Delta x = 0.2$ mm is presented in Figs. 4(a) and (b). The coefficient of magnification is $0.2\times$. The arrow shows the region with a dramatically dropped contrast of interference fringes. Regions with disappeared interference due to refraction are also observed.

Interesting behavior of an interference pattern could be observed in regions with a high level of fluctuations, if the experimentally chosen lateral shear is in excess of some value. Shearing interferometry is more attractive and flexible in comparison with its reference beam counterpart, since it allows changing of sensitivity of interference measurements. The sensitivity could be enhanced due to enlargement of a lateral shear, s.

If this value is still small, it is permitted [8] to write the fringe equation in the form

$$2\pi N(x,y) = ks\frac{\partial \Phi}{\partial x} = (ks)\int_{z_1}^{z_2} \frac{\partial}{\partial x}\rho(x,y,z)\,\mathrm{d}z, \qquad (1)$$

where $N(x, y)$ is fringe shift, k is propagation vector, Φ is phase, K is the Gladston–Dale constant, and ρ is air density. Thus, the fringe shift is directly proportional to the lateral shear, s. In [4], it was found experimentally that the degradation of the contrast occurs due to excessive lateral shear.

At the same time in Fig. 4(b) this region is absent due to smaller lateral shears ~0.1 mm.

Thus, we have discovered two experimentally observed mechanisms of lost interference fringes in some regions of a bow shock, diagnosed by a lateral shear holographic technique. The first mechanism is determined by the effect of a strong refraction for some rays traveling in compressed deep gradient regions. The second mechanism is connected to regions with strong flow fluctuations and excessive lateral shifts.

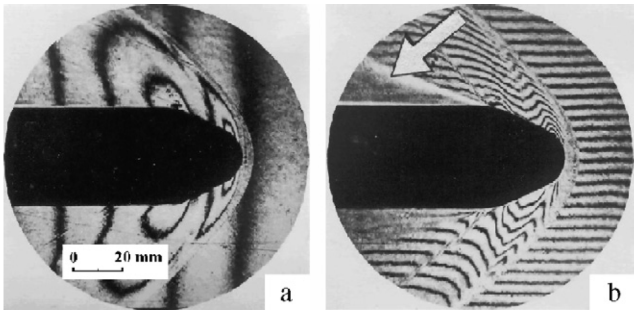

Fig. 4. Reconstructed shearing interferograms at Mach number $M = 2.0$.

3. Microscopy investigation

Microscopy made it possible to accurately study of the structure of a shock flow and measure spatial frequencies of signal holograms. It was found that shearing holograms were recorded with the widths of holographic fringes from ~5.5 to 22.2 μm. Usually, interferograms were recorded on photo film with magnification 0.2. Special measures were particularly taken for enhancing the spatial resolution of the area under interest. Thus, the lowest spatial frequencies correspond to signal holograms, which were recorded with maximum possible magnification $M = 0.475\times$. The magnification is limited by the size of the frame of a photo film $24 \times 36\,\mathrm{mm}^2$.

Microscopic observations also allowed determining and measuring the geometrical sizes of the area attached to the front of a bow shock, which is free of holographic fringes. This area around the aerodynamic model is well suited to the area visualized on reconstructed shadowgraphs. Besides that in signal holograms a double structure of this area is seen. The area is forwarded with a thin ~200 μm layer, which is attached just to the front of a bow shock. This layer corresponds to the distance ($s = \Delta x = 0.2\,\mathrm{mm}$) between fronts of bow shocks arising due to lateral shear in the horizontal direction.

Microscopic testing of a signal hologram in the vicinity of the top of the aerodynamic model shows that the area attached to a bow shock in the central and peripheral regions is free of holographic fringes.

4. Simulations of refraction of diagnostic rays in a bow shock

We have calculated ray propagation in the vicinity of the central part of a bow shock using a numeric solution of the differential equation of light rays [9]:

$$\frac{\mathrm{d}}{\mathrm{d}s}\left(n\frac{\mathrm{d}}{\mathrm{d}s}\vec{r}\right) = \nabla n, \tag{2}$$

where $r(x, y, z)$ is a position vector of the point on a ray, $n(x, y, z)$ is the refractive index, and s is the length of the ray measured from the fixed point on it.

We fit the form of shock wave front with a hyperbolic function

$$x + a_0\sqrt{y^2 + z^2} = p + p_0, \tag{3}$$

where a_0 and p_0 are fitting parameters, and p describes the position where the hyperbola crosses the x-axis ($y = z = 0$). For calculation, we assume that the refractive index distribution around the shock wave is a p-dependent function. $n(p)$ is shown in Fig. 5.

