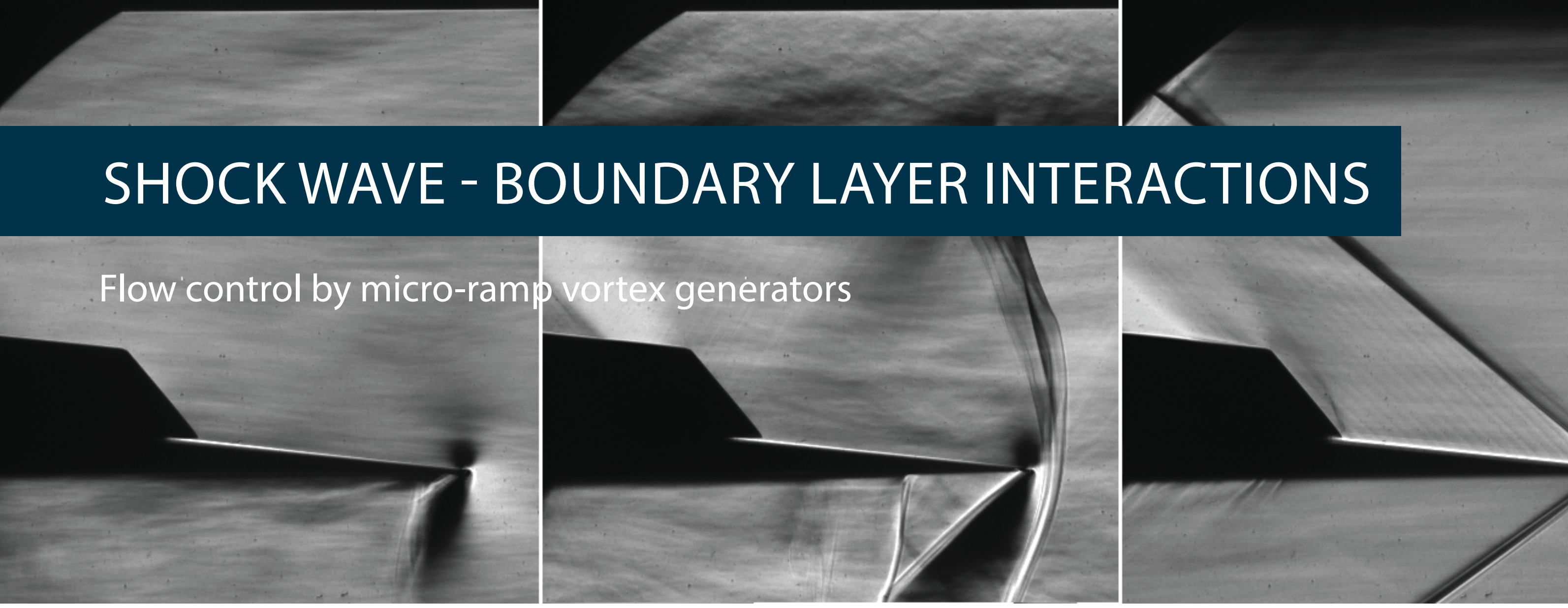

SHOCK WAVE - BOUNDARY LAYER INTERACTIONS

Flow control by micro-ramp vortex generators

Shock wave-boundary layer interactions are a very common feature in both transonic and supersonic flows. They can be encountered on compressor and turbine blades, in supersonic jet inlets, on transonic wings, on the stabilization fins of missiles and in many more situations. Because of their major importance on the performance and safety of high-speed flight vehicles, they have now been studied for over 60 years, but their control remains challenging. This article presents the results of a study on a new type of flow control device: the micro-ramp vortex generator.

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It was April 9, 1945; Guido Mutke was on a high-altitude training mission with his Messerschmitt Me-262 airplane, when he receives an emergency call from a Luftwaffe colleague under attack by an American P-51 Mustang. He goes full throttle in a steep dive and within a couple of seconds reaches speeds of over 1100 km/h. His plane starts vibrating violently, rivets are popping and all control authority is lost. Somehow, however, using just his horizontal stabilizer, he is able to regain control of his airplane and safely bring it back to solid ground. Although not validated, Guido Mutke might have been the first pilot to break the sound barrier. Back then, the knowledge of transonic / supersonic aerodynamics was still very limited and the drastic changes in flight properties when entering the transonic regime could not be properly explained. In the years after the war it was, however, realized that many of these events could be explained by the formation of shock waves on the (locally) supersonic wings.

