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Introduction

Experimental interferograms, schlieren, and shadow-graphs are used for quantitative and qualitative flow-field studies. These images are created by passing light through a flow field, and the recorded intensity patterns are functions of the phase shift and angular deflection of the light. As part of the grant NCC 2-583, techniques and software have been developed for obtaining phase shifts from finite-fringe interferograms and for constructing optical images from Computational Fluid Dynamics (CFD) solutions. During the period from November 1, 1992, to June 30, 1993, research efforts have been concentrated in improving these techniques.

Experimental Interferograms

Many of the experimental interferograms that have been obtained in the 16 inch shock tunnel at NASA Ames Research Center have dark and light areas that are caused by variations in the film exposure. These variations are undesirable and often obscure flow details. A filter that smoothes these variations has been written and added to software that is used for interpreting finite-fringe interferograms. This filter presumes that the image is a finite-fringe interferogram and that the gray-scale values should range from nearly black to white within the spacing

of one to two freestream fringes. To correct the exposure,
the average gray-scale value as well as the range of gray-
scale values is calculated within the distance of two
free-stream fringes. A linear transformation then adjusts
the average and range.

Examples of an unfiltered and filtered finite-fringe
interferogram for an Aeroassist Flight Experiment Model is
shown in Fig. 1. The top half of the figure is the unfil-

Fig. 1   Filtered and unfiltered finite-
fringe interferogram.

tered interferogram; the bottom half is filtered. In the unfiltered interferogram, the freestream fringes in front of the model are underexposed and almost lost in the dark background. Interpretation of the wake flow is complicated by the dark and light ring pattern caused by the light source. In the filtered interferogram, the freestream fringes are now easily discernible, and the ring patterns have been minimized.

CISS Code

The CISS (Constructed Interferograms, Schlieren, and Shadowgraphs) code constructs images from ideal- and real-gas flow-field simulations. It was originally written in Fortran, and it has been executed on the CRAY-YMP and on IRIS workstations. The constructed "images" are arrays of numbers that represent gray-scale values; these arrays can be displayed using other software, such as the public domain program *Image*.[1] No graphical interface has been included in the CISS code.

The CISS code has been incorporated into FAST.[2] Although this does provide the needed graphical interfaces, the incorporated version of CISS does not have all the options of the original CISS code. Furthermore, CISS has merits as a stand alone code. Therefore, efforts have been

made to add graphical interfaces to CISS and to create a
stand alone version of CISS.

The programming systems used for the graphical
interfaces are X-Windows and Motif. By using these two
graphical programming systems, the resulting CISS software
should be transferable between various computer systems,
including the CRAY-YMP and the IRIS and Sun workstations.
To facilitate the inclusion of the graphical interfaces,
the CISS code has been rewritten in C. Although most of the
graphical interfaces have been added to CISS, this work
will not be completed until 1994.

In addition to the modifications of the CISS code, a
user's manual has been written. A draft of this manual has
been attached. This manual will be modified once the stand
alone version of the CISS code has been completed.

References

[1]Rasband, W.H., "NIH Image 1.47," National Institute of
Health, Bethesda, Maryland, Oct. 1992. Available from
zippy.nimh.nih.gov.

[2]Walatka, P.P, Plessel, T., McCabe, R.K., Clucas, J., and
Elson, P.A., "FAST User's Manual, Draft," NASA Ames
Research Center, Sept. 1991.
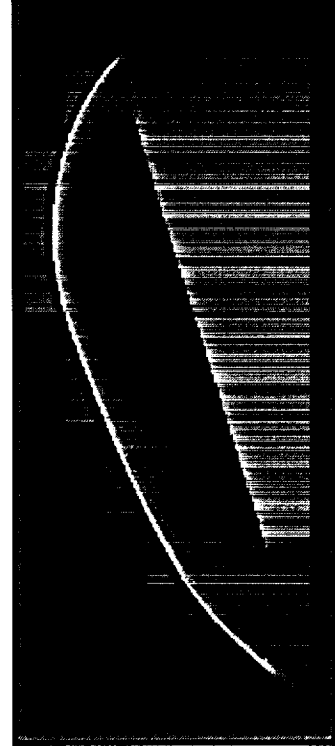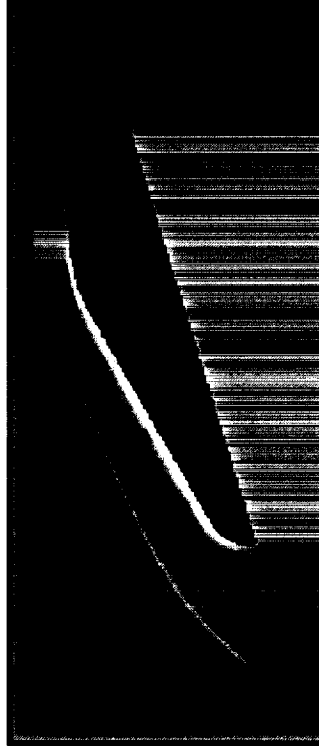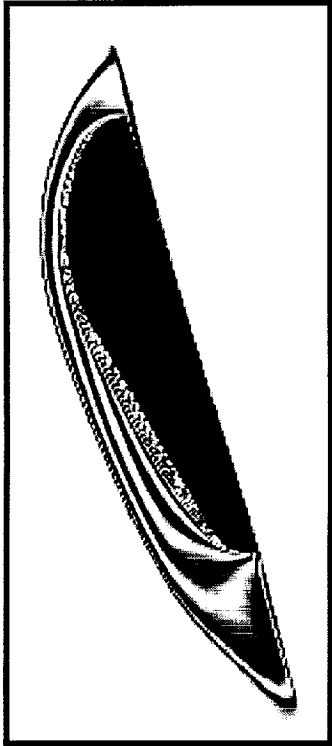
CISS

CONSTRUCTED INTERFEROGRAMS, SCHLIEREN, AND SHADOWGRAPHS: A USER'S MANUAL

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CISS User's Manual

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Introduction

The CISS (Constructed Interferograms, Schlieren, and Shadowgraphs) code constructs optical images from two-dimensional (2-D), axisymmetric, and three-dimensional (3-D) flow-field solutions. It is written in Fortran and has been run on IRIS and SUN workstations as well as a CRAY YMP. The CPU time required for constructing an image is a linear function of the number of grid points in the flow-field solution and the number of pixels defining the image. For 2-D flow-field solutions, images can be constructed in only a few seconds; for axisymmetric and 3-D solutions, a few minutes on a CRAY YMP are required. Once the images have been constructed, CISS stores the dimensions and gray-scale values (from 0 to 255) for each image in ASCII files. These files can be transferred to and displayed on other computers.

In this manual, the types of optical images that can be constructed by CISS are described, and the methods that CISS uses to construct these images are summarized. Sample input listings and descriptions of the user inputs are also included.

Optical Images

Interferograms, schlieren, and shadowgraphs are created by passing light through a flow field and recording the resulting intensity patterns. These patterns are caused by changes in the phase and direction of the light, and they are functions of variations in the refractive index. Since the refractive index is a function of the flow-field density and species concentrations (parameters which are calculated by flow-field codes), these images can be constructed from computed flow fields, and one-to-one comparisons of computation and experiment are possible. In the following sections, these three optical images and their dependency on the refractive index are described.

Interferograms

The intensity patterns in interferograms are created by the interference of two laser beams: a reference beam and an object beam. Both of these beams are initially coherent (in phase). The reference beam does not pass through the flow field, and it remains coherent. The object beam passes through the flow field, and its phase is changed by variations in the refractive index (density and species concentrations). A schematic illustrating this change in phase is shown in Fig. 1. In this figure, the coherent light is represented by the parallel wave fronts. After the light has passed through the flow field, the phase is spatially distorted; this distortion is depicted by the
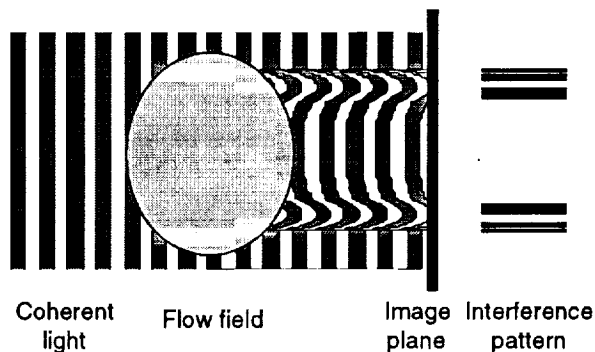

Coherent   Flow field   Image Interference
light   plane   pattern

Fig. 1 Interferogram schematic.

