TRAINING CENTER FOR EXPERIMENTAL AERODYNAMICS

TECHNICAL NOTE 3

LAMINAR SEPARATION IN SUPersonic FLOW
WITH EMPHASIS ON
THREE-DIMENSIONAL PERTURBATIONS AT REATTACHMENT

By Jean J. Ginoux

Rhode-Saint-Genèse, Belgium.
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FOREWORD

The author would like to thank the European Office of ARDC for the sponsorship of this work and also to record his thanks to CNERA, without whose support this programme of research would not have been started and from which the author has received every possible help and encouragement.
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LAMINAR SEPARATION IN SUPersonic FLOW
WITH EMPHASIS ON
THREE-DIMENSIONAL PERTURBATIONS AT REATTACHMENT

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Jean J. Ginoux

ABSTRACT

It was shown that regular and repeatable span-wise
flow perturbations existed in the reattachment region of a
laminar supersonic boundary-layer on a two-dimensional back­
ward-facing step model. It was found that the model span and
leading-edge thickness, when below 0.1 mm, had no effect on the
wave-length of the flow perturbations.

On backward facing-steps, at a Mach number of 2.16,
the ratio of wave-length of the flow perturbations to boundary­
layer thickness was a function of the ratio of step-height to
boundary-layer thickness.

Similar perturbations were found at the reattachment
region of a laminar boundary-layer on forward-facing steps, on
compression-corners, on rectangular cavities and in the case
of interaction between a shock-wave and the boundary-layer.
They were also detected in unseparated boundary-layers.

The presence of three-dimensional perturbations seems
to be related to the general question of boundary-layer stability.
INTRODUCTION

In the course of a research programme undertaken at TCEA on laminar separated supersonic flow, the author found that three-dimensional perturbations existed in the reattachment region of the flow around a backward-facing step model that completely spanned the tunnel. It was shown that possible irregularities in the air-flow upstream of the model or in the model itself could not explain the existence of strong, regular and repeatable span-wise perturbations in the boundary-layer (3).

In a continuation of the work, a detailed investigation was made on backward-facing steps; the influence of step-height and boundary-layer thickness on the wave-length of the flow perturbations was examined. Other types of supersonic separated flows were also investigated with emphasis on the presence of span-wise flow perturbations.

DESCRIPTION OF THE EQUIPMENT

Wind-tunnels

The bulk of the work was made in the TCEA 40 x 40 cm² (16" x 16") supersonic wind-tunnel (tunnel S-1) at a Mach number of 2.16 (3). Measurements were also made for comparison in a 15 x 15 mm² (0.6" x 0.6") supersonic wind-tunnel at the same Mach number. Tunnel S-2 was continuously operated with dry-air using the vacuum pump of tunnel S-1 and its auxiliary dryer. The nozzle was asymmetric; only one block was contoured,
the other one being flat. The stagnation pressure was slightly below the atmospheric pressure.

Model configurations

The geometry, dimensions and designations of the various models that were used in tunnel S-1 are given in figure 1. Most of the models were formed by assembling together a certain number of interchangeable pieces. The leading-edge thickness was equal to 0.1 mm (0.004 inch) with the exception of model S-6 which was 0.02 mm thick. Models completely spanned the 40 cm test section, except CC-1, CC-2, S-6 and S-7 models having a 150 mm span and S-8 model having a 250 mm span. The models were mounted on a double support allowing for the adjustment of the angle of attack. Figure 2a shows model S-1 in the test section of tunnel S-1.

In tunnel S-2, backward-facing steps were directly machined in the flat wall of the nozzle as shown in figure 2b.

Test techniques

Transition from laminar to turbulent flow was detected on shadowgraphs and schlieren pictures, taken with a conventional optical system, using parabolic mirrors and a spark light source.

The flow on the surface of the models was qualitatively observed by the use of a sublimation technique. The indicator was chosen as azobenzene (3), which had a slow response, to allow for rather long starting and stopping times of the wind-tunnel. An indication of the surface-flow pattern was
generally obtained (depending upon the thickness of the azo-benzene layer) after 3 to 9-hours running time of the tunnel.

