The Development of the Technique of Computer Simulating Color-Schlieren

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Abstract : The computer simulation study for color-schlieren is to provide a new method for validations between experiment and theory, which can get color-schlieren image from the computational flow field data. This paper gives a brief description about the theory of method, technical way, algorithm, key problem that has been solved, the computational results and the future development direction.

Keywords : Flow Visualization, Color, Schlieren, Image Processing .

1. Introduction

The optical flow visualization technique is a significant tool in wind tunnel tests to develop flow field characteristics. The flow refractive index will be changed when the light passes through the test section due to the changeable flow density. So the light will be disturbed and produce shadow, schlieren and interference images which are usually used in wind tunnel tests to analyze flow density changes qualitatively and quantitatively.

The technique of CFI(Computational Flow Imaging) is mainly based on CFD(Computational Fluid Dynamics) numerical data. They will compute schlieren, color-schlieren, shadow and interference images to simulate the optical flow visualization. In recent years, more and more complicated flow field characteristics can be calculated out by CFD with the further development of CFD techniques. But the calculation data can't be compared directly with the experimental results, so it is urgent to perform a computational flow imaging technique study which enables to provide a new approach to verifications between experiment and theory.

Computational flow imaging is an optical observation method and art of digital imaging based on flow phenomenon in order to simulate real flow. It involves numerical value calculation, image processing, computer graph and many other techniques. Hence, we have developed the computer simulation software for flow visualization using

S :   lamp-house
F₁ :   filter
L :   lens
F₂ :   color light filter
m₁,m₂ :   plane reflector
M₁,M₂ :   sphere reflector
K :   knife-edge
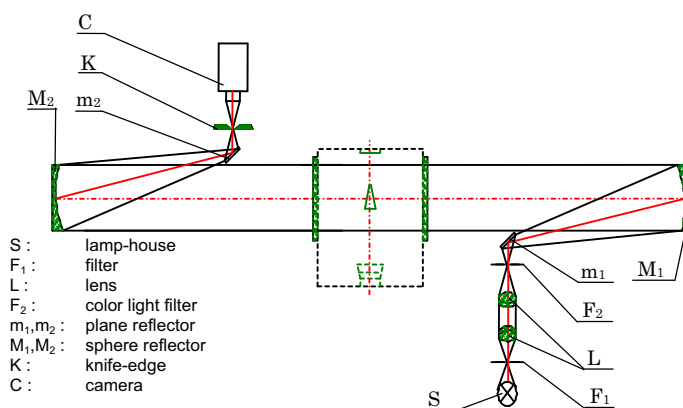C :   camera
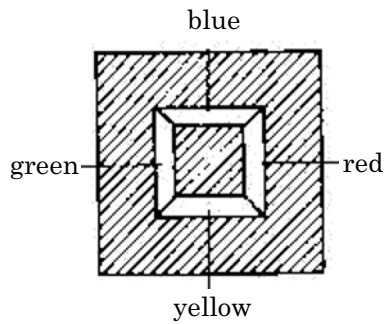
Fig.1. The principle of color schlieren.

Fig. 2. Color light filter.

VC++6.0 with the operation system Windows 98. This software computes the CFD data with some algorithm to get flow visualization simulating images include CFI-Schlieren, CFI-color Schlieren, CFI-Shadow, CFI-Interferometery and some functions for conventional image processing. The CFI-color Schlieren technique is only described in this paper.

2. Computational color-schlieren imaging

2.1 The principle of the Color-schlieren system

The schlieren imaging is a technique indicates deflection angles after light passing through flow field. The principle of schlieren system is cutting the image of light source with the edge of a knife. It can transform the change of rays due to disturbance of flow field into the distribution of light intensity on the record plane. Schlieren photography is the technique that describes the rays passing through the flow field and produces the deflection angle. Color schlieren system (Fig. 1) leads color into schlieren technique. The circle cutting system is the same sensitive in all deflection directions. Introducing color into this method, we can distinguish the direction of deflection angle on X or Y plane. One white light source is focused on a color source filter. The filter consists of red, green, blue and yellow narrow cracks, which are arranged in square (Fig. 2). Put this filter at the focus of the first reflection spherical mirror. The four-color rays overlap and mix together. If there is not flow disturbance, the schlieren image is a single well-distributed color image. Adopt square narrow crack at the edge of the knife of the schlieren system. The length of the narrow crack is a little shorter than that of the outside edge of the light source filter. The direction of the density gradient in the experiment field determines the color of the schlieren images that pass through the narrow crack. The color combination of the light source is fixed. The rays from the light zone close to filter can be mixed in the schlieren image. The recorded color combination describes the direction of the density gradient in experiment field.