The appearance of shock waves is, however, not restricted to external surfaces like wings. They can also appear on the internal components of an aircraft: the engine's inlet, on the fast rotating turbine and compressor blades etc. The physics encountered for all these cases is very similar, however, to reduce the scope of this article, we will restrict ourselves to the example of a supersonic jet inlet, as presented in Figure 1. When entering the engine, the flow experiences an abrupt change in flow angle and an oblique shock wave is formed that reflects off the inlet's walls multiple times, up to the point where the flow turns subsonic. In itself, this is not a bad thing, the flow needs to be decelerated before entering the compressor stage of the engine, and oblique shock waves are well suited for this job.

The shock reflections on the other hand can be problematic, because of the boundary layer developing along the walls of the inlet. Without the presence of this boundary layer (inviscid flow), the shock wave would reflect from the same location as where it hits the surface (see Figure 1). However, in any real life application, there will be friction / viscosity and consequently also an interaction between the oblique shock waves and wall boundary layer. Figure 2 zooms in on this interaction and shows the typical flow topology that is encountered for an oblique shock wave reflection.

As is known, disturbances in a flow travel with the speed of sound, therefore they can only travel downstream in a supersonic flow. The incoming freestream and the supersonic part of the incoming boundary layer are, therefore, not aware of the presence of the incoming shock wave. However, close to the wall, the boundary layer is still subsonic, which allows for information to be transferred in the upstream direction of the flow. Via this route, the incoming boundary layer is 'warned' that there is a region of strong adverse pressure gradient (caused by the shock) ahead. In response to this information, the boundary layer will thicken even before reaching the incident shock wave. The supersonic part of the boundary layer is therefore turned into itself and compression waves are created, which usually converge just outside of the boundary layer to form the reflected shock wave. Depending upon the strength of the incident shock wave and the stability of the incoming boundary layer, the boundary layer may separate and an expansion fan and reattachment shock will also be formed.

Comparing Figures 1 and 2, clearly simple inviscid flow theory does not provide an adequate description when considering the flow behavior close to the wall. To complicate matters even further, a shock wave-boundary layer interaction with separation is also inherently unstable. The separation bubble will be growing / shrinking over time and as a consequence the reflected shock wave, expansion wave and reattachment shock wave will be moving as well. Shock instability is a well-known cause of air-intake buzz, which leads to large fluctuations in the thrust output and if not handled properly by the pilot can result in the engine to unstart.

Due to the major impact on the performance and safety of high-speed flight vehicles, shock wave-boundary layer interactions have been an active field of

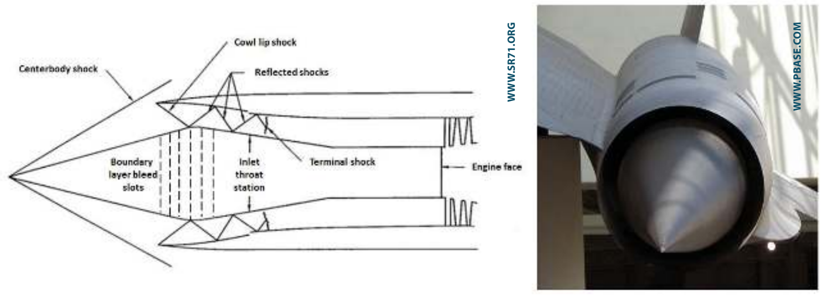

Figure 1. Inlet of a Pratt & Whitney J-58 engine, as used on the SR-71 Blackbird

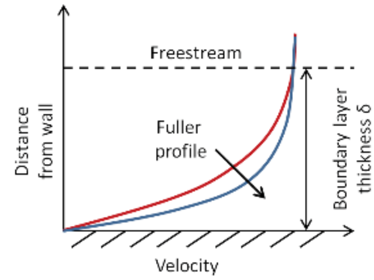

Figure 3. The purpose of flow control is to increase the 'health' of the boundary layer by adding more momentum to the near-wall region of the flow, thus creating a fuller profile.

