Investigation of Görtler vortices in a hypersonic double compression ramp flow by means of infrared thermography

by F.F.J Schrijer*

*Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS, Delft, The Netherlands, f.f.j.schrijer@tudelft.nl

Abstract

An experimental investigation is performed on the occurrence of Görtler vortices in a hypersonic flow by means of infrared thermography. A double compression ramp model with varying second ramp angle is tested at Mach 7.5 in a hypersonic Ludwieg tube. Due to the concave curvature of the streamlines in the separated region, a centrifugal instability exists that is responsible for generating stream-wise vortices. In the investigation vortices are generated with varying span-wise wavelengths by means of a comb-shaped element near the nose of the model. Using infrared thermography the amplification of these vortices is measured so that a critical wavelength and Görtler number can be identified. It is found that the vortex growth rate is the highest for the largest second ramp angle. Furthermore it is found that the growth rate decreases with increasing Görtler number.

1. Introduction

In the design of next generation hypersonic vehicles, the occurrence of shock wave boundary layer interaction over control surfaces plays an important role due to its high associated heat loads and pressure fluctuations in the flow reattachment region. For this reason the subject has been investigated extensively in literature. Over the past few years, the Mach 7.5 flow over a double compression ramp has been studied at the aerodynamics group at TUDelft using schlieren, particle image velocimetry and infrared thermography [9]. It was found that the interaction was transitional (laminar at separation and turbulent at reattachment) and inside the separated region the flow was highly three dimensional [8]. Furthermore three dimensional measurements by means of stereo-PIV and infrared thermography showed the presence of stream-wise streaks in the separated shear layer indicating the presence of Görtler vortices which increases the surface heat flux even more, see Figure 1. In this paper the effect of the Reynolds number and second ramp angle on the occurrence of Görtler vortices is investigated. In the experiments initial disturbances are generated which are in turn amplified by the Görtler mechanism. Disturbances are created with different spatial wavelengths (in span-wise direction) to investigate the dependence on the amplification rate.

![Fig. 1. Heat flux distribution over a double compression ramp at Mach 7.5](image1)

![Fig. 2. Schematic of Görtler vortices in a boundary layer over a concave wall [saric]](image2)
Boundary layers that develop over a wall having a concave curvature are subject to centrifugal instability that results in the formation of counter-rotating streamwise vortices. This instability was first studied by Görtler and the vortices are known as Görtler vortices. Upon investigation of the instability phenomenon using normal mode analysis, an eigenvalue problem results [5]:

\[ F(G, \beta, \sigma) = 0 \]

Here the three parameters are: the Görtler number \( G \), a non-dimensional wave number \( \beta \) and the amplification rate \( \sigma \).

The Görtler number defined as:

\[ G_\delta = \frac{Re_\delta}{\delta} \frac{\delta}{R}^{1/2}, \]

where \( R \) is the radius of curvature, \( \delta \) is boundary layer thickness and \( Re \) is the local Reynolds number. The Görtler number is a measure for the influence of the centrifugal effects. The second parameter is the non-dimensional wave number \( \beta \), which is defined as:

\[ \beta = \frac{2\pi \delta}{\lambda}, \]

where \( \lambda \) is the spacing between two adjacent vortices, see Figure 2. The last parameter is the amplification rate \( \sigma \), which determines the vortices are stable \( \sigma < 0 \) or unstable \( \sigma > 0 \). Generally, these parameters are plotted so that \( G = f(\sigma, \beta) \).

However since \( \beta \) depends on the boundary layer thickness, it varies in downstream direction which makes the analysis more difficult. Therefore the wavelength parameter is introduced, which is a constant and is defined in a similar way as the Görtler number:

\[ \Lambda = \frac{Re_\lambda}{\lambda} \frac{\lambda}{R}^{1/2} \]

In the current experiments a row of vortices is generated using a comb-shaped roughness element near the leading edge of a double compression ramp wind tunnel model. These vortices then travel inside the boundary layer that separates due to the presence of the second compression ramp. Upon separation the boundary layer streamlines become concave and the vortices will be subject to the centrifugal instability. Depending on the vortex pitch (\( \beta \) or \( \Lambda \)), the vortices will either be amplified or damped out. The amplification or growth rate is then given as the ratio of heat flux fluctuations in spanwise direction at separation compared to the fluctuations at reattachment:

\[ \sigma = \frac{\Delta q_{\text{reattachment}}}{\Delta q_{\text{separation}}}. \]

