

# LEADING-EDGE EFFECT ON SEPARATED SUPERSONIC FLOWS

JEAN J. GINOUX

University of Brussels and TCEA

## ABSTRACT

Tests were made on two-dimensional backward facing step models. They showed the existence of regular spanwise perturbations into the full thickness of the boundary layer at and after reattachment, both in the laminar and turbulent regions of the flow. It was found that the amplitude of these perturbations depended upon the accuracy of machining of the leading edge although their wavelength was independent. It was concluded that the phenomenon is essentially one of instability in the two-dimensional flow, the main triggering action arising from small irregularities in the leading edge.

## INTRODUCTION

In the course of a research program undertaken at the Training Center for Experimental Aerodynamics (T.C.E.A.) at Rhode-Saint-Genèse (Belgium) the author found that three-dimensional perturbations existed in the reattachment region of two-dimensional separated supersonic flows.<sup>1</sup> The periodical spanwise distribution of these perturbations could not be explained by irregularities either in the air-flow upstream of the models or in the models themselves. Three-dimensional perturbations were initially observed by the use of a sublimation technique and also by probe surveys in the flow over backward-facing step models and were later detected in various types of separated flows produced by shock-wave boundary-layer interactions, by cutouts in a flat surface and by upstream facing steps.<sup>1</sup> In all cases the boundary layer was laminar at separation. Surveys made on backward-facing step models with total-head probes moved in contact with the model surface showed that at Mach 2.2 the ratio of the wavelength  $\lambda$  of the flow perturbations to boundary-layer thickness  $\delta$  at separation was a function of the ratio of step height  $h$  to boundary-layer thickness. This is shown in Fig. 1 from Ref. (1).

In a continuation of the work, spanwise surveys were made at various heights in the boundary layer in the reattachment region of the flow as well as upstream

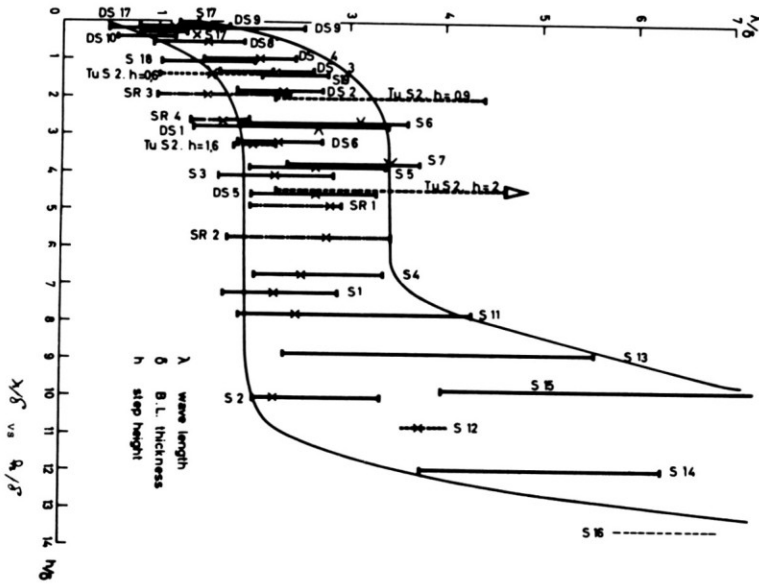


Fig. 1.

of the step, in the separated shear layer and in the transition region. More attention was given to the amplitude of the spanwise pressure variations. The study was completed by a detailed analysis of the influence of leading-edge irregularities on the intensity of the flow perturbations. The research reported in this document has been sponsored by the Air Force Office of Scientific Research, through the European Office, Aerospace Research, United States Air Force under contract AF 61 (052)-350.