Detailed surveys were made with a total-head probe using the device described in reference 3. A good agreement was found (3) between the results of the sublimation and the surveying techniques. In the early tests, the probe was manually operated. Later, the probe was moved at a constant and low speed using an electric motor while the pressure was measured on a Brown recorder. The repeatability of the measurements was good as shown in figure 5 for model CC-1 at \( \alpha = 0 \) and \( x_c = 20 \) mm; two successive surveys were made for the same stagnation conditions (\( p_0 = 200 \) mm Hg abs.) and two others at \( p_0 = 146 \) and 116 mm Hg.

**EFFECT OF MODEL SPAN**

Tests were made on three models (S-5, S-8 and S-7) having the same cross-section (\( h = 4 \) mm and \( L = 56 \) mm) and a span respectively equal to 400 mm, 250 mm and 150 mm. There were no end-plates at the models. The leading-edge thickness was equal to \( \varepsilon = 0.1 \pm 0.02 \) mm.

The sublimation technique was used to get the surface-flow pattern; this is shown in figures 3i, 3q and 3u. Figure 8 shows the results of total-head transverse surveys made downstream of reattachment. \( \Delta p \) is the difference (in mm of water) in the readings of the fixed and the moving probes. The wavelength (\( \Lambda \)) is the distance between successive pressure peaks; it varied for each model in the range indicated.
in figure 8. Also shown is a mean wave-length defined as the ratio of a certain distance \((\Delta y)\) by the number of pressure peaks measured along \(\Delta y\).

Figure 8 shows that, within the accuracy of measurement, there was no span effect on the wave-length of the flow perturbations in the region of the model axis.

**EFFECT OF LEADING-EDGE THICKNESS**

The effect of the leading-edge thickness on the flow perturbations was examined by comparing the results of transverse surveys made on models S-6 and S-7. Both models had a 150 mm span.

Figures 3g and 3u show the surface-flow patterns that were given by the sublimation technique.

The results of total-head surveys made on these models are compared in figure 9. \(\lambda\) was found to be within 2 to 4 mm on model S-6 having a 0.02 mm leading-edge thickness and within 2.5 to 4 on model S-7 having a 0.1 mm leading-edge thickness.

The step-height was not the same for both models \((h = 3\ mm\ on\ S-6\ and\ h = 4\ mm\ on\ S-7)\); however, as shown below, this difference could not appreciably affect the wave-length of the flow perturbations.

It was concluded that \(\lambda\) was not affected when the leading-edge thickness was reduced from 0.1 mm to 0.02 mm.
Figure 10 gives the results of total-head surveys made on model S-1 when the leading-edge thickness was increased from 0.1 mm to 0.3 mm. It shows that the mean wave-length increased from 6 mm to 12 mm, probably due to a thickening of the boundary-layer (see the effect of boundary-layer thickness in the following section).

EFFECT OF STEP HEIGHT AND BOUNDARY-LAYER THICKNESS

The effect of step-height (h) and boundary-layer thickness (δ) on the wave-length (λ) of the flow perturbations has been investigated in tunnel S-1. The models are shown in figure 1. δ and λ were varied within the following ranges

\[0.1 < \delta < 3 \text{ mm}\]
\[0.3 < h < 21 \text{ mm}\]

where δ is the boundary-layer thickness at separation; it was computed assuming an adiabatic flat plate with zero leading-edge thickness. δ was varied by using different lengths (L) for the flat plate and by changing the tunnel stagnation pressure. The leading-edge angle of the models was kept below 10 degrees; in these circumstances, it was found difficult to get separation of very thin boundary-layers and still have an acceptable range of step-heights. The difficulty was overcome by using compression-corners located at a small distance behind the leading-edge of a flat plate; the models (CC-models) are shown in figure 1. By varying the angle of the compression-corner and its position on the flat plate, separation could be obtained very close to the leading-edge, thus giving small values of δ; an example is given by a schlieren picture in figure 4 h (model CC-1, α = 0, x₀ = 20 mm
$p_0 = 115 \text{ mm Hg}$. CC-models had a 150 mm span and were not fitted with end-plates.

A few tests were made for comparison at the same Mach number in tunnel S-2. Backward-facing steps were located in the flat nozzle-wall. The boundary-layer was laminar and its thickness at separation was equal to 0.6 mm; this value was measured by surveying the boundary-layer with a small circular total-head probe. An example of the surface flow pattern is given in figure 3v.

