Experimental investigations of transition between regular and Mach reflection in ITAM wind tunnels initiated by M.S. Ivanov

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Introduction

- It is well known that two different configurations, the regular (RR) and Mach one (MR), can be observed when a steady shock wave reflects from a surface.

Schematic of steady regular (RR) and Mach (MR) reflections

Transition criteria

- For strong shock waves there exists a range of angles of incidence $\alpha_N < \alpha < \alpha_D$ (dual solution domain) where both reflection types are theoretically possible. Here $\alpha_N$ and $\alpha_D$ are the angles deduced from so called von Neumann and detachment criteria, respectively. MR is impossible below $\alpha_N (M)$. RR is impossible above $\alpha_D (M)$.

It can be expected that the angles of transition from RR to MR, $\alpha_{tr}^F$ and of the reverse transition, $\alpha_{tr}^B$ can differ, namely $\alpha_{tr}^F = \alpha_D, \alpha_{tr}^B = \alpha_N$. However, in experiments of Hornung & Robinson (1982) it was found that $\alpha_{tr}^F \approx \alpha_{tr}^B \approx \alpha_N$.

- Which criterion is correct?
Historical Background and Motivation

- **1943** – von Neumann analytically considers shock wave reflect phenomena introduce two possible criteria of transition between regular and Mach reflection – detachment and mechanical equilibrium ones.

- **1975** – Experimental results of Henderson and Lozzi give some evidence that von Neumann criteria is correct for transition in steady flows.

- **1979** - Hornung, Oertel and Sandeman predict the hysteresis phenomenon should exist in steady reflection, i.e. at continuous increasing and decreasing the angle, the forward and back transition must occur in accordance with different criteria.

- **1982** - Experiments of Hornung and Robinson in the blowdown wind tunnel S3 (Australia) do not confirm the existence of hysteresis. Both forward and back transition are observed near von Neumann angle.

- **1995-1996** - The hysteresis at steady reflection of shock wave was found in both DSMC (Ivanov, Gimelshein and Beylich) and Euler (Ivanov, Zeitoun, et al.) computations. It was also observed in experiments (Chpoun, Passerel and Ben-Dor). Numerical simulations are in agreement with Hornung’s prediction. In experiments the transition angle from regular to Mach reflection is different.
• In experiments of Hornung & Robinson both forward \( RR \rightarrow MR \) and reverse \( MR \rightarrow RR \) transitions took place near \( \alpha_N \), which was explained by possible instability of the RR to free-stream disturbances in the range \( \alpha_N < \alpha < \alpha_D \).

• Chpoun et al. (1995) observed some hysteresis in experiments performed in an open jet wind tunnel, but these results differ from theoretical predictions. In their experiments, Chpoun et al. were forced to use wedges of a small aspect ratio, which caused some doubts whether the results indeed confirm Hornung’s predictions or they were caused by 3D effects.

• Ivanov et al. (1998) showed both numerically and experimentally that the influence of 3D effects on hysteresis is negligible for spanwise aspect ratios greater than two.

• It means that the most acceptable explanation for the disagreement between theoretical or numerical and experimental results are influence of free-stream disturbances.
Thanks to availability of different wind tunnels at ITAM SB RAS, we had a possibility of conducting experiments in wind tunnels with different levels of freestream disturbances and compare the results obtained.

The experiments were performed in three ITAM wind tunnels.

<table>
<thead>
<tr>
<th>№</th>
<th>Wind tunnels</th>
<th>S3 Australia</th>
<th>T-313 Russia</th>
<th>T-326 Russia</th>
<th>T-325 Russia</th>
<th>NAL Japan</th>
<th>SH2 France</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Type</td>
<td>blowdown</td>
<td>blowdown</td>
<td>free-jet</td>
<td>blowdown low-noise</td>
<td>blowdown</td>
<td>free-jet</td>
</tr>
<tr>
<td>2</td>
<td>Size of test section</td>
<td>152×178</td>
<td>600×600</td>
<td>200</td>
<td>200×200</td>
<td>1000×1000</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>Span of wedges, b</td>
<td>102</td>
<td>300</td>
<td>100</td>
<td>100</td>
<td>330</td>
<td>60</td>
</tr>
<tr>
<td>4</td>
<td>Length of wedges, w</td>
<td>50</td>
<td>80</td>
<td>40</td>
<td>30</td>
<td>130</td>
<td>60</td>
</tr>
<tr>
<td>5</td>
<td>Span/chord ratios b/w</td>
<td>2.04</td>
<td>3.75÷0.66</td>
<td>2.5÷0.6</td>
<td>3.37</td>
<td>2.53</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>Mass fluctuation £ %</td>
<td>1.0</td>
<td>0.5</td>
<td>&lt;0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The results obtained in different wind tunnels allowed us to obtain extensive information about the influence of the free-stream quality on the RR-MR-RR transitions.
Supersonic blowdown wind tunnel T-313

Test section 600x600 mm and Mach number range from 1.5 to 7.0; the integral level of mass-flow fluctuations is about 1%.

The experiment RR- MR transition in this wind tunnel was performed at $M_{\infty} = 4$ and 5;
The Model in T-313 test Section

For investigation of 3D effects we used wedges of different span/chord ratios $b/w = 0.66, 1, 2, 3.75$

Wedge chord $w = 80$ mm.

