# Study of Flow Visualization Techniques in Subsonic and Supersonic Wind Tunnels

*by* Mr. Yash

# SUMMER INTERNSHIP REPORT 2020

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DURATION - **30 Days**

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# DECLARATION BY THE STUDENT

I **Yash Raj** student of **B.Tech + M.Tech(AE)- Intg.** hereby declare that the Seminar titled ***"Study of Flow Visualization Techniques in Subsonic and Supersonic Wind Tunnels"*** which is submitted by me to **Dr. Sanjay Singh, Amity Institute of Aerospace Engineering, Amity University Uttar Pradesh, Noida**, in partial fulfilment of the requirements for the award of the degree of **B.Tech + M.Tech(AE)- Intg.**, has not been previously formed the basis for the award of any degree, diploma or other similar title or recognition.

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(Student)

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**Semester**: - 6th

# GUIDE CERTIFICATE

I hereby certify that the project report **Yash Raj**, student of **B.Tech + M.Tech (AE)-Intg. 6, A3705517028,** ***Study of Flow Visualization Techniques in Subsonic and Supersonic Wind Tunnels*** which is submitted to **Amity Institute of Aerospace Engineering, Amity University Uttar Pradesh, Noida** in partial fulfilment of requirement for the award of the degree of **B.Tech + M.Tech(AE)-Intg.** is an original contribution with existing knowledge and faithful record of work carried out by him/her under my guidance and supervision and to the best of my knowledge this work has not been submitted in part or full for any Degree to this University or elsewhere.

# ACKNOWLEDGEMENT

I would like to express my special thanks of gratitude to my project guide **Dr. Sanjay Singh** who gave me the golden opportunity to do this wonderful project of **Aircraft Stability and Controls** on ***"Study of Flow Visualization Techniques in Subsonic and Supersonic Wind Tunnels"***, who assisted me in completing my project. I came to know about so many new things and for that I am really thankful to him.

Secondly, I would also like to express my gratitude for my parents and friends who helped me a lot in finalising my project within the limited time frame.

# TABLE OF CONTENTS

# Introduction

## ➢ Principles of Flow Visualization

One of the methods used in theoretical fluid dynamics is flow visualisation. It differs from other theoretical methods in that it explicitly opens up the visual perception to the properties of a flow field.

The insight into a physical process is always improved if visual inspection can observe a pattern produced by or related to that process. If we think of a fluid-mechanical process in which a fluid flows in a channel or around a solid obstacle, this becomes obvious. By observing such a flow pattern, which with time may be stationary or variable, one can get an idea of the entire flow growth. However, most fluids, whether gaseous or liquid, are transparent media, and during a direct observation their motion remains invisible to the human eye. Therefore, in order to understand the fluid 's motion, one must have some technique by which the flow is rendered clear. These approaches are called techniques for flow-visualization, and have also played an important role in understanding fluid-mechanical problems. Nevertheless, the greater importance of many flow-visualization techniques apart from such instructive applications is that one can derive quantitative data from the obtained flow picture. Such techniques provide knowledge about the entire flow area under analysis without interacting physically with the fluid flow. By comparison, a single flow-measuring instrument, such as a certain pressure or temperature probe, provides data for only one point in the flow field, and therefore, due to the physical existence of the measuring probe, the fluid flow is disrupted to some degree. For example, the experimental evaluation of certain fluid-mechanical processes, the origin and creation of turbulence, still suffers from the fact that the interaction between the flow under analysis and the measuring device significantly affects the results of the experiment. To resolve these fundamental difficulties, there is a continuous progress to which the physical size of the measuring probes and, on the other hand, to enhance the quantitative measurement characteristics of flow-visualization or optical techniques.

Reynolds and Prandtl have carried out a great number of flow-visualization studies to help and demonstrate their groundbreaking work in fluid mechanics. Nonetheless, if one tries to find a person who has played a pioneering role in the creation of flow visualization, one should think mainly of Ernst Mach who was already acquainted with the techniques of schlieren and interferometer, high-speed photography and several other methods. His approach to flow visualization was more fundamental than simply from an engineering point of view.The flow simulation methods can be divided loosely into three classes, the first class involves all the techniques by which a foreign substance may be applied to the moving fluid which may be gaseous or liquid. The foreign material must be visible, and if the particles of which the substance is composed are sufficiently small, one may conclude that the motion of such particles is the same as that of the air, in direction and velocity magnitude. Therefore, visualization is an indirect process, since one examines the motion of the foreign material rather than the fluid itself.The disparity between the fluid 's motion and that of the foreign particles can be minimized, but not entirely eliminated, by giving the particles a density that almost corresponds with the fluid's one. These methods provide excellent results in stationary flows but, due to the finite size of the particles, the errors can be big for turbulent flows.

The ranges of applicability of the two visualization concepts outlined so far, the inclusion of foreign material and the optical approaches, roughly correspond with the groups of incompressible and compressible flows, respectively. A third group of visualization techniques can now be distinguished, which is somehow a combination of the two principles mentioned above. In this case, energy (e.g., in the form of heat or electric discharge) is the foreign substance introduced into the flowing fluid. The fluid elements thus identified by their increased energy level often need an optical visualization system in order to discriminate against the rest of the fluid. For other cases the release of energy is so high that the identified fluid elements are self-luminous, and can be observed directly. Sometimes these methods are used to flow at low average density. Changes in density that occur in such flows can be too small to detect with an optical method. A third group of visualization techniques is therefore applicable, at least in part, to a third class of flows, which is often distinguished from the "standard" incompressible and compressible flows, namely the rarefied or low-density gas flow class. One must be aware that this third technique of visualization is not a non-disturbing process, because it more or less affects the original flow according to the amount of energy produced. The use of flow-visualization techniques in engineering sciences and experimental physics covers a wide area.

# Addition of Foreign Sources into Fluids

## 1. Visualization of the Flow Direction by Means of Dye, Smoke, Vapour, and Tufts

The flow velocity is a vector, and in measuring it one must provide for determinations of both the magnitude and the direction of the velocity as a function of spatial position and time.

### A. Streamlines, Filament Lines, and Particle Paths

Across all points of the flow field, streamlines are the curves tangential to the instantaneous direction of the flow velocity. Such vectors, defined by small arrows, would be tangential to the respective streamlines if we make a two-dimensional drawing of a field of velocity vectors for a given moment. In a three-dimensional field of flow, the relation gives the streamlines.

$$u : v : w = dx : dy : dz,$$

where u, v, and ware the three components of the velocity vector. No fluid is flowing across a streamline at the instant considered.

A filament line is the instant locus of all fluid particles that have passed through the flow field through a particular fixed point. Thus, filament lines (sometimes also called streak lines) can be visualized from selected positions by continuously injecting dye or other appropriate material into the flow.

A particle path is the curve traversed by a single fluid particle as a function of time within the flow area. The particle path includes the integral time history of a single fluid particle's motion. It can be visualized if one takes a long-term exposure photograph of the motion of one foreign particle that was introduced into the flow. If the flow field is stationary, those three curves coincide. But the three forms of curves vary from each other in a flow which also depends on space and time.

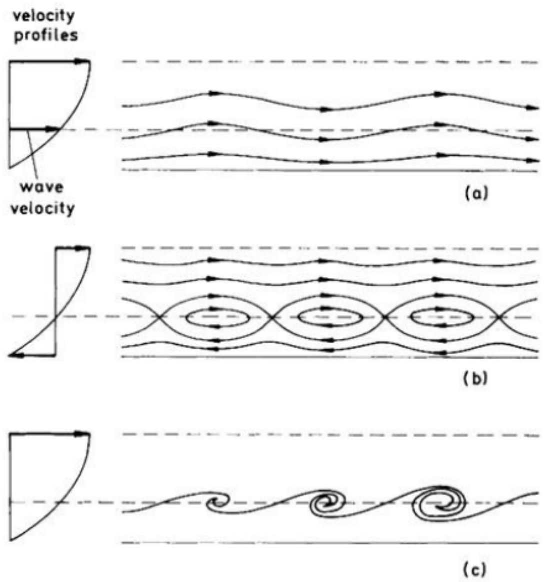



***Fig.*** : Shear layer flow with traveling instability waves. (From Hama, 1962, and Bradshaw, 1970.) (a) Streamlines seen by stationary observer. (b) Streamlines seen by observer traveling at the wave velocity. (c) Filament lines.

