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Dynamic shock wave reflection phenomena.

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Abstract

There have been numerous studies on the steady state transition criteria between regular reflection (RR) and Mach reflection (MR) of shock waves for a stationary, two-dimensional (2D) wedge in a steady supersonic free stream since the original shock wave reflection research by Ernst Mach in 1878. The steady, 2D transition criteria between RR and MR are well established. There has been little done to consider the dynamic effect of rapid wedge rotation on RR $\leftrightarrow$ MR transition.

This thesis presents the results of an investigation of the effect of rapid wedge rotation on transition between 2D regular and Mach reflection in the weak and strong-reflection ranges, with experiment and computational fluid dynamics. A novel facility was designed to rotate a pair of large aspect ratio wedges in a 450 mm $\times$ 450 mm supersonic wind tunnel at wedge rotation speeds up to 11000 deg/s resulting in wedge tip speeds approximately 3.3 % of the free stream acoustic speed. Steady state, baseline experiments, in which the wedges were rotated very gradually, were also completed. High-speed images and measurements are presented for the steady and dynamic experiments. Numerical solution of the inviscid governing flow equations was used to model the steady case and to mimic the experimental motion in the dynamic experiments. The two-dimensional, Euler CFD code was developed at the University of the Witwatersrand.

Steady state experiments were completed in the weak and strong-reflection ranges and transition measurements were compared to 2D steady, theoretical values and Euler computations. There was close agreement between theoretical, computational and experimental transition for the steady case, with the following exception. Due to the levels of free stream noise in the supersonic wind tunnel, incidence-induced hysteresis was not observed in the strong-reflection region and transition occurred at the von Neumann condition for increasing and decreasing incidence. In the ideal case, RR $\rightarrow$ MR transition occurs at the detachment condition and the reverse transition occurs at the von Neumann condition. Therefore, there is discrepancy between steady theory/CFD and experiment for RR $\rightarrow$ MR transition in the strong-reflection range only, which is consistent with observations in other facilities with sufficient levels of free stream noise.

Dynamic RR $\rightarrow$ MR Transition : Rapid wedge rotation did generate a measurable dynamic effect on RR $\rightarrow$ MR transition. This thesis presents the first experimental evidence of RR $\rightarrow$ MR reflection transition

beyond the steady detachment condition in the weak and strong-reflection ranges. In all instances, there was good agreement between experiment and 2D CFD, including dynamic RR → MR transition in the strong-reflection region. The agreement between the experiment, in which small perturbations are always present in the free stream, and the CFD, in which the free stream is without perturbations, implies that RR → MR transition in the strong-reflection region becomes insensitive to free stream noise above a certain critical rotation speed. Due to the close agreement between CFD and experiment, the Euler code was also applied to scenarios beyond the limits of the current facility to explore the influence of variables in the parameter space, viz. rotation speed, initial incidence and rotation centre. CFD was also used to investigate the dynamic transition mechanism over a limited number of simulations. For dynamic RR → MR transition, a distinction is drawn between the sonic, length scale and detachment conditions. The point at which the flow downstream of the reflection point goes sonic is not necessarily the point at which the wedge length scale, from the wedge trailing edge expansion, is communicated to the reflection point. There is evidence to support that the RR → MR transition criteria for the rapidly rotating wedge is neither the sonic or length scale conditions, but rather the condition at which the reflected wave can no longer satisfy the boundary condition at the reflection point. Dynamic simulations showed that RR could be maintained with a length scale present at the reflection point. Other dynamic simulations showed, for the first time, that transition to MR was possible without the wedge length scale being communicated to the reflection point.

Dynamic MR → RR transition : Rapid wedge rotation generated a measurable effect on MR → RR transition. The first experimental evidence of MR → RR transition below the steady von Neumann condition is presented. Once again, there was good agreement between experiment and 2D CFD. CFD was used to investigate the sensitivity of transition to rotation speed, initial incidence and rotation centre in the strong and weak-reflection ranges. Due to impulsive wedge start and rapid wedge rotation, there are very marked dynamic effects on the variation of Mach stem height with wedge incidence and the deviation from the steady transition conditions is significant. The MR → RR transition was found to be dependent on the initial condition and the transient variation of Mach stem height with wedge incidence.