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curved wave fronts. When the object beam reaches the image plane, it is combined with the reference beam, and the resulting fringe patterns are functions of the differences between the phases of the two beams. When calculating interferograms from computed flow fields, the phase shift of the object beam relative to the reference beam is obtained by integrating

$$\delta\phi = \frac{2\pi}{\lambda}(n - n_0)$$

along a line of sight. Here, n is the refractive index of the fluid, n_0 is a reference value for the refractive index, and λ is the wavelength of the light. For infinite-fringe interferograms, the intensity pattern is simply proportional to the sine of the phase shift ϕ. For finite-fringe interferograms, the reference and object beams are at a slight angle, and the intensity pattern is proportional to

$$\sin(\phi + \kappa_x x + \kappa_y y)$$

where κ_x and κ_y are functions of the angle between the two beams.

Schlieren

Schlieren are created by passing collimated (parallel) light through the flow field, focusing this light to a point, using a knife edge to block out a portion of the light, and then re-focusing the remaining light onto an image plane. The light intensity at the image plane is a measure of the quantity of light not blocked by the knife edge. For example, consider a horizontal knife edge (Fig. 2) and a rectangular section of the initial light source with height h. As this rectangular section passes through the flow field, it is deflected and exits the flow field at an angle. When this light is focused at the plane of the knife edge, the rectangular element has a height of h', and it has been

Fig. 2 Schlieren schematic.

deflected vertically by a distance $\gamma\varepsilon_y$ where γ is a function of the distance between the flow field and the knife edge and ε_y is the vertical deflection. If the horizontal knife edge is placed at the center of the plane, the ratio of light not blocked by the knife edge to the amount of the original light is

$$0 \qquad \text{for} \qquad \frac{\gamma\varepsilon_y}{h'} \leq -\frac{1}{2}$$

$$1 \qquad \text{for} \qquad \frac{\gamma\varepsilon_y}{h'} \leq \frac{1}{2}$$

$$\frac{1}{2} + \frac{\gamma\varepsilon_y}{h'} \qquad \text{for} \qquad -\frac{1}{2} < \frac{\gamma\varepsilon_y}{h'} < \frac{1}{2}$$

The intensity at the image plane is proportional to this ratio.

The angular deflections, ε_x and ε_y, which control the intensity patterns in schlieren are functions of the refractive-index gradient. The incremental change in the angular deflection at any point in the flow field is

$$\delta\varepsilon_x = f(n) = \frac{1}{n}\frac{\partial n}{\partial x} \qquad \text{and} \qquad \delta\varepsilon_y = f(n) = \frac{1}{n}\frac{\partial n}{\partial y}$$

Integrating these functions along a line of sight gives the total angular deflections, ε_x and ε_y.

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Shadowgraphs

In shadowgraphs, dark and light regions are caused by the concentration and divergence of light (Fig. 3). In CISS, the function of the refractive index that is used for constructing shadowgraphs has been chosen to be equal to that used for schlieren. At the exit of the computed flow field, the angular deflection is known. If the distance to the image plane is also known, then the area on the image plane where the deflected light falls is known, and the shadowgraph can be constructed by adding the contribution of the deflected light beams at each pixel on the image plane. It should be noted that if
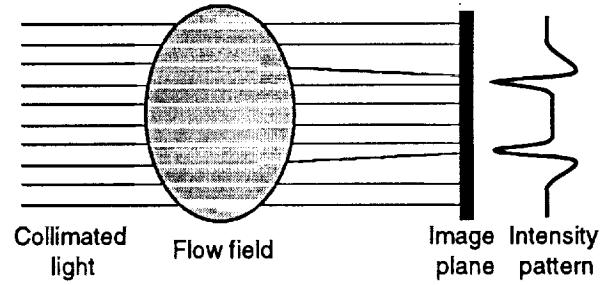

Collimated light   Flow field   Image plane   Intensity pattern

Fig. 3 Shadowgraph schematic.

$$\frac{\partial \varepsilon_x}{\partial x} + \frac{\partial \varepsilon_x}{\partial y} = \frac{\partial}{\partial x} \int \frac{1}{n} \frac{\partial n}{\partial x} ds + \frac{\partial}{\partial y} \int \frac{1}{n} \frac{\partial n}{\partial y} ds = 0$$

there will be no convergence or divergence of the light and, hence, no variation in shade. In many texts, the function used to describe shadowgraphs is the line integral of the second derivative of the refractive index. The form of this equation provides the motivation for using this description; however, bringing the derivatives inside the integral signs does not simulate the experimental technique. The advantage of constructing shadowgraphs by projecting the deflected light onto the image plane is that the thickness of the dark and bright regions can be controlled by the placement of the image plane. This dependency of the dark and bright regions on the image plane's position is observed in experimental shadowgraphs.

Refractive Index

As indicated in the previous sections, the intensity patterns in optical images are governed by integrals of functions of the refractive index. For ideal-gas flows, the refractive index is simply

$$n = 1 + \kappa \rho$$

where κ is the Gladstone-Dale constant for the gas and ρ is the density. For real-gas flows, the refractive index is

$$n = 1 + \sum_i \kappa_i \rho_i$$

where the i summation is over all species, κ_i is the Gladstone-Dale constant for each species (values for some common species are listed in Appendix C), and ρ_i is the density of the species in the appropriate units.

In CISS the refractive index is calculated using the equation

$$n = 1 + \kappa \rho_{\infty,exp} \frac{\rho}{\rho_{\infty,comp}}$$

Here, ρ is the computed density obtained from the solution file, $\rho_{\infty,comp}$ is the freestream density in computational units, and $\rho_{\infty,exp}$ is the freestream density in kg/m³. The Gladstone-Dale constant has been set equal to the constant for air: $\kappa_{air} = 0.000226 = 0.000292/(1.293 \text{kg/m}^3)$. If the flow-field solution is a real-gas solution, some preprocessing of the solution is required. By defining a scaled density,

$$\bar{\rho} = \frac{\sum_i \kappa_i \rho_i}{\kappa_{air}}$$

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and by replacing the density term in the flow-field file with this scaled density, images can be constructed from real-gas solutions. (Note: if the flow-field solution is for an ideal gas other than air, the experimental and computational density can be scaled to account for the change in the Gladstone-Dale constant and preprocessing is not necessary.)

Integration Scheme

During the construction of any optical image by CISS, the image is first broken into an $M \times N$ array of pixels, and a light ray is associated with each of these pixels. Line integrals of the appropriate functions of the refractive index are then calculated for each light ray, and the path of integration is the path that the light follows through the flow field. The integral for the (m,n)th element of the array is

$$F_{m,n} = \int_0^\zeta f\left[n\left(x_m(\zeta), y_n(\zeta), \zeta\right)\right] \frac{ds}{d\zeta} d\zeta$$

where ds is the element of arc length. The light's path, defined by $(x_m(\zeta), y_n(\zeta), \zeta)$ for $0 \le \zeta \le z$, intersects the image plane at the (m,n)th element. This integral can be written as

$$F_{m,n} = \sum_i \int_{z_i}^{z_{i+1}} f\left[n\left(x_m(\zeta), y_n(\zeta), \zeta\right)\right] \frac{ds}{d\zeta} d\zeta$$

where the i summation is over all computational cells that contain segments of the line of integration. The interval $z_i \le \zeta \le z_{i+1}$ defines the intersection of the line of integration with the ith computational cell (Fig. 4).

