Fully computerized evaluation of interferograms from fluid flow investigations

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An interactive computerized system capable of evaluating interferograms, obtained for example in gas flow studies, has been developed. The program takes full advantage of the facilities offered by the Apple 2 microcomputer and is designed so that the user needs no previous knowledge of computers and/or software. The program is constructed of several main programs invoking other sub-programs; each program can be active at each step of the process and is menu driven. Thus, the user does not have to remember either the questions or their order of appearance.

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Optical measurement techniques have many advantages in flow investigations. For practical purposes they are free from inertia lag, they do not require the introduction of a disturbing mechanical probe into the flow field, and they record conditions throughout an extended area of flow field rather than conditions at one point. Of the three useful and complementary techniques for gas flow studies – shadowgraph, schlieren, and interferometry – interferometry is the most important for obtaining quantitative information about density fields. Thus the interferometer has been used in studies of, *inter alia*, boundary layers, natural (free) convection heat transfer, and subsonic, transonic, supersonic and hypersonic flows.

At low moderate temperatures, when dissociation and ionization are negligible, a relatively simple expression[1] relates the density ρ to the refractive index n:

$$n-1=K\rho \tag{1}$$

where K is the Gladstone-Dale constant of the gas under consideration. The Gladstone-Dale constant depends on the wavelength of the light source and the nature of the gas, and to a large extent is independent of the pressure of the gas.

If the phenomenon considered involves free convective heat transfer, or boundary layers, then the pressure can be assumed to be constant. Thus, using the equation of state $P=\rho RT$, the density ρ in Eq (1) can be replaced by the temperature:

$$n-1=\frac{K_1}{T}$$

where $K_1=KP/R$ and R is the gas constant.

In most gas dynamics applications one wants to know the density at a definite position in space. For this purpose it is normally required that the fringes be located at this point to obtain the appropriate interferogram needed for the evaluation[1].

The Mach-Zehnder interferometer[2,3], developed in the early 1890's, allows location of fringes at any desired place by suitable rotation of its mirrors and/or beam-splitters and is, therefore, suitable for this purpose. A beam-splitter and plane mirror divide light from one source into two coherent and parallel beams, one of which travels through the gas flow being studied, while the other serves as a fixed reference arm. A second beam-splitter and mirror combination reunites the two coherent beams to produce interference fringes. For relatively large-scale technical applications in wind-tunnel or shock-tube studies, the Mach-Zehnder arrangement has proved to be most practical. The fact that the flow under study is traversed only once by the test beam, unlike the Michelson arrangement, renders interpretation of the interferograms relatively straightforward. Detailed reviews and discussions of the theoretical aspects of the Mach-Zehnder interferometer as well as its history and construction can be found elsewhere[1,4-7].

The interferometer measures refractive index, which can be obtained at any point in a given interferogram[1]. Eq (1) can then be used to determine the density at any point. Clearly, therefore, the major task in evaluating interferograms is to determine the refractive index at any desired point.

Until recently refractive index was deduced from the interferograms manually. Unfortunately the manual process was inaccurate and inefficient. Ben-Dor, Whitten and Glass[8] developed a semi-computerized (digital) method for the evaluation of interferograms. In their approach the spatial coordinates (x,y) of the various lines of interference (fringes) on the interferograms were digitized, making computer analysis possible. Once the interferograms were digitized, corrected, and stored on a computer disc, the density could be obtained along any predetermined line within several minutes[8].

Unfortunately, the digitizing process was time-consuming and tiresome; digitizing two fairly simple

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interferograms, one 'flow' and one 'no flow', took about 1.5 h. Most of the errors which had to be corrected were introduced during digitization. The purpose of this study was to develop a totally automated computerized method of evaluating interferograms.

Method

The rapid developments in electronics and computer sciences provide new and powerful means for improving the technique of evaluating interferograms. First, the suggested method of evaluating interferograms, based on the theoretical approach developed earlier[8], will be presented briefly.