Shadowgraphs and schlieren pictures were taken of each flow to locate the position of transition; examples are shown in figure 4. The sublimation technique was used to obtain a qualitative picture of the flow on the surface of the various models; examples are given in figure 3.

For quantitative information, detailed surveys were made using a total-head probe which was moved across the model at a constant distance ($x$) from the step-base. Except in a few cases, a survey was made on each model for only one value of $x$; because it was found (see figure 6 related to model S-1) that $\lambda$ was the same as measured for various values of $x$. The same cylindrical probe was used for all the various flow conditions and models. It had an external diameter of 1 mm and an internal diameter of 0.5 mm; the probe was always moved in contact with the model surface.

The results of such surveys are given in figure 11, where $\Delta p$ is the difference (in millimetre of water) in the readings of the moving probe and of an identical fixed probe, located at the same distance ($x$) from the step-base.
Figure 11 shows that span-wise variations of $\Delta p$ existed in the region of reattachment where the pressure peaks and valleys were almost precisely equally spaced. The wavelength of the flow perturbations was measured on these diagrams. Not much attention was given on the recorded amplitudes of the pressure peaks because of their irregular form and because the same probe diameter was used, although $\delta$ was different in each case. The strongest peaks were found to exist on compression-corners (CC-models); $(\Delta p)_{s}$ of about 300 mm of water were measured.

On the other hand, for small values of $(h)$ on step models $(h = 0.8$ and $0.3$ mm), the total-head probe gave no indication of pressure variations (within the accuracy of measurement, i.e. a few mm of water) although a striation pattern was clearly indicated by the azobenzene (see for example figures 31 and 3n). In these cases, quantitative information, such as the wavelength of the perturbations, was taken directly from the pictures of the surface flow.

In all cases, the striation pattern existed up to the point where transition occurred (as determined from the shadowgraphs), with the exception of models S-18 and S-19 where the flow perturbations seemed to vanish well upstream of transition; this is shown in figures 3h and 3j, and in figures 4j and 4k. The sublimation technique gave no indication of a striation pattern in the turbulent region of the flow. However, surveys made with the probe in that region did show pressure variations over a certain distance downstream of transition. The results are shown in figure 6 for model S-1, the striation pattern being also indicated. Figure 4f gives a shadowgraph of the flow.
Table 1 summarizes the results obtained on the various
types of models. The distance between successive pressure
peaks ("wave-length") was not exactly constant on each model,
but varied within the range indicated. Values of $\delta$ were
computed from the distance $L$ (figure 1) and from the tunnel
stagnation pressure given in table 1 ($p_o$ in mm of mercury).

Except for compression-corner models (CC-models) for
which ($h$) could not be accurately defined, non-dimensional
quantities such as $\lambda/\delta$ and $h/\delta$ were introduced and plotted in
a diagram as shown in figure 7. A mean wave-length defined
as the ratio of a certain basic span-wise length divided by
the number of pressure peaks recorded along that length is
also indicated in the graph.

Figure 7 shows that a good correlation was obtained
between the experimental results by using these non-dimensional
quantities. $\lambda/\delta$ increased when $h/\delta$ was increased from zero to
about 3; then stayed constant for $h/\delta$ up to 8 and then increa­
sed again for higher values of $h/\delta$. Correspondingly, transi­
tion moved upstream when $h/\delta$ was increased; it reached the
point of reattachment for $h/\delta$ between 8 and 13.

$\lambda/\delta$ did not tend towards zero as $h/\delta$ approached zero.
This result was confirmed as a striation pattern was observed
incidentally on the flat surface of model S-17 upstream of the
step; the phenomenon is shown in figures 3c and 3d. There
was no indication of a boundary-layer separation in that
region of the flow; weak perturbations were present in the
wind-tunnel, one being created by a rubber joint which was not
correctly fastened to the model-side. $\lambda/\delta$ was found to be
within 1.2 to 1.4 in that case; these values are plotted on
the vertical axis of figure 7. Furthermore, three-dimensional
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perturbations were also observed in the boundary-layer on the contoured wall of tunnel S-2, this is shown in the last section of this report. The boundary-layer was unseparated \((h = 0)\) and \(\lambda\) was equal to 1 mm; the boundary-layer thickness was taken approximately as 0.5 mm giving thus \(\lambda/\delta\) of about 2.