Wedge span $b=300$ mm

This wind tunnel can be considered as a facility rather similar to S3 (test section size $152 \times 178$ mm), which used in experiment by Hornung & Robinson, but it has a considerably larger size.
Schlieren Photographs of RR and MR

Flow parameters

\( M_\infty = 5 \)
\( g/w = 0.3 \)
\( b/w = 3.75 \)
\( \alpha_N = 30.8^\circ, \quad \alpha_D = 39.3^\circ \)

Continuous variation of the angle of attack in T-313 with span/chord ratios b/w=3.75
Comparison of experimental and numerical schlieren RR. (density gradient integrated along transverse axis)

\[ M_\infty = 4, \quad \alpha = 39.7^\circ, \quad b/w = 0.66, \quad g/w = 0.3 \]
$M_\infty = 4$, $\alpha = 40^\circ$, $b/w = 2$, $g/w = 0.3$
Visualization system

In our experiments at T - 313 wind tunnel we used a modified laser sheet technique with the laser sheet plane oriented along direction of the flow. This allows us to obtain flow slices at different position along the transverse axis.
3D Regular reflection

Flow parameters

\[ M_\infty = 4 \]
\[ b/w = 0.66 \]
\[ g/w = 0.15 \]
\[ \alpha = 35^\circ \]
3D Mach reflection

Flow parameters

\[ M_\infty = 4 \]
\[ b/w = 3.75 \]
\[ g/w = 0.3 \]
\[ \alpha = 37^\circ \]
Comparison of experimental and numerical results for Mach stem height

\[ M_\infty = 4, \ b/w = 3.75, \ g/w = 0.56 \]

\[ M_\infty = 4, \ b/w = 2, \ g/w = 0.3 \]
Mach stem height variation in spanwise direction

- Mach stem height distribution along transverse coordinate was measured from flow images taken at different positions and compared with the results of our Euler simulations

\[ M_\infty = 4, \; b/w = 3.75, \; g/w = 0.3, \; \alpha = 37^\circ \]
Combined MR-RR-MR reflection

Flow parameters

\[ M_\infty = 4 \]
\[ b/w = 3.75 \]
\[ g/w = 0.3 \]
\[ \alpha = 35.5^\circ \]
It is shown that 3D effects do not influence the transitions for the wedges of large enough span.

In our experiments at T-313 wind tunnel both RR→MR and MR→RR transitions occur at the small range of angles near α_N in the dual solution domain.

The existence of spontaneous transitions from RR to MR and back supports the idea that some free-stream disturbances have significant effects on RR→MR transition.

In order to analyze possible influence of flow disturbances we conducted a series of experiments in another ITAM facility, namely wind tunnel T-326.
The experiment RR - MR transition in this wind tunnel was performed at $M_\infty = 6$ and stagnation temperature $T_0 = 420\text{K}$. 

Free-jet wind tunnel T-326 with a 200 mm nozzle-exit diameter and Mach number range from 6 to 15; the integral level of mass-flow fluctuations is about 0.5%.
Hysteresis during RR-MR-RR transition in T-326 wind tunnel

$M = 6, \alpha_N = 29.0^\circ, \alpha_D = 39.5^\circ$

The sequence of images during continuous variation of the angle $\alpha$. 
● This experiments confirmed the existence of a hysteresis loop in transition between steady regular and Mach reflection of strong shock waves in a supersonic flow.

● This phenomenon, hypothesized by Hans Hornung as early as 1979, was first observed in numerical simulations performed in 1995, but it had not been entirely reproduced in wind tunnels.

● The main difficulty was the influence of the wind tunnel “noise,” free-stream disturbances that promoted earlier transition to Mach reflection in the range of flow parameters, where possible (the dual solution domain).
Ivanov M.S. at al used a special low-noise wind tunnel with a low level of free-stream disturbances to perform experiments in conditions close to free flight.

Experimental model in the T-325 test section.

- Model sizes:
  - $w = 30$ mm
  - $b/w = 3.37$
  - $g/w = 0.43$
  - blockage area $< 15\%$

$M_\infty = 4.$
Low-noise wind tunnel T-325 of ITAM

Low-noise wind tunnel T-325 has a closed test section of 200x200 mm size. Integral level of mass flow fluctuations < 0.2%. Experiments were performed at free-stream Mach number $M_\infty = 4$. 

*Mass flow fluctuations spectrum*
Transition from RR to MR in T-325
Hysteresis during RR-MR transition in T-325 wind tunnel at $M_\infty = 4$, $\alpha_D = 39.2$, $\alpha_N = 33.4$

The sequence of images during increase and decrease of the angle of attack
Hysteresis during RR-MR transition in T-325 wind tunnel at \( M_\infty = 4, \alpha_D = 39.2, \alpha_N = 33.4. \)

Mach stem height vs incident shock angle: open symbols - \( \alpha_{tr}^F \), black symbols - reverse transition, \( \alpha_{tr}^B \).
CONCLUSIONS

- In these experiments both RR and MR reflections were observed everywhere in the dual solution domain.

- Experiments performed in the low-noise ITAM wind tunnel T-325 confirmed the existence of a hysteresis loop in transition between steady regular and Mach reflection of strong shock waves in a supersonic flow in accordance with theoretical predictions with good repeatability of results.

- The existence of two steady shock wave reflections at the same flow parameters has apparent practical meanings in designing hypersonic inlets, and in other aerospace applications.
THANK YOU FOR ATTENTION