The interferogram is attached to a flat plate and, using a television camera, transferred to the computer memory. Fig 1(a) is a 'flow' interferogram showing a planar shock wave propagating from left to right. The measured shock wave Mach number, M_s, is 2.13, the initial pressure $P_0 = 50$ torr, the initial temperature $T_0 = 294.4$ K and the test gas pure argon. The corresponding 'no-flow' interferogram is shown in Fig 1(b). These two interferograms were fed into the computer and results are shown in Figs 2(a) and 2(b), respectively.

Comparing Fig 2 to the original interferograms indicates that while some information is missing, some extra information is added. For example, the fourth fringe from the top is discontinuous, all the fringes are discontinuous at the position of the shock wave, and on the bottom of the right-hand side (Fig 2(a)) the space between the black fringes which should have been white (Fig 1(a)) is filled with black spots. The reason for the difference between Fig 2 and the originals is probably due to the non-uniform illumination used when the original interferograms were recorded by the TV camera. The computer program described here enables the user to reconstruct the original interferogram fairly easily.

As a first step, the 'level of greyness' is reduced by the usual procedure on the microcomputer. The result after reduction of the 'level of greyness' of the 'flow' interferogram Fig 2(a) is shown in Fig 3. Comparison of Figs 2(a) and 3 indicates that while the extra information (the black spots in the white fringes) was cleared out (bottom right-hand side) some vital information was lost (see, for example, the eighth and ninth fringes from the top).

The second step involves the replacement of all the missing information. This is done by moving a cursor to any desired point and replacing white spots by black spots or vice versa.

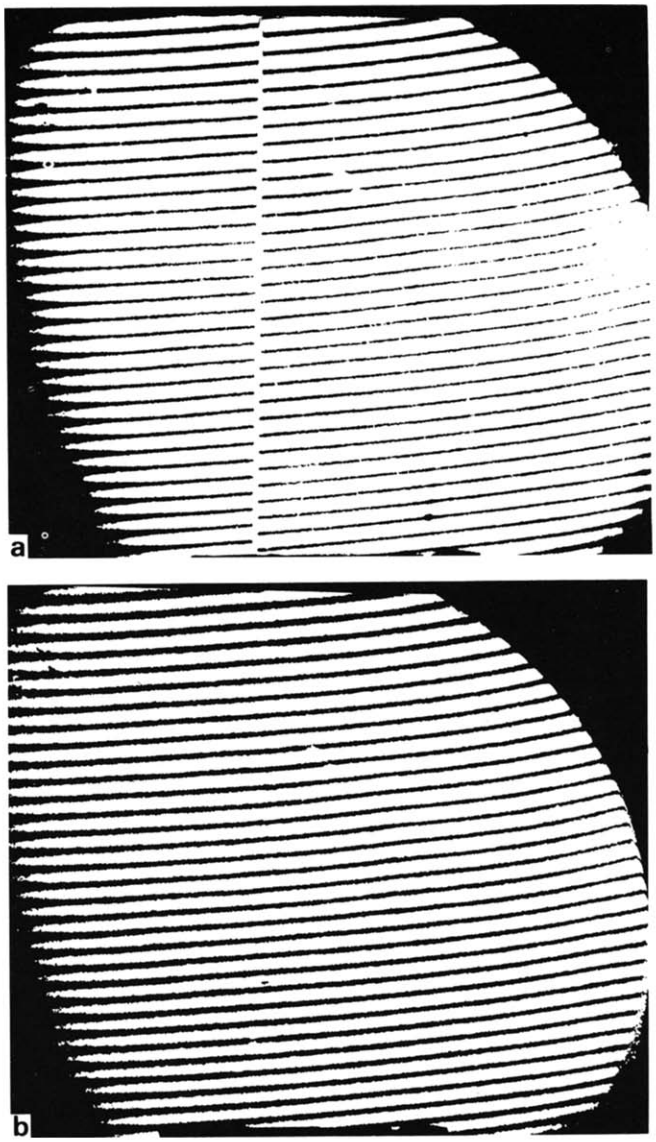

Fig 1 (a) 'Flow' interferogram of an incident shock wave propagating from left to right into pure argon; $M_s = 2.13$, $P_0 = 50$ *torr,* $T_0 = 294.4$ *K. (b) 'No-flow' interferogram corresponding to the thermodynamic conditions of (a)*

