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Laser Pencil Beam Based Techniques for Visualization and Analysis of Interfaces Between Media

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Abstract

Traditional optical methods that include interferometry, Schlieren, and shadowgraphy have been used successfully for visualization and evaluation of various media. Aerodynamics and hydrodynamics are major fields where these methods have been applied. However, these methods have such major drawbacks as a relatively low power density and suppression of the secondary order phenomena. A novel method introduced at NASA Lewis Research Center minimizes disadvantages of the “classical” methods. The method involves a narrow pencil-like beam that penetrates a medium of interest.

The paper describes the laser pencil beam flow visualization methods in detail. Various system configurations are presented. The paper also discusses interfaces between media in general terms and provides examples of interfaces.

1. Introduction

Flow visualization methods have been used for years to evaluate parameters of various flows. Descriptions of these methods, which utilize interferometers, Schlieren, and shadowgraphs, can be found in a number of references¹⁻³. The methods are based on the accumulative variations either in the phase of an optical beam propagating through a medium or in its derivatives. With an interferometer, the changes in the density of the medium along the beam propagation are evaluated. On the other hand, Schlieren methods are employed to detect changes in the first derivative of density distribution. Finally, shadowgraphs are used to visualize the second derivatives of the density. It is obvious that for very slow variations in the density interferometric systems are the most appropriate. Shadowgraphs are the best for visualization of flows with very rapid changes of density. For instance, shocks, which are characteristic of supersonic flows, are observed the best by shadowgraphs. These three basically different flow visualization methods have one thing in common. They all usually require a large diameter collimated beam. This requirement leads to a relatively low spatial power density and consequently low contrast. To compensate for a low contrast the power of the light source has to be increased. Another problem arises from the fact that a large diameter collimated beam suppresses the second order phenomena that accompany the wave propagation. An example of such phenomena is light diffraction from inhomogeneities.

Inhomogeneities in the medium cause the beam to deviate from its original path. The deviation is often accompanied by such optical phenomena as diffraction and interference. The pattern of transmitted light carries information about inhomogeneities in the medium. Furthermore, information about the medium itself may be extracted from the pattern. The issue is closely related to inhomogeneities. Interfaces can be abrupt or distributed. An interface may be described mathematically by a derivative of a particular physical property with respect to space. An abrupt interface is the boundary between two distinct fluids. The two fluids then exhibit different physical properties across the interface. The spatial derivatives of the physical properties, in this case, have singularities at the interface. An air bubble in water forms an abrupt interface. The physical properties across a distributed interface change gradually and the corresponding spatial derivatives are finite. The type of interface determines the dominant optical phenomenon that accompanies the beam propagation through the medium. Thus, evaluation of the resultant optical pattern may help to retrieve information about the interface itself.

2. Theory and Analysis

Propagation of electromagnetic waves is governed by the four coupled Maxwell's equations. Solutions of these equations that also satisfy appropriate boundary conditions describe analytically the phenomenon of wave propagation. For nonmagnetic dielectric spatially inhomogeneous media with no electric charges or currents two second order partial differential equations result. These equations describe the propagation phenomena in terms of either electric or magnetic fields. Just one of these equations is sufficient for analytical and computational purposes. The equation presented in terms of the electric field vector in the Cartesian coordinate system is given by:

$$\nabla^2 \bar{E} + \nabla \left[\bar{E} \cdot \frac{\nabla \epsilon}{\epsilon} \right] = \epsilon \mu \frac{\partial^2 \bar{E}}{\partial t^2} .$$

The second term on the left side of this equation reflects a presence of inhomogeneities in the medium. If ϵ does not vary in space the equation assumes the form of the wave equation. Spatial variations in the permittivity ϵ could be presented mathematically and inserted in the above equation. That could lead to further simplifications and to more manageable partial differential equations. The incident electromagnetic field also plays a role in the simplification process. For instance, assume that the incident field is a plane wave that propagates in the Y direction. We can decompose this incident plane wave into two mutually orthogonal linearly polarized waves. Select these waves in such manner that the electric field of one of them is transverse to the plane of incidence (the XY plane). This is a TE wave with the electric field vector in the Z direction and the magnetic field vector in the X direction. The other wave, with the magnetic field vector being transverse to the XY plane, is a TM wave with the electric field vector in the -X direction and the magnetic field vector in the Z direction. Assume also that the medium has one-dimensional variations in the permittivity that occurs in the X direction. This describes a case when the one-dimensional inhomogeneities occur in a direction normal to the direction of the wave propagation. Then the following partial differential equation for the magnetic field vector of the TM wave results:

$$\left(\nabla_{xy}^2 - \frac{1}{\epsilon} \frac{d\epsilon}{dx} \frac{\partial}{\partial x} + k_0^2 \epsilon \right) H_z^{TM} = \left(\nabla_{xy}^2 - \frac{d(\log \epsilon)}{dx} \frac{\partial}{\partial x} + k_0^2 \epsilon \right) H_z^{TM} = 0$$

A similar expression could be derived for the electric vector of the TM wave.