### DESCRIPTION OF THE EQUIPMENT

The tests were made in the T.C.E.A. 16 × 16-in. continuous supersonic wind tunnel S-1 at a Mach number of about 2.2. Backward-facing step models were used, the dimensions of which are indicated in Table I, where  $L$  is the length of the flat plate upstream of the step,  $h$  the step height,  $\epsilon_m$  the mean thickness of the leading edge and  $\Delta\epsilon_{m,ax}$  the maximum variation of  $\epsilon_m$  along the span, measured with a microscope. A sting-support rig incorporated in the diffuser was used to allow for displacement of a total-head probe in three directions (normal to the model surface  $y$ , spanwise  $z$ , and streamwise  $x$ ; the origin of the axes is taken at the step base on the centerline of the model).

Table 1

Model	$L$ , mm	$h$ , mm	Span, $S$ , mm	$\epsilon_m$ , microns	$\Delta\epsilon_{\max}$ , microns
S-3	225	10	400	72	10
S-20-c-B	80	6	200	224	3
S-20-e-B	80	7	200	165	20
S-20-f-B	80	7	200	96	3

Transition from laminar to turbulent flow was detected on flow pictures. The flow on the surface of the models was qualitatively observed by the use of a sublimation technique. An indication of the surface-flow pattern was generally obtained after 3 to 6 hr running time of the tunnel.

### DETAILED SURVEY OF THE BOUNDARY-LAYER FLOW ON MODEL S-3

A detailed survey of the boundary-layer flow was made at a stagnation pressure of 170 mm of mercury absolute on model S-3 (Table I) which had a 10 mm step height and a flat plate length of 225 mm upstream of the step. The model completely spanned the working section of the wind tunnel. Transverse pitot-pressure profiles were recorded at different heights  $y$  in the boundary layer and at several distances  $x$  from the step base; only a portion of the span was surveyed (from  $z = 0$  to  $z = 60$  mm, except in the separated layer where  $0 < z < 40$  mm). A cylindrical probe was used having an inside diameter of 0.15 mm and an outside diameter of 0.25 mm.

The spanwise pressure variations are expressed as a fraction of pitot pressure measured on the centerline of the model ( $z = 0$ ) using the following relationship

$$\Delta\rho_P = \frac{\rho_P(xyz) - \rho_P(xy0)}{\rho_P(xy0)}$$

Typical results of spanwise surveys are shown in the graphs of Fig. 2; more detailed results are given in Ref. 2. The measurements made downstream of reattachment (i.e., for  $x$  larger than about 70 mm) indicate that the flow perturbations, previously detected in the vicinity of the model surface<sup>1</sup> extend into the full thickness of the boundary layer with a maximum variation of pitot pressure occurring slightly below mid-thickness (Fig. 2a), the perturbations in pressure vanishing as the outer edge of the boundary layer is reached. The fact that periodical transverse total-head variations were found at various heights in the boundary layer was an indication that the boundary-layer profile was periodically distorted along the span of the model. This was confirmed by direct measurement of this profile along the span (not shown here but reported in