The corrected interferogram is shown on Fig 4. The reader is advised to briefly go through Figs 1(a), 2(a), 3 and 4 to see the sequence through which the final recorded

Notation

K	Gladstone–Dale constant
K_1	Constant ($=KP/R$)
L	Width of the test section
M_0	Molecular weight
M_s	Shock wave Mach number
n	Index of refraction
P	Pressure
P_{10}	P_1/P_0
R	Gas constant
S	Fringe shift
T	Temperature
x	Spatial coordinate
y	Spatial coordinate
α	$(\gamma+1)/(\gamma-1)$
β	$(\gamma-1)/2\gamma$
γ	Specific heat capacities ratio, C_P/C_V (7/5 for a diatomic gas and 5/3 for a monatomic gas)
λ	Wavelength
ρ	Density
ρ_{10}	ρ_1/ρ_0

Subscripts

0	State ahead of the shock wave
1	State behind the shock wave

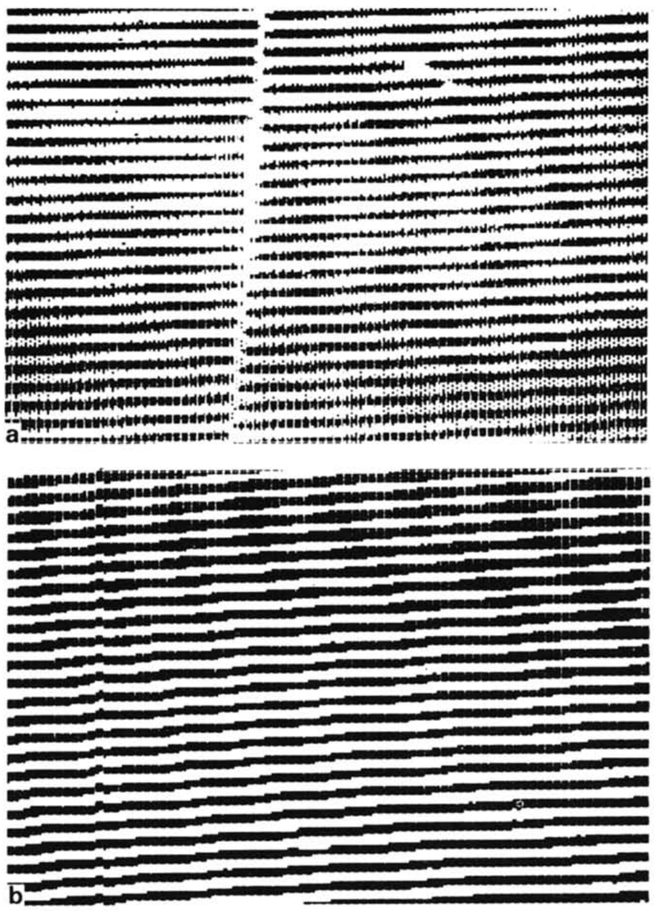

Fig 2 (a) Recorded 'flow' interferogram and (b) 'no-flow' interferogram

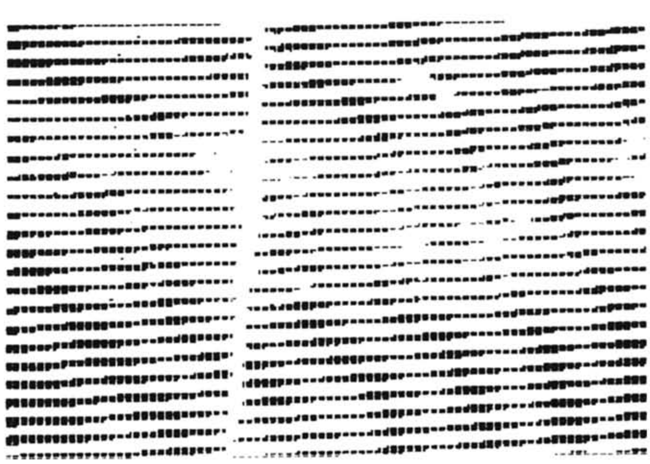

Fig 3 Recorded 'flow' interferogram after reduction of 'greyness'