In general, an inhomogeneous medium of interest may be treated as a combination of homogeneous media with transition regions between them. Those transition regions are interfaces. The interfaces could be either abrupt or distributed. In case of an abrupt interface between two homogeneous media solutions of the wave equation are sought separately in each of the media. The solutions are then coupled on the interface using matching conditions for normal and tangential components for the electric field and magnetic fields. For a distributed interface the process is more complicated. Depending on the "profile" and geometry of the interface and a mutual orientation of the interface and the incident EM field, the governing equations could take various degrees of simplification^{4,5}. In some simple cases an exact analytical solutions may be obtained. However, in the most cases the equations cannot be solved exactly. Even when the solution can be written in an algebraic or closed form, the practical impact of having such solution is minimal unless there are numerical values associated with the solution.

The arguments presented in the last paragraph emphasize the importance of modeling and numerical computations of the electromagnetic wave propagation through media with interfaces. The in depth analysis of wave propagation through inhomogeneous media, various modeling approaches, and numerical methods may be found in the literature^{6,7}. One of the reported methods includes computing the passage of a Gaussian beam through an inhomogeneity and then propagating the resultant wavefront into the far field using the Fresnel diffraction equation⁸. Such numerical methods as the FD-TD⁹, integral¹⁰, and a ray optics approximation¹¹ have been proposed to compute propagation through the inhomogeneity with a shock-like profile of the refractive index. Computational results of a Gaussian beam propagating through an inhomogeneity of a cylindrical shape are shown in Fig. 1. The results were obtained using the finite difference-time domain (FD-TD) method. Among other candidate

methods an anomalous diffraction approximation could also be used if variations in the refractive index across the interface are very small¹². The use of laser pencil beams with the Gaussian profile has certain advantages. The obvious one is very high power density that a laser has. Another advantage comes from the fact that the laser power density is confined, especially within the Rayleigh zone, to a profile described by a Gaussian. When such incident beam strikes an interface or inhomogeneity, the resultant diffracted and scattered waves propagate beyond its spatial domain defined by a Gaussian. Separation of the scattered field from the total one results and a more detailed structure of the pattern can be observed and evaluated¹³.

3. Experiments and Applications

A simple setup has been constructed to demonstrate the principle of pencil beam propagation through a medium with various interfaces. It consisted of a laser beam striking the interface at a grazing incidence. A conventional shadowgraph could be added for visualizing the interface. Descriptions of such experimental setup may be found in the References cited above. Schematic of the setup is given in Fig. 2. It depicts a Gaussian beam striking an interface between two media at a grazing incidence. This configuration permitted observation of various phenomena associated with light propagation through normal and bow shocks. In both cases the beam splitting and spreading were seen. Large angle scattering on a bow shock was also observed. An example of a laser beam splitting by a bow shock is shown in

Fig. 3. The bow shock was obtained in a supersonic tunnel by placing a blunt body in the flow. The laser beam was sent through a transparent section of a tunnel normal to the flow direction. The picture shows the pattern seen by a camera (Fig. 3a) and the relative distribution of light intensity (Fig. 3b). An example shown in Fig. 4 displays intensity distributions across two patterns resulted from a laser beam propagating through a water chamber with a thermal gradient. One pattern is generated by a negative temperature gradient inside the chamber (19.9 °C at the top and 59.9 °C at the bottom). The other pattern corresponds to a case with a positive gradient (56.6 °C at the top and 20.3 °C at the bottom).

In addition to flow evaluation a similar system has been used to study abrupt interfaces produced by air bubbles in water. The bubble is generated in test chamber¹⁴ filled with distilled water. The laser pencil beam penetrates the chamber through transparent walls, grazes the air-water interface, and upon the exit from the chamber produces a pattern. The water temperature is controlled using two thermostatic circulators. One circulator maintains a constant temperature at the top of the surface inside the chamber and the other at the bottom. Thus, a constant temperature is maintained inside the chamber or a temperature gradient can be introduced. Different patterns have been observed under different thermal conditions inside the chamber.

The system configuration used to analyze experimentally the mentioned above phenomena has utilized a stationary laser beam. In order to enhance capabilities of the pencil beam method a scanning mechanism may be added to allow the laser beam to change its position in space. Various scanning techniques have been reported. Various mechanical, electro- and acousto-optical scanners¹⁵ as well as their applications to flow visualization¹⁶ have already been discussed.

