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Flow visualization techniques in wind tunnels –optical methods (Part II)

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An attempt is made to describe and review the most widely used methods for flow visualization. The first part described the basis and applications of different visualization methods for subsonic and supersonic flow in wind and water tunnels. This part concentrates on optical methods (shadow, schlieren and interferometry) and their application in compressibe flow visualization. Almost all presented photos have been made in the laboratories of the VTI.

Key words: **flow visualization, wind tunnel, optical methods, shadow method, schlieren method, holographic interferometry.**

Introduction

FLOW visualization is essential for exploring, and understanding fluid behavior and can be both qualitative and quantitative [1-52].

The flows described in the first part of this article [52] were considered as incompressible flows with a constant, uniform density. The other group of flows, i.e. compressible flows have variable density which depends on flow velocity. The optical index of refraction $n(x,y,z)$ of a gas is a function of the gas density. For practical purposes, the density difference of 2% can be considered as an appropriate limit between incompressible and compressible flows. This occurs if $M_\infty > 0.2$ [1].

Rapid advances during the past decades concerning issues associated with high speed flights have brought into focus the need for competent treatment of the fundamental aspects of aerodynamics and the need for application of basic sciences in solving practical problems. The different physical methods and techniques are employed to measure density, pressure, velocity and temperature in gas dynamics.

The main methods for visualization of these flows are optical methods. The three principal optical methods are: shadow, schlieren and interferometry [1-12].

The optical flow visualization has been expanded due to the innovation of the optical laser. Laser light is highly monochromatic and coherent with high-energy concentration. The laser light sources have successfully been used in conventional optical visualization systems, but they have led to the development of completely new methods. The lasers are attractive as light sources especially for interferometry [1, 9,12,18-49].

Compressible air field as an optical object

Airflow around aerodynamical models is a very complex phenomenon. In optical sense, this flow field is a transparent environment with a complex light refraction index. The light refraction index in each flow field point is the function of air density in that point, which, on the other side, is the function of speed, pressure and air temperature [1,6,7-12]. The relation between air density $\rho(x,y,z)$ and the refraction index $n(x,y,z)$ is called the Gladstone-Dale equation: $n = 1 + K\rho$ The Gladstone-Dale constant K has a value of ρ^{-1} and is different for each gas. The refractive index for gas, which is a mixture of several components e.g. air, eq. (1) becomes: $n = 1 + \Sigma K_i \rho_i$. The Gladstone-Dale constant for air at a temperature of 288 K varies between 2.239 10^{-4} to 2.33 10^{-4} m^3/kg.

According to Snell's law, a light ray, passing through a nonhomogeneous refracted field, is deflected from its original direction and a light path is different from that of an undisturbed ray. If a recording plane is placed in front of the light ray, after disturbing media, three quantities can be measured: the vertical displacement of the disturbed ray, the angular deflection of the disturbed ray with respect to the undisturbed one and the retardation of the deflected ray, i.e. the phase shift between both rays, owning to their different optical path lengths.

Optical visualization methods are based on the recording of one of these three quantities (or a combination of them). The shadowgraph is used for the first phenomenon, the Schlieren method is used for the second one, and interferometry for the last one.

There are significant differences between these methods, since the shadowgraph is sensitive to the changes of the density second derivative (or the refractive index) second derivative $\partial^2 n / \partial y^2$, the Schlieren method is sensitive to the changes of the density first derivative $\partial n / \partial y$, and interferometry is capable to measure absolute density n changes. If, using an optical method, the light refraction index $n(x,y,z)$ in flow field is determined, other physical parameters of tested environment, significant for aerodynamic testing, can be indirectly determined as well.

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Shadowgraph method

The oldest and the simplest of all optical methods for flow visualization is the shadowgraph [1-15]. Fig.1 shows a typical setup for shadow methods. A light beam passing through the wind tunnel test section is parallel. A spherical mirror or lens makes the light parallel. The light source should be small to ensure good sharpness of the obtained image. Observation and recording the deflected beam parts are in the perpendicular plane screen at a distance of l from the test section.

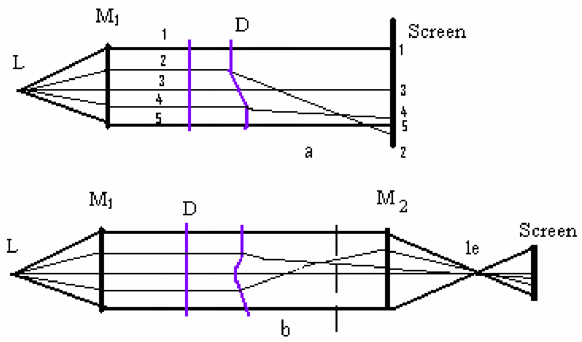


Figure 1. Schematic arrangement of the shadowgraph system, deflection of light rays in a field of the variable $\partial^2 n / \partial y^2$

If the test section is large, the recording is impossible without focusing the image onto the film. For this purpose it is preferable to use a second spherical mirror (or lens). The camera lens in that case is placed in the focal plane of the second mirror. The recorded shadowgraph is linearly reduced, but it is identical with that obtained by the arrangement presented in Fig.1.

To understanding the shadow image, it is useful to analyze the paths of three rays in the section where there are parts with a different amount of $\partial^2 n / \partial y^2$ (Fig.1). If ray 2 passes through the section with a higher value of $\partial^2 n / \partial y^2$ then along two other ray, 2 will be deflected to a great extent, so ray 5 on the photographic plate or screen will fall between ray 4 and 2. A darker region appears therefore on the screen between ray 1 and 3 - it represents the shadow of the disturbance through which ray 2 has passed. The uniform illumination of the screen is destroyed. The investigation of these intensity alterations gives a lot of useful information about the flow field. A shock wave and turbulent motion in a compressible flow can be detected and recorded with a shadowgraph [1-15].

Fig.2a shows the bow shock wave ahead of a sphere in the wind tunnel T-36 at M_∞ = 1.86 [7]. The trace of the shock wave in the photo is a band of absolute darkness bounded on the downstream side by an edge of intense brightness. The exact geometrical position of the shock front is the other edge of the dark zone. Diffraction effects are visible on the bright edge of the shadow because the shock wave represents a jump of the refractive index and because of low gas density in the free stream. The air density increases after the shock and the incident ray deviates to the inside edge. It is an analog result to that obtained with a convex lens.

Since the density in the disturbance is lower than in the surrounding field, (Prandtl-Meyer expansion fan at the sharp end of the nozzle) the bright band appears at the beginning of the shadow[7,12]. The same result is obtained when the compressible boundary layers is visualized. Its effect on a light ray can be compared with the effect of a concave lens. Fig.2b is a typical shadowgraph showing the flow around the spherical tipped cylinder mounted on the flat plate [13].

Shadowgraph methods with short duration light pulses can be used for fine visualization of turbulent compressible flows.