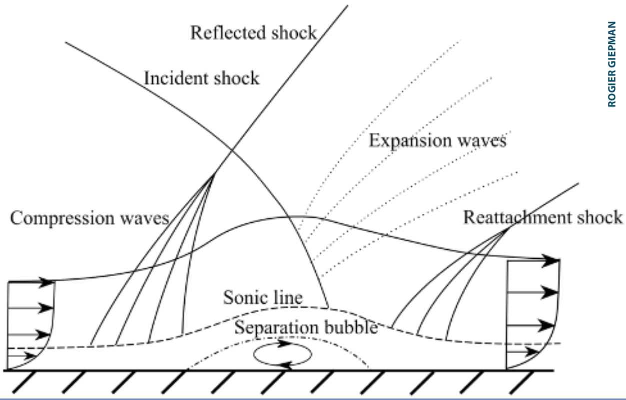

Figure 2. Flow topology encountered for an oblique shock wave reflection, for the case of a separated boundary layer

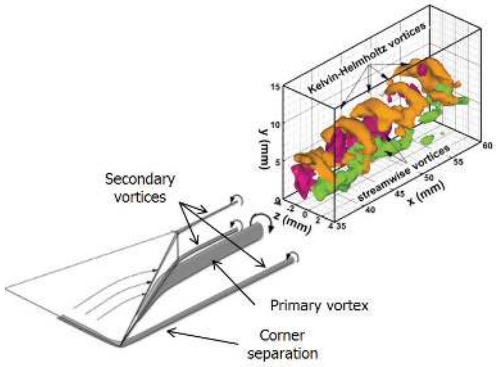

Figure 4. Flow development downstream of a micro-ramp vortex generator, showing a conceptual model (Babinsky, 2009) and the instantaneous vortical structures measured by Sun using a tomographic PIV system (Sun, 2012).

research for over 60 years now. And in this period of time, a large body of data has been gathered and a great deal has been learned about the mean and instantaneous flow behaviour of shock wave-boundary layer interactions. The effective control of shock wave-boundary layer interactions, however, still remains a very active and open topic. With the development of new experimental and numerical techniques, it is possible to gain a better understanding of the physics involved in shock wave-boundary layer interactions than ever before. At the aerodynamics department of the TU Delft, we have mostly focused our efforts on the experimental side of the problem and approached it using a variety of measurement techniques, with Particle Image Velocimetry (PIV) serving as our main flow diagnostics tool.

PARTICLE IMAGE VELOCIMETRY

The basic idea of PIV is simple: small tracer particles are added to the flow and a camera is used to track the movement of the particles that travel with the flow. Two images are acquired in short succession (the time delay is typically $\Delta t \sim 1\mu s$ in supersonic flows), such that the same particles are recorded in both images although shifted by a small amount. Using computer algorithms, the particle movement from the first to the second image can be obtained. Since the time separation between both images is known, the velocity of the particle and thus of the flow can be computed.

To capture these tiny and fast moving particles on film, a large amount of light is required. This is delivered by a special laser that can produce two high-energy pulses for the given time separation Δt and 'freezes' the location of the particles in both frames.

FLOW CONTROL DEVICE

The goal of flow control for shock wave-boundary layer interactions is to reduce the *size of the separation bubble* and the associated *unsteadiness of the interaction region*. The size of the separation bubble depends on two critical factors: *the shock strength and the 'health' of the incoming boundary layer*.

Weaker shocks would reduce the size of the separation bubble, but unfortunately reducing the shock strength is not always an option. For instance, in supersonic jet intakes, a series of oblique shocks is used to decelerate the incoming flow to a subsonic Mach number. Weaker shocks can be used, but then to reach the same compression ratio, more shocks are needed and consequently also a longer / heavier inlet is required. The shock strength is therefore usually a given, which follows from the early stages of the design process and does not allow for too much tweaking.