Tracing the actual light path as it bends through the flow-field solution and integrating the appropriate function

Fig. 4 Schematic for the integration process.

of the refractive index along this path is computationally expensive. The computer resources required for producing constructed images can be reduced appreciably by approximating the light's path by a straight line perpendicular to the image plane. With a straight line approximation, x_m and y_n become independent of ζ, and $F_{m,n}$ can be rewritten as

$$F_{m,n} = \sum_i \int_{z_i}^{z_{i+1}} f\left[n\left(x_m, y_n, \zeta\right)\right] d\zeta$$

The order of evaluation and summation of the integrals has no effect on $F_{m,n}$ and, therefore, no ray tracing is required. It is necessary only to find the intersection of the line of integration with each computational cell, calculate the integral for this segment, and add it to the appropriate sum.

To determine whether the line of integration intersects the computational cell, it is necessary to determine if the point (x_m, y_n, ζ) falls within the computational cell for any value of ζ. In CISS, the test procedure is as follows. Each computational cell (for example, the cell shaded in gray in Fig. 4) is defined by eight points, $x_i = (x_i, y_i, z_i)$, and six surfaces. Each surface is then described by two triangles, and for each triangle, three cross products are formed:

$$\left(x_a - x_{m,n}\right) \times \left(x_a - x_b\right)$$

$$\left(x_b - x_{m,n}\right) \times \left(x_b - x_c\right)$$

$$\left(x_c - x_{m,n}\right) \times \left(x_c - x_a\right)$$

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In these equations, $\mathbf{x}_{m,n} = (x_m, y_n, z)$ gives the position of the (m,n)th pixel of the image array, and the $\mathbf{x}_i = (x_i, \ y_i, \ z_i)$ for $i = a$, b and c are the projections onto the image plane of the vectors that define the vertices of the triangle. To minimize CPU time, testing is performed only for x_m and y_n that lie within the minimum and maximum x and y values for the computational cell. The sign for all three cross products is the same if and only if the point lies within the triangle, and the triangular surfaces through which the line of integration enters and exits the computational cell can be determined. Once these surfaces are determined, interpolated values for z_i, z_{i+1}, $f(x_m, y_n, z_i)$, and $f(x_m, y_n, z_{i+1})$ are obtained, and the line integral of the function f is evaluated using the trapezoidal rule. To further minimize CPU time, three functions of the refractive index are integrated simultaneously: $n-n_0$, $(1/n)\partial n/\partial x$, and $(1/n)\partial n/\partial y$.

For regions of the flow without shocks, the straight line approximation should have a minimal effect on the constructed images. In shock regions, the refractive index changes rapidly, and the approximation may introduce errors; however, these errors are usually on the order of, or smaller than, the solution and experimental errors. An analysis of the errors introduced to the images by this straight line approximation is contained in Ref. 1.

CISS Code

The CISS code is written in Fortran and has been run on IRIS and SUN workstations as well as a CRAY YMP. Images can be created for 2-D, axisymmetric, and 3-D solutions with single or multiple grids. The entire solution or subsets of the solution can be used to generate the image; the subset option allows the user to focus on complicated regions of the flow field. The total number of pixels in the image ($M \times N$) is specified by the user; the aspect ratio (M/N) is chosen by CISS to maximize the size of the flow-field image. For both axisymmetric and 3-D solutions, it is strongly suggested that CISS first be run with the total number of pixels less than or equal to 20,000. The user can fine tune parameters, such as the image distance and exposure, with smaller images, and then use a higher resolution for the final image. The total CPU time requirements can be significantly reduced by constructing multiple images during a single run. Integration of the refractive-index functions requires the vast majority of the CPU time; the construction of the images from these integrals requires less than a second. For 3-D solutions, a silhouette of the body can be projected onto the image; for 2-D and axisymmetric solutions, regions of the image that are not covered by any part of the solution grid are automatically blacked out.

Several input parameters are required by CISS. These parameters are used to specify the form of the flow-field solution, to define the image characteristics, and to transform the computational units into metric units. The user enters these parameters in response to queries made by CISS. The alphanumeric responses may be lower or upper case, and most parameters have default values. To maintain compatibility with other flow-field visualization software, CISS uses PLOT3D[2] formats for the grid and solution files.

The CISS code outputs the images to ASCII files, and the dimensions of the image are sent to the screen. The formats for the grid and solution files, the requested user inputs, and the output files are described in the following sections.

Grid and Solution File Formats

Both 2- and 3-D grids in PLOT3D[2] format can be read by CISS. For axially symmetric solutions, CISS does require a 2-D grid. In all cases, single and multiple grids are options, and the solution files must be written as unformatted binary files. The file formats are:

```
2-D and axisymmetric file formats
  Single grid
      xy file:   READ(UNIT)  IDIM,JDIM
                 READ(UNIT)  ((X(I,J),I=1,IDIM),J=1,JDIM),
              &              ((Y(I,J),I=1,IDIM),J=1,JDIM)

      q file:    READ(UNIT)  IDIM,JDIM
                 READ(UNIT)  FSMACH,ALPHA,RE,TIME
                 READ(UNIT)  (((Q(I,J,NX),I=1,IDIM),J=1,JDIM),NX=1,4)
```

Multiple grid:

```
    xy file:   READ(UNIT) NGRID
               READ(UNIT) (IDIM(IGRID),JDIM(IGRID),IGRID=1,NGRID)
               DO 10 IGRID= 1,NGRID
                 READ(UNIT)((X(I,J),I=1,IDIM(IGRID)),J=1,JDIM(IGRID)),
               &              ((Y(I,J),I=1,IDIM(IGRID)),J=1,JDIM(IGRID))
           10  CONTINUE


    q file:    READ(UNIT) NGRID
               READ(UNIT) (IDIM(IGRID),JDIM(IGRID),IGRID=1,NGRID)
               DO 10 IGRID= 1,NGRID
                 READ(UNIT) FSMACH,ALPHA,RE,TIME
                 READ(UNIT)(((Q(I,J,NX),I=1,IDIM(IGRID)),J=1,JDIM(IGRID)),NX=1,4)
           10  CONTINUE
```

3-D file formats
  Single grid:

```
    xy file:   READ(UNIT) IDIM,JDIM,KDIM
               READ(UNIT) (((X(I,J,K),I=1,IDIM),J=1,JDIM),K=1,KDIM),
               &              (((Y(I,J,K),I=1,IDIM),J=1,JDIM),K=1,KDIM),
               &              (((Z(I,J,K),I=1,IDIM),J=1,JDIM),K=1,KDIM)


    q file:    READ(UNIT) IDIM,JDIM,KDIM
               READ(UNIT) FSMACH,ALPHA,RE,TIME
               READ(UNIT) ((((Q(I,J,K,NX),I=1,IDIM),J=1,JDIM),K=1,KDIM),NX=1,5)
```

Multiple grid:

```
    xy file:   READ(UNIT) NGRID
               READ(UNIT) (IDIM(IGRID),JDIM(IGRID),KDIM(IGRID),IGRID=1,NGRID)
               DO 10 IGRID= 1,NGRID
                 READ(UNIT)
               &  (((X(I,J,K),I=1,IDIM(IGRID)),J=1,JDIM(IGRID)),K=1,KDIM(IGRID)),
               &  (((Y(I,J,K),I=1,IDIM(IGRID)),J=1,JDIM(IGRID)),K=1,KDIM(IGRID)),
               &  (((Z(I,J,K),I=1,IDIM(IGRID)),J=1,JDIM(IGRID)),K=1,KDIM(IGRID))
           10  CONTINUE


    q file:    READ(UNIT) NGRID
               READ(UNIT) (IDIM(IGRID),JDIM(IGRID),KDIM(IGRID),IGRID=1,NGRID)
               DO 10 IGRID= 1,NGRID
                 READ(UNIT) FSMACH,ALPHA,RE,TIME
                 READ(UNIT)((((Q(I,J,K,NX),I=1,IDIM(IGRID)),J=1,JDIM(IGRID)),
               &              K=1,KDIM(IGRID)),NX=1,5)
           10  CONTINUE
```

Input Parameters Required Prior to Integration

The following input parameters are used during the integration of the refractive-index functions. The underlined portions of the queries represent numbers supplied by CISS. The default values are shown in parenthesis at the end of each query.

