Compressibility Effects on Turbulent Shear Flows

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Compressibility effects are present in many practical turbulent flows, ranging from shock-wave/boundary-layer interactions on the wings of aircraft operating in the transonic flight regime to supersonic and hypersonic engine intake flows. Besides shock wave interactions, compressible flows have additional dilatational effects and, due to the finite sound speed, pressure fluctuations are localized and modified relative to incompressible turbulent flows. Such changes can be highly significant, for example the growth rates of mixing layers and turbulent spots are reduced by factors of more than three at high Mach number. In this paper we review some of the basic effects of compressibility on canonical turbulent flows and attempt to rationalise the different effects of Mach number in different flows using a flow instability concept. Figure 1 shows the growth rate of disturbances in a compressible mixing layer relative to incompressible flow, as a function of convective Mach number M_c and wave angle θ. The behaviour of this plot helps to explain the growth rate reduction with Mach number and the tendency towards oblique roll-ups at high M_c . It is also interesting that there is a dead zone of shear layer instability for $M_c \cos \theta > 1$. We discuss how this plot may be extended to other flows including turbulent spots and turbulent boundary layers in adverse pressure gradients. We then turn our attention to a fully three-dimensional problem of shock-wave/boundary-layer interaction in a closed duct, considering direct effects of shock waves, due to their penetration into the outer part of the boundary layer, as well as indirect effects due to the high convective Mach number of the shock-induced separation zone. It is noted in particular how shock-induced turning of the detached shear layer results in strong localized damping of turbulence kinetic energy. This is illustrated in figure 2, which shows pressure and streamwise velocity fluctuations. It can be seen how the shock reflects from close to the sonic line and how turbulence fluctuations along a streamline in the shear layer are reduced in amplitude by a factor of two, due to the stabilising effect of curvature in the region where the impinging shock reflects as an expansion fan.

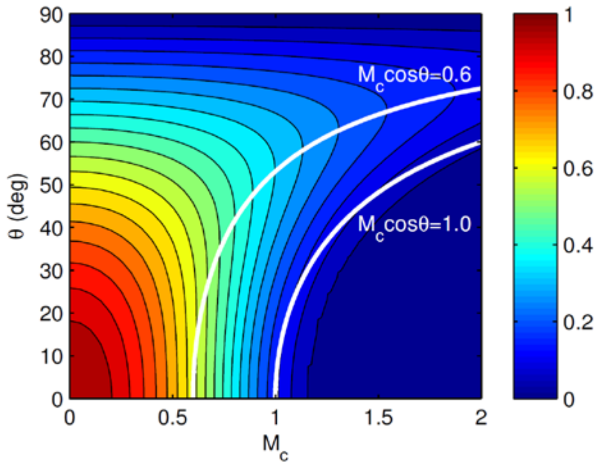

Figure 1. Contours of disturbance growth reduction factor Φ as a function of wave angle θ and convective Mach number M_c.

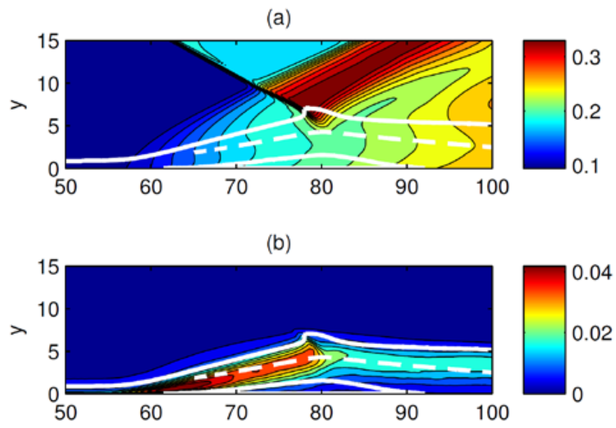

Figure 2. Mean flow in the interaction region: (a) pressure (b) $\overline{u'^2}$. The upper white contour in each frame shows the sonic line and the lower contour shows $\overline{u} = 0$. The dashed line is a sample streamline.