Image-based processing simulation of shock wave propagation through the area of ionization instability

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Abstract. A partially automatic method of digital processing images (photographs, shadow and Schlieren pictures) for the analysis of experimental data is proposed. The method is utilized to investigate the effect of the region of ionization instability created by a glow gas discharge on the front of an initially flat shock wave. The proposed method is based on a composition of simple image processing operations and makes it possible to perform simulations taking into account the real geometry of the ionization strata and the shape of the front of a shock wave based on the obtained experimental images. First, as a result of digital processing the geometry of experimental objects is extracted from the images. This information is then embedded in the Navier-Stokes code for conducting simulations. New results for the real geometry of ionization strata of different scales are presented which confirmed the previous ones obtained for the density homogeneously stratified source model.

1. Introduction

Currently, image processing methods are used in an increasing number of studies, which has become possible due to the technological capabilities of big data processing. Image processing techniques provide a set of tools for analyzing experimental data, such as Schlieren images, shadow images, photographs, and so on. The set of such image data is important in particular for the analysis of various modes of gas flows. Recently, the next generation of image processing based on deep learning algorithms for processing experimental data has been introduced.

A method for processing experimental data based on machine learning of computer vision for the study of non-steady flows in a channel is considered in [1]. At the same time, the evolution of flows with discontinuities in the channel of a rectangular shock tube during high-speed filming of the flow dynamics is studied. Another code system based on image processing methods is described in [2]. It was applied to shock wave detection and tracking problem for high-speed experimental image data. A modified method of background oriented Schlieren (BOS) image processing is proposed and the corresponding software is described in [3]. This method aims to avoid some incorrect results in the case of millimeter-scale objects. The method was applied to the obtained images of a hot airflow at a given temperature. The core of the method contains background subtraction, object recovery, filter, edge detection, etc. The research of a shock wave dynamics, distortion and generation of instability was performed, as well.

A method for shock wave detection for two-dimensional viscous/non-viscous flows on Cartesian grids was introduced in [4, 5]. The method allows to detect shocks in a viscous flow and represent the...
shocks. In [6] a new indicator based on the edge detection techniques by machine learning and computer vision was introduced. The indicator is embedded into the high-order code based on discontinuous Galerkin (DG) approach. The detection and spatial localization of the shock wave position is carried out by neural networks via detecting edges and is implemented by considering the solution of the internal element associated with the image and the nodal degrees of freedom as its pixels. A review of the current state of research in the field of turbulence closure problem modeling based on big data analysis is presented in [7]. It describes open problems and also lists the perspectives of machine learning (ML) methods used for parameter estimation and model identification in terms of large vortex modeling.

The key issue is the consistency of the training data, the underlying physics model, and the discretization which must be taken into account for successful computer simulations. A controlled method for predicting the values of the pressure force on the cylinder from the velocity distributions in its trace flow was developed in [8]. Such a task is relevant for a large number of engineering applications where it is necessary to develop a model that relates the load around the structures to the detected flow features. A convolutional neural network (CNN) consisting of convolutional and fully connected layers has been developed which can process velocity information by extracting features fed to the input of fully connected layers to obtain pressure coefficients. Broad perspectives of convolutional neural network can be predicted in fluid dynamics.

The problems of flow control with the help of external energy sources are important problems of aerodynamics [9–12]. When solving problems of flow past aerodynamic bodies in supersonic and hypersonic modes, an urgent problem is the energy effect on a bow shock wave because the strong drag force and thermal heating acting on the body can be reduced. As a result, the flight range increases, fuel consumption is saved, etc. Such questions have been considered by various research groups, resulting in a number of methods that vary depending on the control mechanism.

