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Feasibility of integrating moiré tomography and shadowing in flow field's visualization and diagnosis

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ABSTRACT

In this paper, some issues about moiré tomography and shadowing in visualizing and diagnosing flow fields are summed up and studied both theoretically and experimentally. These two optical methods are compared on two aspects: the structural visualization and parameter diagnosis for flow fields. Based on which, the feasibility of integrating moiré tomography and shadowing in visualizing and diagnosing flow fields is proposed, and the experimental setup is established. Besides, flame flow fields are chosen as practical examples for experiment. The experimental results manifest that integrating moiré tomography and shadowing may be one of the reasonable and feasible means for structural visualization and parameter diagnosis of complex flow fields.

1. Introduction

The application of optical methods in flow fields' structural visualization and parameter diagnosis has been discussed for many years. Among these, optical computerized tomography (OCT) as a branch of computerized tomography (CT) has become the first chosen method for visualizing and diagnosing the transient states of phase flow fields due to the real-time, non-contact and stable characteristics. Thereinto, moiré tomography and interference tomography have been widely used in various flow fields' qualitative visualization and quantitative measurement, including flame [1], compressible flows [2], mixing fluid flows [3], hypersonic shock tunnel [4], supersonic jets and convective flow [5], plasmas [6], etc.

It is well known that shadowing and schlieren are famous for qualitative analysis, while moiré and interference tomography can realize parameter's 3-D quantitative measurement. Furthermore, we found that only one method cannot solve the structural visualization and parameter diagnosis at the same time for complex flow fields well. Therefore, integrating different methods to realize the structural visualization and parameter diagnosis of complex flow fields may be a possible way in the current case. Hence, comparing different methods and finding special advantages of them , as well as analyzing the feasibility of integrating them may be one of the achievable ways to solve the complex flow fields' structural visualization and parameter diagnosis better.

Moiré deflectometry, firstly proposed by Kafri, could be used to measure the refractive index or refractive index gradient of phase objects [7]. In particular, this method is famous for simple devices, big dynamic range, and low requirement for mechanical stability compared with interference tomography. Meanwhile, shadowing is also famous for simple devices. Therefore, in this paper, these two methods will firstly be compared in flow fields' structural visualization and parameter diagnosis, based on which, the feasibility of integrating them will be discussed. This research will provide a basis for determining whether integrating different methods can solve complex flow fields' visualization and diagnosis better.

2. Principle and theory

2.1. Shadowing

A parallel light, passing through a flow field with uneven refractive index distribution, will be deflected. As a result, the undeflected parts will correspond to the dark areas (i.e. shadow). At the same time, the parts where the deflected light can reach will be the bright area. Consequently, the uneven intensity distribution can be formed on the projection screen. In other words, shadowing reflects the uneven characteristic by the contrast of the projection on the screen. And, the contrast R_c is described as [8]

$$R_c = -Z_{sc}\int_L \left(\frac{\partial^2 n}{\partial x^2}+\frac{\partial^2 n}{\partial y^2}\right)dz, \tag{1}$$

where Z_{sc} is the distance between the tested region and the observing screen, n represents the refractive index, and L is the light propagation distance in the medium.

