Semiautomated method for the determination of density profiles from Mach-Zehnder interferograms

Hai-Tao Chen

Institute of Mechanics, Chinese Academy of Sciences, Beijing, People's Republic of China

Walter H. Christiansen

Department of Aeronautics and Astronautics, University of Washington, Seattle, Washington 98195

(Received 11 December 1984; accepted for publication 25 April 1985)

The determination of a density field by means of digital imaging of a Mach-Zehnder interferogram and processing by a microcomputer is described. The apparatus used in this study are an optical single-bit digitizer, a microcomputer, and a dot matrix printer. Photographs of the interferograms are semiautomatically digitized by the apparatus. The fringe count and the spatial locations of the fringes are calculated using BASIC programs, and the density field is plotted as an output.

INTRODUCTION

Mach-Zehnder interferometers¹ are commonly used to measure the variation of the density field or the optical density field in gas flows. However, manual evaluation of the resulting interferograms can be a tedious and time-consuming job. Furthermore, it is subject to errors introduced by the manual method of data reduction of the interferogram. One would prefer an automated method of reducing the data. In Refs. 2 and 3, the manual method for measuring and calculating the index of refraction profile of a gas jet was largely replaced by a simple computer processing method. In this paper, a detailed description of the method and basic program is presented. It is believed that this method can also be simply extended to other flow fields, as well as other types of interferograms.

1. OPTICAL DENSITY PROFILE

In this paper, it is assumed that the Mach-Zehnder interferograms have been obtained in some related experiment. An example of an interferogram using a HeNe laser light source is shown in Fig. 1, which is taken from a test of a

low-speed nozzle flow with gas mixture of 62% Ar-38% He into ambient air. AB is the nozzle exit, and BC is the region associated with the surrounding air. The flow is in the direction from left to right. The displacements of each fringe are due to the difference of the density and, hence, the index of refraction of the gas inside the shear layer.¹ The particulars of this experiment are not too important; rather, the figure is only needed to illustrate the method.

The optical density profile of a flow field is calculated from the data of the fringe numbers and locations of both tare (a test taken without the flow field present to evaluate the optics of the Mach-Zehnder interferogram) and test interferograms. The fringe shift between these two pictures at the same point is equal to the phase angle difference and also equal to the optical length difference of two coherent beams that combine and form fringe patterns in the Mach-Zehnder interferograms. The relations between the fringe number, N , the laser beam wavelength, λ , the index of refraction, n , and the test section thickness, L , for the test, F , and the tare, T , picture are

$$N_F \lambda = (n_F - n^*)L, \quad (1)$$

and

$$N_T \lambda = (n_T - n^*)L, \quad (2)$$

respectively, where $*$ represents the surrounding air.

Subtract Eq. (2) from Eq. (1) and use the relation between the gas density, ρ , and

$$n = 1 + \beta \rho, \quad (3)$$

where β is the Gladstone-Dale constant; the product of $\beta \rho$ of the gas inside the shear layer can then be obtained by

$$\beta \rho = (\lambda / L)(N_F - N_T) + (\beta \rho)^*. \quad (4)$$

$\beta \rho$ is called the optical density. Once the value of β is known, the gas density ρ can be determined.

II. APPARATUS AND THE PROGRAM

The apparatus used in this study are a set of a Microneye Bullet,⁴ an Apple II Plus computer, and an Epson RX-80

FIG. 1. An example of the Mach-Zehnder interferogram.

TABLE I. Camera parameters.

Microneye picture size	512 × 128 pixels
Apple monitor screen size	280 × 128 pixels
Exposure time	250 ms
Lens aperture	$f/8-f/11$
Focus distance	1 ft

printer with graphics capability. Although these particular apparatus were employed, most any microcomputer and dot matrix printer may be used if the Microneye hardware is compatible with the computer system and the program statements are slightly modified according to their characteristics. The Microneye Bullet has an IS32 OpticRAM element that contains two 128 × 256 photosensitive arrays (5.504 × 1.088 mm each) separated by a narrow nonphotosensitive strip of 0.150 mm width. The camera is only capable of single-bit intensity resolution. This is all that is required for reading most interferograms. Software is supplied with the device to run the instrument with the prescribed microcomputer. After running the MICRONEYE program, the image of the interferogram is optically focused on the surface of the OpticRAM, and a picture of black and white dots can be displayed on the computer screen. Table I shows the camera parameters used in this study. Using this method, pictures of test and tare interferograms are displayed and saved in a diskette with different names.

As there was no ready-made computer program for the determination of the density profile from an interferogram on hand, a program was created for this purpose. This program consists of two files, called LDEN and LSITY. When the file LDEN is being run, the computer counts the number and calculates the center location of each fringe along 16 horizontal lines according to the information of black and white dots. File LSITY is run automatically after the end of the file LDEN, and the pictures are displayed on the screen with the corresponding center locations of the fringes suc-

FIG. 2. Double picture.

FIG. 3. Optical density profile in a shear layer.

cessively. The center locations can be corrected manually if needed at that time. After inputting two constants, $B1$ and $B2$, which are the values of λ/L and $(\beta\rho)^*$ in Eq. (4), respectively, a plot of the $\beta\rho$ profile can be displayed on the screen and printed by the printer.

Copies of these BASIC source files are available by writing to the second author or by using PAPS.⁵ A floppy disk of the files may also be made available by the second author, provided a blank diskette is included with the request.