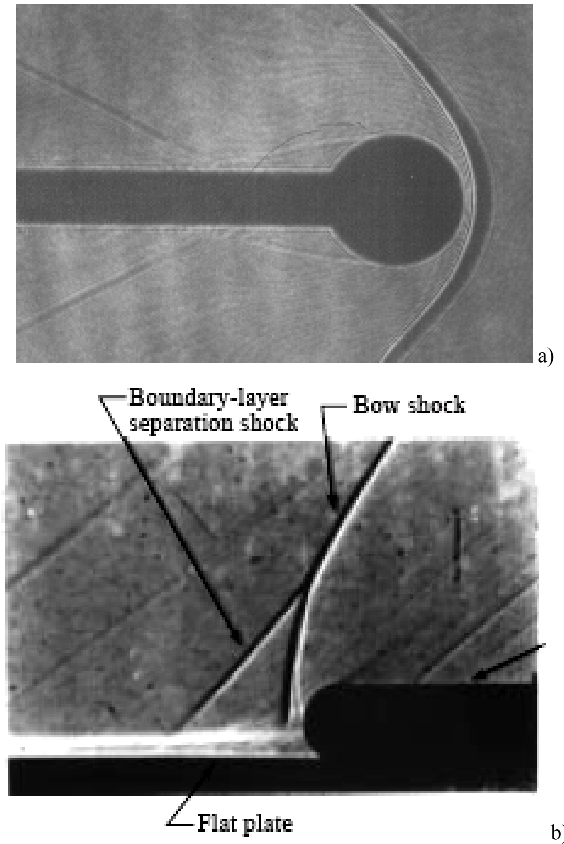


Figure 2. Shadowgraph visualization around a sphere (a), and typical shadowgraph images showing the spherical tipped cylinder mounted on the flat plate (b) [13]

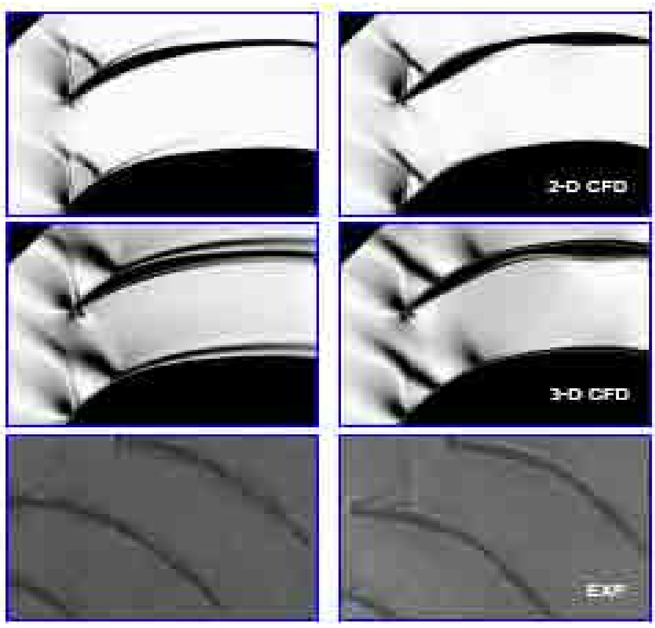


Figure 3. Numerical and experimental shadowgraph visualization of the supercritical cascade flow M_∞=0.87 [14]

The shadow performances can be illustrated by Fig.3. The blade performances were experimentally confirmed in the Virginia Tech High Speed Cascade Wind Tunnel [14].

The numerical and experimental methods were performed to reveal the associated flow physics, particularly the loss mechanisms. Flow diagnostic techniques such as blade surface pressure measurement, blade surface oil flow visualization, and shadowgraph were used in the experiments to study the pressure/velocity distribution, shock pattern and boundary layer behavior.

Schlieren method

As mentioned before, the Schlieren method is sensitive to the changes of the first derivative of density (or refractive index) and it can record the angular deflection of the disturbed ray with respect to the undisturbed in a transparent medium with local non homogeneities [1-19,27].

Today the Schlieren method is the most frequently used in aerodynamic laboratories, since it is relatively simple and very useful.

If a parallel beam of light passes trough the air where there is a density gradient normal to the beam direction, the light travels more slowly where the density is greater and the beam is refracted towards the region of greater density.

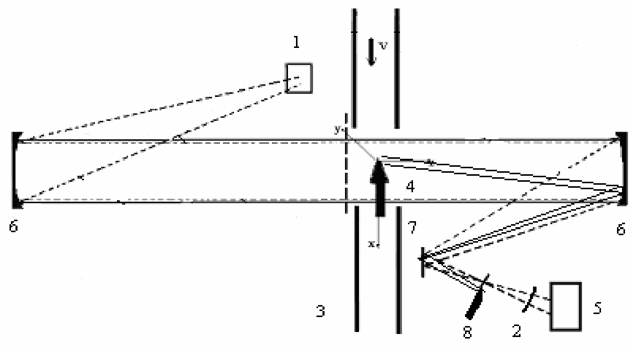


Figure 4. Töepler schlieren system

The most simple one is the Schlieren system with parallel light through the wind tunnel test section. In practice there are different systems with lenses or mirrors. Töepler system as the base of all other modificated systems is illustrated in Fig.3. The detailed description of the system is given in [7,9,10,12].

Today many different systems are used, e.g.: schlieren system with finite slit, with lens for projection, double lens system, single mirror system, system with two mirrors, plane concave mirror system and Twin mirror, (asymmetric twin mirror system) ,etc.

The new dimension has been introduced into the schlieren system replacing the knife-edge by a filter consisting of several parallel, transparent, colored strips (most often three colored sheets, red - blue - yellow or blue - green - red). The color filter can be consist of four differently colored strips arranged in a square filter to visualize the grad *n* in two directions. If the flow is axisymmetric, complementary colors appear for the same event (compression or expansion) above and below the flow axis. The recorded pure colors and color combinations are a measure for the local direction of density gradient in the test section. A contemporary modification of the schlieren system concerns the replacement of the knife-edge by optical elements which influence somehow the phase of the schlieren light beam. Fig.4 shows scheme of töepler schlieren system. Fig.5 shows the parts of schlieren systems in the T-34 hypersonic wind tunnels in the MTI [9,18].

Figures 6 and 7 illustrate schlieren effects recorded with the schlieren system with the knife edge (black and white schlieren).

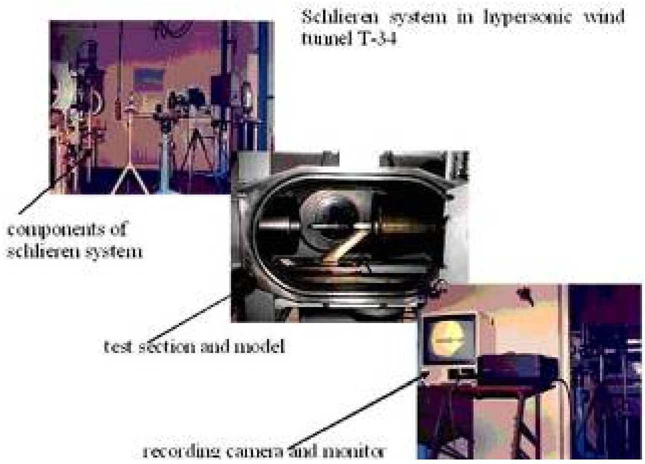
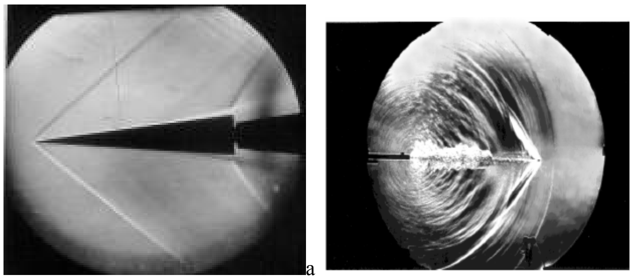


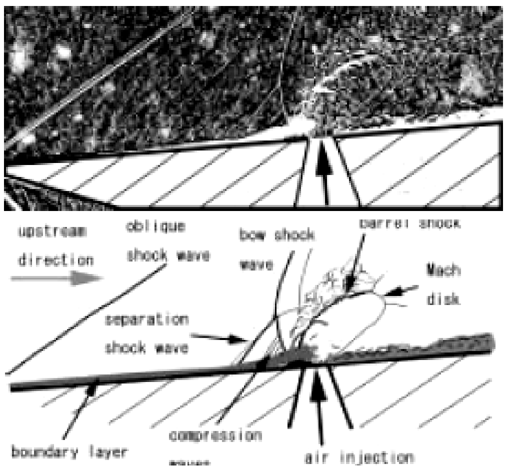
Figure 5. The photos of schlieren system components, model in the test section of the T-34 hypersonic wind tunnel and TV camera with monitor



a b

Figure 6. Black and white schlieren photos obtained in the T-36 wind tunnel for M_∞ = 1.56 (a) and instantaneous image of Bullet and Muzzle Blast from a 22-Caliber Rifle (b) [13]

In order to investigate the interaction between the boundary layer on the injector plate and the jet, a transverse sonic jet was injected into a supersonic cross flow (Mach 1.7) [16]. Fig.7a. shows a typical result of schlieren flow visualization. The jet expansion led to the barrel shock and the Mach disk shown in Fig.7a. On the other hand, the injectant jet caused interaction phenomena between the cross flow and the jet itself. In other words, the jet acted on the cross flow as an obstruction. The schematic of the flow field obtained from the schlieren photograph is shown in Fig.7b.



a

b

Figure 7. Schlieren photograph of the flow field. (Mach 1.7) a) and Schematic of the flow field obtained by the schlieren flow visualization b).