## B. Dye Lines in Liquid Fluid Flows

Dye injection has long been a common method for the visualization of filament lines in a water flow. The dye is released either from a small ejector tube positioned at the desired location in the flow area, or from small orifices established under investigation in the wall of a given model. In both cases the fact that the main flow is disturbed to some degree by the presence of the ejecting devices can not be avoided. When studying the flow around a model in a water pipe, the tube from which the dye is spread must be positioned far enough upstream of that model to avoid tube interference with the flow pattern to be examined.

If the dye is released from small holes in a rigid test model surface, it must be ensured that the dye solution does not have a velocity component perpendicular to the model surface; otherwise the injected dye flow would interfere with the main flow around the model. In particular, because of the mass and momentum injected, the nature of the boundary layer at the body wall would be altered.

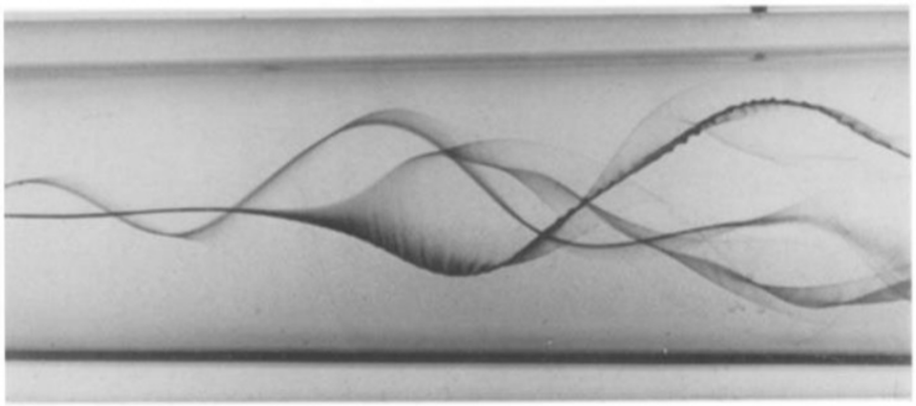


***Fig.*** Dye lines in swirling flow in a cylindrical tube. Fluid, water; dye, food coloring. (From Sarpkaya, 1971.)

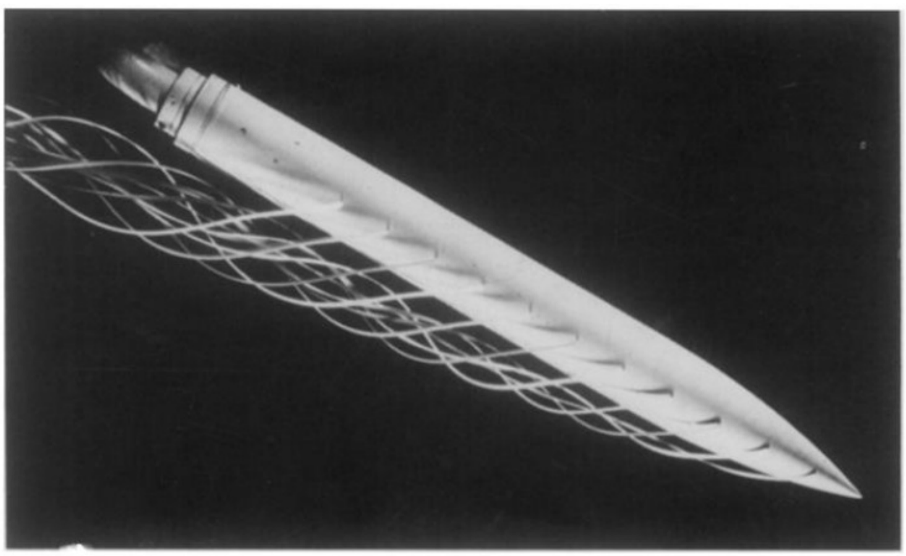


***Fig.*** Dye lines in the vortex flow behind a yawed cylinder. Fluid, water; dye, mixture of ink, milk, and alcohol. Color of original dye lines is red, yellow, and blue. (From Fiechter, 1969.)

c. Smoke Lines

In theory, the technique of labelling filament lines or other flow regimes in an air stream using smoke is the same as visualizing the flow pattern of a liquid fluid by ejection of dye. There are many facets to the option of using smoke for a wind tunnel experiment. The smoke, particularly when applied in an open tunnel network, must be dense and white for visibility, nontoxic, and noncorrosive. Most smokes don't meet any of these criteria so they need to find a solution.

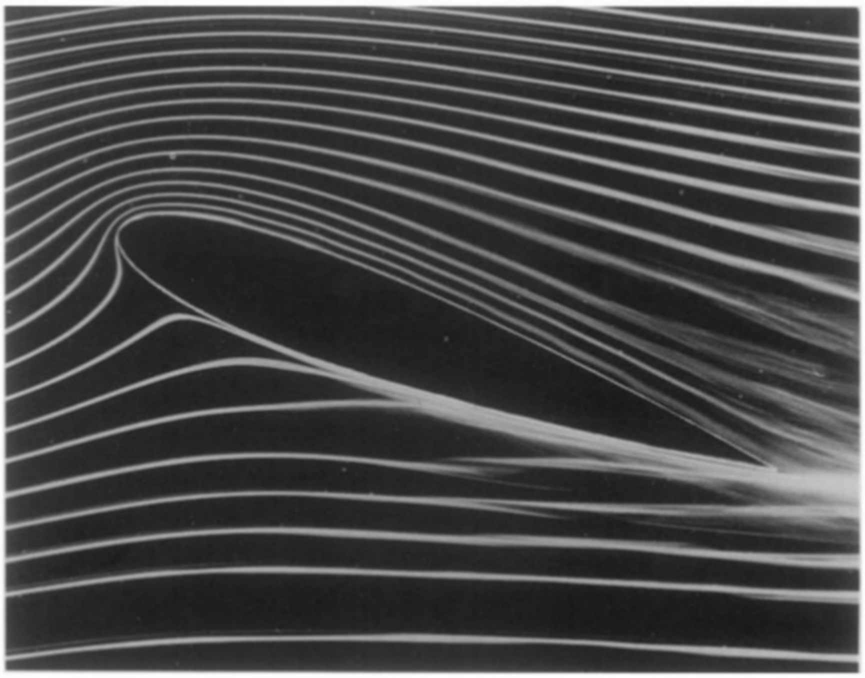


***Fig.*** **. Smoke lines around the model of an airfoil in a wind-tunnel stream. (From Educational Services, Inc.)**

## D. Smoke-Screen and Vapor-Screen Methods

A wind tunnel facility where smoke is inserted at the front of the test section to allow a long, diffused stream of smoke to flow through the test model is often called a smoke tunnel (Maltby and Keating). Unlike the flow path representation through smoke filaments, where the width of these smoke lines is small relative to the test model 's diameter, here one has the case that the smoke stream 's diameter is greater than the test model 's diameter.

The principle of this approach is to operate the tunnel with moist air; the air cools as it expands through the supersonic nozzle, and the humidity condenses to create a fog in the tunnel's test area. Due to the existence of a rigid test model, the uniform distribution of fog in a normal cross section to the tunnel axis is disrupted, and the patterns of wakes and vortices that be visualized behind the model if one applies the same slit as the illumination defined for the smoke-screen technique.

