COMPRESSIBILITY EFFECTS AND SOUND PROPAGATION IN TURBULENT CHANNEL FLOW

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Summary Large-Eddy Simulations of supersonic channel flow and the advection of a passive scalar oscillating at the walls are presented. A new and non-local scaling of the wall co-ordinate y^+ is proposed. In the quasi-incompressible regime, the oscillating passive scalar obeys the laminar Stokes law at high driving frequencies and exhibits increasing wall shear at decreasing frequency below $\omega^+ \sim 0.01$.

Direct and Large-Eddy Simulations of plane channel flows have proved helpful to better understand wall-bounded turbulence, in particular in supersonic and unsteady cases (see e.g. [1] and [2], resp.), in which the streamwise and spanwise homogeneity helped the interpretation. We have attempted to continue these investigations with a two-fold motivation:

a) reach higher Mach numbers to clarify the scaling of statistics with the Mach number, with particular interest in the spanwise correlations and the streak spacing, which is of crucial interest for the design of riblets for future supersonic transport aircraft;

b) understand the most basic mechanisms through which turbulence affects sound propagation. The advection by a quasi-incompressible channel flow of a passive scalar oscillating at the walls is considered here, as a starting point.

In both cases, LES are carried out with the macro-temperature closure of the compressible equations in conservation formulation [3], with the same subgrid-scale model and numerical methods as in [4], namely, the *filtered structure-function model* and an explicit McCormack scheme with 4th order accurate discretization of the inviscid fluxes. All calculations presented here have been performed at bulk Reynolds number $Re_b = 3000$, in a domain of size $(L_x/h, L_y/h, L_z/h) = (4\pi, 2, 4/3\pi)$ as in the DNS in [1], with $128 \times 65 \times 80$ grid points, instead of $144 \times 80 \times 119$. The subsequent friction Reynolds number $Re_\tau = \rho_w h u_\tau / \mu_w$ ranges from 180 for Mach number $M = u_b/\sqrt{\gamma R T_w} = 0.3$ to 522 for $M = 5$. However, the level of turbulence is found to decrease as M increases, as can be seen from Figure 1. This confirms that Re_τ is not the appropriate scaling parameter. Indeed, it has been known since [5] that no locally defined wall unit is satisfactory. Among the possible choices, that proposed as the best in [6], viz., $\rho(\tau_w/\rho)^{1/2} y/\mu$ yields corresponding Reynolds numbers h^+ decreasing from 180 for $M = 0.3$ to 84 for $M = 5$. Attempts to scale the mean velocity and temperature profiles lead one of us (C.B.) to propose an alternative to the van Driest transformation. It stems from the near-wall law $du^+ = (\mu_w/\mu) y^+$, integrated in the form $\overline{U}^+ = \int_0^{y^+} \frac{\mu_w}{\mu} dy^+ = y_c^+$. It yields an improved scaling of the mean profiles in the buffer region (Figure 2), and the spanwise correlation of the velocity fluctuations (Figure 3). It thus appears that the preferential spanwise streak spacing $\lambda_{z_c}^+$ settles around 130 for M between 0.3 and 2. This is consistent with [1], in which λ_z/h and $\lambda_{z_c}^+$ (approximately evaluated by us), hardly vary between $M = 1.5$ and $M = 3$.

The transport equation of a passive scalar oscillating at the walls is solved for several pulsations ω^+ at $M = 0.3$, for which compressibility is negligible. Figure 4 shows the evolution with ω^+ of the phase-averaged scalar gradient at the wall $\langle \left(\frac{dc}{dy}\right)_w \rangle = A_\tau(y)\cos[\omega t + \Phi_\tau(y)]$, compared with experimental and numerical counterparts in pulsating flows ([2],[7],[8]). The general trends are recovered, namely, negligible departure from the laminar Stokes solution at high frequencies, and increasing shear with decreasing phase shift at low frequencies. The dip of A_τ below its Stokes value, whose origin is controversial, is not recovered in this linearized scalar approach. Note that, in these calculations, the scalar's diffusivity has been set in such a way that the Stokes thickness $l_s^+ = \sqrt{2/(Sc\,\omega^+)}$ is kept constant ($l_s^+ = 30$, which is expected to be large enough for the shear wave to reach the buffer region). Other choices are under investigation.

