DNS of the interaction between a shock wave and a turbulent shear flow

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1 Numerical considerations

We solve the three-dimensional Navier-Stokes equations in non-dimensional conservative form using a finite difference approach. The inviscid part is resolved using a fifth-order Weighted Essentially Non-Oscillatory scheme (WENO). Viscous terms are computed using a sixth-order accurate compact scheme. A third-order Runge Kutta algorithm is used to advance in time.

Equations are solved on a cubic domain of size 2π in the three directions and a grid of $176 \times 128 \times 128$ points is used. The mean flow is aligned with x. Periodic conditions are specified in the z direction, and non-reflecting boundary conditions with a sponge layer are used for the top and bottom boundaries along y as well as for the outflow where the flow is subsonic. At each time step, velocity, pressure, temperature, and density fields are specified at the inflow. These fields are superpositions of a supersonic mean flow and turbulent fluctuations in velocity, pressure, temperature, and density. The mean velocity at the inflow varies linearly across streamlines while the mean pressure is uniform. The mean temperature and density vary such as the mean Mach number is uniform : $\overline{U}_1(y) = U_0 + S(y - y_{\min})$, $\overline{V}_1 = \overline{W}_1 = 0, \overline{P}_1(y) = 1/(\gamma M_r^2)$, $\overline{T}_1(y) = M_r^2 U_1^2 / M_1^2$, where the overbar denotes the conventional Reynolds average and the subscript 1 indicates the upstream state. A fluctuating field is then superposed onto the mean upstream flow and advected through the shock. This field comes from a preliminary calculation. The anisotropy of the turbulent velocity field used in the inflow plane is either of axisymmetric type or typical of a turbulent shear flow.

2 Results

Several simulations were conducted with the following values of the reference parameters: $Re_r = \frac{\rho_r^* u_r^* L_r^*}{\mu_r^*} = 94$, $M_r = \frac{u_r^*}{c_r^*} = 0.1$, $Pr = 0.7$, where f_r^*

refers to a dimensional reference variable. The mean Mach number is fixed to $M_1 = 1.5$, and the turbulence parameters in the inflow plane are the following : $Re_\lambda = Re_r \frac{\lambda u_{1_{rms}}}{\overline{\nu}} = 47$ and $M_t = \frac{q}{\overline{c}} = \frac{\sqrt{\overline{u'_i u'_i}}}{\overline{c}} = 0.173$. Table 1 summarizes the characteristics of the different runs. They differ by the nature of the mean flow (sheared or not), by the anisotropy of the upstream turbulent flow and by the amount of $\widetilde{u''^2}$ immediately upstream of the shock wave.

Table 1. Characteristics of the different runs (i = inflow ; b.s. = just before shock)

Run	S	$\left(\frac{q^2}{2}\right)_{\mathrm{i}}$	$(\widetilde{u''^2})_{\mathrm{b.s.}}$	$\left(\frac{\widetilde{u''^2}}{q^2}\right)_{\mathrm{b.s.}}$	$\left(\frac{\widetilde{v''^2}}{q^2}\right)_{\mathrm{b.s.}}$	$\left(\frac{\widetilde{w''^2}}{q^2}\right)_{\mathrm{b.s.}}$	$\left(\frac{\widetilde{u''v''}}{q^2}\right)_{\mathrm{b.s.}}$
RunSI	1.5	1.5	1.04	0.42	0.28	0.31	-0.14
RunSA1	1.5	1.5	1.10	0.44	0.27	0.30	-0.12
RunSA2	1.5	1.5	1.11	0.40	0.29	0.31	-0.17
RunI	0	2	1.00	0.35	0.33	0.32	0.005
RunA1	0	1.7	1.04	0.43	0.28	0.30	0.007

Previous works lead to the conclusion that the amplification of the kinetic energy behind the shock wave is strongly dependent of the upstream anisotropic state, and that it is clearly determined by the amount of the longitudinal normal Reynolds stress $\widetilde{u''^2}$ upstream of the shock (see e.g. Jamme *et al.* [1]). The mean flow was uniform without shear stress is these studies.