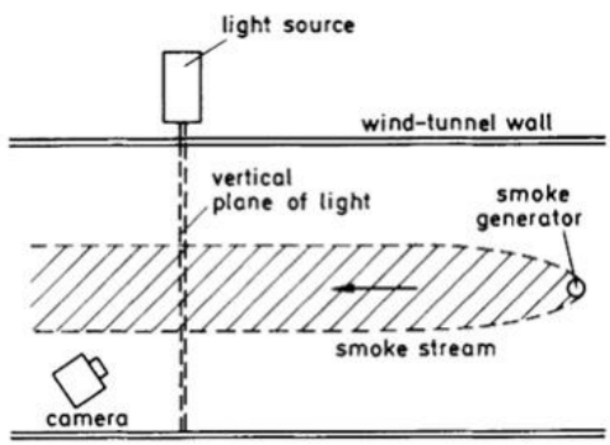



***Fig.*** Arrangement for smoke-screen tests in a wind-tunnel flow.

## E. Tufts and Tuft Screens

A fairly easy way to get an idea of the direction of flow around a solid test body is to add one end of short tufts to the surface of that body. Those tufts show the local direction of flow in a laminar air flow. However, when the mean flow is constant, the tufts show some erratic motion, this can be taken to mean that the boundary layer of the wall has become turbulent. A more aggressive tufts movement, or a tendency to rise off the surface, suggests a separate flux system. Tufted nylon yarn is a material appropriate for such simulation of the tuft flow, provided the air speed is not too high. On the other hand, air velocity in the tunnel should not decrease below 1 or 2 m / sec, as material rigidity and gravity would otherwise affect the outcome. For this purpose ordinary yarn will serve at air velocities above about 30 m / sec. The tufts should not exceed 2 cm in length, and a general rule is that their length should be small compared with the projected curvature radius of the streamlines.

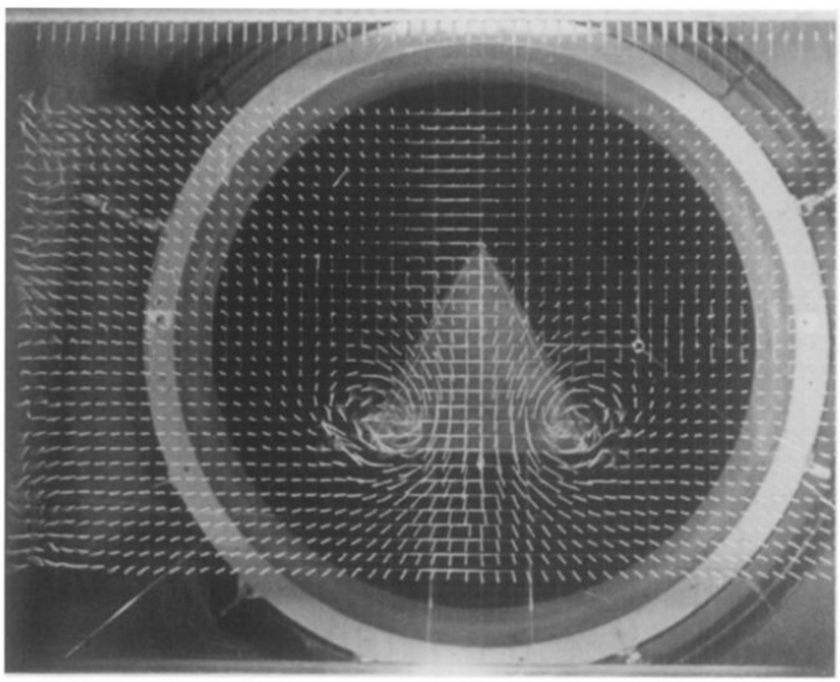


***Fig.*** . **Trailing vortices behind an inclined delta-wing as visualized by a tuft screen. (From Gersten, 1956.)**

## 2. The Hydrogen-Bubble Technique

After dealing with tracer particles whose densities surpass those of the fluids, we are now considering the case where the tracer particle density is lower than the density of the fluid whose movement should be made clear. Gas bubbles in water are an example of such a mixture of particles / fluids but it is also possible to produce a reduced density of either the same or foreign gas in a gaseous flow "bubbles."

Unless the flowing fluid is an electrolytic conductor, the electrolysis of this fluid will produce gas bubbles, e.g. hydrogen and oxygen bubbles, by means of an electrolytic aqueous solution. For flow visualization purposes, it is desirable to use these electrolytically induced gas bubbles as the bubbles can be formed at a controlled rate and at any desired place in the flow. It turns out that regular tap water is an ideal electrolyte conductor for implementing this theory. Once two electrodes are inserted into such a water flow and a dc voltage is applied between the electrodes, bubbles of hydrogen are formed at the cathode and bubbles of oxygen at anode. Since the hydrogen bubbles grow much smaller than the oxygen bubbles, they only use the hydrogen bubbles as tracer particles. For flow visualization purposes, it is desirable to use these electrolytically induced gas bubbles as the bubbles can be formed at a controlled rate and at any desired place in the flow. It turns out that regular tap water is an ideal electrolyte conductor for implementing this theory. Once two electrodes are inserted into such a water flow and a dc voltage is applied between the electrodes, bubbles of hydrogen are formed at the cathode and bubbles of oxygen at anode. Since the hydrogen bubbles grow much smaller than the oxygen bubbles, they only use the hydrogen bubbles as tracer particles.

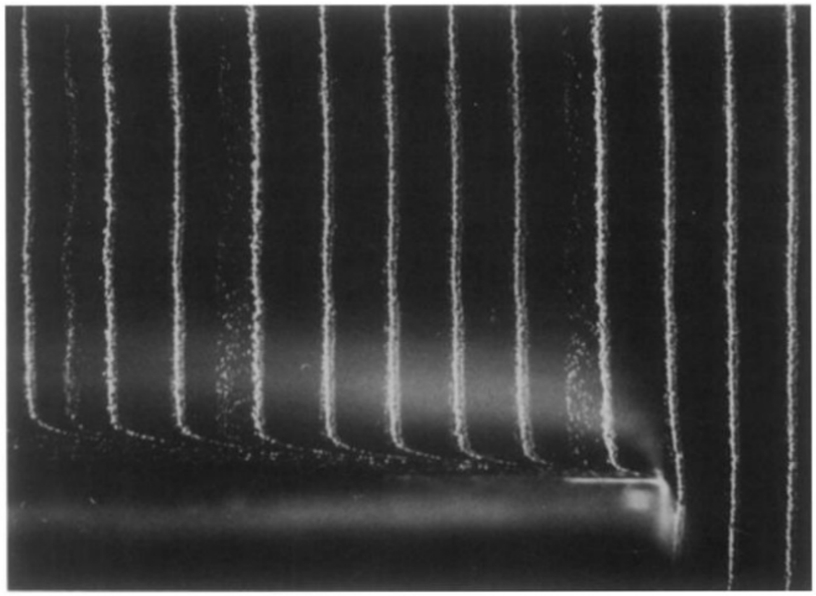


***Fig.*** Consecutive rows of hydrogen bubbles indicating the velocity profile in the boundary layer over a flat plate. (From Bippes and Görtler, 1972.)

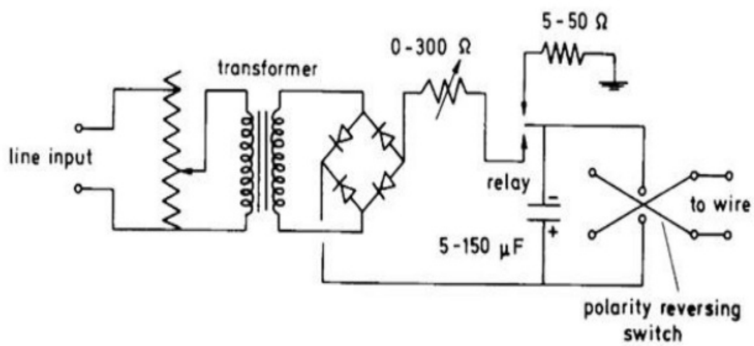



***Fig.*** Electric circuit for hydrogen-bubble wire. (From Schraub *et al.*, 1965.)

# Optical Methods for Compressible Flows

## 1. The Shadowgraph

The system used in the shadow method, usually credited to Dvorak (1880), an E's coworker. Mach, is the simplest of all types of optical visualization.

This system uses no optical equipment to make the light identical, except the circular mirror (which can also be a lens). The photographic plate is a distance l to the segment of examination. The sharpness of the image obtained on this screen depends on the size of the source of light. By tracing the most separate rays that emerge from an extended light source, one finds that the lack of image sharpness is roughly given by ld / fI, where d is the source diameter and fI is the mirror (lens) MI's focal length. This follows, however, that the source of light should be small-not greater than a certain limit where the loss of sharpness due to diffraction effects is apparent.