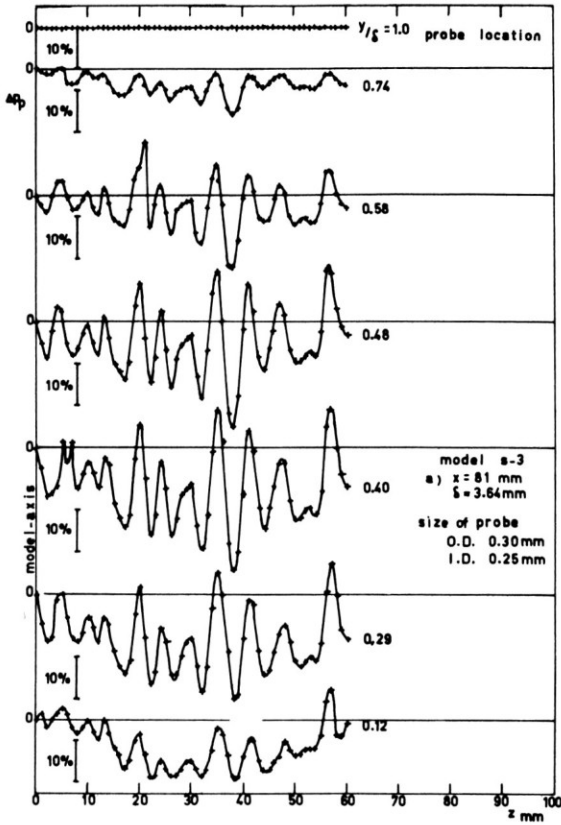


Fig. 2a.  $\Delta\rho_p$  vs.  $z$ .

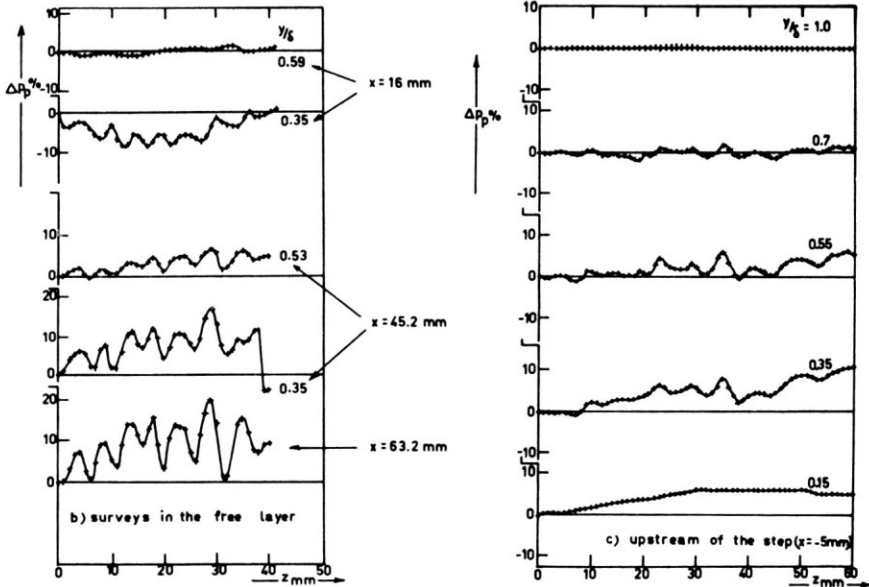


Fig. 2b. Continuation of Fig. 2a.

Ref. 2). It was also shown that spanwise periodic variations of the boundary-layer thickness existed.

Surveys were made in the separated boundary layer at  $x = 16$  mm,  $x = 45.2$  mm, and  $x = 53.2$  mm. The nose of the probe was bent in order to align it with the flow direction. The results shown in Fig. 2b indicate that the flow perturbations were mainly localized in the inner part of the shear layer (i.e., for  $y$  less than about  $\delta/2$ ).

Measurements made upstream of the step (i.e., for negative values of  $x$ ) also showed the existence of three-dimensional perturbations. An example is given in Fig. 2c. The variation of pitot pressure had its maximum value at about mid-thickness and vanished near the outer edge of the boundary layer. They also vanished near the model surface, which explains why they were never clearly detected in the early part of the research,<sup>1</sup> either by a probe which was moved in contact with the model surface or by the sublimation technique.

Figures 3a and 3b give a summary of the results. For each  $x$ , one value of  $y/\delta$  for which the amplitude of the pressure variations was maximum was selected. These values  $y/\delta$  are indicated in the upper part of the figure which represents a cross section of the model (plane  $x$ - $y$ ) and the corresponding spanwise pressure variations are shown in the lower part of the figure which gives  $\Delta\rho_p$  (in percent) as a function of  $z$ .

