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Aero-optical transmitting effect in the compressible mixing layer

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Abstract : The handicap for investigating the aero-optical effect focuses on the accurate prediction on the index refraction fluctuation or density fluctuation. In recent years, with the development of CFD techniques and optical experimental techniques, the comprehension have developed on the aero-optical transmitting effect in many kinds of complex flow. This study mainly introduces the optical aberration in compressible mixing layer. And then the debates about the mechanism of aero-optical effects and assessment of image blur also present.

Key Words : Aero-optical effect, Compressible mixing layer, Image blur, Image tilt/jitter

1. Introduction

Distortion of optical signals by turbulent flow is widely observed in nature and technological applications (i.e. aero-optical effects). Aero-optical effects reducible from irradiance measurements are defined as image blur, boresight error, image jitter[1]. For a complex flow, the most challenging to predict the optical distortion mainly focuses on the accurate prediction of density fluctuation including turbulence scales over all optically relevant wave number and frequencies, which poses a significant trouble for computational expenses, numerical accuracy and experimental design[2]. Therefore, how to assess the aero-optical effect by a complex flow becomes a handicap. Liepmann[3] analyzed the random refraction of a single ray throught turbulent flow. His interpretation was that the RMS deviation of ray was the blur, however, Sutton[4] referred it as the RMS jitter of the centroid of the beam. Hence, this article mainly introduces the advancements and debates on aero-optical effects on compressible mixing layer.

2. Aero-optical effects on compressible mixing layer

2.1. Mechanism of aero-optical aberration

In general, the mixing layer (shown in fig.1), formed by two parallel flows with different speed, grows from laminar, transition to a fully-developed turbulence.

Fig.1 Spatial development of compressible mixing layer at Mc=0.4

As for the mechanism of aero-optical effects, the researchers basically accepted coherent structures resulting in seriously optical aberration. However there is a debates on which part of large-scale

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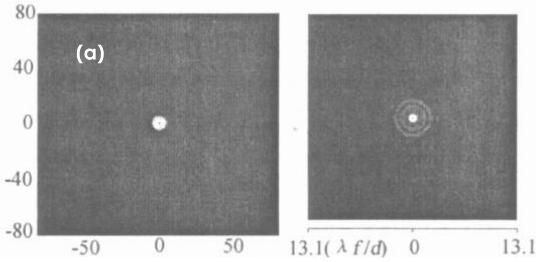
structure causes larger optical distortion. For example, Dimotakis, Catrakis & Fourgette[5] discussed the wave front distortions created by shear layers at different convective Mach numbers (Mc). They proposed that the interface effect (i.e. the sharp density gradient) plays an important role of root-mean-square of optical path difference (OPDrms). However, Fitzgerald & Jumper[6] found that velocity fluctuations and streamline curvature can produce larger variation in refractive index. To further investigate the nature of this discrepancy, Visbal[7] performed numerical simulations for laminar mixing layer with either matched total or static temperature. His results indicate that OPD is dominated by compressible effects rather than index interfaces. However, his numerical results have not been verified by experiments. Recently, Gan et al. [8] discussed the optical distortion for a laminar mixing layer in virtue of statistics theory and wind tunnel experiments. According to their theoretical analysis, the flow dynamic properties of interface among mixed region and free stream dominate the time-averaged optical aberration.

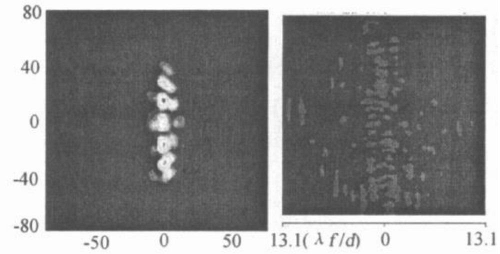
So it is not decided conclusion about more detailed mechanism of aero-optical effect.