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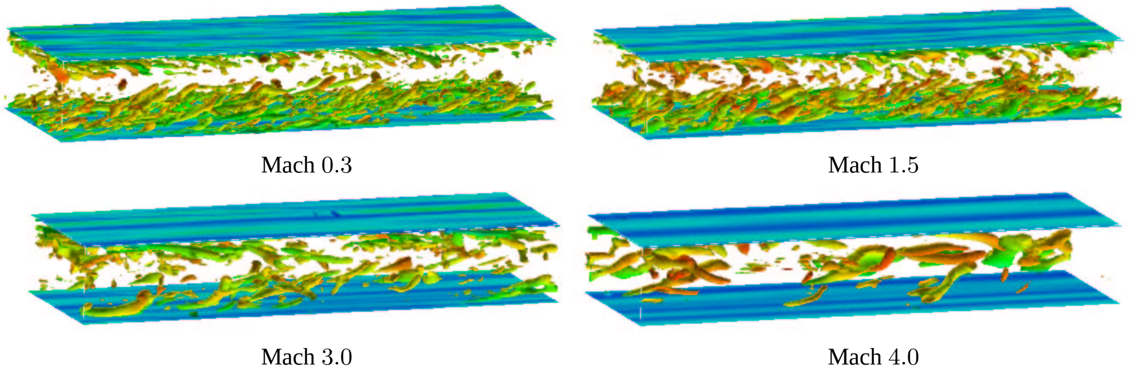

Figure 1. Coherent structures materialized by the isosurface $Q = 6\frac{u_\tau}{h}$ and slices of streamwise velocity near the walls.

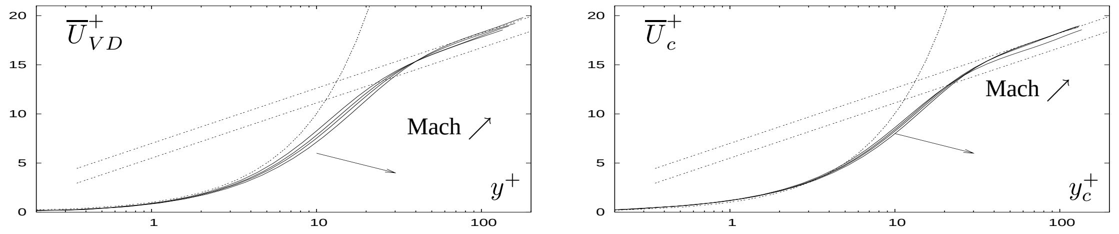

Figure 2. Mean velocity profiles after van Driest transformation (left) and the propoosed scaling (right).

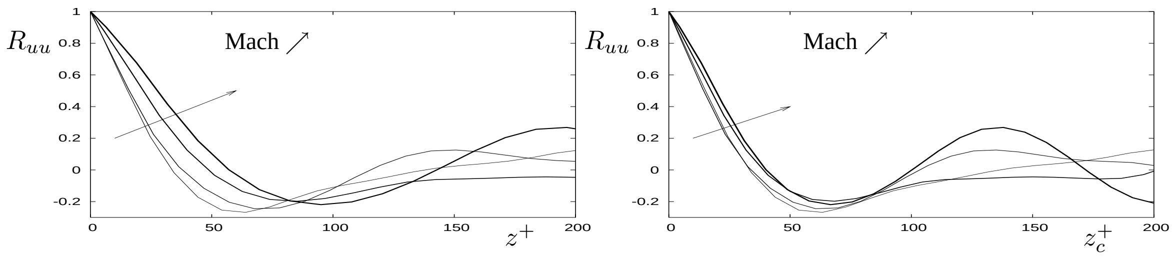

Figure 3. Spanwise correlations of the streamwise velocity fluctuations in the near-wall region ($y^+_c = 2.5$) in standard scaling (left) and with modified wall unit (right), for $0.3 \leq M \leq 2$.

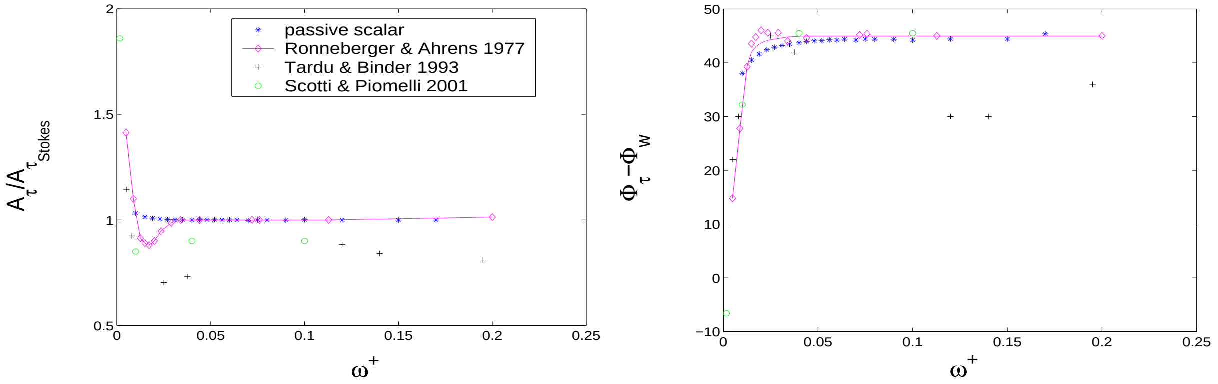

Figure 4. Normalized wall shear impedance as a function of the pulsation ω^+. **Left:** amplitude normalized by the laminar Stokes value $A_{\tau_{\mathrm{Stokes}}}$. **Right:** phase shift between the shear and the forcing at the wall. The laminar Stokes solution corresponds to $45° \; \forall \omega^+$.

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