Another embodiment shown in Fig. 5 utilizes a spectral scanner. Major components in spectral scanners are a tunable light source and an optical dispersive element. Examples of the dispersive elements are dispersion prism and diffraction gratings. These components are installed in the transmitting part of the sensing system, which also includes a controller. The tunable source generates a narrow beam of light (i.e., a pencil beam) whose optical frequency changes in time in a prescribed manner. It is a known fact that the direction of a light beam after interaction with a fixed dispersive element depends on the optical frequency of the light. This space-frequency or space-wavelength scanning generates a "rainbow" with the difference that each "color" appears in its place at a given time. The dispersive element is placed in the focal plane of a collimating lens. This arrangement converts a cone of light of different colors into a series of mutually parallel pencils of light of corresponding colors.

The pencil beam may contain several individual beams with different optical frequencies (wavelengths). The wavelengths may be cooperatively or independently changed in a time-prescribed manner. Thus, the fixed dispersive element produces several "rainbows". The term "fixed" is used to indicate spectral scanning by a stationary dispersive element in contrast with other embodiments in which the light beam is physically translated or otherwise manipulated.

The optical dispersive element may also replace a reflecting mirror or prism in the angular scanner. Such a hybrid system combines a spectral scanner with an angular electromechanical one. The hybrid scanner may also employ a plurality of optical beams with different wavelengths. These optical beams strike the angular scanner that has its reflecting element, mirror or prism, replaced by the dispersive element. A multiplicity of spectral cones or “rainbows” will result.

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$$dx=dy=0.05*\text{wavelength}$$

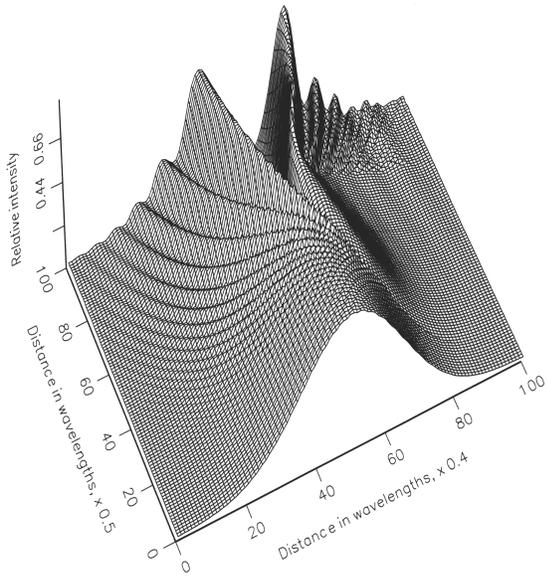


Fig. 1: Propagation of a Gaussian beam through inhomogeneous media under a grazing incidence (computational results).

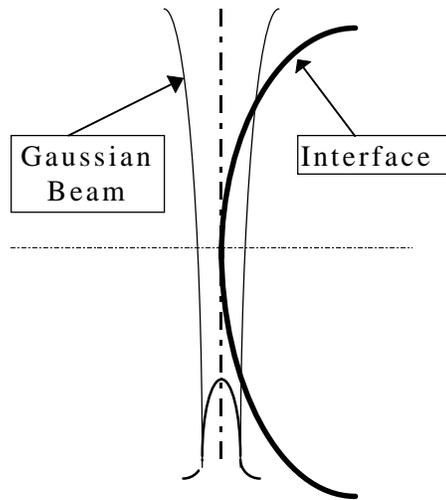
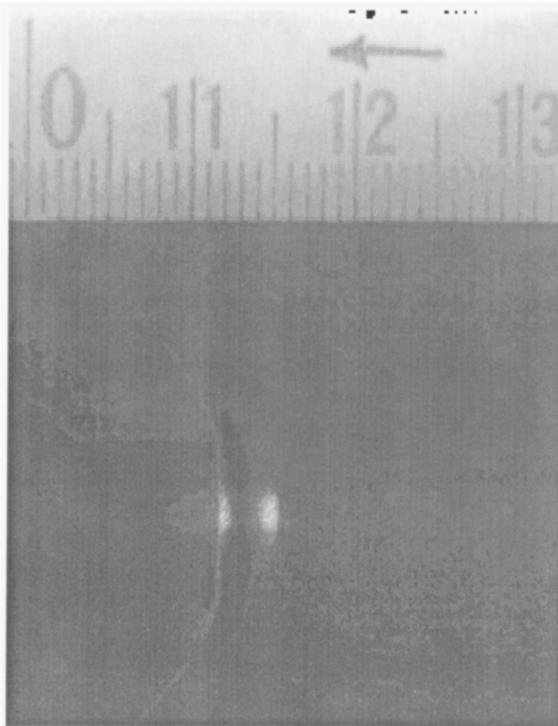


Fig. 2: Schematic diagram of a Gaussian beam striking an interface at a grazing incidence



a)

b)