Therefore, the option that remains for flow control is to manipulate the 'health' of the boundary layer. It is well known that fuller boundary layers (see Fig.3) are less prone to separation. Full in this context means that there is high-momentum fluid present close to the wall. In traditional supersonic jet inlets, a full boundary layer profile is usually obtained by means of boundary layer bleed. Slots are introduced in the wall, which remove the low-momentum portion of the boundary layer close to the wall from the flow (see also Fig.1). The new boundary layer that forms is much fuller and less prone to separation. The mass flow removed from the inlet (~2% of the capture inlet mass flow) is typically not reinjected elsewhere in the engine and is vented overboard. So, to achieve the same mass flow rate through the engine, the frontal area of the engine needs to be increased, which also increases the engine's weight and drag.

Micro-ramp vortex generators form a promising alternative to boundary layer bleed. A micro-ramp is a small wedge-like ramp, with a typical height of half the boundary layer thickness (see Fig.4). When placed in a boundary layer, two counter-rotating vortices are formed downstream of the micro-ramp that transport high-momentum fluid from high up in the boundary layer down towards the wall. They act as mixing devices and create a boundary layer profile that is fuller and less prone to separation. Compared to boundary layer bleed, this system is more robust and does not reduce the mass flow, therefore allowing a smaller engine intake. However, before these devices can be used on an actual engine, some fundamental questions need to be answered:

1. Can the size of the separation bubble / interaction unsteadiness be reduced, and if so, by how much?

2. What is the optimal location of the micro-ramp with respect to the shock system?

3. What are the effects of Mach and Reyn-

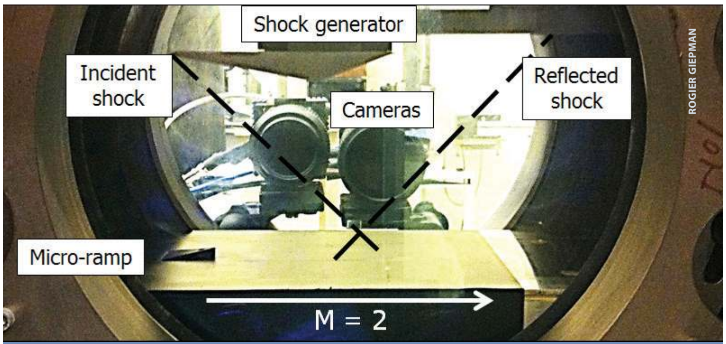

Figure 5. Test section of the ST-15, showing the micro-ramp, the 12° shock generator and two cameras recording the flow.

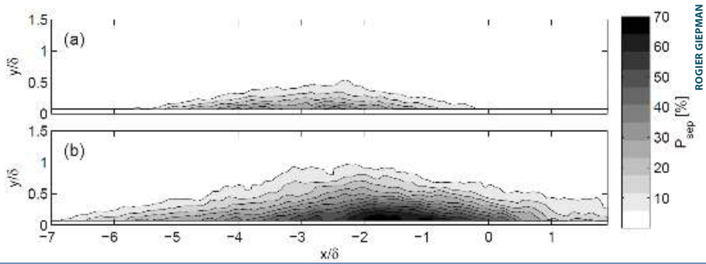

Figure 8. The separation probability Psep with a micro-ramp (h = 4 mm, x = -17.3δ) upstream of the interaction (a) and without a micro-ramp (b).

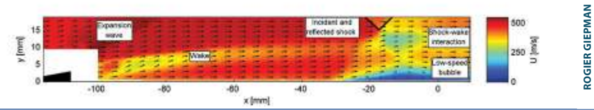

Figure 6. Flow field overview for the case of a micro-ramp (h=3 mm) mounted 108 mm upstream of the wall impingement location of the incident shock.

