Kelvin-Helmholtz Vortices and Intermittent Shock Oscillations Past a Supersonic Micro Ramp

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ABSTRACT

Micro ramp vortex generators are one of the robust passive flow control devices for various aerospace applications, e.g. enhancing the fuel-air mixing in scramjet engines, separation control in the shock wave boundary layer interactions, etc (Panaras and Lu 2015, Giepman et al 2014). Micro ramps induce a stream-wise vortex pair, enhancing the outer-inner momentum exchange necessary to achieve a fuller boundary-layer profile. However, the potential benefits of micro ramps have only been argued based on the time-averaged flow field but their unsteady instantaneous flow features are expected to contribute to the vibrations of wall and downstream shocks---similar to protrusions on launch vehicles. Therefore, this work focuses on the instantaneous features of the micro ramp wake.

Experiments were performed in the supersonic blow-down wind tunnel, called ST15, at the high speed lab of Aerospace Engineering, Delft University of Technology, The Netherlands. The tunnel is operated with a Mach 2 nozzle block with a 150mm wide test section. A micro ramp of 4mm height (h) (60-70% of the boundary layer thickness) is pasted on the floor/sidewalls, where the turbulent boundary layer is 6mm thick. The flow field is measured with Schlieren and 2C+3C particle image velocimetry (PIV). Micro ramps with different span (θ_s) and ramp (θ_r) angles are tested. Based on this parametric study, a new scaling and circulation model was formed and have been reported (Tambe, Schrijer, van Oudheusden 2021) with which the recent studies agree (Wu et al 2022, Della Posta et al 2023). Here, we revisit the experimental data to focus on the instantaneous features of the micro ramp wake, e.g. Kelvin-Helmholtz vortices and intermittent shock oscillations.

Figure 1 shows the typical time-averaged (a) stream-wise and (b) wall normal velocity, respectively, past the micro ramp through 2C (at symmetry plane) and 3C (at cross-flow planes) PIV measurements. The wake features a low momentum region with a 3D shear layer where the Kelvin-Helmholtz instability induces hairpin/ring-like vortices around the stream-wise vortex pair and a 3D oblique shock system surrounds the wake.

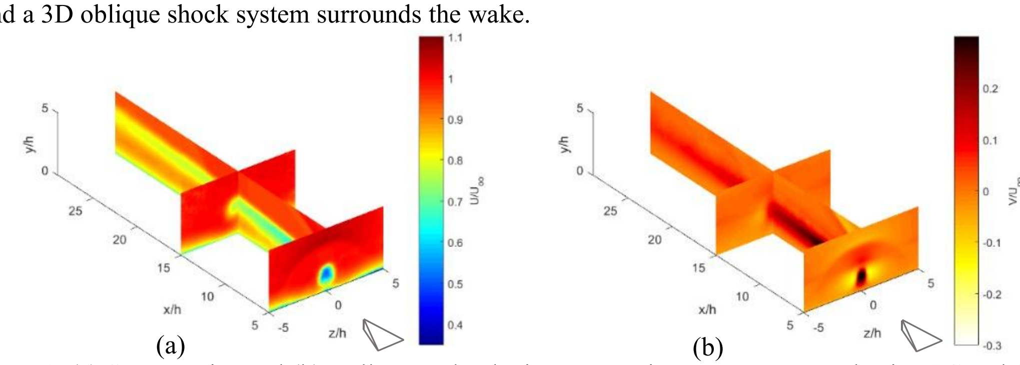

Figure 1. (a) Stream-wise and (b) wall-normal velocity past a micro ramp measured using 2C and 3C PIV.

Figure 2 shows the instantaneous Schlieren snapshot that captures the Kelvin-Helmholtz vortices and the oblique shock system surrounding the micro ramp wake, as annotated. Just downstream of the micro ramp trailing edge, the 3D oblique shock system interacts with the separated shear layer past the micro ramps and primary vortices which come together from the micro ramp side-edges. These interactions cause oscillations in the shock system.

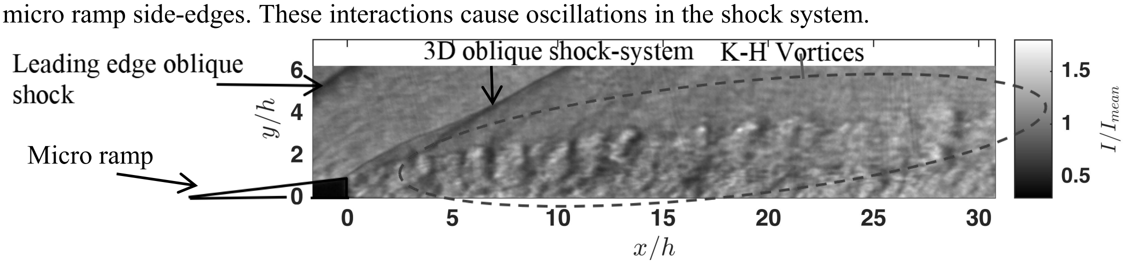

Figure 2 Instantaneous Schlieren snapshot of the micro ramp wake.