Color schlieren image adopts different colors to represent the distribution of the flow parameters. Because the color resolution of human eyes is higher than the black and white resolution, the sensitivity of color schlieren photograph is two quantity levels higher than that of black-white schlieren photograph taken by the same schlieren system at the same observation condition. Hence, the method comparing the digital color schlieren computed according to CFD data with the image gained in experiment can provide a new way to test and verify experiment and theory results.

2.2 Algorithm of CFI (Computational Flow Imaging)-Color Schlieren software

The calculation method of digital color schlieren image is that four schlieren images of red, yellow, blue and green light are separately calculated and then color schlieren image is gained after four images are added up into one normalization image.

The method of calculating black and white schlieren image is explained in the ensuing chapter.

According to the theory of schlieren, there is the following relation.

$$\frac{\Delta I}{I} = \pm \int_L \frac{\partial \ln n}{\partial y} ds \quad \text{(The direction of knife-edge is vertical to the direction of Y-axis)} \qquad (1.1.a)$$

$$\frac{\Delta I}{I} = \pm \int_L \frac{\partial \ln n}{\partial x} ds \quad \text{(The direction of knife-edge is vertical to the direction of X-axis)} \qquad (1.1.b)$$

where $\Delta I / I$ is the change index of brightness of a point relative reference field. L is the length of the experimental field along the direction of Z-axis, and n is the index of refraction.

The Gladstone-Dale equation is

$$n = K_{GD}\rho + 1 \qquad (1.2)$$

In the equation, K_{GD} is the Gladstone-Dale constant, ρ is the function of density. Substituting

equation (1.2) into equation (1.1.a) and equation (1.1.b), we have

$$\frac{\Delta I}{I} = \pm C \frac{K_{GD}L}{K_{GD}\rho_0 + 1} \frac{\partial \rho}{\partial y} \qquad (1.3.a)$$

$$\frac{\Delta I}{I} = \pm C \frac{K_{GD}L}{K_{GD}\rho_0 + 1} \frac{\partial \rho}{\partial x} \qquad (1.3.b)$$

In the above two equations, ρ_0 is the density of reference flow. The partial differential is gained in calculating plane. Equations (1.3.a) and (1.3.b) reveal that the schlieren image has a close relation with the change of the gas density gradients.

2.3 The computational schlieren image

Among the grid of flow field, according to the relation between flow data and schlieren image, the image value of every point on the grid can be computed including the value of brightness and colority. Then the image value of the other points among the grid can be calculated with the two-dimension interpolation algorithm or region filled algorithm. Then we can get the whole digital schlieren image.

2.3.1 Computation of the density gradient and elimination of queer point

The computation of digital schlieren image first involves the calculation of density gradient. Equation (1.3) describes that the density gradient has a relation with the direction of the knife-edge. If the direction of knife-edge is vertical to that of X-axis (Y-axis),the density variety along the X-axis (Y-axis) direction must be calculated. The variety of density is the partial differential of density. In this course of calculation, there is a coordinate transform between the physical grid and the computational data grid to be done. According to the theory of coordinate transform, we can deduce two equations.

$$\frac{\partial \rho_{i,j}}{\partial x_{i,j}} = \frac{(\rho_{i+1,j} - \rho_{i-1,j})(y_{i,j+1} - y_{i,j-1}) - (\rho_{i,j+1} - \rho_{i,j-1})(y_{i+1,j} - y_{i-1,j})}{(x_{i+1,j} - x_{i-1,j})(y_{i,j+1} - y_{i,j-1}) - (x_{i,j+1} - x_{i,j-1})(y_{i+1,j} - y_{i-1,j})} \qquad (1.4)$$

$$\frac{\partial \rho_{i,j}}{\partial y_{i,j}} = \frac{-(\rho_{i+1,j} - \rho_{i-1,j})(x_{i,j+1} - x_{i,j-1}) + (\rho_{i,j+1} - \rho_{i,j-1})(x_{i+1,j} - x_{i-1,j})}{(x_{i+1,j} - x_{i-1,j})(y_{i,j+1} - y_{i,j-1}) - (x_{i,j+1} - x_{i,j-1})(y_{i+1,j} - y_{i-1,j})} \qquad (1.5)$$

