Development of Laser Induced Fluorescence Focusing Schlieren system (LIF-FS) and its application in a scramjet combustor

Ruixu Zhou

Institute of Mechanics, Chinese Academy of Sciences

Beijing, China

Huan Lian*

Institute of Mechanics, Chinese Academy of Sciences

hlian@imech.ac.cn
Beijing, China

Xinyu Chang

Institute of Mechanics, Chinese Academy of Sciences

changxy@imech.ac.cn
Beijing, China

INTRODUCTION

Schlieren imaging visualizes flow structures with variations in density gradient and has been widely applied in the study of non-reacting transverse unsteady jet in supersonic crossflow (Kouchi et al. 2011; Ben-Yakar & Hanson 2002; Ben-Yakar et al. 2006) as well as supersonic reacting flow applications (Fotia & Driscoll 2012). The supersonic combustion experiments are always accompanied by high temperature and pressure, which causes distortions of the optical window and changes of its refractive index (Kouchi et al. 2015). Schlieren technique captures density gradient variation in the entire length of the light path, thus is sensitive to the change of temperature induced window distortion especially during long test run. In addition, the traditional Schlieren captures the three-dimensional flow structure. To fully utilize the planar images of the flame reaction zones towards understandings of interactions of the flame and flow structures, it is desirable to develop two-dimensional flow visualisation technique.

Focusing Schlieren is a two-dimensional flow visualisation technique with short depth of focus (DOF) (VanDercreek et al. 2010). The narrow DOF of focusing Schlieren reduces the effect of the changes in the refractive index induced by high temperatures, thus is considered a suitable two-dimensional flow visualization technique in supersonic combustion experiments. Weinstein (1993) developed a large-field high-brightness focusing Schlieren system which has been widely used by other researchers. Kouchi et al. (2015) implemented the focusing-Schlieren measurements in a dual-mode

scramjet and compared images obtained in cold flow and stagnation temperature of 1200K. The results show that the focusing-Schlieren have the ability to reduce the influence of window's thermal distortion. Later, Förster et al. (2016) used focusing Schlieren as well as the CH* chemiluminescence imaging to study the flame characteristics in a scramjet combustor and successfully obtained different combustion stability regimes. Recently, Martínez-González et al. (2018) used focusing Schlieren technique together with a calibration procedure to measure planar temperature fields of fluid flows. In most of the previous studies, the nanosecond pulse width Nd:YAG laser was used to illuminate the highly transient supersonic flow field for sufficient flow freezing. However, coherent noise is not evitable when applying laser as the light source, which would cause appearance of strong diffraction fringes in the images (Laurence et al. 2011). Thus, efforts should be made to reduce the coherent noise in light source and improve the quality of the focusing Schlieren images. VanDercreek et al. (2010) employed copper vapor laser as light source in focusing schlieren system because of its low coherence. Kouchi et al. (2015) used three of the polypropylene sheets stacked with a 1-mm air gap as the beam diffuser to reduce coherent noise in focusing schlieren system. Regert et al. (2014) removed the coherent nature of laser light source in schlieren system through the laser-induced fluorescence principle.

Based on above methods, we propose a measurement technique combining the Laser Induced Fluorescence and Focusing Schlieren system (LIF-FS), which uses

fluorescence induced by the laser as the light source that significantly reduce the coherent noise. The full paper includes the optical design of the proposed LIF-FS system and its application in the transient operation supersonic combustion facility at Chinese Academy of Sciences (CAS).

Experimental setup

Experiments were performed at the direct-connected supersonic combustion test facility in CAS. A configuration of the facility is shown in Fig. 1, which has been described by Lian et al. (2018). The facility include a hydrogen-oxygen vitiator, a variable throat Laval nozzle controlled by a cam shaft and a precise motion control unit. The air is heated by heat addition from hydrogen and oxygen combustion in the vitiator to achieve the desired stagnation temperature. The stagnation temperature is from 800K to 1900K with the corresponding flight Mach number from 4.5 to 6.5. The test section includes a constant area isolator with the cross section of 80mm×40mm and a model combustor with two ramped cavity flame holders. Each cavity has a depth of 17mm, a length of 65mm and 22.5° angle aft face and is equipped with the conventional spark ignition source. The distance between the two cavity is 150mm. Kerosene and pilot hydrogen are injected upstream of the cavities. To visualize the flow structure, quartz windows are mounted on each side of the first cavity.

Figure 1 Configuration of the direct-connected supersonic combustion test facility (Lian et al. 2018).

A schematic layout of the focusing Schlieren system is shown in Fig.2 (Weinstein 2010). In Fig. 2, Laser-induced fluorescence was used as light source to reduce the coherent noise in the illumination of the focusing Schlieren system. The light is converged by the Fresnel lens to the test section. In order to emphasize the density gradient in streamwise direction, a source grid, which consist of multiple alternating dark and clear apertures, is placed between the Fresnel lens and the test section. A camera lens is placed behind the test section to obtain both images of source grid and combustor center plane on the position of each optical conjugate position and enables the focusing capability. A cutoff grid is placed on the optical conjugate plane corresponding to the source grid for keeping out a fraction of the light from the

Figure 2 Experimental Setup of the developed Focusing Schlieren system

source grid. Finally, another Fresnel lens was placed on imaging plane to relay the image into camera.

Design of the Focusing Schlieren System

The design of the current focusing Schlieren system is based on the work of Burton (1949) and Weinstein (2010).