It was found occasionally that very irregular, weak and localised striations existed on the model surface upstream of the step, although these were not clearly indicated. This is shown in figure 3 b of reference 3 (model S-1) and is also shown in figure 3r. It might be thus possible that three-dimensional perturbations existed initially in the laminar boundary-layer and as the flow separated and reattached, the perturbations corresponding to a given wave-length were amplified, the selected wave-length being related to the boundary-layer thickness. The perturbations then travelled for a certain distance, function of the ratio \(h/\delta\) before transition appeared.

**EFFECT OF STREAMLINE CURVATURE**

The effect of the streamline curvature, related to the positive pressure gradient that always existed at reattachment, is presently being investigated. Only a few tests have been made so far. The radius of curvature of the surface upon which reattachment occurred was variously chosen as 1000 mm and 250 mm as shown in figure 1 (SR-models) and by the shadowgraphs given in figures 4b and 4c.

The importance of the streamline curvature has been pointed out by Görtler in a theoretical investigation on
incompressible boundary-layers (4,5). However, three-dimensional perturbations have been detected experimentally at low speeds by Hama et al (6), and also by Klebanoff (7) that could not be attributed to streamline curvature. Moreover, the tests made on the SR-models showed that the flow perturbations still persisted when the boundary-layer was flowing along convex surfaces. The results from total-head surveys are given in figure 7 and examples of striation patterns obtained by the sublimation technique are shown in figures 3k and 3s.

SURVEYS WITH OTHER PROBES

A transverse survey was made in the reattachment region of one model with a total temperature probe which did not show any variation.

A survey was made on model CC-1, using a directional probe instead of the usual total-head probe. The probe was formed by assembling two cylindrical tubes (0.5 mm I.D. and 1 mm O.D.), soldered together; its nose had the shape of 90° wedge. The difference in the readings ($\Delta p$) of the two pressure holes was recorded as the probe was moved across the model. The result is shown in figure 12 and compared with the result given by the total-head probe. Essentially the same pressure variations were recorded and the wave-length was found to be the same.
RESULTS ON VARIOUS TYPES OF SEPARATED AND UNSEPARATED FLOWS

Various types of separated flows were examined in relation to the existence of span-wise perturbations in the boundary-layer. The tests were made in tunnel S-1.

A separated flow was obtained by interacting a laminar boundary-layer with two-dimensional oblique shock-waves. The shock strengths were so chosen that separation occurred with a laminar reattachment as shown in figure 4a. Figure 3b shows that a striation pattern existed downstream of reattachment.

The flow around an upstream-facing step (model DS-11) was also investigated. A 0.6 mm step height was used. Figure 4g is a schlieren picture of the flow around model DS-11. The result of a test made with the sublimation technique is given in figure 3m; it shows the existence of span-wise perturbations in the flow downstream of reattachment.

The reattachment of a laminar boundary-layer behind a rectangular cavity located in a flat plate was observed. The width (B) of the cavity was 20.6 mm and its depth (H) was 10 mm. The stagnation pressure was equal to 154 mm Hg. A shadowgraph of the flow is given in figure 4i; it shows that the flow was slightly unsteady as could be expected for that opening (B/H = 2.06) of the cavity. Figure 3t shows that a striation pattern existed upstream of transition; the picture, which was obtained after a running time of the tunnel of three hours, gives a wave-length ($\lambda$) of about 4 mm.
Finally, separated flow was studied on a body of revolution in which a "backward-facing step" was formed by a sudden decrease in the diameter (figure 1). Figure 3(0) shows the existence of essentially similar perturbations to those found in the earlier models.

A test was made in tunnel S-2, using the sublimation technique, to visualize the flow on the surface of the contoured nozzle-wall in the presence of a laminar boundary-layer. Figure 3(p) shows that three-dimensional perturbations existed in the boundary-layer upstream of transition. The wave-length was about 1 mm. The perturbations were located on the flat portion of the wall (i.e. downstream of its curved portion); there was no indication of separation in that region.

These tests seem to show that the existence of three-dimensional perturbations in a laminar boundary-layer is not restricted to a particular type of flow but is more fundamental.

