Intrinsic compressibility effects in wall-bounded turbulent flows - understanding the physical mechanism

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The majority of the literature on compressible wall-bounded flows assume that intrinsic compressibility effects—associated with the density changes of fluid elements in response to changes in pressure[1]—are insignificant, and that only mean fluid property variations matter for these flows. This is Morkovin's hypothesis[2], a key building block in the theory of compressible turbulence. Based on tailored Direct Numerical Simulations (DNS) of high Mach number compressible channel flows, we argue that Morkovin's hypothesis is not strictly accurate and that intrinsic compressibility effects do modify turbulence dynamics. In these simulations, we isolate intrinsic compressibility effects by eliminating mean property variations, which is achieved by removing viscous heating from the energy equation[3]. The velocity field is decomposed into solenoidal and dilatational components using Helmholtz decomposition, and we observe a change in the solenoidal anisotropy due to reduction in the solenoidal pressure-strain correlation with increasing Mach numbers [Fig. 1(a)]. This reduction is due to the weakening of the quasi-streamwise vortices [Fig. 1(b)] that play a significant role in the inter-component energy transfer[4]. The weakening of these vortices is explained as follows: the quasi-streamwise vortices initiate the sweep event in which fluid moves towards the wall (negative wall-normal velocity). This event is associated with a reduction of wall-pressure fluctuation (negative $\partial p'_w/\partial t$)[5,6], which causes an increase in fluid volume as dilatation near the wall $d_w \sim -\partial p'_w/\partial t$. The fluid expansion generates positive wall-normal dilatational velocity which opposes the streak movement, eventually weakening the vortices.

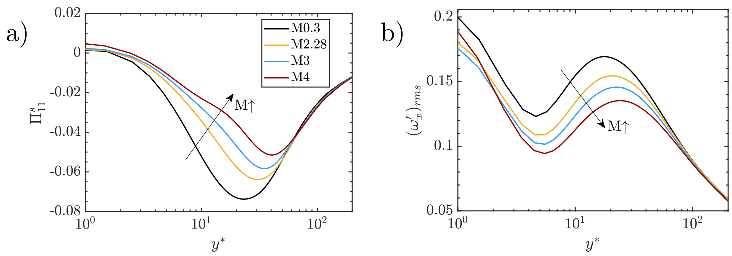

Figure 1: (a) Streamwise pressure-strain correlation as a function of the semi-local coordinate y^*. (b) Streamwise vorticity root-mean-square (rms). The curves represent channel flows with bulk Mach numbers of 0.3, 2.28, 3 and 4 and friction Reynolds number $Re_\tau \approx 550$.

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