The refraction caused by density gradient variations in the test region bends the light from the Fresnel lens, resulting in movement normal to the cut of grid and finally change the brightness of images. If the smallest of change in brightness was selected as 10%, the sensitivity for the focusing Schlieren system is given by

$$\varepsilon_{min} = 20626\alpha L/[L'(L-l)] \text{ arcsec} \quad (1)$$

Because the angle of refraction is caused by density gradient variations, the smaller value of ε_{min} , the smaller density gradient is required on images (VanDercreek et al. 2010). However, the value of $20626L/[L'(L-l)]$ in focusing Schlieren usually is very large, which will reduce the sensitivity of the system. Thus, A very small value of α is required to obtain high sensitivity.

For focusing Schlieren system, the resolution of features in test section is

$$\omega = \frac{2(l'-L')\lambda}{l'l/b} \quad (3)$$

Which is depend on the width of cut off grid slit, b , the wavelength of the light source, λ and optical layout. After the resolution of focusing Schlieren system can be determined, the sharp focus depth DS and the unsharp depth of focus, which are defined by Weinstein (2010), are

$$DS = \frac{2\omega l}{A} \quad (4)$$

$$DU = 2\delta f_{\#} \frac{l}{F} \quad (5)$$

Here, A is the aperture of the Schlieren lens, $f_{\#}$ is the f-Number of Schlieren lens, F is the focus of the Schlieren lens and δ is the circle of confusion. Generally assuming $\delta = 2$.

If the width between cut off grid are too large, only small number of lines have effect of forming each points on image, the number of pairs of lines blended is

$$\phi = \frac{AN(l'-L')}{2l'} \quad (6)$$

Now N is the number of lines per unit dimension in the cutoff grid, and $\phi > 8$ is best for uniform exposure. Table 1 summarise the important design parameters for the focusing Schlieren.

Table 1 Specification of focusing Schlieren system

Detectable light deflection angle	$\varepsilon_{min}(\text{arcsec})$	28.25
Sharp depth of focus	$DS(mm)$	0.92
Unsharp depth of focus	$DU(mm)$	9.44
Diffraction limit of resolution	$\omega(mm)$	0.19
No. of gridlines in cutoff grid	$N(mm^{-1})$	1.67
No. of blended images	ϕ	28.12

Image processing Method

Image processing techniques are developed for shade correction and noise reduction. The flowchart of imaging processing is shown in Fig 3. Shade correction procedure deal with uneven illumination which is a common issue in focusing Schlieren images, as shown in Fig. 4a. Kouchi et al. (2015) solved this problem by subtract background image. The background image was acquired using a Gaussian low-pass filter to process the original image. Standard deviation (σ_g) of Gaussian filter were locally changed for dealing overexposed and under-exposed near the wall which can obstruct the detail structure. However, overexposed is not serious in our experimental images. That means locally change σ_g have little effect to enhance small structures near the wall. In addition, the effect of different standard deviations and kernel size of Gaussian filter are tested. The results show that relatively large σ_g (≥ 30) and kernel size (≥ 100) are suitable to capture small structures. Without loss of generality, we chose $\sigma_g = 50$ and the kernel size fixed to be 401×401 . After shade correction procedure, a mean filter was applied in noise reduction procedure to remove salt-and-pepper noise. The more lager the kernel size of mean filter, the more blurred the image is. In addition, the kernel size should be odd number to ensure do not change the symmetry of image. Thus a 3×3 mean filter was used to deal with salt-and-pepper noise. Fig. 4c shows the noise reduction image. In addition, compared with laser schlieren image obtained by Regert et al. (2014), as shown in Fig 4d, no speckles and fringes due to laser coherence appear in original images, indicate that laser-induced fluorescence have ability to eliminate the coherence noise in light source.

Figure 3 Flowchart of image processing

(a)

(b)

(c)

(d)

Figure 4 Typical images in image processing. (a) initial image, (b) shade correction processed image. (c) noise reduction processed image. (d) schlieren image with laser light source (Regert et al. 2014)

Results and Discussion

Figure 5 shows typical images of the pilot hydrogen transverse jet injection in the isolator and at the entrance of the model combustor.

Figure 5 LIF-FS images of the non-reactive transverse jet injection upstream of the cavity

In the front of transverse injection, a thin bow shock can be seen clearly. The bow shock has a lift distance from the wall. Behind the bow shock, large-scale structures bend with the bow shock, mixing with the incoming air. At the bottom of the large-scale structures, a small area with high image brightness appeared a short distance above the wall is possibly a Mach disk. Notice that another bow shock wave in the middle of the images is caused by uneven installation.

Figure 6 LIF-FS images of the reacting flow with shock train induced by combustion

The reacting flow is illustratively shown in Fig. 6. Shock train structures induced by heat addition from combustion are observed. Superimposing the LIF-FS images with the common path chemiluminescence images, quantitative information of flow flame interaction can be obtained for further evaluations.

Conclusion

1. A measurement technique combining the Laser Induced Fluorescence and Focusing Schlieren

system (LIF-FS) is proposed, which uses fluorescence as the light source that significantly reduces the coherent noise. Image processing methods are developed for shade correction and noise reduction.

2. The proposed measurement technique provides non-illuminated and two-dimensional visualization and was applied in a model scramjet combustor. Large-scale structures of the transverse jet injection and combustible flow field can be extracted for quantitative studies of flow dynamics and flame flow interactions.

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