CONCLUSIONS

1. Regular and repeatable span-wise flow perturbations exist in various types of separated and unseparated flows.

2. The presence of three-dimensional perturbations seems to be related to the general question of boundary-layer stability.

3. On backward-facing steps, at a given Mach number
the ratio of wave-length of the flow perturbations to boundary-layer thickness is a function of the ratio of step-height to boundary-layer thickness.

* * *

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6. F.R. HAMA, J.D. LONG and J.C. HEGARTY

7. P.S. KLEBANOFF and K.D. TIDSTROM
Single step (S-) models.

<table>
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<td>S - 17</td>
<td>1</td>
<td>25</td>
</tr>
</tbody>
</table>

Double step (DS-) models.

<table>
<thead>
<tr>
<th>Model</th>
<th>$h_{mm}$</th>
<th>$L_{mm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS - 1</td>
<td>4</td>
<td>120</td>
</tr>
<tr>
<td>DS - 2</td>
<td>4</td>
<td>120</td>
</tr>
<tr>
<td>DS - 3</td>
<td>2</td>
<td>225</td>
</tr>
<tr>
<td>DS - 4</td>
<td>2</td>
<td>225</td>
</tr>
<tr>
<td>DS - 5</td>
<td>7</td>
<td>120</td>
</tr>
<tr>
<td>DS - 6</td>
<td>7</td>
<td>225</td>
</tr>
<tr>
<td>DS - 7</td>
<td>0.41</td>
<td>120</td>
</tr>
<tr>
<td>DS - 8</td>
<td>0.82</td>
<td>120</td>
</tr>
<tr>
<td>DS - 9</td>
<td>0.3</td>
<td>225</td>
</tr>
<tr>
<td>DS - 10</td>
<td>0.82</td>
<td>225</td>
</tr>
</tbody>
</table>

SR-models.

<table>
<thead>
<tr>
<th>Model</th>
<th>$h_{mm}$</th>
<th>$L_{mm}$</th>
<th>$R_{mm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR - 1</td>
<td>10</td>
<td>225</td>
<td>1000</td>
</tr>
<tr>
<td>SR - 2</td>
<td>10</td>
<td>120</td>
<td>1000</td>
</tr>
<tr>
<td>SR - 3</td>
<td>4</td>
<td>225</td>
<td>250</td>
</tr>
<tr>
<td>SR - 4</td>
<td>4</td>
<td>120</td>
<td>250</td>
</tr>
</tbody>
</table>

CC-models.

<table>
<thead>
<tr>
<th>Model</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC - 1</td>
<td>14°</td>
</tr>
<tr>
<td>CC - 2</td>
<td>25°</td>
</tr>
</tbody>
</table>

Cone-cylinder

Figure 1. Model configurations and designations.
Figure 2. Tunnels S-1 and S-2
a) Model S-1: $p_0 = 220$
The width of each white band of the scale is 5 mm

b) Shock-wave B.L. interaction: $p_0 = 126$

c) Model S-17: $p_0 = 200$

d) Model S-17 - Details

Figure 3. Sublimation technique
e) Model CC-1 - $\alpha = 0 \ ; \ x_c = 10$
   $p_o = 198$

f) Model CC-2 - $\alpha = 0 \ ; \ x_c = 20$
   $p_o = 196$

g) Model S-6 ; $p_o = 201$

h) Model S-18 ; $p_o = 200$

i) Model S-5 ; $p_o = 209$

j) Model S-19 ; $p_o = 195$

Figure 3. Continued
k) Model SR-2: $p_o = 162$

l) Model DS-9: $p_o = 206$

m) Model DS-11: $p_o = 198$

n) Model DS-8: $p_o = 205$

o) Body of revolution: $p_o = 210$

p) Contoured wall of tunnel S-2: $p_o = 750$

Figure 3. Continued
q) Model S-8; $p_o = 209$

r) Model DS-7; $p_o = 194$

s) Model SR-3; $p_o = 208$

t) Cavity flow; $p_o = 154$

u) Model S-7; $p_o = 208$

v) Tunnel S-2; $h = 0.6 \text{ mm}; p_o = 750$

Figure 3. Concluded.
Figure 4. Shadowgraphs and schlieren pictures of separated flows
d) Model DS-1 \( p_o = 213 \)

e) Model DS-5 \( p_o = 191 \)

f) Model S-1 \( p_o = 209 \)

g) Model DS-11 \( p_o = 198 \)

h) Model CC-1, \( \alpha = 0, x_c = 20 \) \( p_o = 115 \)