Because of the calculation error, the calculated partial differentials at some points are probably very big or very small and they are very different from true partial differential. These points are called queer point. Because of these queer points, the brightness value different represented by every grey scale is probably very big. It will lose many details that can be described by grey scale. It makes the computational flow image idealess. To solve this problem two grey scales are chosen to be up-threshold value and down-threshold value, band filter is applied to process the data.

2.3.2 Compute image value among the grid

In this software, two algorithms are applied to compute the image value among the grid. One is 2-D interpolation algorithm. The other is region filled algorithm. Region filled algorithm is suitable for the fast computation of image value in which the points are among the irregular computational grid. The two algorithms won't be discussed in details in this paper.

2.4 Obtain the color schlieren image

The color-schlieren image shows flow parameters distribution by different colors. The eyes are more sensitive to color changes than to black-white changes. For observation, the sensitivity of the schlieren to the color-schlieren image is two-magnitude higher than that to the black-white schlieren image under the same conditions. So the color-schlieren image can reflect more clearly the density gradient distribution of the test section.

The following four equations indicate the brightness change ratio of four colors (red, yellow, blue and green respectively) obtained from the color-schlieren principle.

Red: $\dfrac{\Delta I}{I} = \pm C \dfrac{K_{GD}L}{K_{GD}\rho_0 + 1} \dfrac{\partial \rho}{\partial x}$ (knife-edge vertical to X)   (1.6)

Green: $\dfrac{\Delta I}{I} = \mp C \dfrac{K_{GD}L}{K_{GD}\rho_0 + 1} \dfrac{\partial \rho}{\partial x}$ (knife-edge vertical to X)   (1.7)

Yellow: $\dfrac{\Delta I}{I} = \pm C \dfrac{K_{GD}L}{K_{GD}\rho_0 + 1} \dfrac{\partial \rho}{\partial y}$ (knife-edge vertical to Y)   (1.8)

Blue: $\dfrac{\Delta I}{I} = \mp C \dfrac{K_{GD}L}{K_{GD}\rho_0 + 1} \dfrac{\partial \rho}{\partial y}$ (knife-edge vertical to Y)   (1.9)

Where, the brightness change ratio of red color is inverse to that of green color, the same to yellow color and blue color. In RGB color model of the computer, red is shown as (255,0,0), yellow (255,255,0), green (0,255,0), blue (0,0,255). The four colors can be separately used to predict flow field data by CFD technique. The digital schlieren images of four colors are to be calculated out with the same computation method as the black-white schlieren image. Each pixel of every color schlieren image can be expressed as the following color equation with RGB color model.

$C(C) = R(R) + G(G) + B(B)$ (1.10)

The digital color schlieren image can eventually be obtained by overlapping four color-schlieren images. The generalization will be done at the same time.

The method mentioned above is a new method that compares the experimental images with the digital color-schlieren image and gives a mutual validation for experiment and theory. The computational color-schlieren imaging obtains the digital color image through these steps. First density gradient of the flow field can be obtained from CFD-data, and then the brightness change ratio relative to the reference flow field of every pixel can be computed. The end digital color-schlieren image can be obtained through image processing.