Attempts to increase the amount of information extractable from the schlieren photography have led to the use of various opaque filter geometries other than a knife-edge as well as of transparent phase and color filters [1-27,29,30,38,43,49].

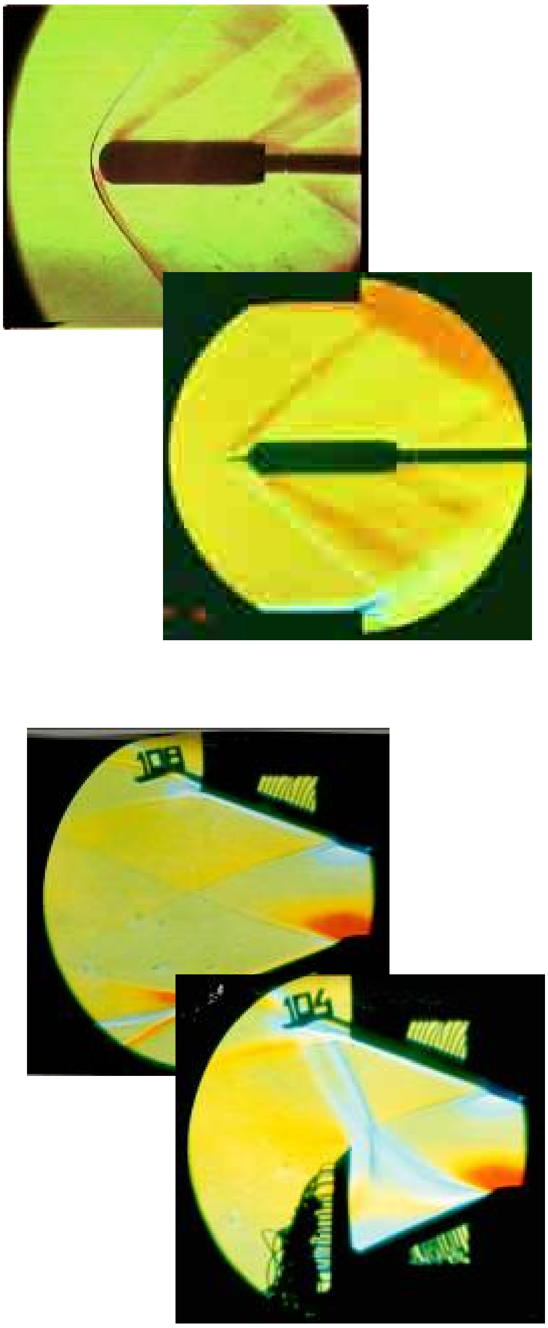


Figure 8. Color schileren effects around blunt body and thin protruding probe mounted in front of a blunt body for $M_\infty = 1.86$ (a) and supersonic flow in the twodimensional model of the supersonic rocket nozzle, (b) [9,12,17,29,32,49]

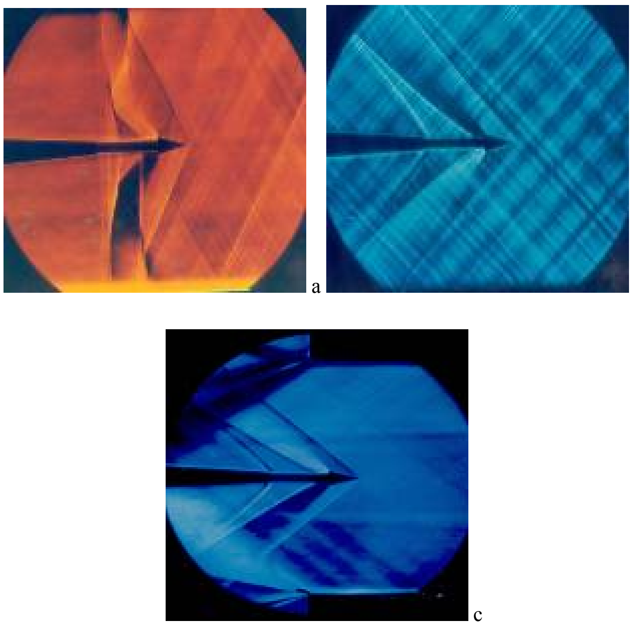
Color schileren effects around a blunt body and a thin protruding probe mounted in front of a blunt body, used to reduce the drag and the rate of heat transfer, are presented in Fig.8a [9,12,40,41,43] for $M_\infty = 1.86$. Flow visualization in a two-dimensional model of the supersonic rocket nozzle is tested by the schlieren method and the effects are presented in Fig.8b. The two-dimensional supersonic nozzle model is placed in the wind tunnel test section, where the windows are mounted. The nozzle is designed for a Mach number in the output plane $M_\infty = 2.6$. Fig.8b shows the flow into the nozzle with and without a barrier, Prandtl-Meyer expansion past a nozzle wedge, separation area and flow into the nozzle throat.

The classical schlieren photos obtained by the color schlieren system are presented in Figures 9 - 11. The flow around a cone with a top angle of 15° is tested in the T-36 supersonic wind tunnel for different Mach numbers and positions of color filters [9,11,25].

A combined holographic interferometer and schlieren device [9,36,44,46-48], has been designed, made and tested for the T-38 trisonic wind tunnel. It is a basis for various optical flow visualization experiments. The device can be included in tests either as a schlieren system or as an interferometer. The dimensions of such a system are out of standard (optical field diameter is Φ = 900 mm, uniform, without aberrations). It allows to visualize flows in transonic and supersonic wind tunnel test sections. The detection range of the density gradient is 0,1- 6,52 kg/m^4, the refractive index 10^{-7} to 10^{-4} and the resolution in full scale is 10^{-7}.

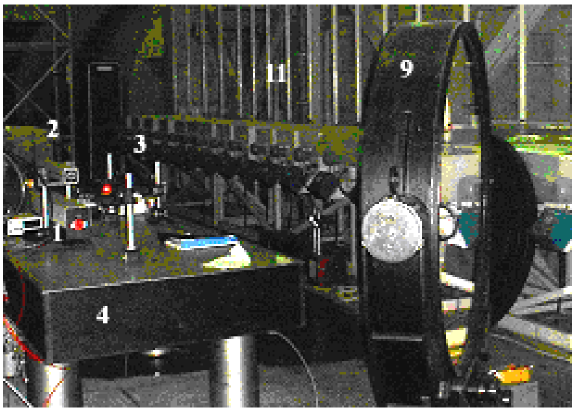
Improvements to this basic schlieren system include the Rainbow Schlieren (Fig.12) [30] where a colored bulls eye filter is used rather than a knife edge to quantify the strength of the refraction. The other variety of schlieren methods is obtained including laser as a light source. Fig.13a ilustrates the schlieren system in the T-36 with He-Ne laser as a light source and 13b shows the schlieren sffects around a cone (30° top angle) for transonic velocity.