2.2. Image blur and brightness

Cassedy [9] first proposed to adopt flow characteristic scale to assess the features of a degraded image.If the scale of a turbulent structure is smaller, the image brightness or Strehl ratio will be reduced. In fact, the large-scale structures during the transition often result in lower Strehl ratio. For example, Truman and Lee [10] performed the first computational studies of aero-optical distortions using direct numerical simulations (DNS) for a homogeneous shear flow. They found that large-scale structures provided the dominant contributions to the refractive index fluctuations. The experimental results [11] and numerical simulation [12] also show that the Strehl ratio (SR) has seriously decreased in the transitional region of compressible mixing layer. The numerical simulation by Pan [13] (displayed in fig.2) also showed that the transition structures makes SR ratio from 0.89 for laminar flow, 0.09 for transition to 0.19 for fully-developed compressible mixing layer. The transitional structures seriously attenuating Strehl ratio, increase of optical path difference (OPD) and image blur can be explained by linking equation (equation (1))



(a) Laminar flow,SR=0.89



(b)Transition,SR=0.09[13]

Fig.2 point spreading function for compressible mixing l ayer

$$\left(\overline{OPD^2}\right) = \alpha K_{GD}^2 \int_0^{z_1} \rho'^2_{rms}(z)\ell(z)dz \qquad \overline{SR} = \exp\left[-\left(\frac{2\pi OPD_{rms}}{\lambda}\right)^2\right]$$

According to formula (1), the larger the characteristic scale of flow field, the greater OPD might be, and then the smaller SR ratio. In fact, density fluctuations also play an important role of SR ratio, however there are larger density fluctuations during transition. Hence, it is normal for a smaller SR ratio during transition than fully-developed turbulent flow, which implies that it is not suitable criterion for turbulent scale as judging the aero-optical effect. However, SR ratio cannot discover how the flow makes image degraded.

It is rational for using OPD to assess blur of a whole image, while the details of image blur cannot be evaluated. To assess the details of blur, Gan and Ma [14] proposed the conception of “comparative diameter” (i.e. the ratio of 4 times energetic area to its corresponding perimeter of light beam). If the “comparative diameter” is more than 1.03 times its original diameter, the image will be defined as blur. Fig.3 presents the distribution of “comparative diameter” during a run for a small beam experiment. It is shown from fig.3 that the image blur is random. In addition, the phenomena of bean contract are also observed from fig.3, which implies that there be also flaw on using "comparative diameter" to assess image blur.

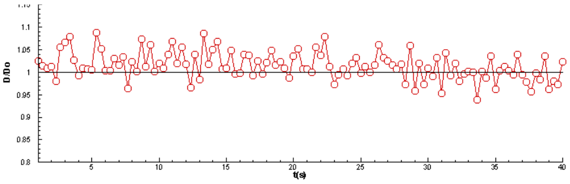


Fig.3 The distribution of "comparative diameter" at Mc=0.17

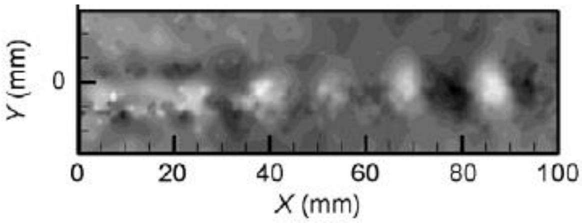
2.3 image tilt and jitter

The image tilt/jitter is defined as the displacement or angular deflection of light centroid of image induced by a turbulent flow. According to Gordeyev and Jumper[15], the OPD can be expressed as

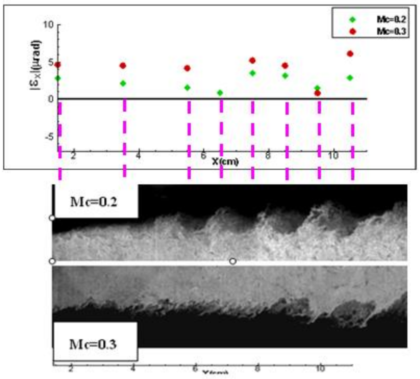
$$OPD(x,y,t)=OPD_{steady}(x,y)+[A(t)x+B(t)y]+OPD_{high-order}(x,y,t) \quad (2)$$