3. Software design method and its function

The object orientation programming technique is applied in the computer simulation software. The programming language is Visual C++. The main function of this software is to process image information and calculate image data. The basic image format of Windows operate system is DIB (Device Independent Bitmap). It stores image in a device-independent format and can display it in different system. Though there is no class can process the DIB in MFC (Microsoft Foundation Class), a special DIB class must be founded, in which effective member data and processing function of DIB must be encapsulated. But constructing this kind of class faces many problems. Because even if Win32 SDK (Software Development Kits) has not provided many API (Application Program Interface) functions to process DIB directly. Hence before constructing class, a set of complete function collection must be designed. It will make code succinct when realizing the function of class
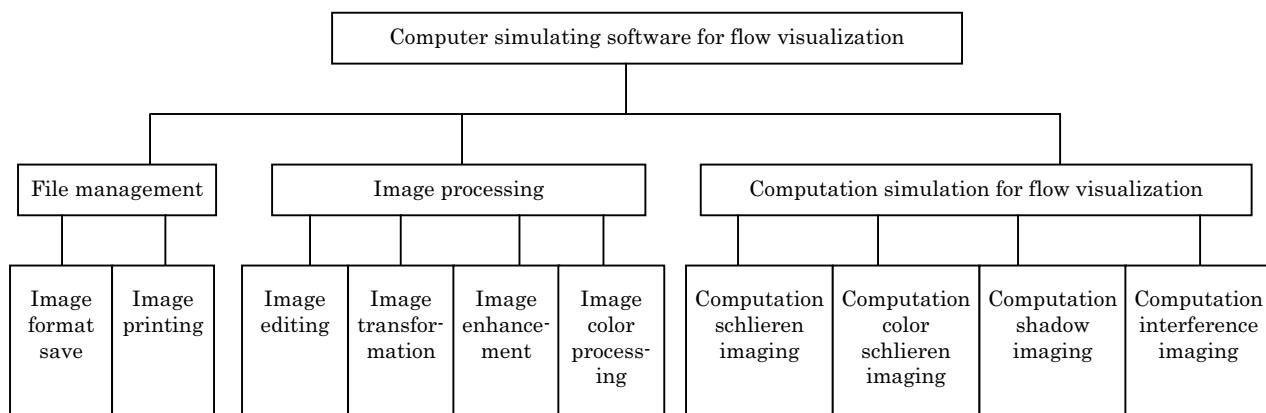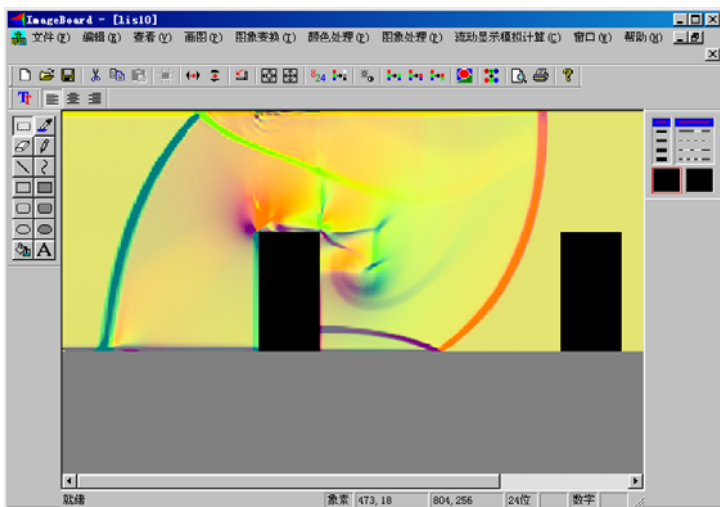

Fig. 3. The structure of the software.

Fig. 4. The function and interface of software.

Cdib and transferring the function collection. When a class is constructed, it should first satisfy the functions inquired. Besides, it should be easy to maintain and expand. If new function is needed, new class can then be constructed. The special property of this class is inherited from class Cdib. Hence the system can be easily expanded.

The software has three major functions: file management, image processing and CFI-simulation for flow visualization. There are another functions such as file format management, drawing, editing, image transformation, color processing, CFI-schlieren imaging, CFI-shadow imaging, CFI-interference imaging and CFI-color-schlieren imaging. Figure 3 gives the basic structure of the software. Its interface is shown in Fig. 4.

4. Computational Result of the Software

The simulation software has realized the computation of the color-schlieren image from CFD flow field data. It can be applied into many kinds of flow field. Figure 5 gives the color-schlieren image computed from CFD the predicted data of the shock wave around the knife-edge flow field. For dual-cube shock wave, the color-schlieren image can be seen in Fig. 6. Two figures show that the adjusting of imaging parameter C, which actually means to adjust the schlieren knife-edge, can change the schlieren sensitivity.

Parameter C=2A   Parameter C=10A

Fig. 5. The CFI-color- schlieren images of the shock wave around
the knife-edge flow field (A is a constant).