The problem of controlling high-speed flows and shock-wave configurations is considered in [13]. The interaction of a plane shock wave with a region formed by ionization instability in a gas discharge plasma which is represented by two types of ionization strata, large-scale and small-scale, is considered. The region formed by an ionization unstable glow gas discharge was modeled using a set of thermal layers with different densities (and temperatures). As a result, it has been shown that the influence of ionization instability leads to distortion of the plane shock wave front up to its complete disappearance. The shape of the shock wave was shown to change, becoming unstable. Various types of discharges, from small-scale to large-scale strata, as well as the conditions for their occurrence and development have been obtained in [14]. Depending on the physical conditions of the discharge, the presence of ionization strata with time leads to a layered structure of the plasma medium. At the same time, it becomes possible to generate layers of different thickness, where not only the electronic temperature differs, but also the temperature of the gas in the layers. Examples of flow modes with the disappearance of the shock wave front caused by the appearance of unstable shear layers are given in [15]. In [16] a problem of energy redistribution during the shock wave passage through the temperature layered plasma region is investigated.

The present paper is devoted to study of the interaction of ionization unstable stratified medium with the plane shock wave on a base of a partially automatic method of digital processing of experimentally obtained images. A composition of simple image processing operations to extract the shape of ionization strata from the experimental images is proposed. The impact of the striation area formed by the ionization unstable glow discharge is analysed on the base of the Navier-Stokes system of equations with the embedded image-based shape of the thermal layers.

2. Methodology

2.1. Statement of the problem

Interaction of the thermally stratified gas medium with a shock wave in a tube is studied. For the simulation the conservative form of the full system of Navier-Stokes equations for a viscous heat-conducting perfect gas is used [17]
\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} = 0,
\]
(1)

\[
\tilde{U} = \left( \frac{\rho u}{E} \right), \tilde{F} = \left( \frac{\rho u}{p + \rho u^2} \right), \tilde{G} = \left( \frac{\rho v}{p + \rho v^2} \right),
\]

\[
\tilde{F}_v = -\left( \frac{\mu}{Re(\frac{4}{3}u_x - 2/3v_y)} \right), \tilde{G}_v = -\left( \frac{\mu}{Re(\frac{4}{3}v_y + 2/3u_x)} \right), \pi_1 = u(4/3u_x - 2/3v_y) + v(v_x + u_y), \pi_2 = v(4/3v_y - 2/3u_x) + u(v_x + u_y),
\]

\[
E = \rho(\varepsilon + 0.5(u^2 + v^2)), N = RePr(\gamma - 1)/\gamma.
\]

Here \( \rho, p, u, v \) are the gas density, pressure, \( x \)- and \( y \)-velocity components; \( \varepsilon \) is the specific internal energy

\[
\varepsilon = \frac{p}{\rho(\gamma - 1)}.
\]

The dependence of the dynamic viscosity \( \mu \) on temperature \( T \) is approximated by the Sutherland's law

\[
\mu = T^{1.5} \left( \frac{1+s_1}{T+s_1} \right).
\]

Coefficient of thermal conductivity \( k \) is assumed to depend on temperature as \( k = T^{0.5} \).

**Table 1.** Values of the parameters.

| Parameter | Value          |
|-----------|----------------|
| Pr        | 0.703          |
| Re        | 9500           |
| M         | 2              |
| \( \gamma \) | 1.4          |
| \( s_1 \) | 0.41 (120 K)   |

No-slip boundary conditions and the conditions of absence of flows normal to the tube walls were utilized. The gas temperature on horizontal walls was set equal to the undisturbed flow temperature. Also, the non-reflection conditions were used at the right boundary of the computational domain. The problem was solved in the dimensionless form, the normalizing values were used in accordance with the parameters of the experiment [13]. Values of the parameters such as Prandtl number (Pr), Reynolds number (Re), Mach number (M), ratio of specific heats (\( \gamma \)) and a constant in the Sutherland law (\( s_1 \)) are introduced in table 1.