General Parameters. These parameters are required for any flow-field solution and image.

```
How many points (up to 400,000) would you like
   to use to define the image plane? (20,000)
```

> Input the total number of pixels used to define the image. This number is equal to the image width times its height. The user specifies the total number of pixels, and CISS calculates an aspect ratio that will maximize the size of the image.

What is the grid name?
> Input the xyz-grid file name. This must be an unformatted binary file.

What is the flow-field name?
> Input the q-file name. This must be an unformatted binary file.

Input the type of flow-field solution. (2)
> 2 for 2-dimensional
> A for axi-symmetric
> 3 for 3-dimensional
> Self-explanatory.

Input m if there are multiple grids,
> s if there is a single grid. (s)
> Self-explanatory.

Input the computational freestream density in CFD units. (ρ)
> Input the freestream density for the flow-field solution. If the calculation was dimensional, input the freestream density in the units used in the computation. If the calculation was non-dimensional, input 1. The default density is equal to the density at an outer grid point.

Input the experimental freestream density in kg/m**3. (ρ)
> Input the freestream density. The units must be in kg/m^3 or the refractive index will not be calculated correctly, and the appearance of the schlieren and shadowgraphs and the number of fringes in the interferograms will be incorrect. The default is the computational freestream density.

Input the reference density in kg/m**3 for the interferograms. (ρ)
> Input the density of the gas in which the reference beam traveled. For most cases, this should be equal to the freestream density of the flow field. Since the reference density is used during the integration of the refractive-index functions, this input is required even when interferograms are not constructed. The default is the experimental freestream density. Caution: if the computational domain is not square and the reference density is not equal to the freestream density, additional fringes may be observed that are caused by variations in the depth of the computational domain. If these additional fringes do not simulate the experiment, use the freestream density; the difference between the constructed and experimental interferogram will be a constant phase. In certain cases, such as flow traveling through a shock tunnel which was initially evacuated and then filled with the test gas, the fringes caused by the geometry of the test section would be observed in the experimental interferogram. For this example, the reference density would be zero.

Input the scaling factor in meters/(CFD length units). (1.0)
> The dimensional units must be in meters. Input the factor for scaling the flow-field solution to meters.

Input the number of passes. For 3-D flows, if the symmetry plane is
  parallel to the image plane and if symmetry conditions were used
  in the computation, double the number. (1)
> The total phase shift and angular deflection can be increased by passing light through the flow field several times before it is recorded. This technique is used experimentally when flow-field densities are low. The user can simulate the experimental images by inputting the appropriate number of passes. In special cases, this number should be doubled. If bilateral symmetry is assumed and only half of the solution has been calculated, then if the symmetry plane is parallel to the image plane, the number of passes should be

doubled. If the symmetry plane is perpendicular to the image plane, the number of passes should not be doubled. If the symmetry plane is not parallel or perpendicular to the image plane, the solution should be reflected, and the image for the entire solution must then be calculated.

Parameters Specific to 2-D Solutions. The following queries occur after the general parameters have been defined. They are specific to 2-D flow-field solutions.

What is the thickness in meters of the 2-D flow? (1.0)
> Input the thickness of the flow in meters. For 2-D flows the image plane is assumed to be parallel to the x,y plane.

When constructing images, do you want to use the entire grid? (y)
> If you wish to use only subsets of the flow-field solution to create the image, input n. The following questions will then be asked.

> For grid n, idim and jdim are idim and jdim.
>> How many subsets of this grid would you like? (0)
>>> The program outputs the number of the grid, n, and the i and j dimensions for that grid. The user should input the number of subsets for grid n to be used in creating the image. This number can vary between 0 and 10; the default is 0.

>> For subset m input imin, imax, jmin, and jmax. (1, idim) (1, jdim)
>>> Input the minimum and maximum i and j values for the mth subset of grid n. These values define the boundaries of the subset. The maximum values in each direction should be at least one greater than the minimum values. The defaults are given by the dimensions of the grid.

No silhouetting of the body is performed for 2-D solutions. The program automatically blacks out any regions not covered by the grid.

Parameters Specific to Axisymmetric Solutions. The following queries occur after the general parameters have been defined, and they are specific to axisymmetric flow-field solutions.

How many planes (maximum of 180) from 0 to 90 degrees? (45)
> Input the number of planes between 0 and 90° used for the axisymmetric solution. The image is constructed by creating a 3-D solution from a single plane. The fineness in the circumferential direction is governed by the number of planes.

When constructing images, do you want to use the entire grid? (y)
> If you wish to use only subsets of the flow-field solution to create the image, input n. The following questions will then be asked.

> For grid n, idim and jdim are idim and jdim.
>> How many subsets of this grid would you like? (0)
>>> The program outputs the number of the grid, n, and the i and j dimensions for that grid. The user should input the number of subsets for grid n to be used in creating the image. This number can vary between 0 and 10.

>> For subset m input imin, imax, jmin, and jmax. (1, idim) (1, jdim)

Input the minimum and maximum i and j values for the mth subset of grid n. These values define the boundaries of the subset. The maximum values in each direction should be at least one greater than the minimum values. The defaults are given by the dimensions of the grid.

No silhouetting of the body is performed for axisymmetric solutions. The program automatically blacks out any regions not covered by the grid.

Parameters Specific to 3-D Solutions. The following queries occur after the general parameters have been defined, and they are specific to 3-D flow-field solutions.

`Would you like to rotate the grid? (n)`

The image plane is assumed to be an x-y plane, and the integration is performed in the z direction. If another orientation of the flow field is desired, input y and the following question will be asked.

`What are psi, theta, and phi for the rotation? (0,0,0)`

Input the viewing angles for the flow. These angles give the orientation of the object relative to the image plane. The rotation matrix used in CISS is:

$$\begin{pmatrix} \cos\theta\cos\psi & \cos\theta\sin\psi & -\sin\theta \\ \sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi & \sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi & \sin\phi\cos\theta \\ \cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi & \cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi & \cos\phi\cos\theta \end{pmatrix}$$

`When constructing images, do you want to use the entire grid? (y)`

If you wish to use only subsets of the flow-field solution to create the image, input n. The following questions will then be asked.

`For grid` n`, idim, jdim, and kdim are` idim`,` jdim`, and` kdim`.`
  `How many subsets of this grid would you like? (0)`

The program outputs the number of the grid, n, and the i, j, and k dimensions for that grid. The user should input the number of subsets of grid n to be used in creating the image. This number can vary between 0 and 10.

`For subset` m `input imin, imax, jmin, jmax, kmin, and kmax.`
       `(1,` idim`) (1,` jdim`) (1,` kdim`)`

Input the minimum and maximum i, j, and k values for the mth subset of grid n. These values define the boundaries of the subset. The maximum value should be at least one greater than the minimum value in each direction. The defaults are the dimensions of the grid.

`Would you like to define the surface? (n)`

If you wish to have a silhouette of the surface projected onto the images, input y. The following questions will then be asked.

`In grid` n `how many surface segments are there? (1)`

To create the silhouette, the i, j, and k values for the surface must be defined. Input the number of segments in grid n that belong to the surface. This number can vary between 0 and 10.

`Input i,j, or k to indicate the computational plane for surface` m`. (i)`

Surface segments are defined by constant i, j, or k planes. Input the type of plane for the mth surface segment of grid n.

If the surface plane is an i plane then the following inputs are requested.
```
Input i for the model surface. (1)
```
Input the constant i value for the surface segment.
```
Input jmin, jmax for the model surface. (1,idim)
```
Input the range of values in the j direction for the surface segment.
```
Input kmin, kmax for the model surface. (1,kdim)
```
Input the range of values in the k direction for the surface segment.