Several variations of large field schlieren systems have been developed to examine aerodynamic flow fields that were previously difficult to study with conventional schlieren systems. In Langley NASA has developed a focusing schlieren system to provide measurements at a particular plane in the flow. Multiple source and cut-off slits are used to eliminate turbulence effects outside the plane of interest [22]. One advantage of this technique is its low cost; the optics are cheaper than conventional schlieren optics, and the windows can be of much lower quality. High-brightness transmission-type focusing schlieren systems were developed for aerodynamic testing in wind tunnels of small-to-moderate size.



a b c

Figure 9. Color schlieren photos obtained in the T-36 wind tunnel for M_∞ = 1.02 (a), 1.1(b) and 1.56(c) around a cone with a 15-degree top angle.



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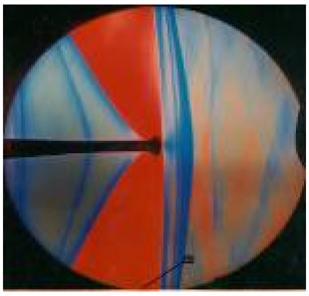
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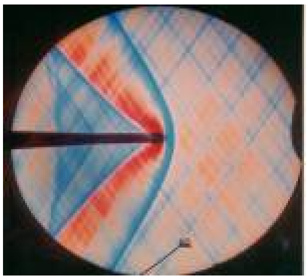
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Figure 10. Parts of combined schlieren-holographic interferometer in the T-38, (a), color schlieren flow around sphere visualization for M_∞ =1.02 (b) and M_∞ =1.1(c).

Figure 11. Schlieren effects around a cone and a slanted slot in the bottom wall for M_∞= 0.81 in the T-36 supersonic wind tunnel [9,12,26,33,35]

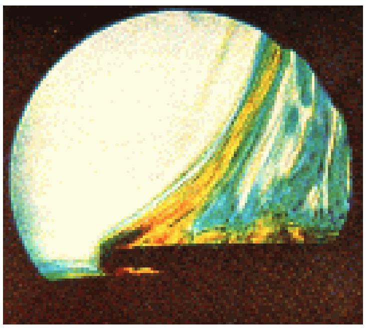
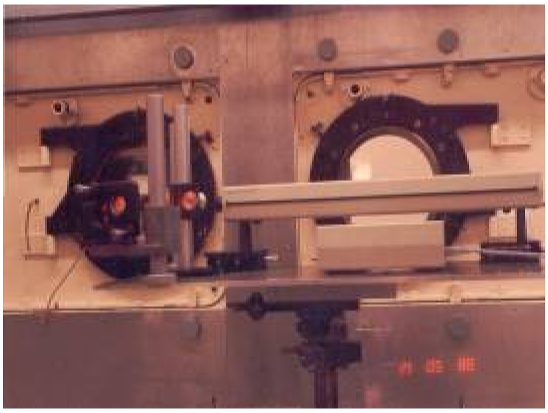


Figure 12. Rainbow Schlieren [22]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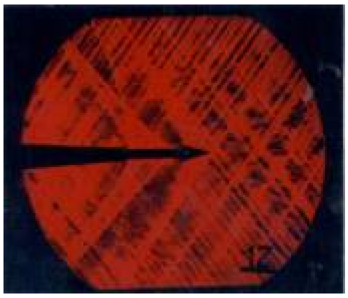


b

Figure 13. Schieren system with laser as a light source in the T-36 and the schlieren effect around a cone for M_∞ = 1.1

Retroreflective versions were also developed for wind tunnel flow and for convection flow studies, both of large scale. Different versions of motion-camera schlieren systems were developed to examine rocket sled flow fields and to obtain the flow field around aircraft in flight. Most images of shock waves have to be generated under highly controlled, artificial situations. However, recent developments at NASA may permit "field" observations of shock waves generated by aircraft (Fig.14). The technique was invented at the NASA Langley Research Center [23]. A discussion of this technique can be found at the NASA Ground to Air Schlieren Photography web site.

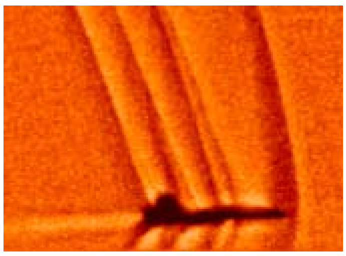


Figure 14. Full-Scale Schlieren Image of the T-38 Aircraft at Mach 1.1 [23, 26]

Interferometry

In most gas dynamics applications, it is useful to know flow density changes in wind tunnels, shock tubes or supersonic jets. The phase alteration beam passing through a disturbed section of a tested field can be compared with an undisturbed beam. The effects of interference make the basis of interferometry. The application of this principle in visualizing compressible flow fields is as old as the schlieren method [1-7,20-49].

Classical interferometry

The most used type of interferometers in wind tunnel tests is the Mach-Zehnder interferometer (MZI) [1,7]. Two light beams (test and reference ones) in the MZI are separated by its four plates. This instrument is suitable for quantitative density measurements in large wind tunnels. It requires an extremely high degree of mechanical precision and complexity of construction. Mechanical and optical tolerances are in order of a wavelength or below. This makes the instrument expensive and its cost grows rapidly with increasing the diameter of the desired size of the field of view.

The basic arrangement of the MZI is shown in Fig.15. The source light is made parallel with the lens S. The amplitude of the beam is divided into two parts by semi-reflecting mirrors. The four plates are situated in the corners of a rectangle and are all parallel in the start. The test section with its two glass windows is brought into the path of the test beam. In order to compensate the phase difference in two beams, two identical glass plates are inserted into the path of the reference beams. After being rejoined, corresponding rays of the two light beams can interfere and a certain pattern of interference fringes appears on the screen or photographic plate. An non homogeneity in the test section produces a certain amount of disturbance of the no-flow fringe system. It can be quantitatively related to the density distribution of the flow field [1,2,7,21].

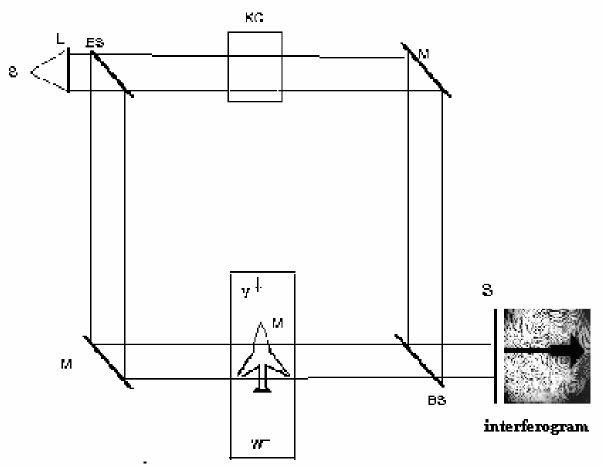


Figure 15. Mach Zehnder interferometer

The most important quality requirements for an "ideal" MZI are: homogeneity in the refractive index of the glass of splitter plates, test section, windows, and compensation plate; constant and equal thickness of each pair of splitter plates and windows; exact plane parallelism and surface quality of all mirrors, plates and windows; exact coating of the surface of beam splitters with the prevention of any absorption; a high degree of reflection of full mirrors; exact mounting which prevents all plates from bending, sagging and other mechanical deformations, and protection of the instrument from mechanical vibrations and other disturbances. The basic adjustment is very difficult. It is necessary to align the test beam parallelly to the surface of a two-dimensional test object to avoid light reflection. The last step in adjusting is always bringing the achromatic fringe (zero order) into the field of view. Much patience is required while adjusting the MZI.