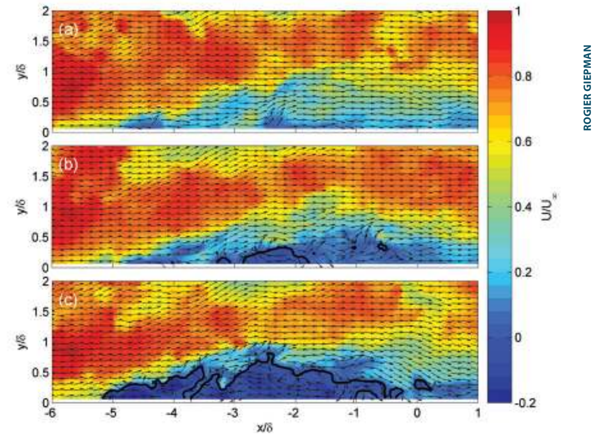

Figure 7. Three uncorrelated snapshots of the low-speed bubble for a 4 mm micro-ramp located at x/δ = –17.3 (x = -90 mm). The solid black line presents the zero-velocity iso-line. (a) No separation (b) Small separation bubble (c) Large separation bubble.

olds number of the micro-ramp's effectiveness?

4. How severe are the 3D effects introduced by the ramp?

This article touches upon the first question, for more information on the first and second question please refer to [3]. The third question is currently being investigated by an MSc Student from the Aerodynamics department (Aabhas Srivastava) and the fourth question still remains to be investigated.

RESULTS

The measurements were performed in the ST-15 supersonic wind tunnel of the TU Delft at a Mach number of 2.0 and a freestream velocity of U_∞ = 524m/s. The oblique shock wave is created by a 12° wedge spanning the entire test section (see Fig.5). Two cameras were used for the measurements; one was focused on the shock wave-boundary layer interaction and the other on the flow between the micro-ramp and the interaction. The tunnel wall boundary layer is approximately δ = 5.2mm thick and micro-ramp heights of 2, 3 and 4mm were tested.

In Fig.6, the data from both cameras was stitched together to create the average flow field from micro-ramp to interaction. For the particular case presented, a micro-ramp height of 3 mm was used and measurements were performed in the symmetry plane of the ramp. The region close to the micro-ramp is blanked, because laser reflections were too strong to allow for an accurate measurement of the seeding particles. Behind the ramp, a wake can be distinguished which lifts off the surface and weakens when moving downstream. Around x = –20 mm, the wake interacts with the shock system, and a low-velocity pocket is formed. Also clearly visible is the low-speed bubble that is formed at the wall and which is the result of the strong adverse pressure gradient imposed by the shock system. On average there is no separation taking place for this particular configuration, however, instantaneously there can still be separated regions.

The unsteady behaviour of the low-speed bubble is presented in Fig.7, which shows three instantaneous snapshots of the flow in the interaction region. The solid black line presents the zero-velocity isoline. For Fig.7 (a) no reversed flow is detected, for 7(b) a small pocket of 6 mm^2 is present and for 7(c), a large pocket of 44mm^2 is measured. Given the unsteady nature of the interaction, it makes sense to talk about the separation probability P_{sep} of the flow, which is defined as the probability that a certain point (x,y) shows reversed flow. For example, when P_{sep}(x,y) equals 50%, then half of the time the flow is reversed and the other half of the time the flow it is attached at the location (x,y).

Fig.8 compares the separation probability with (a) and without a micro-ramp (b). Without a micro-ramp, flow reversal is observed in a region spanning the entire field of view, which is approximately 9δ. By placing a 4 mm micro-ramp 17.3δ upstream of the interaction, this is reduced to 5.5δ. The probability of encountering reversed flow is also reduced. Without a micro-ramp, there are regions close to the wall that shows flow reversal 75% of the time. With a micro-ramp, this peak value has been reduced to 41%. The smaller separation bubble also translates into a reduction of the reflected shock unsteadiness by ~50%.

These measurements highlight the great potential that micro-ramp vortex generators can have as flow control devices for shock wave-boundary layer interactions. However, as mentioned before, there are still a number of steps to take before these ramps can find their way into the engine of a jet fighter. Up to this point, only planar PIV measurements have been performed on the interaction region. The flow structures introduced by the ramp are, however, inherently three-dimensional and the same holds for the separation bubble. In the near future, tomographic PIV measurements will be carried out on the interaction region, which will deliver the velocity field inside an entire volume instead of just a plane. In case you are interested / would like to be involved with these measurements, please contact one of the authors of this article.

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