If the surface plane is a j plane then the following inputs are requested.
```
Input imin, imax for the model surface. (1,idim)
```
Input the range of values in the i direction for the surface segment.
```
Input j for the model surface. (1)
```
Input the constant j value for the surface segment.
```
Input kmin, kmax for the model surface. (1,kdim)
```
Input the range of values in the k direction for the surface segment.

If the surface plane is a k plane then the following inputs are requested.
```
Input imin, imax for the model surface. (1,idim)
```
Input the range of values in the i direction for the surface segment.
```
Input jmin, jmax for the model surface. (1,idim)
```
Input the range of values in the j direction for the surface segment.
```
Input k for the model surface. (1)
```
Input the constant k value for the surface segment.

Image Specific Parameters

When the previous inputs have been entered, the program integrates the refractive-index functions. Depending on the flow-field solution and the number of points defining the image, this integration may take from a few seconds to several minutes. Once the integration has been completed, the user is asked to specify several parameters that define the type and appearance of the images to be constructed. These parameters are described in the following sections.

```
Input the type of image you wish to create. (s)
        i for interferogram
        s for shadowgraph
        k for schlieren
```
Input the appropriate character for the type of image desired. The input can be in upper or lower case. Depending on the type of image chosen, other questions will be asked.

```
Do you want another image (n)?
```
Reply y or n to continue or stop. The most time efficient way of creating images is to vary parameters and to create multiple images during the execution of CISS. A maximum of ten images of a single type can be constructed and stored.

Parameters Specific to Interferograms. The following queries determine the type of interferogram that will be constructed.

```
Input the wave length in meters of the light source. (0.000000600)
```
Input the wavelength of the laser used to create the interferograms in meters.
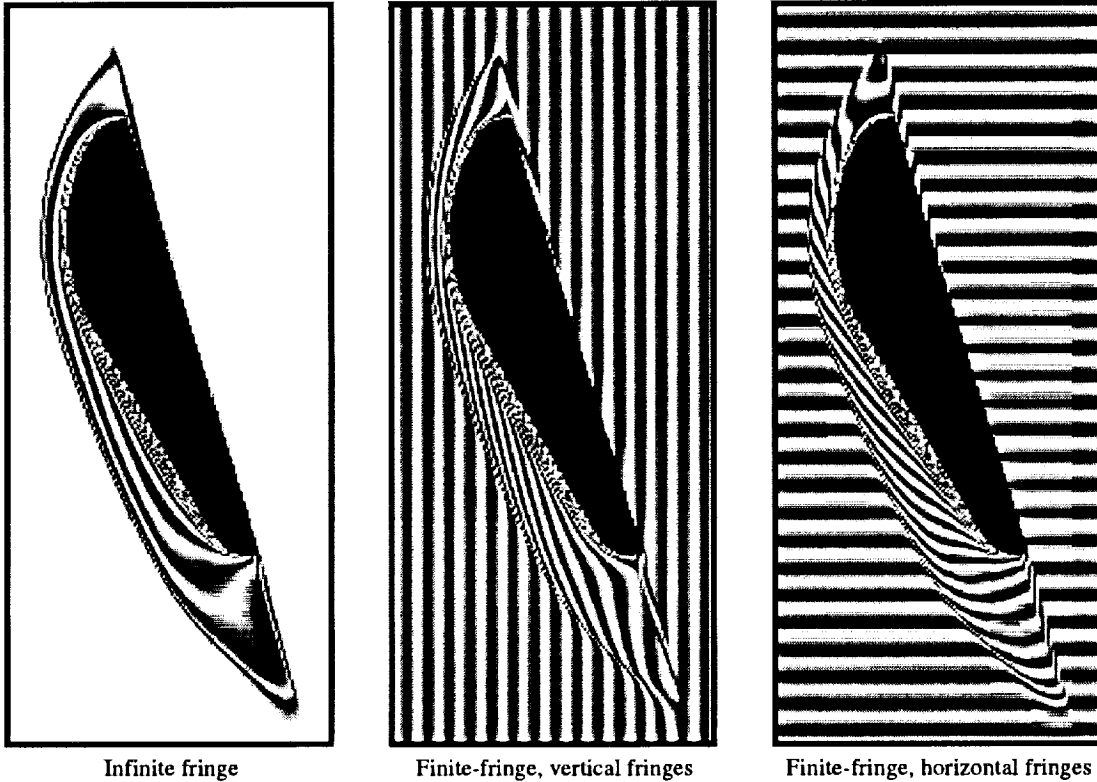
Infinite fringe   Finite-fringe, vertical fringes   Finite-fringe, horizontal fringes

Fig. 5. Types of interferograms which are constructed by CISS.

```
Input the type of interferogram: (i)
    i for infinite fringe
    v for finite fringe with vertical fringes
    h for finite fringe with horizontal fringes
```
Input the character for the type of interferogram you would like to create (see Fig. 5). Infinite fringe interferograms are stored in IFringe.im, finite-fringe interferograms with vertical fringes in VFFringe.im, and finite-fringe interferograms with horizontal fringes in HFFringe.im.

For finite-fringe interferograms with vertical fringes, the following inputs are required.

```
Input the number of vertical finite fringes. (10.0)
    Input the total number of freestream fringes in the horizontal direction.

Input the angle of the fringes. (0.0)
    Input the angle α of the fringes relative to vertical.
```


For finite-fringe interferograms with horizontal fringes, the following inputs are required.

```
Input the number of horizontal finite fringes. (10.0)
    Input the total number of freestream fringes in the vertical direction.

Input the angle of the fringes. (0.0)
    Input the angle α of the fringes relative to the horizontal.
```
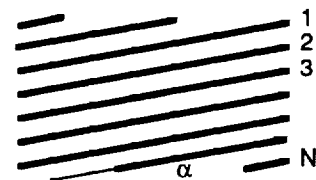
Parameters Specific to Shadowgraphs. T h e
following input parameters define the image plane
location and the exposure for shadowgraphs. The
shadowgraph file is stored in Shadow.im.

```
Input distance of focus plane in
meters from the flow field. (1.0)
```
> The distance between the flow field and
> the image plane controls the thickness of
> the dark and light regions. Input this dis-
> tance in meters. A negative distance will
> reverse the black and white regions. For
> example, in most shadowgraphs, a shock
> is represented by a dark and then a light
> line. However, in some shadowgraph sys-
> tems, a lens moves the image plane to
> behind the model, and the light and dark
> regions are reversed. By using a negative
> distance, the effect of this lens can be
> simulated.

```
Input the linear stretch factor
for gray-scale. (2.0)
```
> The stretch factor controls the "exposure"
> of the image. Generally, the maximum
> and minimum intensity in the image is
> found and the "exposure" is chosen so that
> a maximum range of gray-scale values is
> used without overexposing (large regions
> of white or black) or underexposing (poor
> contrast) the image. To bring out details in
> shear layers or expansion fans, it may be
> desirable to overexpose the image. This is
> achieved by using a linear stretch factor
> greater than 1.