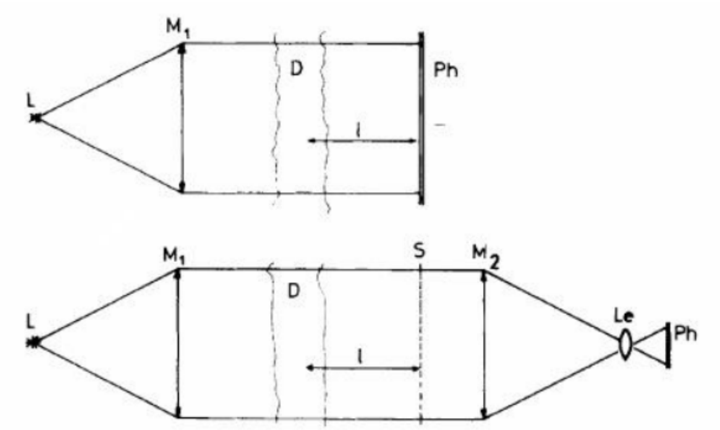



***Fig.*** Schematic arrangement of two shadowgraph systems; L = light source; $M_1$, $M_2$ spherical mirrors or lenses; D = optical disturbance (test object); Le = camera lens; Ph = photographic film or screen.

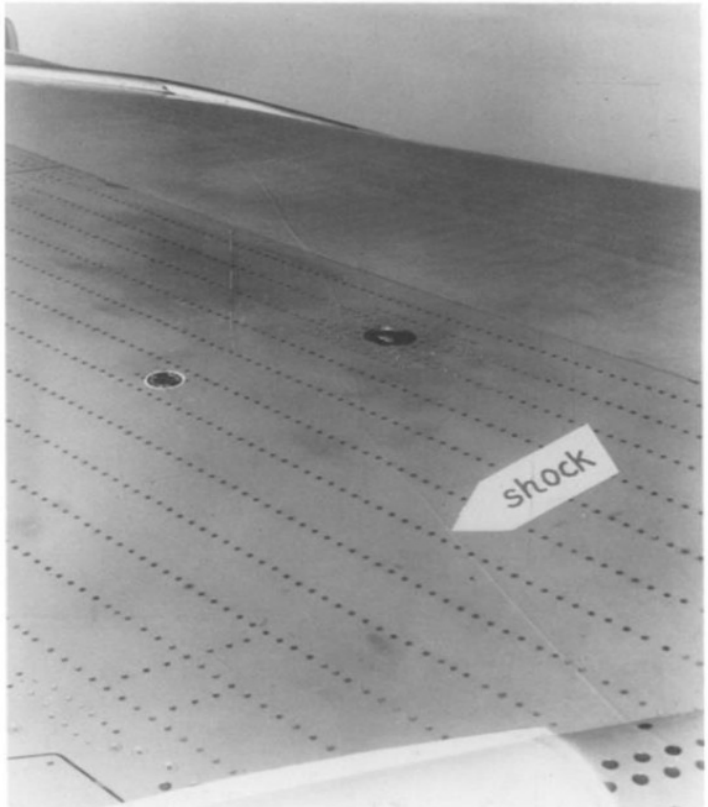



***Fig.*** Shadow of a local shock on the wing of an aircraft flying at high subsonic speed. (From Larmore and Hall, 1971.)

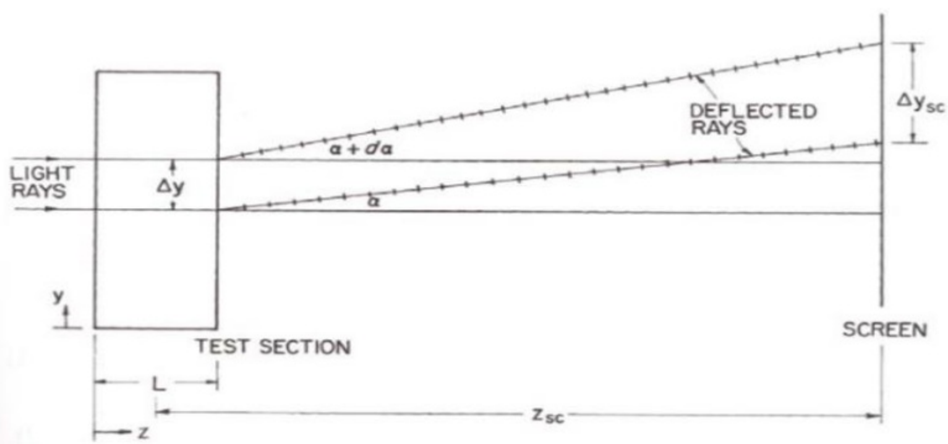
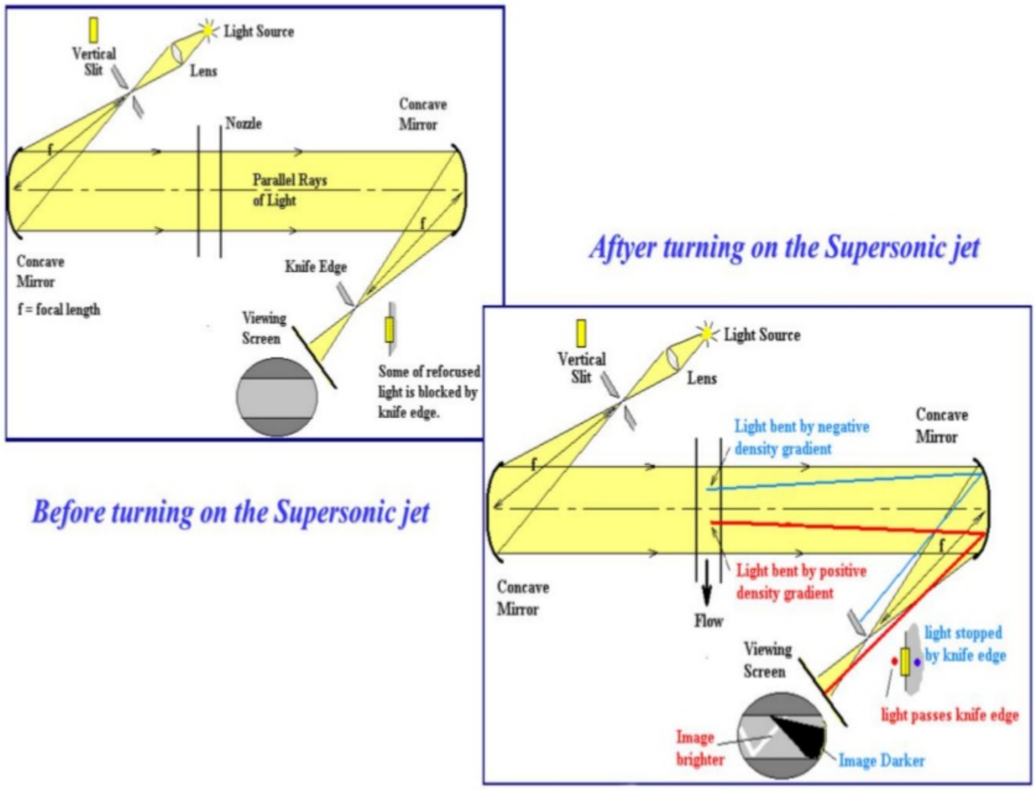



**Figure** Displacement of light beam for shadowgraph evaluation

## 2.The Schlieren Method

Within a transparent medium the German term schliere designates a local inhomogeneity that causes an irregular deflection of light. Many optical instruments have been credited to the word schliere, which helps one to not only imagine qualitatively certain optical inhomogeneities, but also quantitatively calculate the sum of deflection. The theory of the method was developed more than a century ago and is credited to Foucault (1859) and to Toepler (1864), depending on the national choice of the authors. Foucault used this device, the main component of which is a knife edge for checking the quality of optical elements such as lenses and mirrors, whereas Toepler recognized and described in his book the wide applicability of this "knife-edge method," including the visualization of compressible flows; therefore, the name "Toepler method" has become common in this field.

The schlieren approach is probably the most commonly used optical visualization technique in aerodynamic and thermodynamic laboratories, as it combines a fairly simple optical arrangement with a high degree of resolution.




