Flow control of an oblique shock wave reflection by micro-ramps: effects of location and size

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In the design of high speed transportation systems, shock wave boundary layer interactions still pose a challenging problem due to their associated pressure and heat loads [1]. Furthermore when regarded in the framework of inlets, it is well known that the occurrence of large separated areas may significantly decrease its efficiency [2]. Therefore flow control strategies are developed in order to reduce the separated region. One of the most promising approaches is to introduce micro-ramp vortex generators in the flow that entrain high momentum flow towards the wall, thereby producing a fuller boundary layer velocity profile that is less prone to separation [3]. In the work of Blinde et al. [4] it was shown, using Stereo-PIV measurements in planes parallel to the wall, that the separation probability could be reduced by 20-30% when introducing an array of micro-ramps upstream of the interaction.

The goal of this paper is to provide insight into the effects of micro-ramp size and location on the shock induced separation bubble and to identify the flow features responsible for their (in)effectiveness. Planar PIV measurements were carried out, using two camera's in parallel, one zoomed in on the interaction region, the other capturing the incoming boundary layer and freestream (see Fig.1). The experiments were carried out at a Mach number of 2 and a Re_θ of $17.7 \cdot 10^3$. A 12 degree shock generator is used to create a strong shock wave, resulting in separation of the undisturbed boundary layer. The resulting interaction is observed to be highly unsteady, with the size / strength of the separation bubble fluctuating in time and occasionaly it even completely disappears.

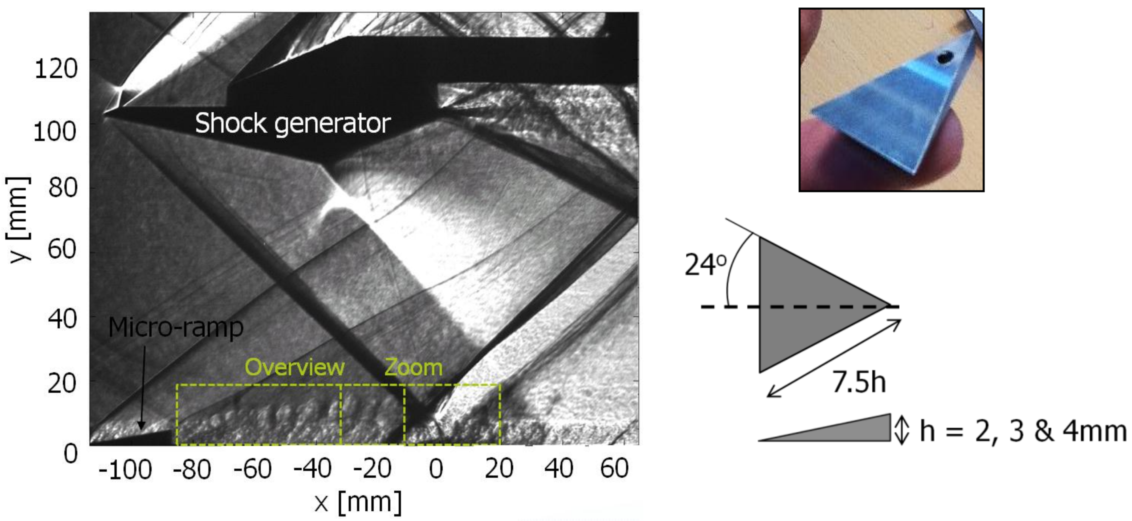

Fig.1: Spark-light Schlieren image of the interaction (left) and micro-ramp geometry (right)

In Fig.2 a comparison is given between the average streamwise velocity field measured for a case with and without a micro-ramp. For this particular configuration, a 4 mm micro-ramp was placed

17δ's (δ=5.2 mm) upstream of the inviscid impingment point of the incident shock wave. The measurement plane is aligned with the symmetry plane of the micro-ramp. The solid black line in the figure represents the dividing streamline, that divides the separation bubble from the outer flow, while the dotted black line is the sonic line. Note that on average there is no separation taking place for the flow with a micro-ramp. Instantaneously there still is separation, but significantly less. The averaged separated area size has been reduced by a factor of 4.

The lower two images of Fig.2 show the in-plane turbulence intensity. The highest values are recorded in the region enclosed by the dividing streamline and the sonic line, an observation that was also made in the work of Souverein [5]. The high values are due to mixing effects taking place in the shear layer. The turbulence intensities recorded in the center of the shear layer are approximately 10-15% smaller for the case with a micro-ramp. Also notice that the shear layer stays closer to the wall.

The effect of the micro-ramp can also be seen in the incoming flow. A clear wake is present in the mean from y = 1-2δ and in that same region higher turbulence intensities are recorded.