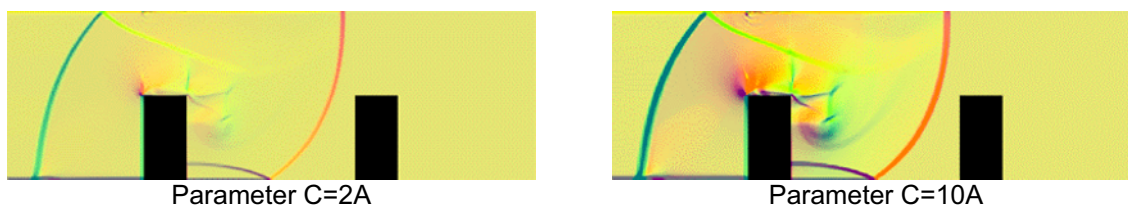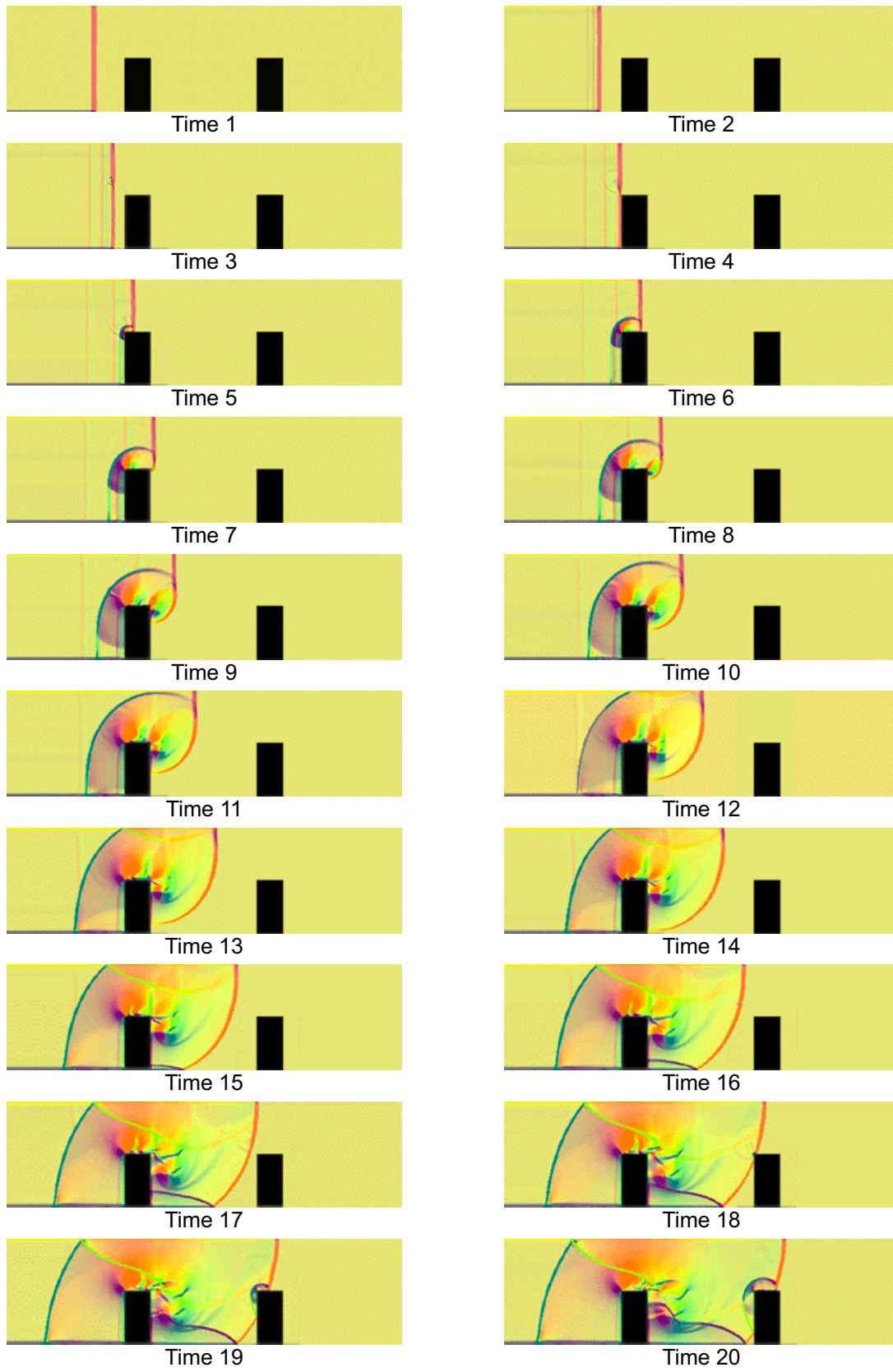Parameter C=2A   Parameter C=10A

Fig. 6. The CFI-color- schlieren images of the unsteady flow field of
shock wave diffracting double cubes (A is a constant).