Figure 4. Continued
i) Flow over a rectangular cavity; $p_o = 154$

j) Model S-18; $p_o = 200$

k) Model S-19; $p_o = 195$

Figure 4. Concluded
FIGURE 6. SUMMARY OF TRANSVERSE SURVEYS
\[ \frac{\lambda}{\delta} \]

**FIGURE 7.**

- \( \lambda \) wave length
- \( \delta \) B.L. thickness
- \( h \) step height
FIGURE 8 - Span effect on wave length ($p_o = 208 \pm 5$ mm Hg)
FIGURE 11 - Transverse distributions of the total-head on model surface
Figure 11 - Continued

**d)** Model DS-1

\[ P_0 = 225 \text{ mm Hg} \]
\[ x = 55 \text{ mm} \]

**e)** Model DS-2

\[ P_0 = 185 \text{ mm Hg} \]
\[ x = 75 \text{ mm} \]
FIGURE 11f - MODEL DS-3

$P_0 = 210.7$

$P_0 = 158$

$P_0 = 127$
MODEL CC2

\[ \Delta P \text{ mm H}_2\text{O} \]

\[ P_0 = 165 \]

\[ P_0 = 200 \]

\[ \Delta P \text{ mm H}_2\text{O} \]

\[ x = 8 \]

\[ x_0 = 20 \]

\[ \alpha = 0^\circ \]

FIGURE 11 l  MODEL CC2
\( \Delta P_{mm} H_2O \)

\( \alpha = 9^\circ \)

\( r_c = 20 \)

\( x = 18 \)

\( P_o = 197 \text{ mm Hg} \)
\[ \Delta p_{mm H_2O} \]

MODEL CG1 \( \alpha = 9^\circ \)

\( P_0 = 139 \text{ mm Hg} \)

\( \alpha = 9^\circ \)

\( x = 20 \)

\( c = 10 \)

FIGURE 11b. CONCLUDED
FIGURE 12 - transverse surveys with total-head and directional probes
L'auteur a montré par ailleurs que des perturbations régulièrement réparties en envergure et répétables existaient dans la région de recollement d'une couche-limite laminaire supersonique dans l'écoulement autour d'une marche descendante bi-dimensionnelle. L'étude a été poursuivie en montrant que l'envergure du modèle et l'épaisseur de son bord d'attaque (lorsqu'elle était inférieure à 0,1 mm) n'avaient pas d'influence sur la longueur d'onde des perturbations. (voir au verso)

---

It was shown that regular and repeatable span-wise flow perturbations existed in the reattachment region of a laminar supersonic boundary-layer on a two-dimensional backward-facing step model. It was found that the model span and leading-edge thickness, when below 0,1 mm, had no effect on the wave-length of the flow perturbations.

On backward-facing steps, at a Mach number of 2.16, the ratio of wave-length of the flow perturbations to boundary-layer... (over)
Une étude détaillée effectuée à $M = 2.16$ sur modèles avec marche a prouvé que le rapport de cette longueur d'onde à l'épaisseur de la couche-limite était fonction du rapport de la hauteur de la marche à cette même épaisseur.

Des perturbations analogues ont été mises en évidence dans la région de recollement d'une couche-limite laminaire dans les écoulements autour d'une marche ascendante, de coins de compression, de cavités rectangulaires et dans le cas d'interactions onde de choc couche-limite. Elles ont également été détectées en écoulement non séparé.

Ces perturbations semblent être liées au problème de la stabilité des couches-limites.


thickness was a function of the ratio of step-height to boundary-layer thickness.

Similar perturbations were found at the reattachment region of a laminar boundary-layer on forward-facing steps, on compression-corners, on rectangular cavities and in the case of interaction between a shock-wave and the boundary-layer. They were also detected in unseparated boundary-layers.

The presence of three-dimensional perturbations seems to be related to the general question of boundary-layer stability.

Copies available at T.C.E.A., Rhode-Saint-Genèse, Belgium.
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