2. Experimental apparatus

The experiments are performed in a hypersonic Ludwieg tube that operates at a free stream Mach number of 7.5 [7]. The wind tunnel test section has a diameter of 30 cm and the flow duration is approximately 100 ms. The free stream unit Reynolds number is varied between \( 5 \times 10^6 \) and \( 11 \times 10^6 \) m\(^{-1} \) by changing the free stream total pressure between \( P_t = 14 \) and 28 bar. The total free stream temperature is constant and equal to \( T_t = 579 \) K.

![Fig. 3. Wind tunnel model (left) and comb-shaped element (right)](image-url)
The wind tunnel model used in the experiments is a planar double compression ramp. The first ramp has a fixed 15° angle with respect to the free stream. The second ramp angle can be varied from 30° to 45° with respect to the free stream, see Figure 3-left. The model is manufactured from Makrolon, which has favourable thermal properties (low conductivity). To maximize the emissivity, the model was painted so that an emissivity of \( \varepsilon = 0.9 \) was achieved.

To generate the initial disturbance for the Görtler vortices, a comb-shaped element was placed at 25 mm downstream from the leading edge (see the metal strip in Figure 3-right). Three elements were used having different distances between the teeth of the comb (\( \lambda = 2, 3 \) or \( 5 \) mm), the height of the teeth was 1 mm.

The thermographic measurements were performed using a CEDIP Titanium 530L infrared camera, which has a 320 × 256 pixel Mercury Cadmium Telluride sensor and operates in a wavelength band between 7.7 and 9.5 μm. The measurement accuracy is ±1 K and the sensitivity is 25 mK. For the current application the acquisition frame rate was set to 218 Hz which results into approximately 20 thermograms per wind tunnel run. The sensor integration time was set to 340 μs or 17 μs depending on the expected temperature increase during the measurement. The spatial resolution of the thermograms is approximately 0.5 mm/pixel. Optical access is provided by a Germanium window, which has a transmissivity of approximately 0.8.

3. Data reduction

The heat flux is computed from the temperature signal using the Cook and Feldermann method [3]. The computed heat flux signal is then averaged for the time duration when constant flow properties are achieved in the wind tunnel. Finally the averaged values are used in the flow analysis.

For the computation of the Görtler number, wavelength parameter and amplification rate a number of input parameters are required. The first is the boundary layer thickness \( \delta \), which is obtained from Blasius theory including the reference temperature concept [1] for the compressibility correction:

\[
\delta = \frac{x}{\sqrt{Re_x}}.
\]

In the current experiments the boundary layer thickness is approximately \( \delta = 1 \) mm. Furthermore the radius of curvature of the flow in the separated shear layer is needed. This is obtained using the same approach as used in [5], see Figure 4. At the reattachment point a circle is defined that is tangent to the first and second ramp. In general the tangency point with respect to the first ramp is further downstream than the separation point.

The amplification factor is defined as the ratio of the heat transfer fluctuations at separation with respect to the fluctuations measured at reattachment. Before the amplitude of the fluctuations is computed, a high-pass filter is used in the form of a fourth order polynomial that is fitted to the measured heat flux values, see Figure 5. This enables to separated the heat flux variations due to Görtler vortices from the global variation due to the three-dimensional velocity field.
4. Results

Figure 6-left shows a schlieren image of the flow over the $15^\circ$-30$^\circ$ model, the shock interaction over the model shows a typical Edney type VI interaction. For the $15^\circ$-45$^\circ$ model (Figure 6-right), the second ramp angle is larger than the maximum deflection angle for a Mach 7.5 flow. In this case the shock interaction is somewhat more complicated and can be identified as an Edney type V interaction. For a more complete flow field discussion, the reader is referred to [9].

![Flow over the 15°-30° (left) and the 15°-45° (right) model by PIV (top), schlieren (center) and QIRT (bottom)](image)

**Fig. 6.** Flow over the $15^\circ$-30$^\circ$ (left) and the $15^\circ$-45$^\circ$ (right) model by PIV (top), schlieren (center) and QIRT (bottom).