## 3.The Mach-Zehnder Interferometer

While the light deflection in a compressible flow field is used for both shadow and schlieren approaches, the related phase alteration is the basic effect for interferometer visualization of such flows. For classical interferometry of two-beams, e.g., with the instrument named after L. Mach and Zehnder, the phase of the disturbed light ray is compared to the phase of an undisturbed ray by interfering with each other with such corresponding rays. The application of this principle to the representation of compressible flows is as old as the schlieren method: E used the well-known interferometer Jamin developed in 1856. Mach and von Weltrubsky (1878) research the phenomenon of gas dynamics. E. Mach realized that it was beneficial to provide a spatially more distinct instrument with test and reference beams for better implementation of the method; Zehnder (1891) and E developed the practical realization of this concept independently. Son of Mach L. (1892) Mach. The Mach-Zehnder interferometer (MZI) is much more suitable for quantitative density measurements, compared to the shadow and schlieren method; nevertheless, its architecture often includes a high degree of mechanical precision and com-complexity.

This demonstrates a simple structure of the MZI. The point source light is composed parallel to the lens (or spherical mirror) L1. The interferometer's essential components are the plane, fully reflecting mirrors l\h and M2, and the plane, semi-reflecting mirrors (beam splitters) Nh' and .M 2' which are arranged here to form a rectangle. The test section is brought into the path of the "test beam" with its two glass windows, whereas two identical glass plates are inserted into the path of the "reference beam" to compensate for a loss of coherence between both light beams. The corresponding rays of the two light beams can interfere after being rejoined behind the plate M2 and a certain pattern of interference fringes appears on the screen or photographic plate, which is focused on a plane in the test section by means of the camera lens Le. An inhomogeneity in the test section results in a certain disruption of the non-flow fringe structure, which may, in certain cases, be related quantitatively to the flow field density distribution.

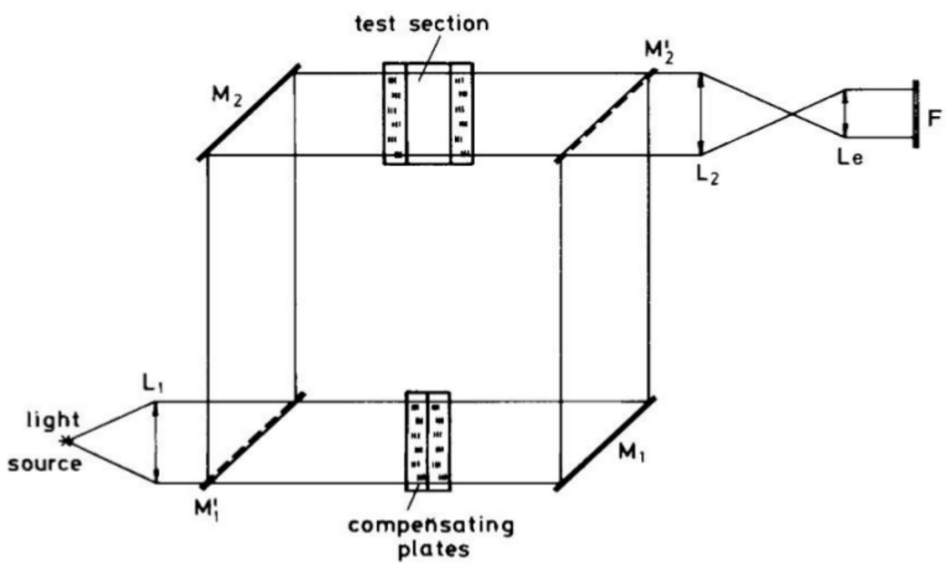



***Fig.*** Basic arrangement of a Mach–Zehnder interferometer.

# 4. Flow Visualization Using Laser Light

Due to optical laser invention, the means for flow visualization is extended across a broad range. Laser light is highly monochromatic and consistent; some types of laser are capable of producing extremely short-lived, high-energy, light pulses. As a result, laser-light sources have been successfully applied to modern optical visualization systems, but have also resulted in the advancement of entirely new approaches such as holography and holographic interferometry. The laser also enabled investigators to measure gas densities and velocities directly, e.g. by using light scattering, which would not be possible with a less monochromatic light source; although these arc methods are not pure visualization systems, they will be briefly described here. Finally , high-energy pulsed lasers can produce small, concentrated spots of plasma that can serve as tracers for measuring gas velocity.

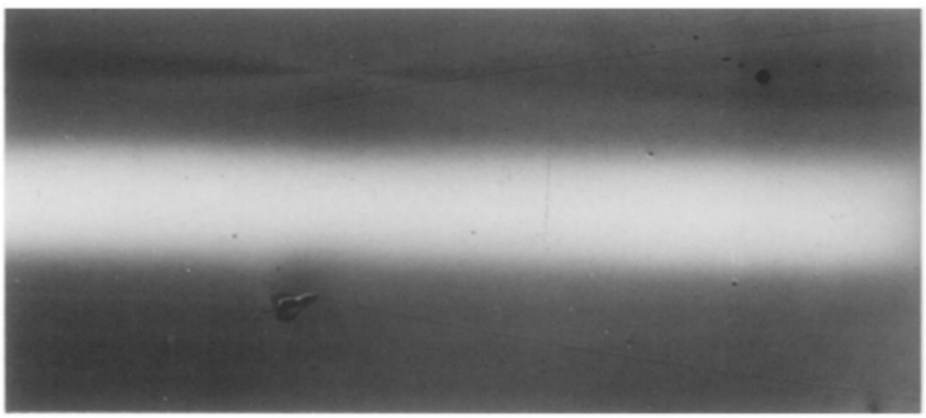


***Fig.*** Spark shadowgraph of a sphere flying with a velocity of 5000 m/sec in air. With an exposure time being much too long, the photographic camera records only the radiation emitted from the hot gas in the stagnation zone of the sphere. A superposed pulsed-laser shadowgraph shows the bow shock of the model. (From Naval Ordnance Laboratory, White Oaks, Md.)

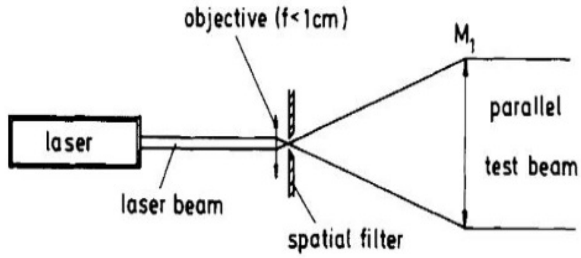



***Fig.*** Spreading and filtering of a laser light beam for the use in an optical visualization system.

## 5. Holographic Flow Visualization

A traditional photographic camera records the three-dimensional scenery's two-dimensional projection, and the image does not contain accurate scene depth information. Nevertheless, in ai hologram one can store all the light waves that come from the scene, and it is possible to recreate these waves at a later time and thus produce a true 3-dimensional image. Holography is not a flow-visualization approach but it can lead to a number of new results in combination with existing visualization systems. The key benefit is the prospect of holographically freezing the flow scene and analyzing it with suitable means later upon restoration.

The holography theory can be represented in mathematical analogy. To evaluate the wave system within a given sector of space, it is necessary to know the amplitude and phase distribution of a wave system on a distinct surface. Therefore the hologram is equivalent to a given set of boundary values, and the wave reconstruction corresponds to the solution of this question of boundary-value. One condition for capturing a hologram is that a particular wavelength and a constant-phase relation describe the wave field, which means one has to work with coherent light. That is why Gabor, who had discovered the holographic principle in 1948, was scarcely able to realize his experimental ideas. Since 1961, only the invention of the laser-light source and the work of Leith and Upatnieks has led to holography becoming an important research tool..