The wall/shock vibration frequency caused by the micro-ramp wake is expected to depend also on the frequency of the passing Kelvin-Helmholtz vortices---which depends on their wavelength and convective velocity. We measure the wavelength of the KH vortices (λ) using a sliding window correlation of the POD-filtered top-view Schlieren images, e.g. see figure 3a and b. The convective Mach number (M_c) and shear-layer height (h_{sl}) are estimated from the time-averaged stream-wise velocity field, measured by PIV. We find a new scaling of the wavelength based on the micro ramp geometry parameters and the shear layer height (h_{sl}) such that all the measurements from different micro ramps collapse on a common curve with respect to the convective Mach number, as shown in figure 3c. This scaling allows estimating the expected fluctuation frequency range past a micro ramp for a wide range of span and ramp angles.

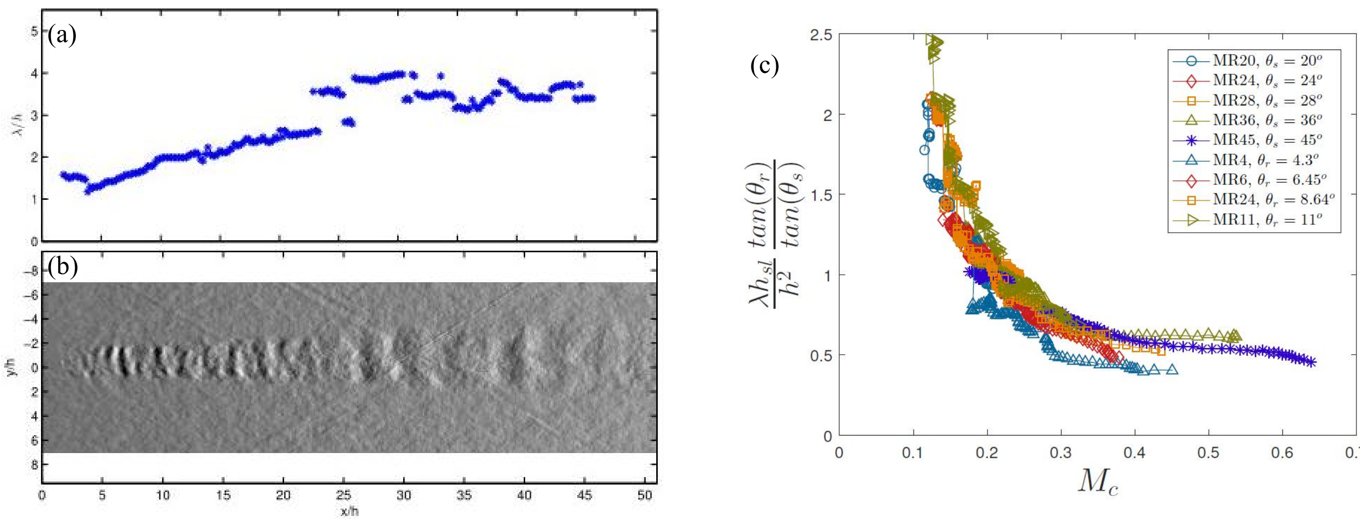

Figure 3 (a) Wavelength of the Kelvin -Helmholtz vortices estimated from the (b) POD-filtered top view Schlieren instance for the baseline micro ramp case. (c) The new scaling of the wavelength shows a well-defined trend with respect to the convective Mach number, regardless of different geometry parameters.

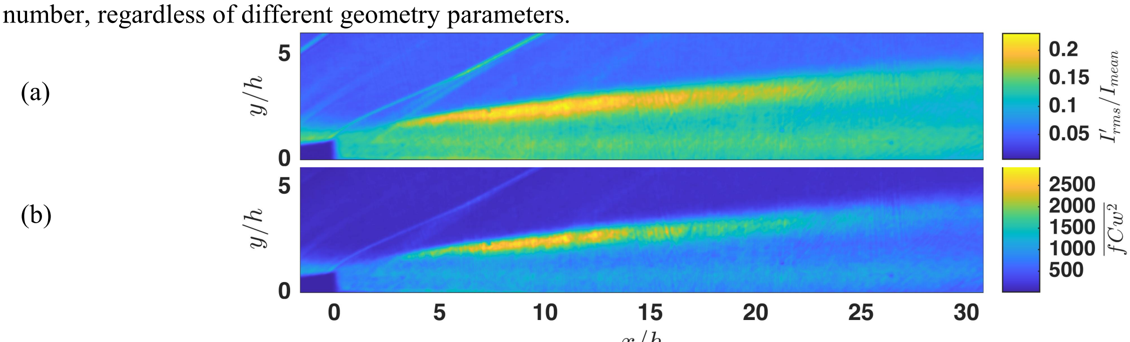

Figure 4 (a) RMS of pixel intensity fluctuations of the Schlieren image (b) mean pre-multipied wavelet coefficients map.

The shock oscillations show a wide distribution of the measured density gradient, represented by the RMS of the measured pixel intensity, see figure 4a. Here, the top edges of the KH vortices show the strongest fluctuations. In the raw time-series at each pixel, the fluctuations are not uniformly distributed but appear intermittent, localised in time. We use wavelet transform using a Mortlet mother wavelet at each pixel to identify time-localised fluctuations, and estimate the mean pre-multiplied wavelet coefficient (fCw^2) at each pixel to assess the strength of the intermittent fluctuations, as shown in figure 4b. Here, only the oblique shock past the micro ramp and top regions of the KH-vortices show high intermittent fluctuations---suggesting a possible correlation between the two. The leading edge oblique shock and other shocklets seen in the RMS plot (figure 2 and 4a) do not appear in the intermittent fluctuations map (figure 4b), suggesting that their fluctuations are random.

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