Sketch of the considered rectangular domain is shown in figure 1. Red line denotes the shock wave initial position (\( x_0 = 1.0 \)). Two difference grids of 800×500 nodes and 1600×1000 were used with spatial steps \( h_x = h_y = 0.002 \) and \( h_x = h_y = 0.001 \), accordingly. The original 2D code was utilized to perform a simulation using the full system of Navier-Stokes equations based on the complex conservative difference schemes of the second-order approximation [12].
2.2. Image processing

Two types of the stratified medium such as small-scale and large-scale strata are obtained in the experiments [13, 14] (figure 2). A composition of image processing operations contains a number of steps of the transformation of the input images of the stratified discharge as follows:

- Input image in RGB (red-green-blue) format.
- Gaussian filtration.
- Grayscale image.
- Shadowgraph (Schlieren-like) image.
- Binary layers image.
- Composed image.
- Output mask layers (binary mask image).

Wolfram Mathematica [18] software image processing built-in functions were utilized during the evaluation of the processing steps (figures 3, 4). The algorithm for processing the original image (figures 3(a), 4(a)) consists of the following steps. In the first step, Gaussian filtering is applied to the RGB color image and it is converted to the grayscale one (figures 3(b), 4(b)). Next, the shadow image is calculated by applying a gradient filter (figures 3(c), 4(c)). Then, threshold binarization is performed (figures 3(d), 4(d)). The result is multiplied pixel-by-pixel with the grayscale image (figures 3(e), 4(e)) and is binarized again (figures 3(f), 4(f)).

At the final stage a binary black and white mask image with the possible values equal to 0 or 1 is obtained. The process of forming the discrete indicator function (binary mask) is presented in figure 5. An original image embedded in the computational domain is highlighted with contours of the mask image for large-scale (figure 5, left) and small-scale (figure 5, right) strata obtained with the help of the Wolfram Mathematica functions (upper row in figure 5). Second row of the images illustrates the mask matrix relative its positioning inside the calculation area. Surface plots of mask matrix for both cases are shown in the bottom row in figure 5. Proposed approach allows to process experimental images automatically, in particular, for large-scale and small-scale stratified gas medium.

Figure 1. Sketch of the domain with embedded image of the ionization stratified discharge.
Figure 2. Various types of ionization stratified medium: large-scale strata (left), small-scale strata (right).

Figure 3. Image processing for large-scale strata.
2.3. Simulation results
The resulting mask matrix of stratified heated layers is embedded in a 2D Navier-Stokes code to perform simulations of the interaction of stratified medium with a shock wave. For this purpose, the numerical array defining by the mask matrix is formed assuming the low density in the layers denoted by the mask matrix array. The pressure is supposed not to change, so the temperature in the layers is increased in comparison with that of the undisturbed flow. It is assumed that the shape of the stratified energy source and its spatial position do not change in time and it is "frozen" in some area of consideration. An undisturbed gas density was set in the whole area and a reduced gas density (with the coefficient $\alpha$, $\alpha < 1$) was set inside the energy source layers.

Relief and surface views of the density fields (for time instants $t = 0.10, 0.15, 0.20, 0.25$) in the case of interaction of a shock wave with large-scale and small-scale homogeneous ionization strata are shown in figures 6, 7, accordingly. The results of numerical simulation of large-scale (figure 6) and small-scale (figure 7) strata show the presence of sharp peaks in the density fields which are caused by the Richtmyer-Meshkov instabilities [13, 19]. At the same time, the amplitude of the shock wave decreases noticeably with the increase in instability and with the propagation of the shock wave along the stratified source region its front is practically deceases (see, for example, figures 6(h), 7(d)). This phenomenon is in the agreement with the experimental results [13].