These figures show that three-dimensional perturbations existed upstream of separation ( $x < 0$ ) although they were rather weak; a maximum variation  $\Delta'P_p$  of about 6 percent was found between a pressure peak and its neighboring pressure valley. As the boundary layer separated and reattached, the perturbations were progressively amplified to reach a maximum amplitude in the transition region ( $\Delta'P_p = 44$  percent). They were then extending in the turbulent region of the flow, being slowly damped ( $\Delta'P_p = 8$  percent at  $x = 164$  mm). It will be noted that the perturbations were not indicated in that region by the sublimation technique.<sup>1</sup> A close observation of Fig. 3 shows that the  $z$ -position

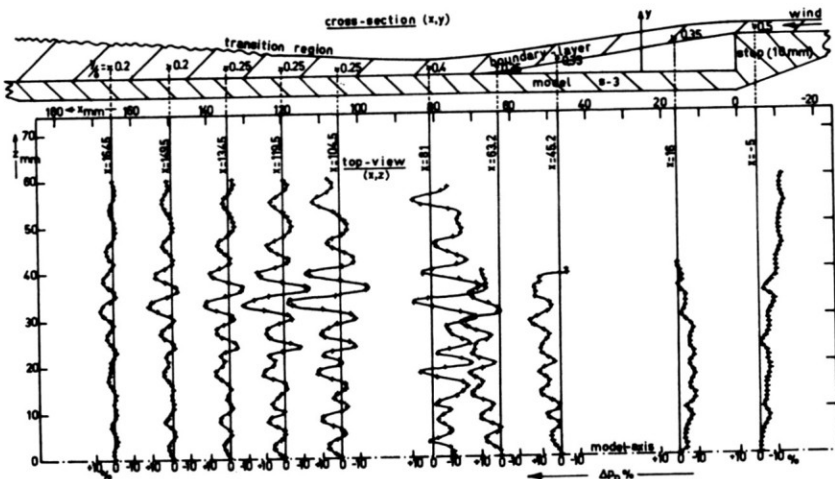


Fig. 3a. Measurements downstream of the step.

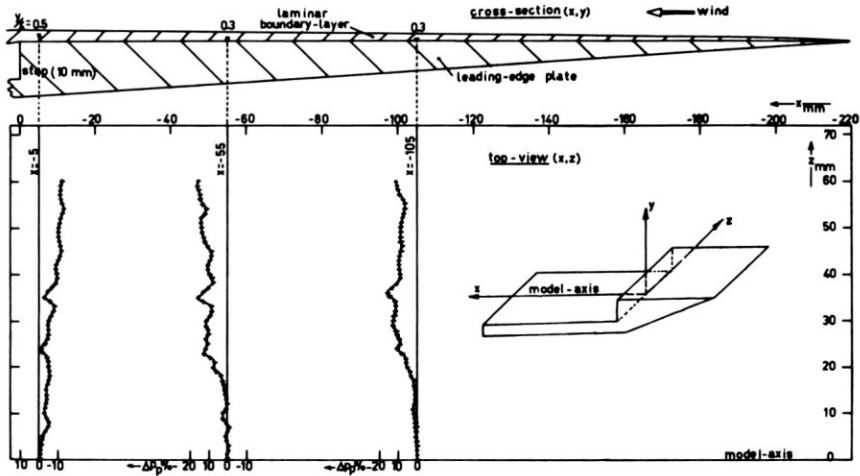


Fig. 3b. Measurements upstream of the step.

of the peaks and valleys did not vary with  $x$ . This is quite clear after separation but not so clear upstream of separation because of the very small amplitude of most of the perturbations. On the other hand, the repeatability of the measurements was not as good for  $x < 0$  as for  $x > 0$ .

It appears from these results that weak perturbations existed in the boundary layer before separation, but their amplitude is much greater, they follow a much more regular pattern and in detail they are more repeatable after reattachment.