picture is obtained. Note also that the fringes are now continuous when they pass through the shock wave. It should be noted here that the extent of the shock induced fringe shift can be identified quite easily in most of the cases in the original interferogram, provided it is well focused. If, however, the interferogram is out of focus, the expected shock induced fringe shift can be calculated using the measured value of the incident shock wave Mach number, M_s, from which the density jump across

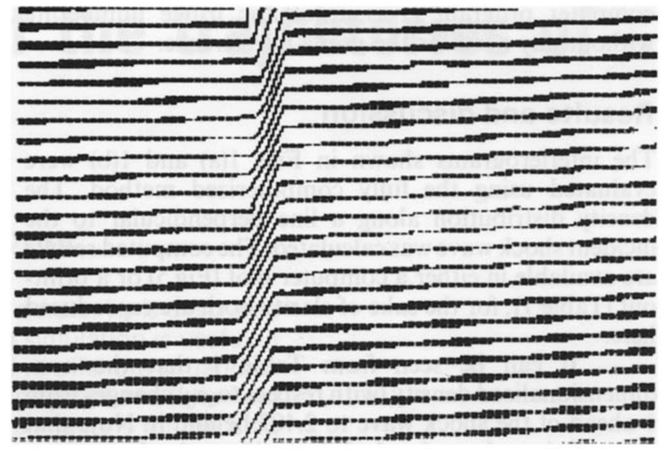

Fig 4 Recorded 'flow' interferogram after the addition of the missing information

the shock wave can be obtained. For example, using the following well known relations[9]:

$$\frac{\rho_1}{\rho_0}=\frac{1+P_{10}}{\alpha+P_{10}} \tag{2}$$

and:

$$P_{10}=\frac{1}{\alpha}\left(\frac{M_s^2}{\beta}-1\right) \tag{3}$$

together with $\alpha=4$ and $\beta=\frac{1}{5}$, which are the appropriate values for a monatomic gas, one gets for $M_s=2.13$, $\rho_{10}=2.408$.

Eq (2.13) of Ref 8 can be rewritten as:

$$S=\frac{L}{\lambda}(n_1-n_0) \tag{4}$$

Inserting n from Eq (1) gives:

$$S=\frac{LK\rho_0}{\lambda}[\rho_{10}-1] \tag{5}$$

For the conditions being considered ($P_0=50$ torr, $T_0=294.4$K), the equation of state $P=\rho RT$ can be used to get $\rho_0=1.056\times10^{-4}\,\mathrm{g\,cm^{-3}}$.

Using this value together with $\rho_{10}=2.408$ as previously calculated, $L=10$ cm, $K=0.1574\,\mathrm{cm^3\,g^{-1}}$ and $\lambda=6943\times10^{-8}$ cm, finally results in $S=3.37$. The fringe shift shown in Fig 4 is in excellent agreement with this calculated value.

At this stage the recorded pictures ('flow' and 'no flow') can be evaluated. For this purpose a special computer program has been developed†, making full use of the facilities available with the Apple-2 microcomputer. The program, designed so that the user needs no previous knowledge of either computers or software, is constructed of several main programs invoking other sub-programs. Each menu-driven program can be active at each step of the process so the user does not need to remember either the questions or their order of appearance.

In the conclusion of Ref 8 it is stated that 'the correct assignment of fringe number over the field of view... would probably still be done manually.' Our

† The computer program can be obtained from Dr G. Ben-Dor without charge.

computer program gives automatic fringe numbering without any need for the user's interference.