III. RESULTS

Figure 2 is the computer-drawn double picture of the interferogram shown in Fig. 1. The black dots in this figure are the center locations of the fringes after correction. The white strip in the middle part is due to the nonphotosensitive strip of the IS32 OpticRAM element of the camera.

Figure 3 is the optical density profile of the shear layer inside the region of Fig. 2. The curves are the optical density distribution along the Y axis at six X positions marked in the figure corresponding to six equally spaced locations downstream from the nozzle exit. $\beta\rho$ is the optical density calculated from Eq. (4) at the points of consideration. Therefore, the upper part of these curves corresponds to the optical density of air, and the lower part to that of the noble gas mixture flowing from left to right. The density distributions shown in Fig. 3 are those expected for an inhomogeneous low-speed shear layer. The transition between the two fluids grows with distance downstream of the nozzle exit as it should. The irregular variations in the curves are caused by read-out errors due to the poor resolution of the interferogram and the finite resolution associated with the computer-drawn field. The results are qualitatively accurate^{2,3} and may be improved in principle by using more than 16 horizontal lines. The length of time needed for the computer operation for each run is almost 1 h.

ACKNOWLEDGMENTS

The authors are grateful to Professor A. Hertzberg for his guidance and encouragement. They wish to thank Professors Robert D. Brooks and Eric Lindahl for their kind help with the computer operation. This research was sponsored by the Air Force Office of Scientific Research.

FIG. 4. Map of the high-resolution graphics screen.

APPENDIX: SOME CONSIDERATIONS ABOUT THE PROGRAM

The files LDEN and LSITY, containing the transform of the information from the photograph to a density field, are somewhat different from an ordinary BASIC program. The following were the problems to be considered and solved during this development.

A. Address of each byte

According to the Applesoft Manual, the information of each byte can be read in the form of a decimal number by means of the PEEK (address) command. In the map of the high-resolution graphics screen shown in Fig. 4, there are 40×16 locations, and each location contains 8 bytes. The address of each byte is a number from 8192 to 16383, which is the summation of three numbers A, B, C, corresponding to the location of this byte in the map. Program line 110 of file LDEN does this summation using $C = 4096$. The decimal number read by the computer at this address can be translated into reverse binary (0 and 1), corresponding to white and black dots. Program lines 120–200 are for this translation.

B. Contrast problem

After a picture is displayed on the screen, the computer counts the number of fringe according to the number of

change of 0–1 in each horizontal line. The location of the beginning of each fringe plus the half-width of the fringe at that position is equal to the center location. This is done by the lines 270–440 of the file LDEN.

Due to the turbulent effect of the jet flow, the fringe inside the shear layer of the interferogram is sometimes blurred (see Fig. 1), so that the computer cannot distinguish fringes easily. This is the contrast problem. It may be solved by changing the brightness level of five pictures of the same object. The computer reads and adds the information of these pictures at each position and calculates the numbers and the center locations of the fringes by comparing the maximum value of each addition. Contrast enhancement of the results are very well handled with this method, but some must still be corrected manually.

C. Double picture

Because the Microneye Bullet consists of an IS32 Optic-RAM of two photosensitive arrays, it is possible to get a picture of twice the height or 256 pixels. The upper and lower parts of the same interferogram can be displayed on the computer screen separately by changing program line 5740 of the MICRONEYE program to

5740 IF AR = 1 THEN CM = CM + 4 .

In file LDEN, F1–F5 are file names of the upper pictures, and L1–L5 are file names of the lower pictures.

D. Manual correction

There are three kinds of errors mislocating the center of the fringes: (1) The directional needle of the nozzle crosses the fringes, as shown in Fig. 1. (2) The uncomplete fringes must be deleted, e.g., there are two near AB in Fig. 1. (3) The contrast problem. Manual correction is sometimes necessary to obtain a reasonable density profile. This is done by using lines 1120–1180 of file LSITY. When these commands are used, a particular white dot can be displayed at any position along any horizontal line on the screen to execute correction demands.

¹A. H. Shapiro, in *The Dynamics and Thermodynamics of Compressible Fluid Flow, Vol. I* (Ronald Press, New York, 1953), p. 63.

²H. Johari, H. Poling, H. T. Chen, D. W. Bogdanoff, and W. H. Christiansen, presented at the AIAA 17th Fluid Dynamics, Plasma Dynamics and Lasers Conference, June 1984, AIAA paper 84-1622, Snowmass, CO, 1984.

³W. H. Christiansen, H. Johari, and D. W. Bogdanoff, in *Proceedings of the Fifth Gas Flow and Chemical Laser Conference*, Oxford, England 1984, Institute of Physics Conference Series No. 72, (Adam Hilger Ltd., Bristol and Boston, 1985), p. 345.

⁴C. Wieland, *BYTE* 8, 316 (1983).

⁵See AIP document No. PAPS RSINA-56-1619-6 for 6 pages of a program for the determination of density profiles from Mach-Zender interferograms. Order by PAPS number and journal reference from American Institute of Physics, Physics Auxiliary Publication Service, 335 East 45th Street, New York, NY 10017. The price is \$1.50 for each microfiche (98 pages) or \$5.00 for photocopies of up to 30 pages, and \$0.15 for each additional page over 30 pages (airmail additional). Make checks payable to the American Institute of Physics.