Hopkins<sup>3</sup> presents photographs of various models coated with fluorescent oil which show evidence of surface vortices at a Mach number of about 3. Some photographs are also presented for the models coated with a sublimation material as was used in the present research. They show that the flow perturbations are more clearly indicated by the fluorescent oil. In particular the "vortices" are visible at a small distance behind the leading edge (i.e., upstream of separation) and it is observed that their spacing increases with the distance from the leading edge, which is in agreement with Görtler's theory<sup>4</sup> derived in the low speed case. The boundary-layer surveys made in the present work did not reveal such a variation of the spacing; it is possible that the probe was not sensitive enough to detect the smallest perturbations.

### LEADING-EDGE EFFECT

Evidence was given from the results of the detailed surveys made on model S-3 that the regular pattern of three-dimensional perturbations that existed at reattachment was triggered by the weak perturbations observed in the boundary layer upstream of separation. The problem was then to find a reason for the existence of these perturbations. In the early part of the research<sup>1</sup> it was found that irregularities in the leading edge of the model could not explain a regular pattern of perturbations. However, not much attention was given to the intensity

of the perturbations and it was therefore decided to reexamine the leading-edge effect more carefully. In a series of preliminary tests, several models were tested with accidental or wilful damage in the leading edge which indicated a strong modification of the intensity of the perturbations. These results finally led to a more systematic investigation during which the effect of the machining accuracy of the leading edge was examined.

An improvement of the machining accuracy of the leading edge, with the available machine tools, was possible only by using smaller models than S-3. The length  $L$  of the flat plate, upstream of the step, and the span  $S$  were reduced to 80 mm and 200 mm instead of 225 mm and 400 mm respectively. The step height was accordingly reduced to 6 or 7 mm, instead of 10 mm. In these circumstances, two identical models (except for the step height), were machined which had a mean leading-edge thickness of 224 and 96 microns respectively, with an accuracy of 3 microns. As no straightforward comparison could be made between the results obtained on these two models and those already recorded on model S-3 (because of its different size), a third identical model was machined with the usual accuracy of 20 microns; it had a mean leading-edge thickness of 165 microns. Finally, provision was made to fix two small plates to the sides of the models, to check the influence of the reduced span. The designation of the models is given in Table I (series S-20), the existence of side plates being denoted by the symbol  $B$ . The mean thickness ( $\epsilon_m$ ) of the leading edge is indicated in microns, as well as the magnitude of the local variation of thickness ( $\Delta\epsilon$ ).

All the tests were made at a free-stream Mach number of 2.2 and at a tunnel stagnation pressure of 150 mm Hg absolute for which transition was located downstream of the reattachment region of the flow. Total-head transverse surveys were made in the reattachment region of the boundary layer at a distance of  $x = 69$  mm downstream of the step base, the probe being kept against the model surface. The flow on the surface of the model was examined by the use of the sublimation technique.

Model S-20- $e$  was tested under these conditions with and without the side plates  $B$ . The results are compared in Figs. 4.1 and 4.2. The removal of the side plates influenced the perturbations, inasmuch as their amplitude decreased by about 50 percent. It also resulted in an increase of the base pressure and in a decrease of the pitot pressure measured on the centerline of the model at  $x = 69$  mm. This proved that a certain amount of air was injected in the separated flow from the sides of the model when the side plates were removed.

With the side plates, the local variation of pressure ( $\Delta'P_p$ ) measured between a pressure peak and its neighboring valley, varied between 20 and 54 percent, with a mean value of 25 percent. The local variations in leading-edge thickness were of about 20 microns at most. Assuming that the flow perturbations were triggered by leading-edge irregularities and that  $\Delta'P_p$  was roughly proportional to  $\Delta\epsilon$  (as suggested by the preliminary tests<sup>2</sup>) these irregularities should be of the order of or less than one micron to maintain a two-dimensional flow within one percent. These results agree quantitatively with the conclusions obtained from testing model S-3<sup>2</sup> and were therefore used as a reference for the effect of improving the accuracy of the leading edge.

