Statistical Evaluation of the Shock Wave Boundary Layer Interaction Phenomenon

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Résumé :

Les corrélations turbulentes de vitesse et de température issues de simulations numériques directes de couches limites compressibles interagissant avec un choc impactant sont discutées. La variation suivant l'épaisseur des moments d'ordre 2 des vitesses et des flux thermiques est examinée, notamment une épaisseur de couche limite en amont de la position d'impact du choc incident. D'autres corrélations statistiques sont alors calculées pour quantifier plus en détails l'effet de l'interaction choc oblique/turbulence.

Abstract :

Turbulent velocity and thermal correlations from direct numerical simulation data of a spatially growing compressible turbulent boundary layer interacting with an impinging shock are discussed. The cross-stream variation of the velocity second-moments and the thermal fluxes one boundary layer thickness upstream of the shock impingement point are discussed. Other correlations are examined to further statistically quantify the effect of the oblique shock-turbulence interaction.

Mots clefs : **compressible flow, supersonic flow, shock-interactions, turbulence**

1 Numerical Simulation and Flow Field Statistics

A spatially evolving, supersonic boundary layer flow with an impinging shock has been computed using direct numerical simulation. The free stream Mach number M_∞ is 2.25 and the momentum thickness Reynolds number (based on free stream conditions) Re_θ is 4000. In performing numerical simulations two main types of strategies are possible. One is based on the simulation of a developing turbulent flow field and the other is based on the simulation within a subset domain where the turbulent flow field is sustained through either a recycling/rescaling procedure or a specification of inflow conditions (see [1]). The approach here is to perform a simulation corresponding to the former case where the flow is allowed to develop from the laminar, through the transitional and into the fully turbulent regime. While this increases the number of grid points required relative to the latter case where only a fully turbulent regime is considered, it precludes any potential for adversely affecting the unsteady motion of the shock.

There is an abundance of mean and turbulent correlations that can be used to verify supersonic boundary layer flow simulations without shocks. Using the van Driest transformation as well as applying the various forms of the (extended) strong Reynolds analogies provides an ample set of verification measures. With shocks, the verification procedures and assessment of simulation quality is less direct. The simulations are complicated by the interactions between the shock and the turbulent field. In the inner layer region, the shock can induce separation and reattachment along the solid boundary, and in the outer layer region the shock amplifies the turbulent field. In addition, the turbulent field and the separation zone can induce a coupled unsteadiness in the motion of the shock.

An example of the effect of the shock on the turbulent velocity and thermal fields can be seen in Fig. 1 where correlation simulation data from [2] is used to obtain a comparison of the Favre and Reynolds averaged fields. Since the relationships between the density-weighted (Favre) averaged turbulent velocity and thermal correlations and the corresponding Reynolds averaged correlations are given by

$$\widetilde{u_i''u_j''} = \overline{u_i'u_j'} + \frac{\overline{\rho' u_i' u_j'}}{\overline{\rho}} - \frac{\left(\overline{\rho' u_i'}\right)\left(\overline{\rho' u_j'}\right)}{\overline{\rho}^2} \ , \tag{1}$$

$$\widetilde{u_i''T''} = \overline{u_i'T'} + \frac{\overline{\rho' u_i' T'}}{\overline{\rho}} - \frac{\left(\overline{\rho' u_i'}\right)\left(\overline{\rho' T'}\right)}{\overline{\rho}^2} \ , \tag{2}$$

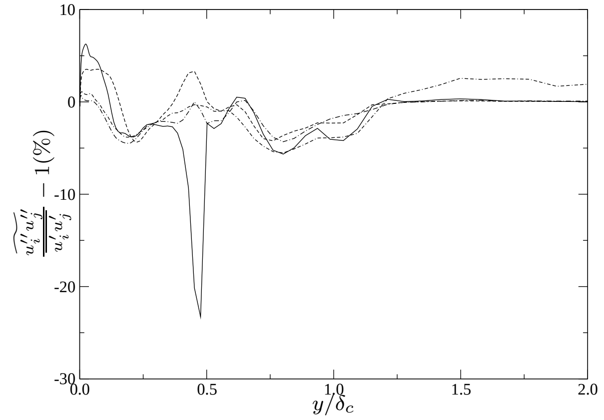

FIG. 1 – Normalized turbulent stress distributions $1\delta_c$ upstream of the (inviscid) shock impingement point. ———, $\widetilde{u''v''}/\overline{u'v'}$; - - - - - -, $\widetilde{u''u''}/\overline{u'u'}$; $- \cdot - \cdot -$, $\widetilde{w''w''}/\overline{w'w'}$.

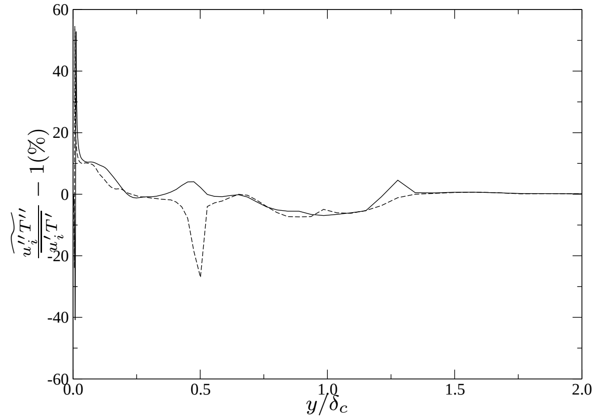

FIG. 2 – Normalized turbulent heat flux distributions $1\delta_c$ upstream of the (inviscid) shock impingement point. ———, $\widetilde{u''T''}/\overline{u'T'}$; - - - - - -, $\widetilde{v''T''}/\overline{v'T'}$.

it is apparent that the mass flux variations involving the normal component of turbulent velocity v' have a significant effect on the application of the different averaging methods. As Fig. 1 shows, in the vicinity of the incoming shock, the mass flux terms in Eqs. (1) and (2) produce a 25% and 30% difference between $\widetilde{u_i''u_j''}$ and $\overline{u_i'u_j'}$, and $\widetilde{u_i''T''}$ and $\overline{u_i'T'}$, respectively.

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Références

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