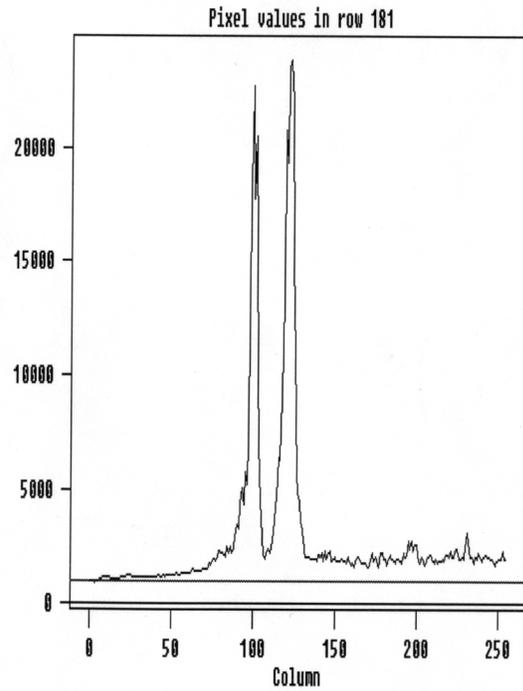


Fig. 3: Laser beam splitting by a bow shock:
 a) pattern observed by a camera;
 b) intensity distribution across the pattern.

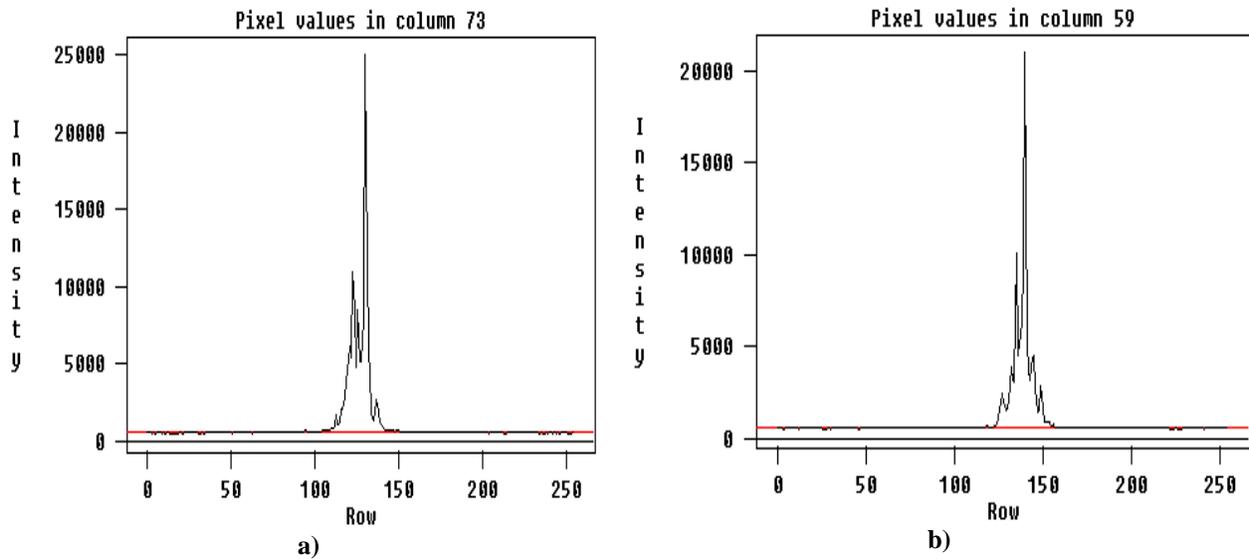


Fig. 4: Diffraction patterns of a Gaussian beam propagated through diffused interfaces generated by two different temperature gradients:
 a) negative temperature gradient (top temperature: 19.9 °C, bottom temperature: 59.9 °C);
 b) positive temperature gradient (top temperature: 59.6 °C, bottom temperature: 20.3 °C).

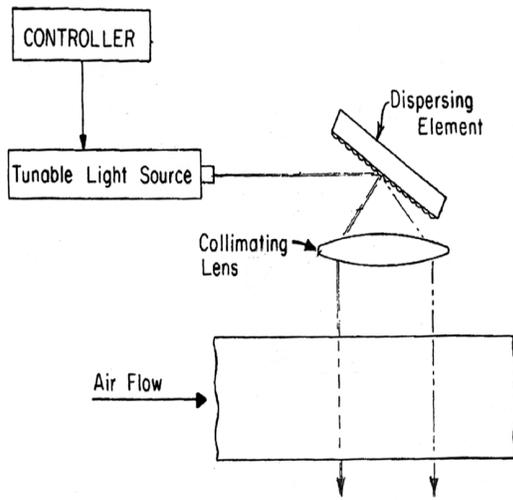


Fig. 5: Diagram of a spectral scanner.

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