It is observed from the second term on the right side of formula (2) that the image tilt/jitter is the first order spatial derivative of OPD. In fact, the equation (2) is particularly useful when an adaptive optics system is used to correct for aberrating wave fronts. However, it is difficult to solve the first order derive of equation (2) only adopting experimental data of OPD. Hence the method of investigating image tilt/jitter often adopts small light beam or background-oriented schliren(BOS) experiments. Zhao et.al. [16] (as seen in fig.4(a)) found that the spatial coherent structure resulted in larger image tilt using BOS technique. Gan [8] carried out small beam experiments to study deflect angle (as seen in fig.4(b)). They also observed that the coherent structure causes the deflect angle fluctuating.

Another advancement on image tilt/jitter focuses on the theoretical analysis [17]. This analysis combines the hydrodynamic feature of mixing layer with the image tilt/jitter. Different from Sutton's method on the base of Maxwell equations and covariance function, Gan adopts compressible RANS equations and ray tracing theory to investigate the optical aberrations.



(a) BOS result(Ref.16)



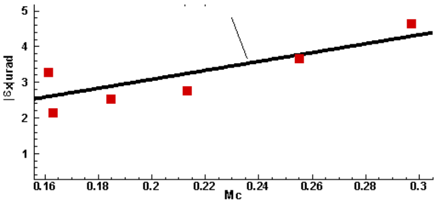
(b) small beam results(Ref.8)

Fig.4 the distribution of deflect angle by compressible mixing layer

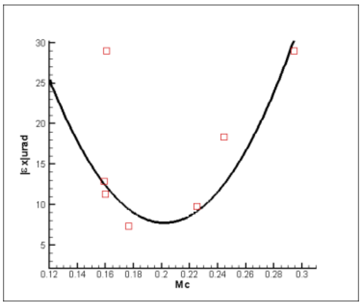
On the basis of characteristic scale analysis and observation for two-dimensional large-scale structures, the fluid dynamic behavior of boresight error (BSE) has been obtained. The equation (3) presents the dynamic expression of streamwise time-averaged deflect angle for a laminar flow. The experimental results displayed in fig.5(a) proved the relation BSE with the Mc expressed by eq.(3).

$$\bar{\varepsilon}_x=C_R\frac{K}{1+K\rho_h}\frac{\mu_h}{\delta_0}\frac{\sqrt{T_h}+\sqrt{T_l}}{2RT_h}Mc(1+\frac{x}{\delta_0}\frac{d\delta}{dx}) \quad (3)$$

$$C_R=\left[\frac{\partial^2\bar{u}^*}{\partial y^{*2}}(\xi)\Bigg|-\frac{\mathrm{Re}_\delta}{(1+xd\left(\delta/\delta_0\right)/dx)}\bar{\rho}^*\left(\bar{u}^*\bar{v}^*\right)\Bigg|_{Y_0^*}^{\delta^*+Y_0^*}\right]+O(s^{n_1})$$



(a) laminar flow



(b) turbulent flow

Fig. 5 the relation between BSE and Mc number for turbulent flow

3. Conclusion

This article mainly introduces the advancements and doubt on distortion of optical signal transmitting a compressible mixing layer. Firstly, the mechanism of aero-optical effects has been discussed. It is a general conclusion that the coherent structures in the mixing layer cause serious optical-aberration, meanwhile, it remains uncertainty about which part of vortices dominating decade or deflection of optical signal. Moreover, this article preliminarily thinks over the advantage and flaw about current optical assessment system of aero-optical effects (such as OPD, deflective angle (BSE), SR ratio etc.). Hence it is necessary to introduce aero-dynamical parameters into this evaluation system in the future.

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