Results and discussion

The interferograms shown in Figs 1(a) and 1(b) were evaluated using the fully computerized method. The density distribution along a line perpendicular to the incident shock wave was calculated. The computed results are available in either a computer plot (Fig 5) or a printout (Table 1); for the sake of clarity both are reproduced here.

It can be seen from Table 1 that the nondimensionalized density (with respect to ρ_0) changes from 1 ahead of the shock wave to 2.407 behind it. Note that some of the values ahead of the incident shock wave are not exactly 1 (eg 1.028) as they should be. The inaccuracy associated with the present method as far as density ratios are concerned is estimated to be $\pm 4\%$. Therefore, the 2.8% difference is acceptable.

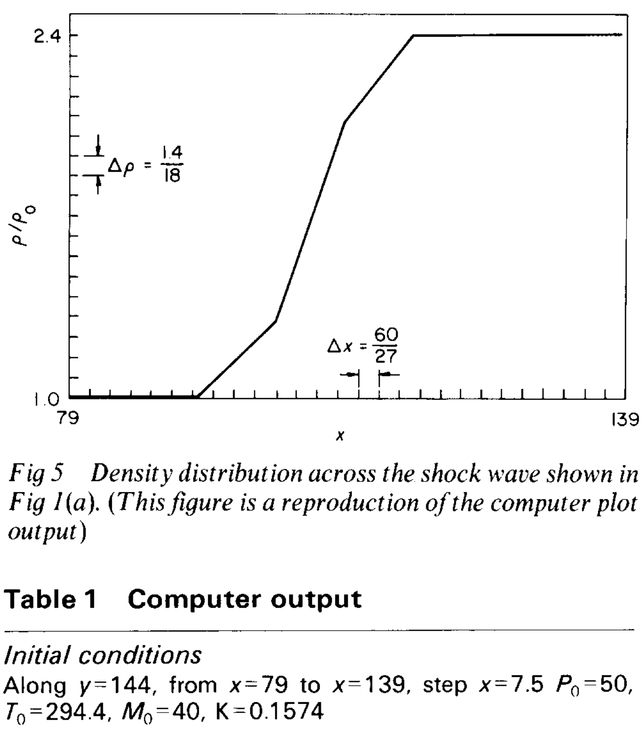

Fig 5 Density distribution across the shock wave shown in Fig 1(a). (This figure is a reproduction of the computer plot output)

Table 1 Computer output

Initial conditions

Along y=144, from x=79 to x=139, step x=7.5 P_0=50, T_0=294.4, M_0=40, K=0.1574

Results

x-coordinate	Density
79	1
86.5	1.028
94	1.028
101.5	1.297
109	2.064
116.5	2.400
124	2.400
131.5	2.407
139	2.407

The density jump across the shock wave as obtained from the computer evaluation is $\rho_{10} = 2.407$ (see Table 1). Using Eq (2) with the measured value of the incident shock wave Mach number $M_s = 2.13$ gives $\rho_{10} = 2.408$. Thus the computer evaluated density jump is in excellent agreement with that obtained from the shock velocity measurement. It is well known, however, that the measurement of the incident shock wave in shock tubes usually involves some uncertainty. For the present case[10] $\Delta M_s = 0.03$. Therefore, the incident shock wave Mach number in this experiment is $2.10 \leqslant M_s \leqslant 2.16$. This in turn implies that the density ratio across the incident shock wave should be $2.380 \leqslant \rho_{10} \leqslant 2.435$. The evaluated value of $\rho_{10} = 2.407$ lies well inside this range.

Conclusions

A fully computerized method for the evaluation of perfect gas interferograms was developed. The computer program developed overcomes all the obstacles of an earlier semi-computerized method[8]. The new method was checked against a simple experiment of a normal shock wave propagating in a shock tube and gave excellent agreement.

The time needed for evaluating the interferograms of one experiment was reduced from 4 h[8] to about 0.5 h. In developing the fully computerized method an important step in simplifying the method of evaluating interferograms was achieved.

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