Figure 6 also shows the corresponding heat flux graphs as measured at the centerline of the model. For the $15^\circ$-30$^\circ$ model, first a laminar boundary layer development is observed where the heat flux decreases in downstream direction. Then, at $x = -30 \text{ mm}$, a sudden decrease is measured which is typical for boundary layer separation caused by the increase in pressure due to the second ramp. Further downstream, a peak in heat transfer is measured that is caused by the boundary layer that reattaches on the second ramp. Downstream of the peak, the heat transfer decreases again due to boundary layer development. In case of the $15^\circ$-45$^\circ$ model the same features are visible, however on the second ramp the heat transfer profile is different. Here two peaks in heat transfer are observed, the first is due to the boundary layer reattachment while the second is caused by the impingement of the shock that emanates from the Edney type V shock interaction.
Fig. 7. Typical heat flux map for 15°-45° model including \( \lambda = 2 \text{ mm} \) element

In Figure 7 a typical heat flux map is shown for the 15°-45° model with the 2 mm wavelength elements. Comparing this map to the heat flux profile for the clean model, it can be seen that the overall flow features such as the double peak at reattachment are unaltered. However the effect of the comb-shaped element on the flow field is clearly visible in the form of span-wise oscillations in the heat flux. Directly downstream of the element (\( y \approx 50 \text{ mm} \) in Figure 7) the oscillations are clearly visible however further downstream the effect decreases. This is due to the increase in boundary layer thickness when moving downstream and the fact that the vortices are mainly located in the upper part of the boundary layer. The effect of the element can also be observed from the schlieren image, see Figure 8. From the visualization it can be seen that the element only has a limited effect on the flow field (only weak waves are generated by the element) and the overall features are similar to those observed for the clean model.

Fig. 8. Schlieren image of the flow over the 15°-45° model including the \( \lambda = 2 \text{ mm} \) element

In Figure 9, the results are presented in a Görtler number versus wavelength diagram for the 15°-30° model and Figure 10 shows the diagram for the 15°-45° model. It can be seen that the amplification rates decrease with increasing Görtler number. And for sufficiently high Görtler numbers even a plateau is reached. This is opposite to the trend found in [5] and [6], although those experiments reported considerably lower Görtler numbers. A possible explanation for the decrease in the growth rate can be found in the fact that an increase in Görtler number also means an increase in Reynolds number. For the higher Reynolds numbers the vortices are broken-up more easily and therefore lower fluctuations are measured. Furthermore it can be seen that the growth rates measured for the 15°-45° model are considerably larger than for the 15°-30°
model. For example at $G_\delta \approx 190$, the growth rates are around 1 to 2 for the 15°-30° model and around 3 to 4 for the 15°-45° model.

Finally in Figures 11 and 12, the diagrams for the Görtler number versus wavelength parameter are given for both models. The labels in the diagram indicate the growth rate. Lines for constant $\lambda$ are straight with a slope of 3/2. Opposite to the trend observed for the Görtler number, the growth ratio seems increase with the wavelength parameter, although the trend is not so clear. Furthermore it can be clearly observed that the current measurements are performed for relatively high wavelength parameters and that, in order to find the maximum amplification wavelength, should be decreased further.

5. Conclusions

The occurrence of Görtler vortices on a double compression ramp in a Mach 7.5 hypersonic flow is investigated by means of infrared thermography. The results are presented in the form of scaling parameters that are obtained from normal mode analysis. In the experiments comb-shaped elements are used to generate vortices near the leading edge of the model that are either amplified or damped by the instability mechanism responsible for the generation of Görtler vortices. The spanwise wavelength of the vortices is varied by using different elements. The growth rate of the vortices is inferred from the heat transfer measurements. From the experiments it can be shown using schlieren visualization and IR thermography that the comb-shaped element, apart from generating the vortices, only has a local influence on the flow field and that the overall flow features are not affected.

Comparing the results for the 15°-30° model to the 15°-45° model it is found that the growth rate is larger for the latter. Furthermore for both models the growth rate of the vortices decreases with the Görtler number and increases with the wavelength pattern. However in the latter case the trends is less obvious. The current results show the opposite trend to that observed in literature. An explanation for this can found in the fact that the Görtler numbers in the current experiments were considerably larger than those in literature. An increase in Görtler number also means an increase in Reynolds number and apparently the Reynolds number becomes so high that the vortices diffuse hence decreasing the growth rate.
REFERENCES