The MZI has been applied in practically all cases of gas flow investigations, where density difference becomes noticeable, such as: thermodynamic data, thermal conductivity of gases, dissociation, aerodynamic application, turbulence, wave or sonic booms.

Holographic Interferometry

Holographic interferometry is an optical method that enables complete flow field testing. The method is non-contact (it does not disturb the flow field) and is used for testing different objects and phenomena [1-7,20-49].

The flow density can be measured directly using interferometry. The greatest advantage of holographic interferometry, in relation to the schlieren method, is the fact that it provides complete information stored in a single plate, allowing a postponement selection of specific types of flow visualization.

This method is based on holography, developed in the last forty five years [21]. The holography represents a two-stage method which, apart to light amplitudes, records light phases as well. The three-dimensional image recording is performed in the first stage, while its reconstruction is performed in the second stage (Fig.16). Lasers are used as light sources. The light from a reconstructed image from a hologram reaching the observer's eye is the same as the one that would come from an original object. A holographic image has the same depth, parallax and different perspectives as those available in the actual object scene.

If the image of one object is recorded two times in different moments, in the process of reconstruction both images (figures) will appear simultaneously and in the same place in space. Since the object waves are mutually coherent (they originate from the same light beam that illuminates the hologram) they interfere and the interference effects can be observed in the reconstructed object image. If no change occurs on the object between the first and the second exposition, then there is no difference in images and there are no interference fringes. If certain difference appears, then the reconstructed image contains the system of interference fringes N that indicate thet change.

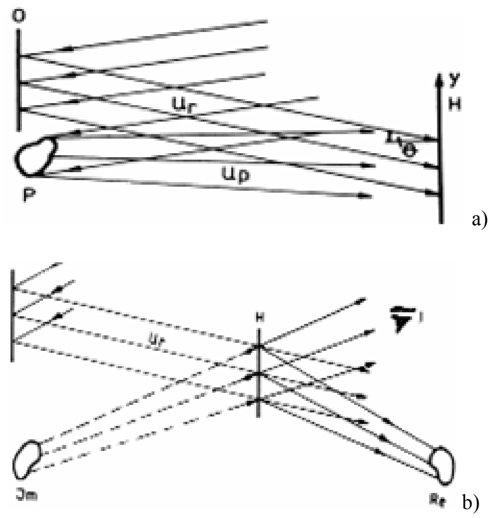


Figure 16. Arrangement for holograms recording a) and reconstruction b)

Quantitative flow testing using holographic interferograms is performed by determining the number of fringes $N(x,y)$ in the field image with respect to a reference point of known density. After that, the index of light refraction $n(x,y)$ and the air density $\rho(x,y)$ can be calculated. For the isentropic flow, there are relations between N, n,, ρ, pressure P, temperature T, velocity V, and Mach number M [9,20,21,36,44]. The physical basics and mathematical interpretation of the holographic interferometry are explaned in references [1,6,7,20,21]. One simple case is the 2D flow [9,21,31-35]

For the processing of interferograms of axisymmetrical phase objects, the method of inversion, based on the Abel transformation, is used. The experiment geometry is usually selected in order to simplify to the maximum the mathematical representation of flow and changes occurring on the path of the laser light beam through the test section [9,21,36-50].

In experimental aerodynamics, the flow field around an axisymetrical model is a typical example for testing the presented method.

Computer tomography is an important technique for reconstructing 3-D fields from holographic interferograms [1,6,21]. It has been under development since the late 1960. Its origins are in the mathematical analysis of Radon. For 3-D field diagnostique three holograms should be recorded over an 180° range of viewing directions.

Therefore, several computational techniques have been developed for computer tomography such as: implicit methods (series expansion, discrete element representations), explicit methods (convolution method), and Fourier transform method. The choice of the best algorithm depends on the density field structure of, the amount and format of available data, the amount of noise in the data, and the nature of the desired information.

In order to demonstrate the advantages of holographic interferometry in complex flow field testings, and comparison with other classical methods, the series of experiments were performed in the MTI wind tunnels at flow velocities from $M1 = 0.7$ to 3.24.

Figures 16 and 17 show the schema and some photos of the holographic interferometers in two wind tunnels. T-36 the wind tunnel test section has windows Φ = 300 mm (schlieren quality) enabling the usage of optical methods. The holographic interferometers with parallel beams, used for the double exposition method [7, 21] are described here.

The light source for recording holographic interferograms is the ruby laser (2, output energy is 3 J, coherence length is greater than 1 m, repetition rate is 4 pulses per minute, the pulse length in the free generation mode is 250 s and 30 ns in the Q-switched mode), while the 6 mW He-Ne laser (3) is used for setting the interferometers in all wind tunnels and for holograms reconstruction. The lasers and all other mechanical and optical components are fixed on the adjusting antivibration table of the height equal to the height of the the wind tunnel axis. Fig.17 shows the schematic drawings of the combined holographic interferometer and schlieren device (side view) in the T-38 with the photos of different components. The dimensions of the interferometer can be illustrated by the object beam length of, which is about 43m and optical field Φ = 900 mm.

The laser light is, by means of lens and mirrors, divided in two parts, enlarged and collimated. One part *Up* passes through the wind tunnel test section (11) and, falls as an object beam on holographic plate (9). The other part of the light beam is conducted across the wind tunnel and sent to the holographic pate. This is a so-called referent or auxiliary light beam (*Ur*). The holographic plate is exposed two times: when the wind tunnel is not operating (when there is homogeneous flow field distribution) and when the wind tunnel is running (when there is a complex flow field, which is the subject of testing). Standard plates with fine grain emulsion (8E75, Agfa Gevaert) are used for hologram recording. With purpose to illustrate holographic interferometry applications, the same photos of holographic images obtained during experiments performed in the MTI wind tunnels will be presented.