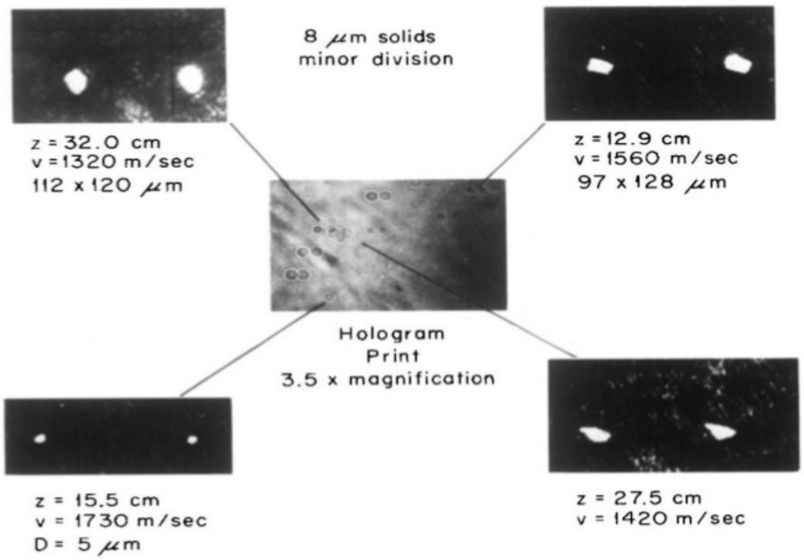



***Fig.*** Double-exposure hologram of a high speed dust flow and four reconstructions obtained by focusing the camera at different planes $z$ = const in the flow field; particle size and velocity $v$ are indicated for each reconstruction; double-pulse separation 0.48 $\mu$sec. (From J. D. Trolinger, ARO Inc., Arnold AF Station, Tenn.)

# 6. Holographic Interferometry

The holography theory has paved the way for new kinds of interferometric methods. The idea is that information of two (or more) light waves can be processed on a holographic plate and these originally separate information released simultaneously. The recovered waves converge and interact with each other, given the conditions for coherence are met. This holographic interferometer is usually operated on the same holographic plate by means of a double exposure. One exposure is produced in the absence of the object being examined, and constitutes the "reference point" in a Mach-Zehnder interferometer; the second exposure shall be made with the item in place and shall constitute the MZI "check spotlight." On illumination of the double-exposed hologram with the holographic device reference light one reproduces the pattern of light waves which is the superposition of the two light waves of the individual recordings. Thus the same pattern of interference as that behind the MZI 's second splitter plate M2 'can be obtained. The key difference between these two interferometers is that the two interfering beams, "guide" and "check," exist simultaneously, but in the case of the MZI they are spatially separated, while they occupy the same spatial location but are separated in time for the case of the holographic interferometer.

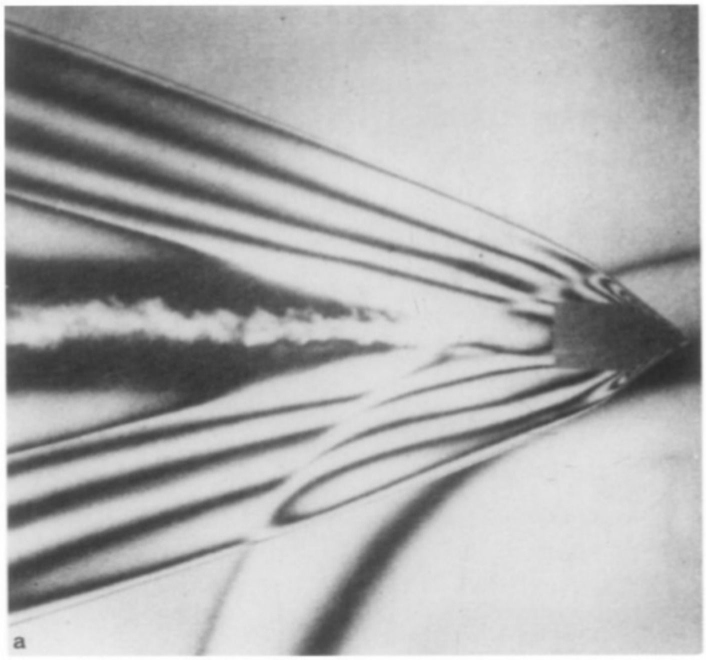



*Fig.* Infinite fringe holographic interferogram of a supersonic projectile—blast wave interaction. −20° view,

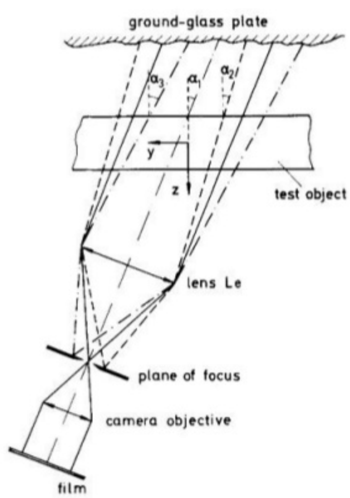



*Fig.* Observation of the interference pattern produced by a parallel light beam which has traversed at a direction $\alpha_1$ through the test object. Other light directions $\alpha_2$, $\alpha_3$ from the diffusing plate are blocked off in the focal plane of lens Le.

# Flow-Field Analysis by Heat and Energy Addition

## 1. Artificially Introduced Density Changes, Sparks, and Hot Spots

In this case the foreign substance is immaterial, it is energy that will be passed to certain portions of the flow. Such parts or fluid components function as tracers in the flow, and due to their elevated energy level, they may be discriminated against the rest of the stream. The manner in which discrimination occurs depends on the form of flow and the amount of energy entered in the fluid.

Through applying the energy to an incompressible fluid field at singular points, the fluid is rendered dynamically for differences in density. Such parts of the fluid having an altered density level can either be visualized using the existing optical methods, or can be directly observed due to a certain degree of luminosity of the respective fluid element if the rate of energy transferred to the flow is high. This luminosity is not only correlated with the production of strong sparks in a gas flow, but also with the methods of electron-beam and glow-discharge. A easy way to add heat to an incompressible gaseous flow is to brace a thin wire that is electrically heated across the stream. The temperature of the fluid elements moving close to the wire is increased, and as the pressure in the flow remains constant, their density is lower than that of the surrounding, undisturbed flow. The difference in density may be controlled by the electric current. Schardin (1942) showed that filament lines can be observed in a two-dimensional low-speed air stream with a grid of these wires. The grid is perpendicular to the direction of flow in a circle, and the filament lines are visualized with the help of a schlieren device that has the light beam parallel to the grid wires. As previously defined, filament lines consist of fluid particles which have all passed the same fixed point in the field of flow, in this case the heated wire. To discern the filament lines over a greater distance downstream of the wire, the rate of diffusion of the heated gas into the undisturbed flow is expected to be small, i.e. the ratio of diffusive velocity to flow velocity remains low. This condition can only be fulfilled in a laminar flow; thus, the method is suitable for detecting changes in a stream laminar-to-turbulent, which would appear on a schlieren picture in the form of a sudden decay of the filament lines. If one uses a periodic pulsed current instead of a stationary current to heat the wire, one can create "hot spots" in the flow that are also observed with the help of a schlieren device (Dewey, 1973). A schlieren photograph made with a sufficiently short exposure time shows several hot spots in the flow field that were created by the wire's repetitive heating. As the time interval between electric pulses is known, one calculates the flow velocity on the images from the distance of the hot spots.

***Fig.*** Shock-tunnel air flow of hypersonic Mach number around a blunt test model. Temperatures in the stagnation zone in front of the model exceed 4000°K, so that the gas in this flow regime becomes luminous. (From NASA Ames Research Center.)

## 2. Velocity Mapping with the Spark-Tracer Technique

The high voltage applied in a gaseous flow between two electrodes can produce an electric spark discharge that can be used to discriminate and visualize certain flow elements, as shown in the preceding section. The ionized fluid element, and thus illuminated by the discharge, is the tracing element in the flow. A special modification of this technique discharge helps to map the distribution of velocity in some fields of flow.

We consider two electrodes with several centimeters of spatial distance in the flow of gas. The first passing of a spark after a discharge produces an ionized path or column in the gas that persists for a period of the order of 100 p.sec; depending upon conditions of discharge. The mean flux sweeps this column downstream. Since the plasma column exhibits less electrical resistance than the surrounding neutral gas, a second spark produced during the lifetime of the column would prefer to follow this preionized path traced by the first spark, rather than taking the shortest and most direct route between the electrodes. If a series of short-lived sparks are created during the flow at intervals smaller than the aforementioned plasma lifetime of approximately 100 p.sec, every spark of the series will follow and thus re-illuminate the column traced by the first spark. Since this column is displaced with almost the flow velocity, an open-shutter image can be used to obtain a profile of this displacement by the flow. One may derive the local flow velocity from the known frequency of the spark series and the measured displacement. The three-dimensional velocity distribution can be calculated by photographing the spark series with a stereoscopic camera. In mapping the velocity profiles the technique resembles the tellurium and the hydrogen-bubble methods used for the visualization of water flows is sketched the application of the spark-tracing technique to three different flow types.