In the present work, we first compare three runs (RunSI, RunSA1 and RunSA2) where a mean shear has been introduced. The anisotropy of the turbulence is slightly different just before the shock for these three cases. The near-field amplification of $q^2/2$ behind the shock wave is found to depend on the amount of the correlation $\widetilde{u''T''}$ immediately upstream of the shock. This correlation is positive in the three cases, but its value is not the same. The more $\widetilde{u''T''}$ is high upstream, the less $q^2/2$ is amplified behind the shock.

In order to get rid of the effect linked to the amount of $\widetilde{u''^2}$, and trying to isolate the influence of the nature of the anisotropy of the incident turbulent flow itself, we conducted two more runs (RunI and RunA1) in which the amount of $\widetilde{u''^2}$ is the same as in RunSI just before the shock, but not the values of the other components of the Reynolds stress tensor. Figure 1 shows that the axisymmetric case displays a greater near-field amplification of $\widetilde{u''^2}$ than the isotropic case, whereas the opposite is true for the sheared case. Concerning the near-field behaviour of $q^2/2$, both the axisymmetric and sheared cases show a greater amplification than the isotropic case. Mahesh *et al.* [2] observed a decrease of $q^2/2$ across a $M_1 = 1.2$ shock for a sheared case, and they attributed this trend to the fact that $\widetilde{u''T''} > 0$ before the shock, which is known to inhibit the amplification of the kinetic energy. In the present case (RunSI), we have $\widetilde{u''T''} > 0$ upstream, but $q^2/2$ is still more amplified in the

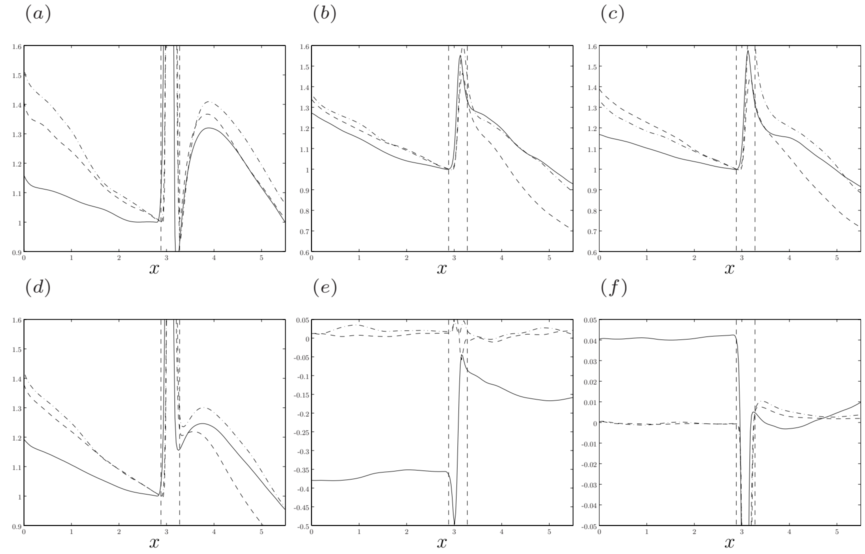

Fig. 1. Streamwise evolution of different turbulent statistics across the shock: (a) $\widetilde{u''^2}$; (b) $\widetilde{v''^2}$; (c) $\widetilde{w''^2}$; (d) $q^2/2$; (e) $\widetilde{u''v''}$; (f) $\widetilde{u''T''}$. In (a), (b), (c), (d), curves are normalized by their value immediately upstream of the shock wave. (——) RunSI ; (− − −) RunI ; (− · −) RunA1.

near field compared to the isotropic situation. This difference with Mahesh *et al.* [2] may be a consequence of the shock strength ($M_1 = 1.5$ in our case instead of $M_1 = 1.2$).

The behaviour of $\widetilde{u''v''}$ is found to be same as the one observed by Mahesh *et al.* [2] : we notice a decrease of the magnitude of $\widetilde{u''v''}$ across the shock wave.

Moreover, a clear influence of the shear stress can be seen on the streamwise component of the vorticity (not shown here). An increase of $\overline{\omega'^2_1}$ in the near field behind the shock is indeed observed for the three cases, but this tendency is much more pronounced for the sheared case. The vortex stretching by the mean flow is found to be responsible for this increase of $\overline{\omega'^2_1}$, which means that this term is enhanced in the sheared case.

References

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