Figure 7 is 32 CFI-schlieren images of the unsteady flow field of shock wave diffracting double cubes for a sequence. The sequence can be made into animation to reach computer dynamic simulation.
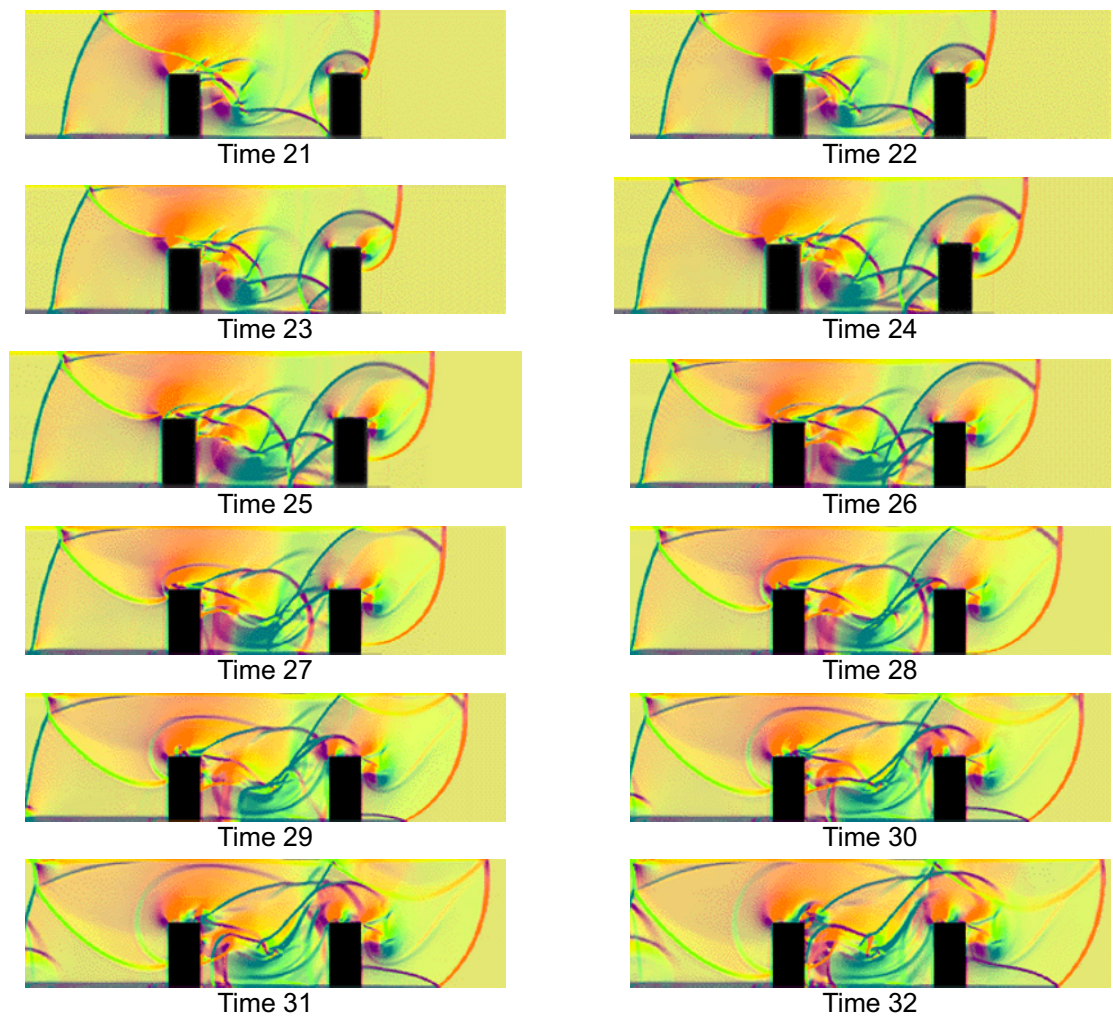
Time 1