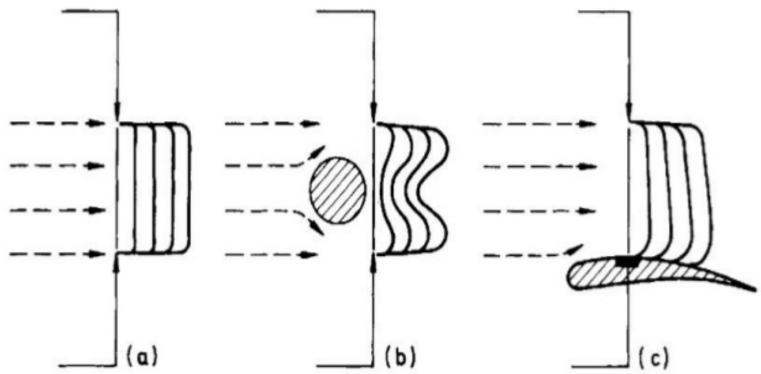



***Fig.*** Principle of the spark-tracer technique applied to three different flows: (a) uniform, parallel flow; (b) wake flow behind a sphere; (c) flow over an airfoil profile.

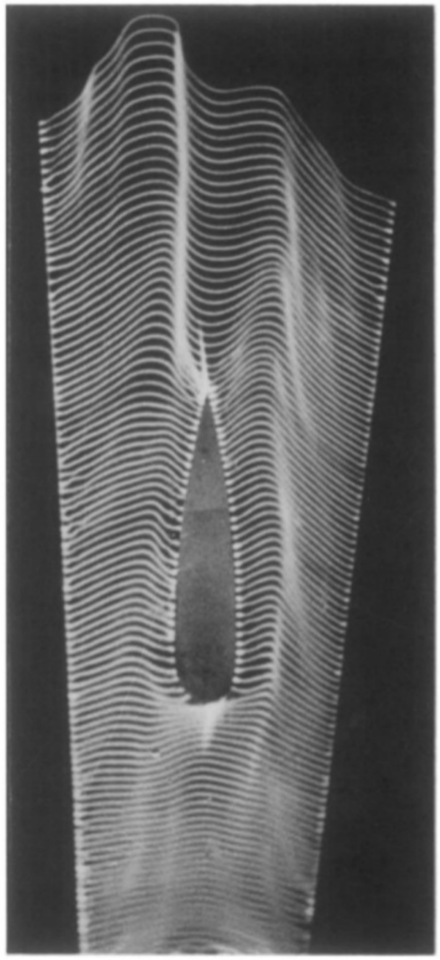


***Fig.*** Laminar flow around a metallic profile. The model is placed between two rod electrodes. (From Früngel, 1970.)

# 3. Electron-Beam Flow Visualization

The optical methods used for the visualization of compressible flows have a certain sensitivity limit when the gas density decreases. A variety of techniques has been developed for the purpose of visualization below this density level. The most promising of these techniques is the electron-beam method, in particular for quantitative measurements; others will be discussed in the paragraph below. The gas flow under investigation is traversed by a narrow beam of high-energy electrons; due to inelastic collisions between fast electrons and gas atoms or molecules; a significant portion of the gas particles will be excited and then return under spontaneous emission of the signature radiation to the ground state. The intensity of this radiation is proportional to the absolute gas density under such conditions , allowing for a quantitative representation of flows in which changes in density occur. For several reasons, the range of useful application of the electron-beam method is limited to low gas density levels , making this method a suitable extension of the optical visualization techniques into the field of rarefied gas flows.

This technique of electron-beam flow-visualization was pioneered by a paper of Grlin et al. (1953). Instead of measuring the total radiation intensity, a spectroscopic analysis of the radiation from the electron-beam can also be provided. The intensities in the radiation spectrum of a single line and a band are proportional to the number density of the test gas particles, the proportionality factor depending on both the test gas vibration and rotational temperature. Therefore, the spectroscopic study and the line and band intensity calculation helps one to determine the vibrational and rotational temperatures as well as the concentration concentrations of the active gas species.

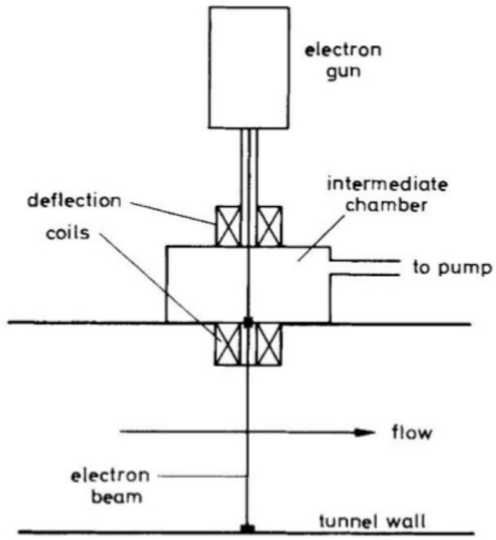



***Fig.*** Principal arrangement of the electron-beam visualization technique.

# 4. Glow Discharge and Chemiluminescence

It is well known that light emission is accompanied by the electrical discharge in gases at low pressures. A typical distribution of the electrical potential in the field between two electrodes which generate the glow discharge and a schematic representation of the respective light emission is shown; this figure applies to the stationary field in an evacuated vessel without flow. The process that induces the discharge glow is somewhat similar to that of the electron-beam technique: the ambient electrical field accelerates free electrons and ions that are unintentionally in the control region, and may generate secondary electrons and ions due to collisions with neutral gas molecules. The primary and secondary electrons and ions can cause gas molecules to excite, which subsequently emit a characteristic radiation under spontaneous transition into ground state. The intensity of this radiation depends on the density of the gas in the volume of control, and therefore one has studied applying this method to the visualization of rarefied gas flows, where the gas in the volume of control is not at rest but flows at a certain velocity.

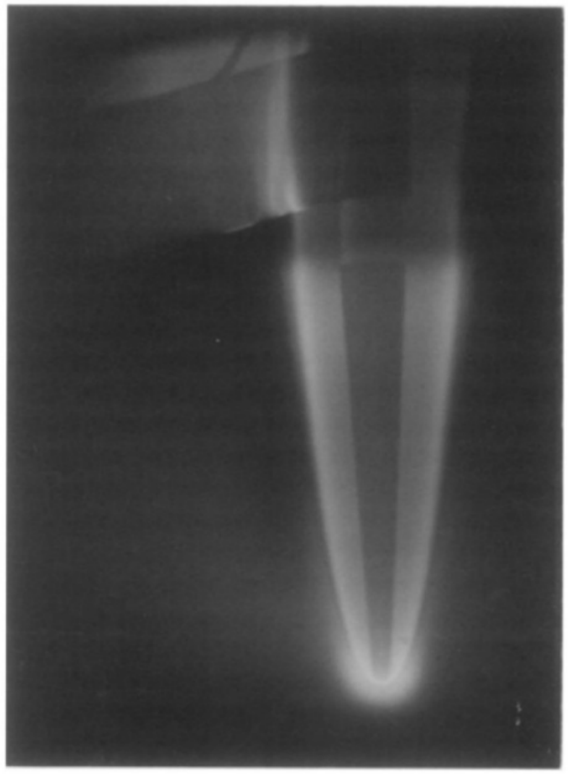


***Fig.*** Glow discharge photograph obtained in a helium wind tunnel with a free-stream Mach number of 40. The test model is a slender cone with spherical nose. Glow appears light violet on a dark blue background. (From E. E. Horstmann, NASA Ames Research Center.)