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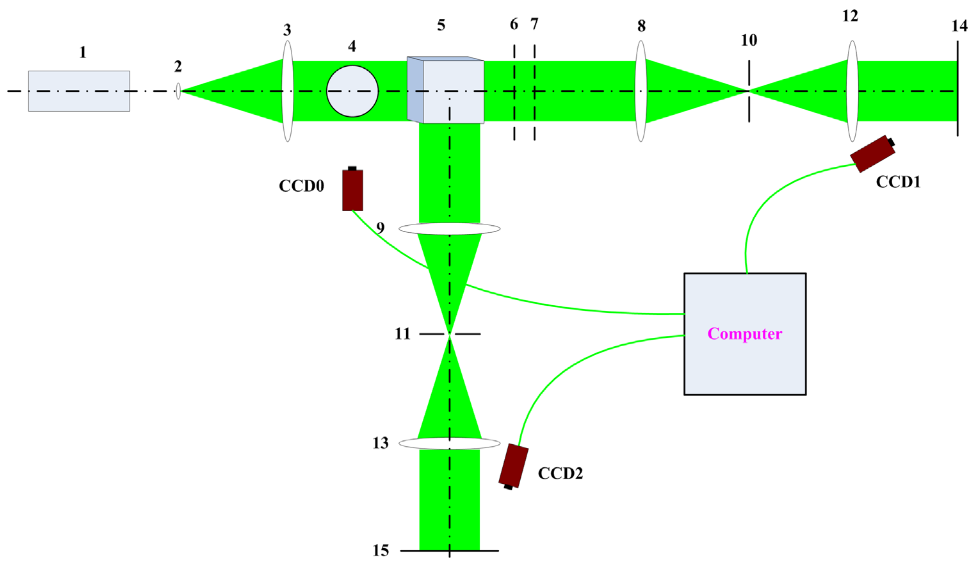

1-Laser (532nm), 2-Extender lens, 3-Collimating lens, 4-flow field,

5-Cube beam splitter, 6,7-Ronchi gratings, 8,9,12,13-Imaging lens,

10,11-Filter, 14,15-Screen

Fig. 1. The schematic diagram.

Obviously, according to Eq. (1), it can be found that shadowing reflects the variation of the refractive index's second derivative in flow field's measurement.

2.2. Moiré tomography

When the light is incident on an uneven medium, the wavefront will be deformed, and the light becomes a continuously deflected curve. As a result, for whichever cross section in the x–y plane, the relation between moiré deflection angle φ and the refractive index n is described as [9]

$$\varphi = \frac{1}{n_s}\int_0^l \frac{\partial n}{\partial y} dx, \tag{2}$$

where n_s is the refractive index of the surroundings, $(\partial n/\partial y)$ is the refractive index gradient in the y-direction, while 0 and l are the boundaries of the flow field.

Obviously, moiré deflection reflects the variation of the refractive index's first derivative in principle. Eqs. (1) and (2) distinctly reflect the difference between shadowing and moiré tomography in recording flow field's refractive index information.

3. Experiment and results

3.1. Experimental setup

The schematic diagram of the experimental setup on integrating moiré tomography and shadowing methods to visualize and diagnose flow fields is shown in Fig. 1. The laser with the central wavelength 532 nm serves as a light source with the maximal output power of 400 mW. The collimating lens owns a focal length of 300 mm and a diameter of 50 mm. The focal length and diameter of imaging lenses are 300 mm and 75 mm, respectively. Two Ronchi gratings, with a grating constant d of 0.05 mm, serve as the key components of the whole experimental system. The filters are used to let 0 frequency spectrum be passed and imaged, while moiré fringes are captured on the screen using CCD1. At the same time, CCD0 and CCD2 record the measured flow field and the shadowing fringes, respectively. In fact, from the back surface of the second Ronchi grating to the screen is a typical 4-f system. In practice, it is necessary to assure that the three CCDs are capturing synchronously. In this study, they are controlled by a synchronous inner trigger.

3.2. Experimental results

Three propane–air flames are chosen as the measured objects for experiment, as shown in Fig. 2. The jet nozzle, with the inner diameter of 10 mm, is flush-mounted in the center of a 28 mm honeycomb annulus which supplies co-flowing dry air for the combustion of propane.

The corresponding deflected moiré fringes of the above three propane–air flames obtained in the experiment are shown in Fig. 3. Moreover, the corresponding shadowing fringes are shown in Fig. 4.

Obviously, Fig. 3 indicates that the definition and contrast of moiré fringes are satisfactory, which is quite important for practical extraction of fringe information and reconstruction of refractive index. In addition, Fig. 4 manifests that the structure of the measured three flames is displayed very well by shadowing fringes.

4. Analysis and discussion

According to the basic principle and experiment of the two optical methods, the following points can be obtained.

1) Theoretically, shadowing reflects the second derivative of the refractive index, but the moiré deflection reflects the first order derivative of the refractive index.