Time 2

Time 3

Time 4

Time 5

Time 6

Time 7

Time 8

Time 9

Time 10

Time 11

Time 12

Time 13

Time 14

Time 15

Time 16

Time 17

Time 18

Time 19

Time 20

Time 21

Time 22

Time 23

Time 24

Time 25

Time 26

Time 27

Time 28

Time 29

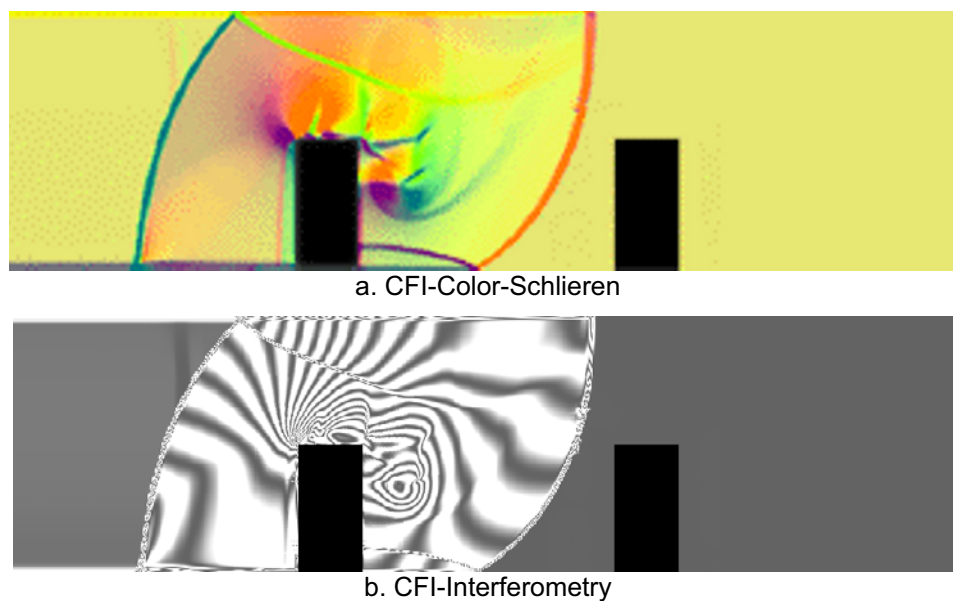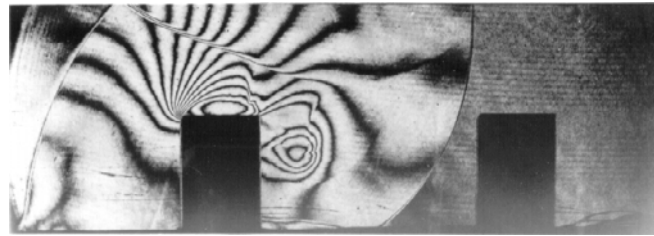Time 30

Time 31

Time 32

Fig. 7. A sequence of CFI-schlieren images of
the unsteady flow field of shock wave diffracting double cubes.

This software has a good effect of converting CFD data into CFI image. The comparison of the CFI image with the optical flow visualization can also be seen in Fig. 8.

a. CFI-Color-Schlieren

b. CFI-Interferometry

c. The experiment holographic interferometry image

Fig. 8. The comparison between CFI-Interferometry and experiment interferometry image.

5. Conclusion

The CFI-color-schlieren technique is a comprehensive intercross disciplinary technology which integrates numerical computation technique, image processing technique and optical flow visualization technique of experimental aerodynamics. Its development will not only bring three techniques into further study and application, but also greatly promote their applications into the aircraft engineering design. With the development of computer technology, this technique will make computational science combined with the experiment and let the existing valuable experimental data do more work. What's more, CFI technique has many advantages that can't obtain from the optical flow visualization such as image enhancement, more convenient comparisons with the optical flow visualization results and uncertainty estimates. As a development direction, this computation method is expected to go forward, especially for the computation of 3-D complicated flow field.

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