Parameters Specific to Schlieren. The following
input parameters define the type of schlieren that
will be constructed and the image exposure.

```
Input the direction of the knife
blade: (h)
        h for horizontal
        v for vertical
```
> Input the character corresponding to the
> desired direction of the knife edge. The
> intensity patterns will be controlled by the
> vertical deflection of the light when a
> horizontal knife edge is used; by the
> horizontal deflection when a vertical knife
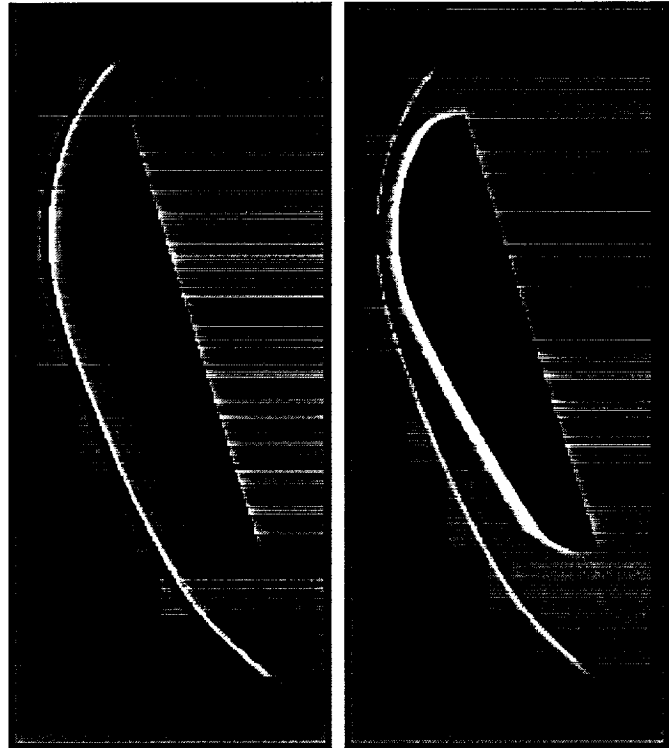
Positive distance   Negative distance

**Fig. 6 Shadowgraphs with positive and
negative distances to the image plane.**
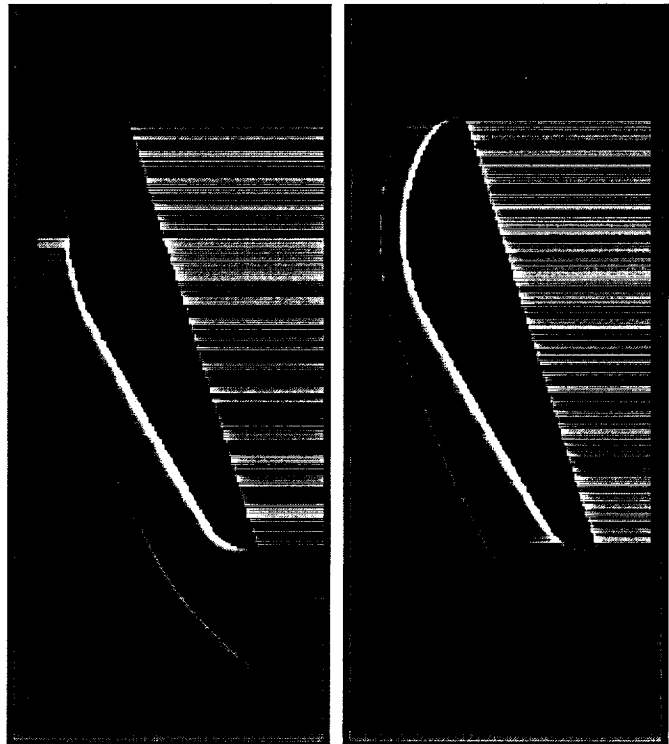
Horizontal knife edge   Vertical knife edge

**Fig. 7 Schlieren created with horizontal
and vertical knife edges.**

edge is used. The images are stored in HSchlier.im and VSchlier.im.

```
Input the linear stretch factor for gray-scale. (2.0)
```
See under Parameters Specific to Shadowgraphs.

CISS Output

When the requested images have been constructed, the dimensions of the images, in pixels and meters, are written to the screen. A sample output is:

```
The adjusted image size is  279 by  713 pixels.

The values for the corners of the image are (in m):
        x1, x2:  -0.1347E+00  0.6391E+00
        y1, y2:  -0.1441E+01  0.5365E+00
```

Since the size of the image is known in meters, it is possible to make one-to-one comparisons of experimental and computed images.

In addition to the screen output, a journal file is written that contains a listing of all input parameters. If defaults were chosen, the defaults are also written to the journal file. The journal files are numbered sequentially from CISS.jou.00 to CISS.jou.99, and they can be used as input files for CISS.

The images are stored in ASCII files. IFringe.im, VFFringe.im, and HFFringe.im contain the infinite fringe, vertical finite-fringe, and horizontal finite-fringe interferograms; VSchlier.im and HSchlier.im contain the schlieren constructed for vertical and horizontal knife edges, respectively; and Shadow.im contains the shadowgraph. Multiple images of each image type can be constructed, and the image files are numbered in the order of construction (for example, Shadow.im.0, Shadow.im.1, ..., Shadow.im.9). Creating multiple images during one run reduces the CPU time requirements; however, if more than ten images of a single type are created, the sequence will be restarted and the image files over written. The first line of each file contains the width and height of the image. The remaining lines contain the gray-scale values for each pixel location. These values range from 0 to 255 with 0 representing white and 255 black. The commands used to write these files are

```
WRITE(8,'(2I7)') IXMAX,IYMAX
WRITE(8,'(40I4)') (INT(P(I)),I=1,IXMAX*IYMAX)
```

where IXMAX and IYMAX are the width and height of the image and P(I) is the pixel shade. This file can then be displayed using other software products.

Displaying the Images

Two software applications, drawim and tomac, can be used to display ASCII files that are created by CISS. The first application displays the images on IRIS workstations; the second translates the ASCII files into a format accessible to Macintosh applications. These two applications are briefly described in the following sections.

Displaying the Images on IRIS Workstations

The software application drawim displays an ASCII file created by CISS and stores the displayed image in an RGB format. This stored image can then be read by image enhancement applications. The drawim application is written in C, and it uses both the IRIS graphics and X Windows (Version 11) libraries. The user inputs the name of the ASCII file (for example, Shadow.im.0) to be displayed in response to the prompt:

```
File to display:
```

The drawim application then reads the dimensions of the image and the gray-scale values from the ASCII file, outputs the dimensions of the image, and scales the image to fill the screen. An image window is created and the image is displayed. The user can continue by clicking on any mouse button while the cursor is inside the displayed image; the image window then disappears and the image is stored in an RGB format. The outputs are:

```
The dimensions of the calculated image are ____ x ____.

The individual pixels have been multiplied by __ to improve visibility.

The image has been stored in the RGB file Shadow.px.0. The stored
image has a one-to-one correspondence between calculated points
and screen pixels. The image size has not been modified to improve
visibility.
```

The most efficient way to create images on an IRIS workstation is to run the CISS and drawim applications concurrently and to view each image as it is created. This allows the user to optimize the exposure and image plane distance without re-integrating functions of the refractive index.

Displaying the Images on Macintoshes

One method of displaying images on a Macintosh first involves translating the ASCII file to an unformatted file on an IRIS workstation. The following code, tomac, will provide the appropriate translation.

```
INTEGER*1 IP(400000)
CHARACTER*15 FILEIN,FILEOUT

WRITE(*,*)' WHAT IS THE INPUT FILE?'
READ(*,'(A15)')FILEIN
OPEN(UNIT=14,FILE=FILEIN,STATUS='OLD')
WRITE(*,*)' WHAT IS THE OUTPUT FILE?'
READ(*,'(A15)')FILEOUT
OPEN(UNIT=7, FILE=FILEOUT,STATUS='UNKNOWN', FORM='UNFORMATTED')

READ(14,'(2I7)')IXMAX,IYMAX
READ(14,'(40I4)')(IP(I),I=1,IXMAX*IYMAX)

WRITE(7)(IP(I),I=1,IXMAX*IYMAX)
CLOSE(7)

STOP
END
```

The output file obtained from this program can then be transferred to a Macintosh using a binary transfer mode with Macbinary disabled (a NCSA Telnet[3] option), and the transferred file can be opened using the Import feature of imaging applications such as NIH Image.[4] When the Import option of NIH Image is chosen, the window shown in the background in Fig. 8 is displayed. By clicking on the Edit button, the Custom feature is chosen, and the width and height of the imported image can
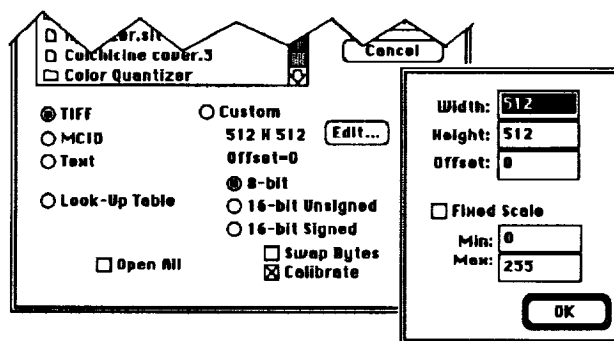
Fig. 8 Import option of NIH Image.

be changed by editing the appropriate boxes in the foreground window. The offset should be set equal to 4. The user can then open the desired image and use the NIH Image application to manipulate the file. Both NCSA Telnet and NIH Image are in the public domain.