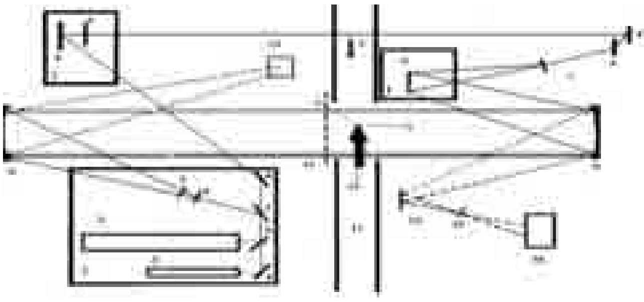


Figure 17. The schema of the holographic interferometer in the T-36 wind tunnel

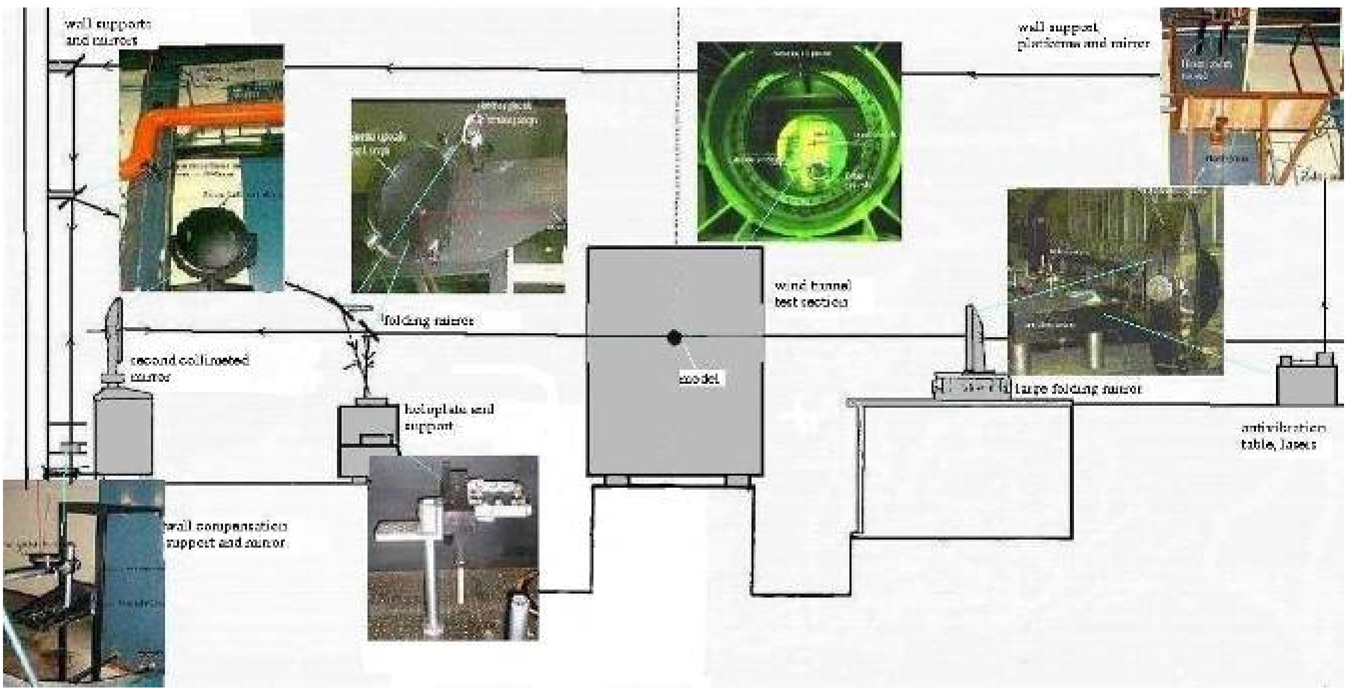


Figure 18. The schema and photos of the holographic interferometer in the T-38 wind tunnel (side view)

Review of holographic interferograms

The usage of classical methods of the nozzle edge flow field testing comprises the introduction of a probe within the expansion region and holes perforation on nozzle surface. These methods significantly change the flow field and give the erroneous image of processes. Furthermore, it would be necessary to have very dense grating of measuring points, thus rendering these methods very inefficient. In realization of this experiment the holographic interferometer represented in Fig.36 was used.

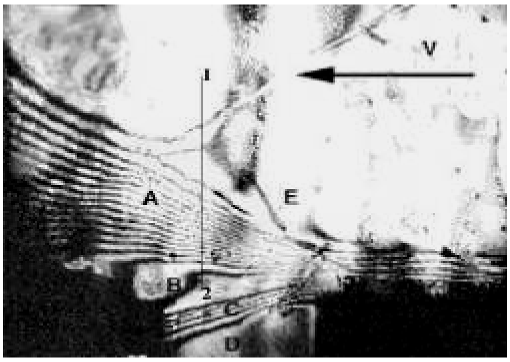


Figure 19. Holographic interferometer of supersonic flow in a two-dimensional model of the nozzle edge (Prandelt-Mayer expansion) M_∞ =1,56

The holographic interferograms were used for numerical calculation of flow field parameters in the vicinity of the nozzle edge where the expansion fen is formed (Fig.19). The fringe number *N* was read from this hologram. The points in front of the expansion fen have *N*=0, since the last fringe has *N*=17. The theoretical and experimental values of the Mach numbers in the expansion area are in good agreement M_{exp} = 2.15, M_{the} = 2.13 [25].

The photos in Figures 20a and 20b present holographic interferograms of the flow around a sphere for M_∞ = 0.8 (without shock wave) and 1.06 (bow shock wave is in front of the model). Fig.20b is a combination of holographic interferograms (upper part) and a schlieren photo of the same flow. The interferometric photo clearly shows: the stagnation point, the detached bow wave, the vortex sheet generated past sphere, etc.

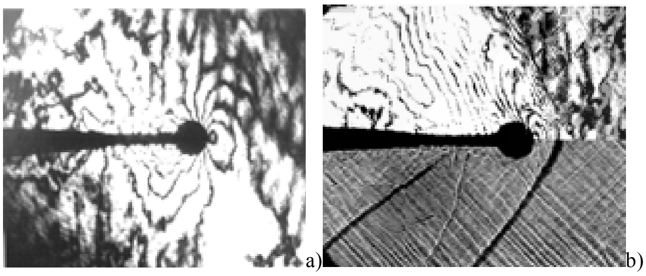


Figure 20. Holographic interferogram of the flow around a sphere for M_∞ = 0.82 (a) and mixed; hologram and schlieren for M_∞ = 1.06 (b)

Flow visualization around tunnel wall perforations [9,26,34,35] is a very interesting example. Many transonic tunnels operate with perforated walls in the test section. A number of investigations have been performed to determine how the flow in the test section is affected by the presence of the perforation. The following photos (Fig.21.) report on a test performed in the T-36, with a single slanted slot in the bottom plate of the test section.

The disturbances originating from the slot are expressed by distortions of the parallel fringe system. A concentration of fringes indicated the formation of a pressure wave. The slanted slot was used because it had been reported that such geometry would considerably reduce the perturbation of free flow.

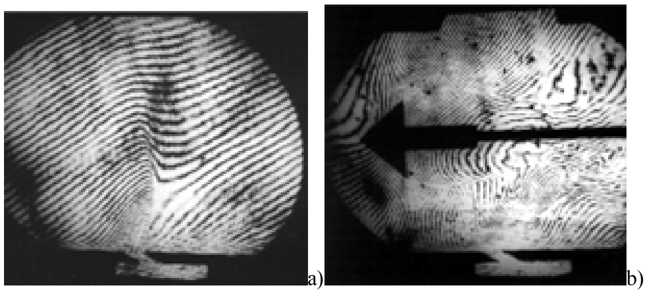


Figure 21. Holographic interferogram of the flow in the empty wind tunnel test section with the wall perforation (slanted slot) (a) and with the cone for M_∞ =0,83 (b) [9, 26,34,35]

The interferogram, however, shows that the disturbance from the slot is not at all negligible and reaches even beyond the axis of the test section (to about 60 % of the test section height). The perturbation has the effect on the model sting mounted in the central line of the test section (Fig.21b). The flow around a model, a cone with Φ=100mm and a top angle of 90°, for M_∞ = 3.24 is very different (Fig.22), related to the flow presented in Fig.21.

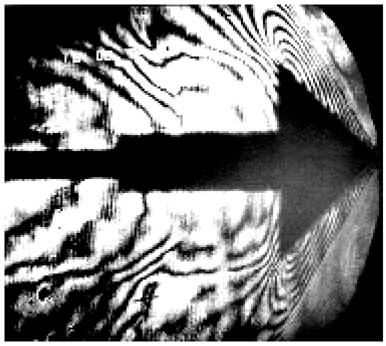


Figure 22. Interferogram of the flow with M_∞ = 3.24 around the cone (top angle 90°)

The combined photos (Figures 20b and 23) are usefull for comparative analysis of different optical flow visualizatiom methods.

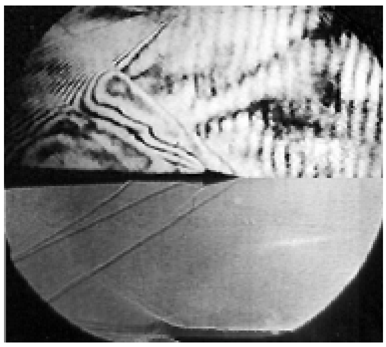


Figure 23. Combined photo: the holographic interferogram and the schlieren effect of the flow around a small cone for M_∞ = 1.56

The interferograms of several different configurations of supersonic rocket nozzle barriers are recorded in order to provide a good insight in to the physical processes of lateral force appearance and the racket control system efficiency by lateral force [7,9,29,32,49]].

