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Spatial Direct Numerical Simulation of Instability Waves in Hypersonic Boundary Layers

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Abstract : Understanding laminar-turbulent transition process in hyper-sonic boundary layers is crucial for designing viable high speed flight vehicles. The study of transition becomes particularly important in the high speed regime due to the effect of transition on aerodynamic performance and heat transfer. However, even after many years of research, the transition process in hyper-sonic boundary layers is still not understood. This lack of understanding of the physics of the transition process is a major impediment to the development of reliable transition prediction methods. Towards this end, spatial Direct Numerical Simulations are conducted to investigate the instability waves generated by a localized disturbance in a hyper-sonic flat plate boundary layer. In order to model a natural transition scenario, the boundary layer was forced by a short duration (localized) pulse through a hole on the surface of the flat plate. The pulse disturbance developed into a three-dimensional instability wave packet which consisted of a wide range of disturbance frequencies and wave numbers. First, the linear development of the wave packet was studied by forcing the flow with low amplitude (0.001% of the free-stream velocity). The dominant waves within the resulting wave packet were identified as two-dimensional second mode disturbance waves. Hence the wall-pressure disturbance spectrum exhibited a maximum at the span wise mode number k = 0. The spectrum broadened in downstream direction and the lower frequency first mode oblique waves were also identified in the spectrum. However, the peak amplitude remained at k = 0 which shifted to lower frequencies in the downstream direction. In order to investigate the nonlinear transition regime, the flow was forced with a higher amplitude disturbance (5% of the free-stream velocity). The developing wave packet grows linearly at first before reaching the nonlinear regime. The wall pressure disturbance spectrum confirmed that the wave packet developed linearly at first. The response of the flow to the high amplitude pulse disturbance indicated the presence of a fundamental resonance mechanism. Lower amplitude secondary peaks were also identified in the disturbance wave spectrum at approximately half the frequency of the high amplitude frequency band, which would be an indication of a sub-harmonic resonance mechanism. The disturbance spectrum indicates, however, that fundamental resonance is much stronger than sub-harmonic resonance.

Keywords : boundary layer, DNS, hyper sonic flow, instability waves, wave packet
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