Acknowledgments

References

[1] Leslie A. Yates, "Images Constructed from Computed Flow Fields," AIAA Paper 92-4030, presented at the AIAA 17th Aerospace Ground Testing Conference, Nashville, TN, July 1992.

[2] Walatka, P.P, Buning, P.G., Pierce, L., and Elson, P.A., "PLOT3D User's Manual," NASA TM 101067, March 1990.

[3] Bulmahn, S. and Whittington, D., "NCSA Telnet 2.4," NCSA Software Development, National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign, IL, March 1992. Available from mactelnet@ncsa.uiuc.edu.

[4] Rasband, W.H, "NIH Image 1.47," National Institute of Health, Bethesda, Maryland, Oct. 1992. Available from zippy.nimh.nih.gov.

Appendix A. Common Problems and Their Solutions

Error in reading the flow-field grid and solution.

Check the file formats.

File must be in unformatted binary. Use PLOT3D to read the files and then list the grid and solution to unformatted files.

Too many fringe shifts in the interferogram:

Check the wavelength of the light and the freestream flow-field density.

Check the computational and experimental densities.

Check the reference density. If the reference density is not equal to the freestream density, additional fringes will be caused by variations in the depth of the flow field. Use the freestream density and add a phase to compensate.

Too few fringe shifts in the interferogram:

Check the wavelength of the light and the freestream flow-field density.

Check the computational and experimental density.

Moiré Patterns or no discernible patterns in the interferograms:

See comments under too many fringes. The images are created using a finite number of pixels, and if the fringe spacing is too small, the fringes will not be resolved in the images.

Shadowgraph is dark:

Reduce the distance to the image plane. It is possible that the light has been deflected to the extent that it misses the image plane.

Flow-field features are not sharply defined in schlieren or shadowgraphs:

Increase the linear stretch factor.

Use grid adaptation for the flow-field solution. Flow-field features such as shocks become diffuse in the solutions. Since the intensity patterns in schlieren and shadowgraphs are functions of the density gradients, the flow-field features will not be sharply defined in the image unless they are well defined in the solution.
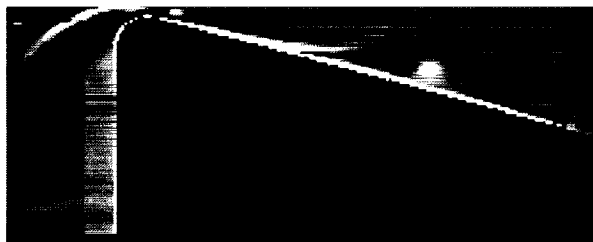
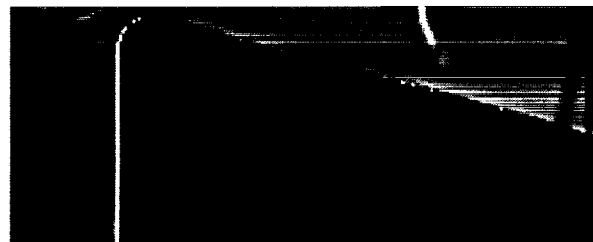# Appendix B. Sample Input Files

2-D Flow-Field Solution

Table I.

CISS Queries	User Responses
How many points (up to 400,000) would you like to use to define the image plane? (20,000)	20000
What is the grid name?	x.dat
What is the flow-field file name?	q.dat

Input the type of flow-field solution. (2)
       2 for 2-dimensional
       A for axi-symmetric
       3 for 3-dimensional
	2

Input m if there are multiple grids, s if there is a single grid. (s)	m
*************************** Reading the Files ***************************	
Input the computational freestream density in CFD units. (0.28768)	0.28767911
Input the experimental freestream density in kg/m**3. (0.28768)	0.28767911
Input the reference density in kg/m**3 for the interferograms. (0.28768)	0.28767911
Input the scaling factor in meters/(CFD length units). (1.0)	1.00000000

Input the number of passes. For 3-D flows, if the symmetry plane is
  parallel to the image plane and if symmetry conditions were used
  in the computation, double the number. (1)
	1.00

What is the thickness in meters of the 2-D flow? (1.0)	1.0000
When constructing images, do you want to use the entire grid? (y)	n
For grid 1, idim and jdim are 252 and 142. How many subsets of this grid would you like? (0)	0

For grid 2, idim and jdim are 252 and 82.
   How many subsets of this grid would you like? (0)
    For subset 1 input imin, imax, jmin and jmax. (1,252) (1, 82)
	1
	1 252 1 82

For grid 3, idim and jdim are 252 and 62.
   How many subsets of this grid would you like? (0)
    For subset 1 input imin, imax, jmin and jmax. (1,252) (1, 62)
	1
	1 252 1 62

For grid 4, idim and jdim are 262 and 62.
   How many subsets of this grid would you like? (0)
    For subset 1 input imin, imax, jmin and jmax. (1,262) (1, 62)
	1
	1 262 1 62

For grid 5, idim and jdim are 262 and 62.
   How many subsets of this grid would you like? (0)
    For subset 1 input imin, imax, jmin and jmax. (1,262) (1, 62)
	1
	1 262 1 62

*************************** Integrating ***************************	

```
Input the type of image you wish to create: (s)          
          i for interferogram
          s for shadowgraph
          k for schlieren                               k
  Input the direction of the knife blade: (h)
          h for horizontal
          v for vertical                                v
  Input the linear stretch factor for gray-scale. (1.0) 500.00

Do you want another image? (n)                          y

Input the type of image you wish to create: (s)
          i for interferogram
          s for shadowgraph
          k for schlieren                               k
  Input the direction of the knife blade: (h)
          h for horizontal
          v for vertical                                h
  Input the linear stretch factor for gray-scale. (1.0) 500.00

Do you want another image? (n)                          n


The adjusted image size is  221 by   89 pixels.

The values for the corners of the image are (in m):
          x1, x2:  -0.4566E-01  0.1437E+00
          y1, y2:  -0.7522E-03  0.7551E-01
```

These images required 3 seconds on a CRAY YMP.

Horizontal knife edge   Vertical knife edge

Schlieren obtained with the input parameters listed in Table I.
Ideal-gas solution for nozzle flow flow (S. Polsky).

Axisymmetric Flow-Field Solution

Table II.

CISS Queries	User Responses
How many points (up to 400,000) would you like to use to define the image plane? (20,000)	30000
What is the grid name?	xy.dat
What is the flow-field file name?	q.dat

Input the type of flow-field solution. (2)
        2 for 2-dimensional
        A for axi-symmetric
        3 for 3-dimensional
	A

Input m if there are multiple grids, s if there is a single grid. (s)	s
************************* Reading the Files *************************	
Input the computational freestream density in CFD units. (3.04436)	3.04436207
Input the experimental freestream density in kg/m**3. (3.04436)	3.04436207
Input the reference density in kg/m**3 for the interferograms. (3.04436)	3.04436207
Input the scaling factor in meters/(CFD length units). (1.0)	1.00000000

Input the number of passes. For 3-D flows, if the symmetry plane is
  parallel to the image plane and if symmetry conditions were used
  in the computation, double the number. (1)
	1.00

How many planes (maximum of 180) from 0 to 90 degrees? (45)	20
When constructing images, do you want to use the entire grid? (y)	y
**************************** Integrating ****************************	

Input the type of image you wish to create: (s)
            i for interferogram
            s for shadowgraph
            k for schlieren
	s

Input distance of focus plane in meters from the flow field. (1.0)	0.50
Input the linear stretch factor for gray-scale. (2.0)	20.00
Do you want another image? (n)	n

The adjusted image size is 529 by   56 pixels.
 	