# Special Problems

## 1. Streaming Double Refraction

One hundred years ago Maxwell (1873) and E. At the same time, Mach (1873) discovered that when subjected to shearing stress certain liquids and solutions become doubly refractory. This phenomenon is sometimes referred to as the "Maxwell effect." These birefringent fluids in a neutral solvent may be pure liquids, and, ideally, solutions or suspensions of other macromolecules. Birefringent fluids may be Newtonian, or a non-Newtonian stress-strain behaviour may be present. The birefringence can be observed through a polariscope; the observation technique is the same as for the analysis of photo-optical stresses. Such visual studies have long been carried out with a view to obtaining knowledge on the physical , mechanical and configurational properties of the molecules solved or suspended. Many investigators have recognized the additional possibility of using the double refraction streaming, or, as it is also called, the birefringence streaming as a tool for visual flow analysis. When composed of optically anisotropic molecules, a transparent medium can be birefringent. As is the case in a crystalline system ( e.g., calcite, quartz) these molecules must have a uniform orientation. In such a medium the light propagation is directionally dependent.
In the birefringent medium an incident light wave is separated into two linearly polarized components, with the polarization planes perpendicular to each other. The phase velocities of the two light components are different, as are the respective refractive indices; this causes the two waves to leave the birefringent material with a certain phase difference. In order to produce interference patterns, both waves must be polarized in the same direction.

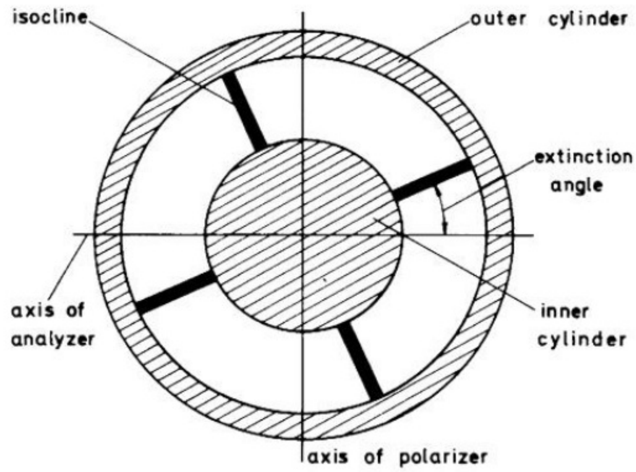



*Fig.* Cross of isoclines in the couette flow between two concentric cylinders.

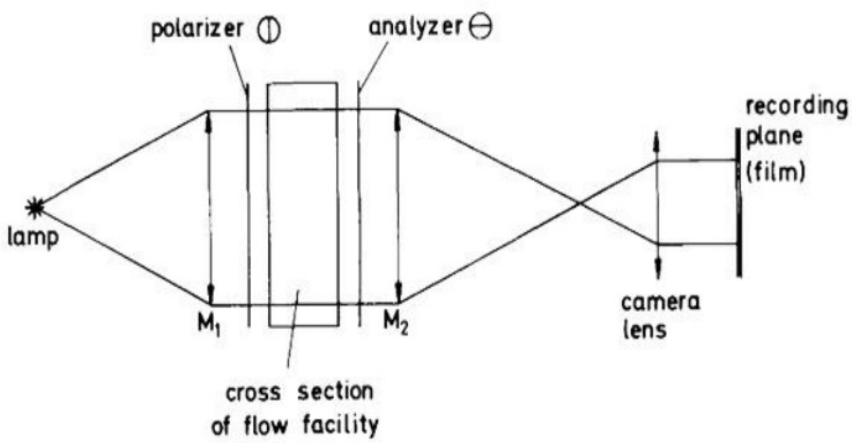



*Fig.* Optical arrangement and polariscope.

## 2. High-Speed Photography

A flow pattern visualized with one of the methods or techniques described can be observed by eye or recorded using photographic media. In the latter case one may either expose single photographic images, or if the flow pattern changes with time, one may record the visualized flow with a movie camera. Under no circumstances have we identified the specifics of the photographic recording, because in this context this must be considered a normal technique. But, at least briefly, there are some arguments to discuss: the principles of high-speed photography and cinematography. All methods of visualization have one common feature: they visualize the spatial pattern of the flow being studied. With time, if the flow pattern changes, one can distinguish between two types of such variations. The variations are so slow in the first case that they can be recognized by visual inspection, and eventually measured. The recording of such time-dependent events is then appropriate for an ordinary film camera. However, the human eye has a certain limit to resolving patterns which change rapidly. If the flow pattern variance is faster than a value correlated with the restricting resolution, or if the cumulative flow time is shorter than the eye's reaction time, the flow remains "invisible" to an observer. High speed photographic technique is the key to visualizing such rapidly changing flow fields. Therefore, high-speed photography can be regarded as a tool that visualizes the reliance on the fourth coordinate of an unstable flow field— its time dependence.

High-speed photographic techniques are typically applied for flow visualization purposes in connection with one of the visualizing methods mentioned in the preceding parts. The turbulent fluctuations in a gas or liquid and unstable gas dynamic events such as moving shock waves or detonation waves are examples of such rapidly changing flows which need high-speed photographic recording. An unstable air shock wave, e.g. with a schlieren system, can be visualised. But it becomes evident that a conventional photographic camera can not be used to record the schlieren picture.

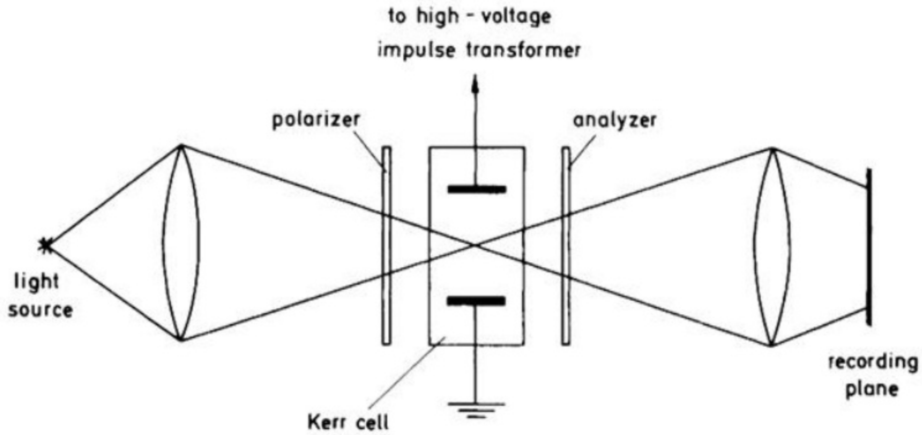



*Fig.* Schematic arrangement of Kerr-cell camera.

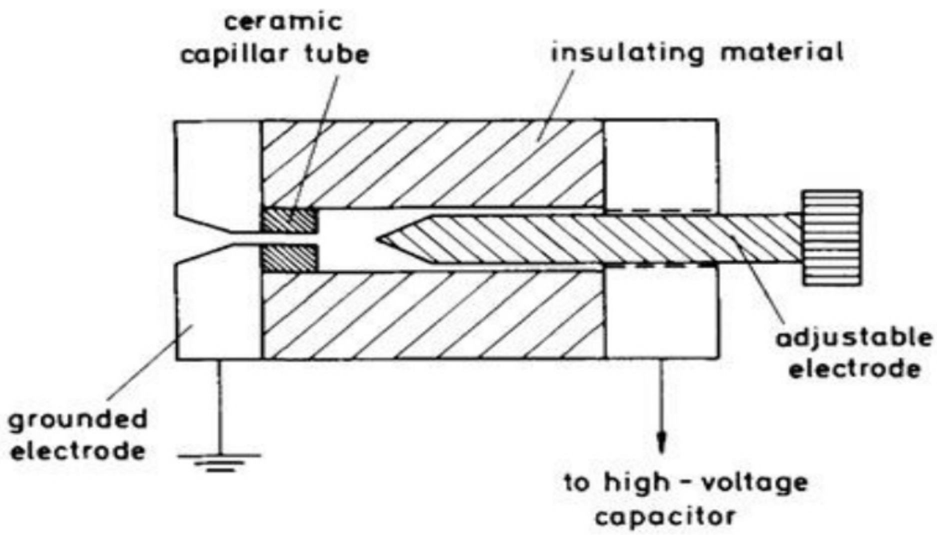



***Fig.*** **Spark flash yielding a point light source.**

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# Study of Flow Visualization Techniques in Subsonic and Supersonic Wind Tunnels

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