The front of the shock wave continues to bend during the shock wave passing through the source area. Analysis of the results also shows that a typical mushroom-like structures indicating the manifestation of Richtmyer-Meshkov instabilities are generated behind the shock wave front which has a deformed shape due to the asymmetry of the energy source (figure 8). Note, that in this case the obtained vortices are characterized by counterclockwise rotation of the upper vortex and clockwise rotation of the bottom one for right boundary/shock wave interaction. On the contrary, for left boundary/shock wave interaction the flow in the upper vortex rotates clockwise and the bottom vortex has the counterclockwise rotation. It can be clearly seen in figure 8 presenting large-scale and small-scale strata – shock wave interaction (see the enlarged inserts in figures 8(a), 8(b)). Additionally, one can see the formation of paired mushroom-like structures caused by the proximity of left and right strata boundaries in this region (figure 8(c)).
The bending of the shock wave has been obtained in the experiments [13]. For modelling the shock wave bending inhomogeneous stratified source was used; the simulations were performed on a fine grid. The central strata were supposed to have higher temperature (smaller density) than the periphery ones. Values of $\alpha$ coefficient in this simulation was chosen non-uniform and it was set with respect to the Gaussian distribution

$$\alpha = 1 - \delta_1 \exp(-\delta_2(x - x_0)^2 - \delta_3(y - y_0)^2)$$

With the fitted parameters $\delta_1 = 0.6$, $\delta_1 = 10^{-5}$, $\delta_2 = 1.6 \cdot 10^{-5}$. Coordinates $x_0, y_0$, are set to be the coordinates of a described rectangle around the strata (blue colour). By this way the inhomogeneous stratified source was modelled via the projection of the continuous Gaussian distribution on the computational grid in accordance with the binary mask metrics (figure 9).

A comparison of the results of numerical simulation and the experiment Schlieren image in the case of bending of the shock wave front is shown in figure 10. Here the model of large-scale strata was used. It can be seen that the higher temperature in the central strata (with the experimental geometry) promotes to the bending of the shock wave front. It should be noted that the obtained results for the real experimental strata shapes confirmed our previous results [13, 15] which have been obtained using the model of the energy source as a set of homogeneous heated layers.

**Figure 5.** Binary mask: large-scale strata (left), small-scale strata (right).
Figure 6. Density fields for large-scale strata: relief plot (left); surface plot (right): (a), (b) – $t = 0.10$; (c), (d) – 0.15; (e), (f) – 0.20; (g), (h) – 0.25.
Figure 7. Density fields for small-scale strata: relief plot (left); surface plot (right): (a), (b) – $t = 0.10$; (c), (d) – 0.15; (e), (f) – 0.20; (g), (h) – 0.25.
Figure 8. Mushroom-like patterns obtained via image-based stratified energy source – shock wave interaction, $t = 0.40$: (a) – large-scale strata, right and left oriented mushroom structures; (b) – the same for small-scale strata; (c) – paired mushroom-like structure

Figure 9. Density fields for inhomogeneous stratified source: large-scale strata (left), small-scale strata (right).

Figure 10. Comparison of the experimental image (upper) and simulation result (bottom).
3. Conclusions
A partially automatic method of digital processing of photographs, Schlieren images, shadowgraphs, etc. for the analysis of experimental data is proposed. The method is employed to study the interaction of thermally stratified medium of real experimental geometry with the initially plane shock wave. The effect of the region of ionization instability created by a glow gas discharge on a shock wave has been researched. New obtained results for the experimental image processing and for the investigation of the effect for real experimental geometry achieved with the proposed method are as follows:

- New approach for the numerical image extracting from the experimental ones is proposed.
- A method of embedding the real experimental geometry to the Navier-Stokes simulations using a mask construction is presented.
- Destruction of the shock wave front in density field in the region of the stratified glow discharge was achieved.
- Curvature of the shock wave front via the more heated central strata was obtained.
- Generation of the Richtmyer-Meshkov instabilities is obtained for real experimental geometry of the ionization strata which are characterized by the vortices of the opposite rotation for right and left strata boundaries/shock wave interaction.
- The formation of paired mushroom-like structures caused by the proximity of left and right strata boundaries has been obtained.
- Results for the energy source model of homogeneously heated layers have been confirmed.

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