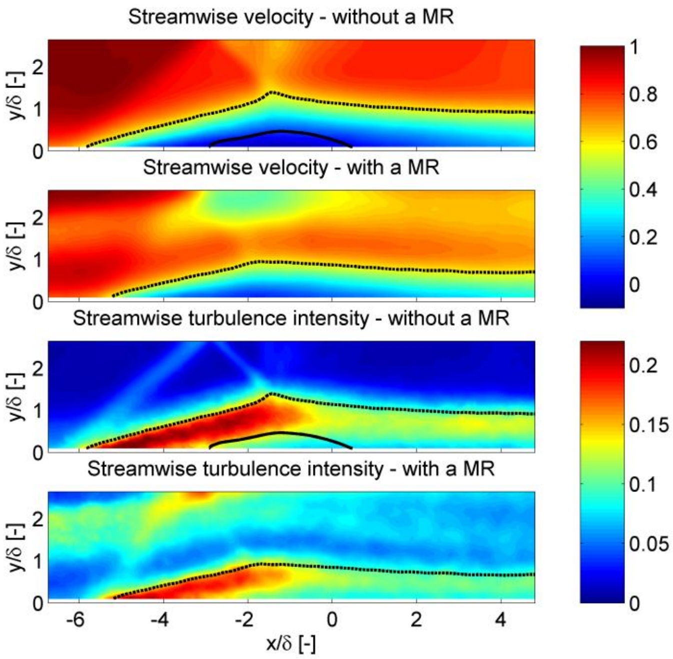

Fig.2: Streamwise velocities / turbulence intensities within the interaction region for a case with and without a 4 mm micro-ramp (at x = -17δ). Values are normalized with the freestream velocity.

The state of the boundary layer can, to a certain extent, be quantified by the incompressible shape factor. Fig.3 shows that with a micro-ramp the shape factor of the incoming boundary layer is lower (1.16 instead of 1.25 at x = -10δ), indicative of a fuller velocity profile. This difference becomes even more pronounced when the boundary layer encounters the adverse pressure gradient imposed by the reflected shock wave around x = -7.5δ. From x = -2.5δ until 0.5δ the boundary layer is separated for the case without a micro-ramp. The fuller incoming velocity profile explains partially why there is less separation taking place, it is however not the complete story. Factors like the location where the low-momentum wake impinges on the shock system and the instantaneous vortical structures carried along this wake are also expected to affect the separation bubble.

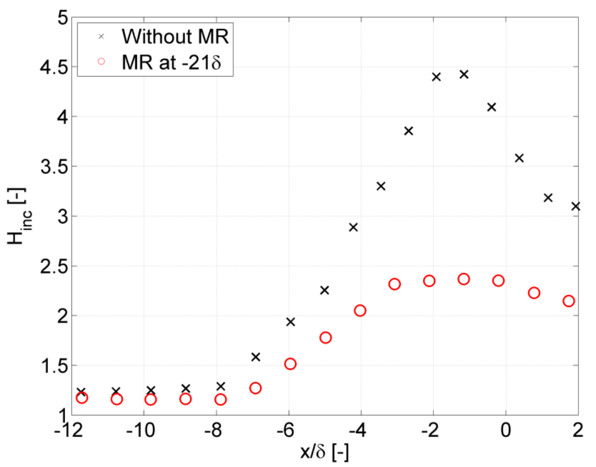

Fig.3: Development of the incompressible shape factor throughout the interaction

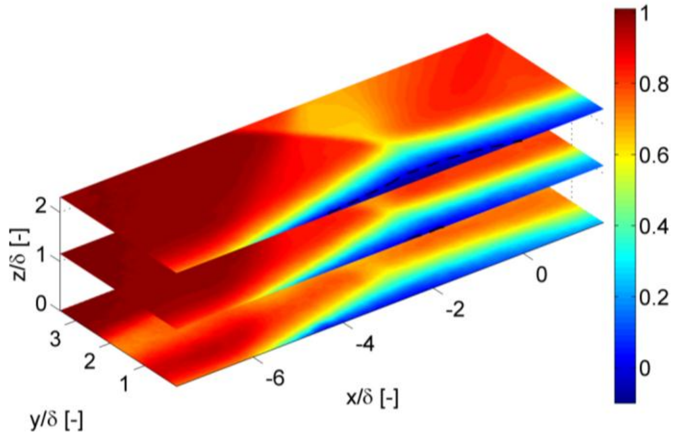

Fig.4: Normalized streamwise velocity distribution in the interaction region, for a 4 mm micro-ramp located at x = -17δ. The three planes correspond to a cut through the centerline (z=0), at 25% span (z=1.15δ) and 50% span (z=2.3δ). The dashed line presents the zero-velocity contour.

A parametric study was carried out, to investigate the effects of micro-ramp height and streamwise location of the ramp with respect to the impinging shock location. When the micro-ramp is placed too close to the interaction ($x_{trailing}$<-12δ) it is observed that the size of the separation bubble increases instead of decreases. It is believed that this can be attributed to the fact that the mixing distance between the micro-ramp and the shock impingement location is insufficient to transport enough high momentum air towards the surface. Furthermore for a relatively small distance between the micro-ramp and impinging shock the momentum deficit of the wake is large and located close to the wall.

Measurements in different spanwise planes reveal the strongly three-dimensional effect of the micro ramp on the interaction. In Fig.4 three slices are shown, at the center line, 25% span and 50% span. As the measurement plane is moved further off centerline, the separated region increases. At z/δ = 2.3 (50% span), the mean flow field and size of the separated region is similar to that without a micro-ramp. A similar observation was made in the work of Babinsky an Pitt Ford [3], by using oil-flow visualizations and LDA measurements it was shown that the effects of the micro-ramp do not reach far beyond its span.

<u>References</u>

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