The flow in the two-dimensional model of the supersonic nozzle with and without three barriers (spoiler, deflector and cone shaped barrier) (Figures 24 and 25) serving as the trust vector control is recorded by the double exposition method. The numerical results are compared to the results of the pressure distribution measurements on the upper and the bottom wall of the nozzle. The interferometric fringes distribution in the nozzle image without a barrier (Fig.24a) is symmetrical with respect to the nozzle axis and represents the point with equal density.

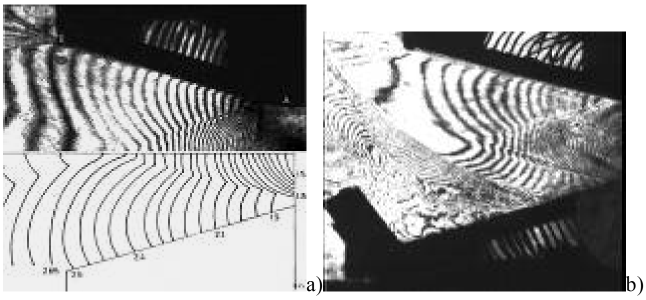


Figure 24. Holographic interferogram of the flow in the two-dimensional model of the a racket nozzle: experimental and theoretical isomach lines in a supersonic nozzle without a barrier a) and with a barrier, deflector, b)

A complex flow field in the nozzle is simulated on a computer through the numerical solution of the partial differential equations and boundary conditions [32]. The identity of the experimental and theoretical isomach line (method of characteristics) is evident. The theoretical value of the Mach number in the output plane of the nozzle is estimated to be M=2.6. The pressure measurements data, result in M=2.46 and holographic calculations give a Mach number of M=2.56. The placing of barriers in the supersonic flow leads to the creation of the stagnation zone and shock and expansion waves (Figures 25a and 25b).

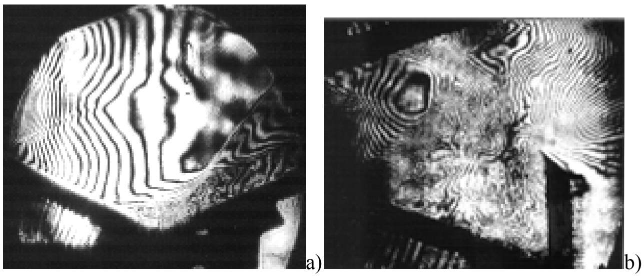


Figure 25. Holographic interferogram of the flow in the two-dimensional model of the rocket nozzle with: a cone shaped barrier a) and a spoiler b)

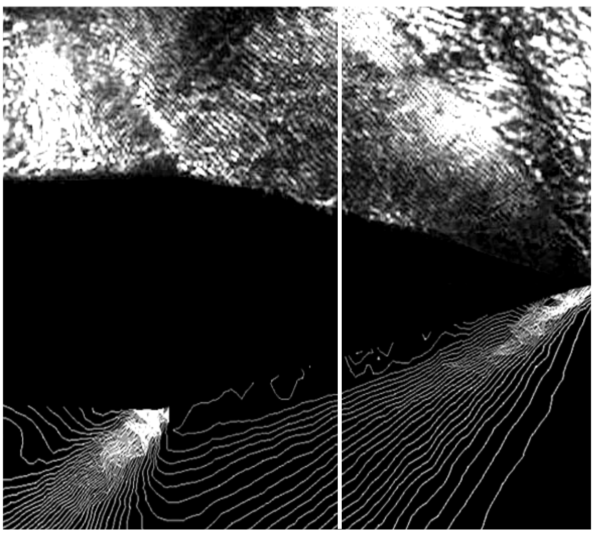


Figure 26. The composite experimental and theoretical image of the flow around the modelof cone-cylinder with M_∞= 1.474

The upper part of Fig.26 is the interferogram of the flow around the model of cone-cylinder (θc=15°, l= 300 mm base Φ=160mm, lc =160mm) for M_∞=1.474, recorded in the T-38 wind tunnel. The calculated flow iso density lines for the experimental conditions and the same model are presented in the lower part of Fig.26.

The Figures 27 and 28 are recorded in the T-36 to illustrate the flow over the plate with a rear step part (noaerodinamical shape) and the flow around a missle for M_∞=1.56.

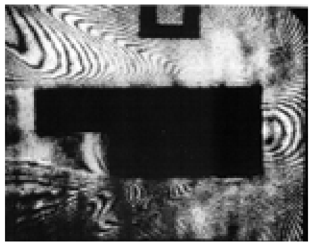


Figure 27. Holographic interferogram of the flow around the 2D plate with a rear step part for M_∞=0.8

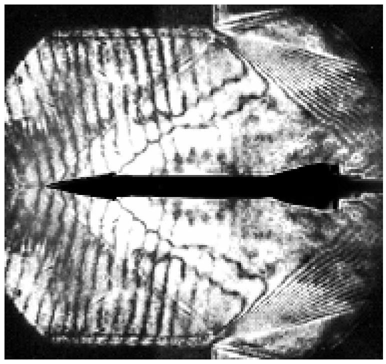


Figure 28. Holographic interferogram of the flow around a missle for M_∞=1.56

Other interferometric methods used for flow visualization world wide

The holographic interferometry, today, is one of very important wind tunnel optical methods for transonic and supersonic flow visualization. In the VTI wind tunnels, the most often used method is the double exposure method.

Other centers apply the real time method, the average or sendvich methods, the specle interferpmetry, refraction interferometry, differential interferometry, etc. Optical holography is most frequent by used, with laser light in the visible spectrum. In standard procedures the interferencial effects are recorded on photo or thermosensitive emulsions. Electronic holography uses CCD cameras. In some specific cases acoustic and microwave holography, with electron beams X – rays, or computer holography can be used. Besides holographic interferometry, similar possibilities today have speckle interferometry, moiré interferometry and shearography. Only two methods of them will be mentioned here as methods used for flow visualization, without pretending to be the best choice.

Laser speckle photography is an optical method which can be applied for quantitative measurements of fluid flow density fields in a wide dynamic range. In the conventional method, the density gradient vector map of a density field is reconstructed by the optical Fourier transform of a double exposed laser speckle pattern recorded on a photographic film. The digital technique, digital laser speckle photography, improves laser speckle photography in the spatial resolution, in the dynamic range and in the efficiency of density field reconstruction. Practical setup of the method is very simple. Since only the light deflection is important for the density measurement in laser speckle photography, a long coherent light length is not required for the laser source and then it has an advantage over other optical methods. The digital images of laser speckle patterns are PC-acquired, and the same algorithm with cross-correlation can be applied to obtained the local density gradient vector [50].

Fig.29 represents the density field analysis of the Mach reflection of the shock wave as a typical problem of compressible fluid flow.

Differential Interferometry is a new technique which enables quantitative analysis of density gradients in flows, based on a Fourier analysis of interferograms and a specially designed interferometer. Differential interferometry produces the first derivative of the refractive index. Real-time color holographic interferometry has been developed to obtain the refractive index *n* 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.

Fig.30 shows visualization examples of diffetential color holographic interferograms [51] .

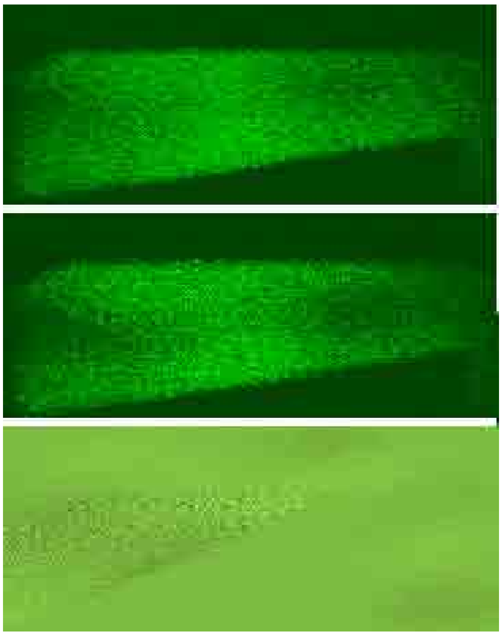


Figure 29. Results of the density gradient vector map by digital laser speckle photography.