The values for the corners of the image are (in m):
        x1, x2:   0.4297E+01 0.4778E+01
        y1, y2: -0.8769E-03 0.5002E-01	

This image required 18 seconds on a CRAY YMP.
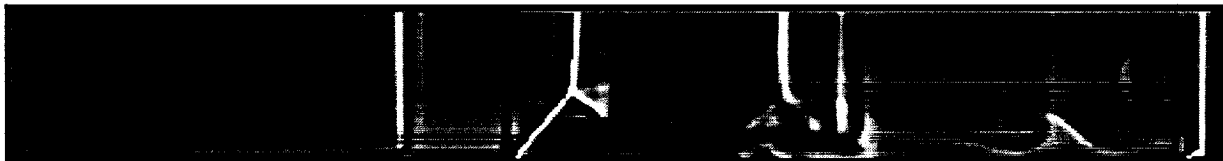
**Shadowgraph obtained with input parameters listed in Table
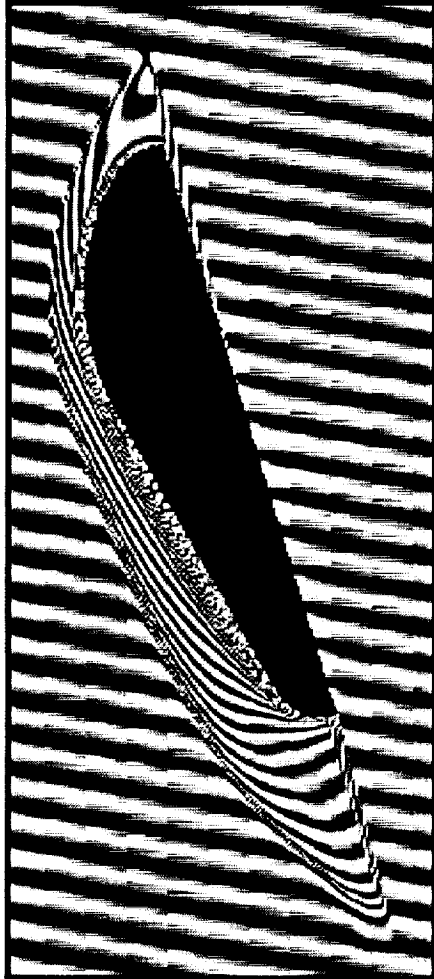II. Real-gas solution for shock tube flow (G. Wilson).**
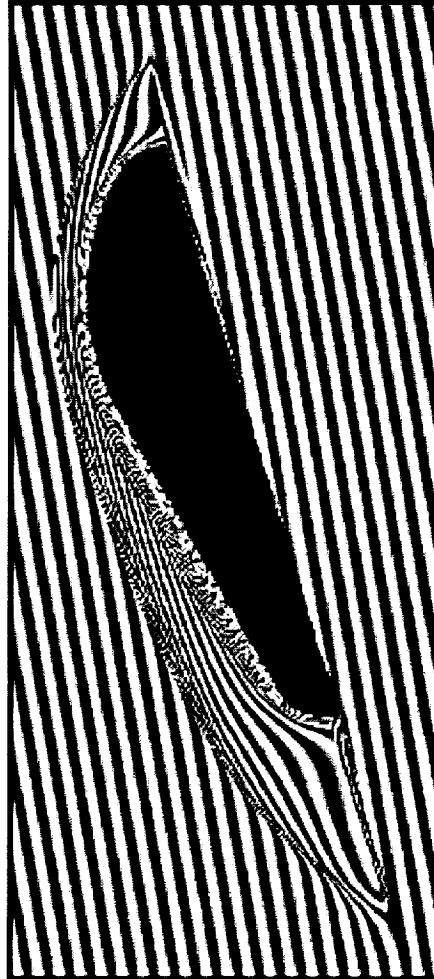
3-D Flow-Field Solution

Table III.

CISS Queries	User Responses
How many points (up to 400,000) would you like to use to define the image plane? (20,000)	100000
What is the grid name? What is the flow-field file name?	adap.21 adap.41

Input the type of flow-field solution. (2)
     2 for 2-dimensional
     A for axi-symmetric
     3 for 3-dimensional
	3

Input m if there are multiple grids, s if there is a single grid. (s)	s
************************ Reading the Files ************************	
Input the computational freestream density in CFD units. (1.00000) Input the experimental freestream density in kg/m**3. (1.00000) Input the reference density in kg/m**3 for the interferograms. (0.00200)	1.00000000 0.00200000 0.00200000
Input the scaling factor in meters/(CFD length units). (1.0)	1.00000000

Input the number of passes. For 3-D flows, if the symmetry plane is
  parallel to the image plane and if symmetry conditions were used
  in the computation, double the number. (1)
	2.00

Would you like to rotate the grid? (n) What are psi, theta, and phi for the rotation? (0,0,0)	y 0.00 0.00 90.00
When constructing images, do you want to use the entire grid? (y)	n

For grid 1, idim, jdim, and kdim are 23, 42, and 34.
  How many subsets of this grid would you like? (0)
    For subset 1 input imin, imax, jmin, jmax, kmin, and kmax.
       (1, 23) (1, 42) (1, 34)
	1
	
	2 22 1 42 1 34

Would you like to define the surface? (n)
In grid 1 how many surface segments are there? (0)
  Input i,j, or k to indicate the computational plane for surface 1. (i)
    Input imin, imax for the model surface. (1, 23)
    Input j for the model surface. (1)
    Input kmin, kmax for the model surface. (1, 34)
	y
	1
	j
	2 22
	1
	1 34

*************************** Integrating ***************************	

Input the type of image you wish to create: (s)
        i for interferogram
        s for shadowgraph
        k for schlieren
  Input the wave length in meters of the light source. (0.000000600)
  Input the type of interferogram: (i)
        i for infinite fringe
        v for finite fringe with vertical fringes
        h for finite fringe with horizontal fringes
  Input the number of vertical finite fringes. (10.0)
    Input the angle of the fringes. (0.0)
	i
	0.0000006000
	
	v
	20.00
	10.00

Do you want another image? (n)	y

```
Input the type of image you wish to create: (s)           |
          i for interferogram                             |
          s for shadowgraph                               |
          k for schlieren                                 | i
  Input the wave length in meters of the light source. (0.000000600) | 0.0000006000
  Input the type of interferogram: (i)                    |
          i for infinite fringe                           |
          v for finite fringe with vertical fringes       |
          h for finite fringe with horizontal fringes     | h
  Input the number of horizontal finite fringes. (10.0)   | 0.00
    Input the angle of the fringes. (0.0)                 | 10.00
                                                          |
Do you want another image? (n)                            | n
                                                          |
The adjusted image size is  197 by  504 pixels.           |
                                                          |
The values for the corners of the image are (in m):       |
          x1, x2:  -0.1347E+00   0.6391E+00               |
          y1, y2:  -0.1442E+01   0.5376E+00               |
```

These images required 22 CPU seconds on a CRAY YMP.

Horizontal finite-fringe interferogram   Vertical finite-fringe interferogram

Interferograms obtained using the input parameters in Table III. Ideal-gas solution for the forebody flow for the Aeroassist Flight Experimeny (E. Venkatapathy).

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Appendix C. Refractive Indices for Various Species

Species	Gladstone-Dale Constant/kg-m^3
Ar	0.000158
H	0.00153
HO	0.000474
H_2	0.00147
H_2O	0.000316
He	0.000201
CO_2	0.000229
N	0.000253
N_2	0.000237
N_2O	0.000256
NO	0.000226
O	0.000153
O_2	0.000193