The total angles of beam deflection are shown in Fig. 5. It is seen that maximal deflection angles are in dozens mill radian range. These angles are approximately one order of magnitude bigger than characteristic angles of diffraction on 1 mm aperture; thus the diffraction can play some role just in front of the model where the deflection angles change substantially, and the body is in close proximity. Fig. 5 confirms in general outline the characteristics of the reconstructed interferograms shown in Fig. 4.

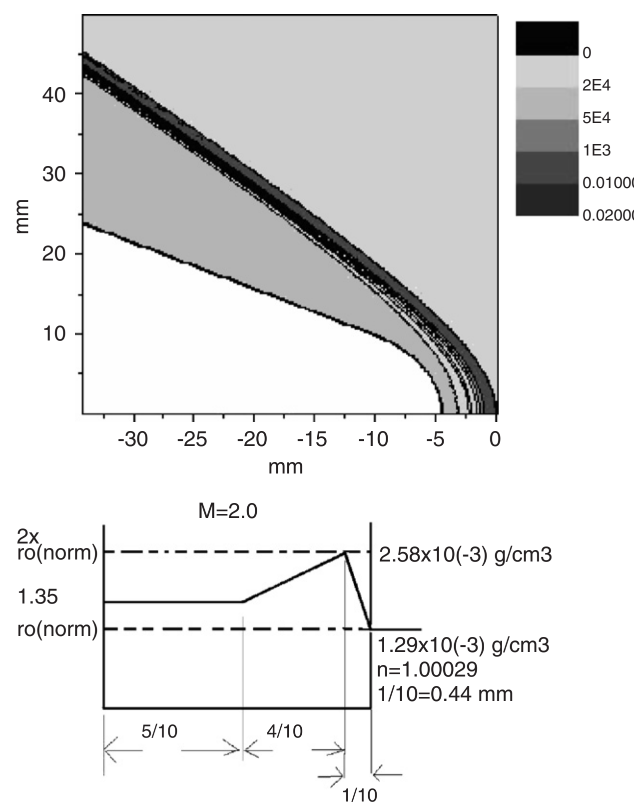

Fig. 5. Calculated full angles of diagnostic rays, deflected from their straightforward propagations at $M = 2.0$ (above); one of the simplified reasonable distributions of the refractive index (below).

5. Discussion and interpretation of obtained experimental results

Optical diagnostics by methods of holographic shearing interferometry has some principal advantages in comparison with classic shear and reference beam holographic techniques. Thus, studying some complicated aerodynamic objects, remarkably refracting a diagnostic beam, for instance, supersonic shock flows over a blunt body accompanies by effects of disappearing interference fringes. Actually, disappearing interference fringes lead to the situation that makes it impossible to calculate of a density distribution in these regions.

Disappearing interference fringes in regions with a high level of flow fluctuations might be overcome by minimizing possible lateral shear, as is seen in Fig. 4(a). At the same time holographic fringes present at the interferogram imaged in Fig. 4(b) with some diminishing the contrast. It is interesting to remark that the effect of dramatically changing the contrast of interference patterns might be used to reveal such regions simply by enlarging a lateral shear.

Disappearance of interference fringes (and first of all, holographic fringes) due to effects of refractions is more difficultd to overcome. In fact, the two-pinhole diaphragm (16) in Fig. 1 works as a spatial filter for the rays suffered at some insignificant angles of refractions, i.e. only these rays are selected. As to the rays, refracted at relatively appreciable angles, they are blocked out. Thus, the scheme of a holographic interferometer is well suited for phase objects only. To accurately diagnose aerodynamic transparent objects, some construction changes must be introduced into the scheme. As the first step, a phase grating with a larger spatial frequency should be chosen, in order to enlarge the distance between diffraction orders in the plane of a two-pinhole diaphragm. The second step is to enlarge the diameters of pinholes to select not only practically undisturbed rays but also the rays affected by some considerable refraction.

On the other hand, a two-pinhole diaphragm might be used for the accurate separation of rays refracted at different angles visualizing the picture of rays refracted in the same region of inclination. In the literature, the problem of measuring ray inclinations was discussed in [10], where deflections were measured by the speckle technique. The lowest boundary between phase and transparent objects was taken to be of the order of 0.1 mrad [10,11]. On the other hand, this value could be a few times larger ($\sim$50 mrad) [12].

Taking into account the algorithm of properly changing the design of a receiver section, the holographic shearing interferometer could be recommended for various aerospace engineering applications due to a simple but mechanically tolerant optical scheme, which might be designed with a small investment on the base of an ordinary Schlieren system.

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