In order to demonstrate and to compare complementary possibilities of optical methods in quantitative flow visualization, Prandlt-Mayer expansion tested by three optical methods is presented.

Figures 31a, b and c shows the flow visualization around a 90° corner end edge of a supersonic nozzle. The interferogram is recorded by double passing collimated object beam through the wind tunnel test section. The shadow is recoded on a holographic plate because of collimated beams. The color schlieren is made immediately after holography. Fig.32 include: diagram grad ρ versus y for line with coordinates *x*=40 mm, -30<y<15 mm and superposed photos: the first layer is holografic interferogram and the second one is color schlieren.

Conclusion

In the wind tunnels of the VTI the visualization of complex flows by optical methods has been used for more than thirty years, starting with black and white schlieren system, developing color schlieren systems in three facilities and introducing holographic interferometry in two wind tunnels. The indirect method of visualizing is the Laser Doppler anemometry used primary for flow velocity measurements [7].

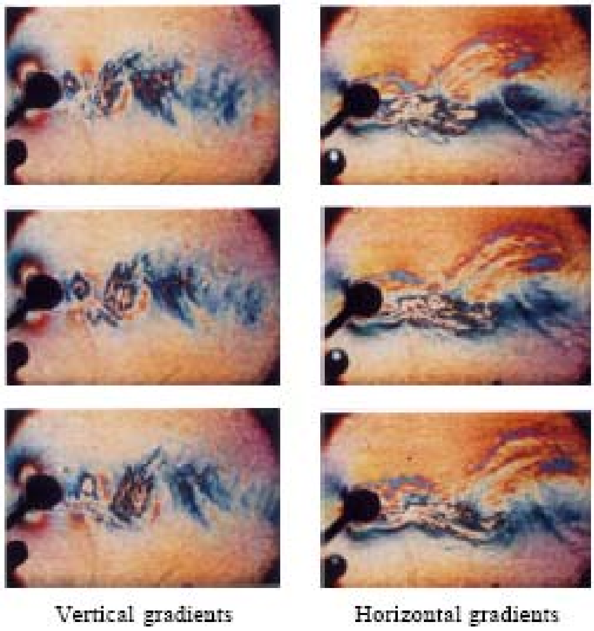


Figure 30. Ultra high-speed direct interferograms of the flow around a cylinder, $\Delta t = 50$ μs [51].

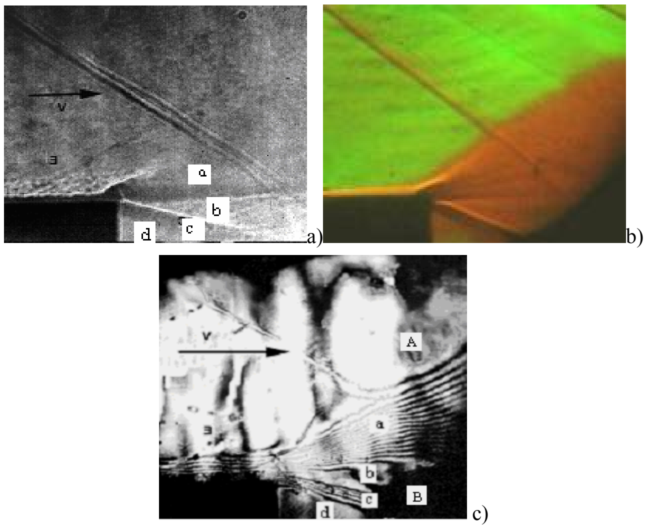
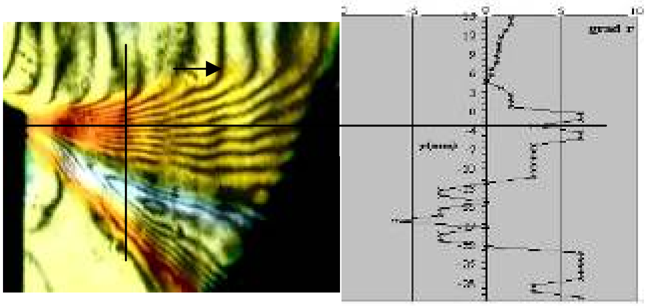


Figure 31. Visualization of the supersonic flow around a two-dimensional 90˚ edge nozzle: a) shadow, b) schlieren and c) interferogram



a) b)

Figure 32. Visualization of the supersonic flow around a 70˚ nozzle edge (the first layer is holografic interferogram and the second is one color schlieren a). The diagram is grad *n* versus y b).

Testing of complex flow fields around models in wind tunnels using the methods of holographic interferometry, showed the significant advantages of this method, compared with shadow and schlieren methods. For a two-dimensional flow, one interferogram is enough to complete flow visualization and calculation. The schlieren method reduces a three-dimensional flow to a two-dimensional image and calculation becomes very complicated. Holographic interferometry gives the best results for transonic and supersonic flows. Holographic interferometry allows a great number of information with high accuracy from a small number of experiments.

Flow visualization methods currently serve as a computational base for different numerical methods.

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Vizualizacija strujanja u aerotunelima – Optičke metode (II)

U ovom radu su prikazane i objašnjene metode vizualizacije strujanja koje se najčešće koriste u aerotunelima. Prvi deo opisuje osnove i primenu različitih metoda za vizualizaciju podzvučnih i nadzvučnih strujanja u aero i vodenim tunelima. Posebna pažnja optičkim metodama (metod senke, šliran metod i holografska interferometrija) i njihovoj primeni u vizualizaciji stišljivih fluida je posvećena u ovom delu rada. Skoro sve prikazane fotografije su snimljene u laboratorijama VTI-a.

Ključne reči: **vizuelizacija strujanja, aerodinamički tunel, optičke metode, metoda senke, holografska interferometrija.**

Визуализация потока в аэродинамических трубах Оптические методы (II)

В настоящей работе приведены и пояснены методы визуализации потока, наиболее и наичаще использованны в аэродинамических трубах. Первая часть описывает основы и применение различных методов визуализации дозвуковых и сверхзвуковых потоков в аэродинамических и во водянных трубах. В этой части настоящей работы особое внимание посвящено оптическим методам (метод тени, шлиран метод и голографическая интерферометрия) и их применению во визуализации сжимаемых потоков. Почти все приведённые фотографии сделаны в лабораториях ВТИ.

Ключевые слова: визуализация потока, аэродинамическая труба, гидродинамическая труба, оптические методы, метод тени, голографическая интерферометрия, методы исследования.

Visualisation du courant dans les souffleries aérodynamiques – méthodes optiques (II)

Les méthodes de la visualisation du courant, utilisée dans les souffleries aérodynamiques le plus souvent, sont présentées et expliquées dans ce papier. La première partie décrit les bases et l'application de différentes méthodes pour la visualisation des courants soubsoniques et supersoniques dans les souffleries aérodynamiques ainsi que dans les tunnels hydrodynamiques. Dans cette partie du travail, l'attention particulière est attirée sur les méthodes optiques (méthode d'ombre, méthode schlieren, intérphérométrie holographique) et sur leur emploi dans la visualisation des fluides compressibles. Presque toutes les photos présentées ont été prises dans les laboratoires de l'Institut militaire technique.

Mots clés: **visualisation du courant, soufflerie aérodynamique, tunnel hydro- dynamique, méthodes optiques, méthode d'ombre, intérphérométrie holog- raphique.**