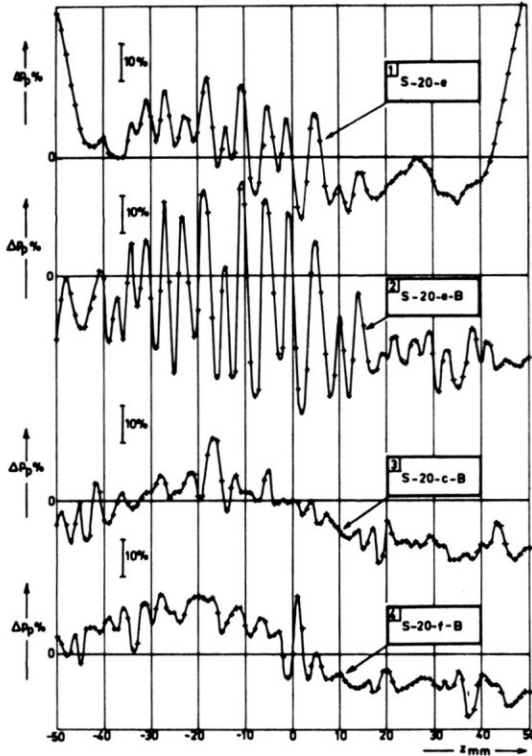


Fig. 4. Surveys made on models S-20.

Fig. 4 (1 and 2) also shows that the wavelength of the flow perturbations was not affected by the removal of the side plates (that is by the model span) verifying the conclusions already obtained.<sup>1</sup> This wavelength which is taken as the distance between successive peaks of the total-head distribution, varied between 3 mm and 6 mm (Fig. 4), with a mean value of 4.2 mm.

Flow perturbations are also shown in Fig. 5 for models S-20-e and S-20-e-B where regions of high sublimation rates correspond to dark areas. It is very easy to see that the wavelength is the same on both models and also that the perturbations are stronger in the presence of side plates. The leading-edge plate was not coated with azobenzene, but only the surface on which reattachment occurred, to avoid a modification of the roughness of the surface.

Models S-20-f and S-20-c have been tested under the same conditions as model S-20-e. The amplitude of the perturbations was again reduced by the removal of the side plates. Only the results obtained with the side plates are shown in Fig. 4 (3 and 4) and compared with the pressure variations measured on model S-20-e-B at the same value of  $x$  (i.e., 69 mm). It is seen that the amplitude of the flow perturbations has been drastically reduced. The mean value of the local change in  $\Delta P_p$  was indeed reduced to about 6.5 percent for both models instead of 25 percent on model S-20-e-B, as the local variations in leading-edge thickness



were reduced to 3 microns instead of 20 microns on model S-20-e-B. Assuming proportionality, and no other effect than that of leading-edge irregularities, it is to be expected that a two-dimensional flow could be maintained within 1 percent ( $\Delta'P_p = 1$  percent) if the leading-edge irregularities were smaller than 1 to  $\frac{1}{2}$  micron approximately.

Figures 5c and 5d show the striation pattern obtained on the surface of models S-20-c and S-20-f by the sublimation technique. Comparison with Fig. 5b shows that the amplitude of the perturbations was reduced.

The wavelength of the flow perturbations was measured on the pressure distributions of Figs. 4 c-d. It varied between 3 and 6 mm on model S-20-f-B and between 2 and 6 mm on model S-20-c-B, with mean values of 4.4 mm and 3.8 mm respectively. Therefore, within the accuracy of measurement, the wavelength remained unchanged (about 4 mm) as the intensity of the perturbations was reduced by improving the leading-edge accuracy. The observation of the models with a microscope never revealed a regular distribution of leading-edge irregularities. Furthermore, the leading edges of greater accuracy were machined by different methods, from those of lower accuracy; so that if such a regular distribution existed, it could not have been systematically the same on all the

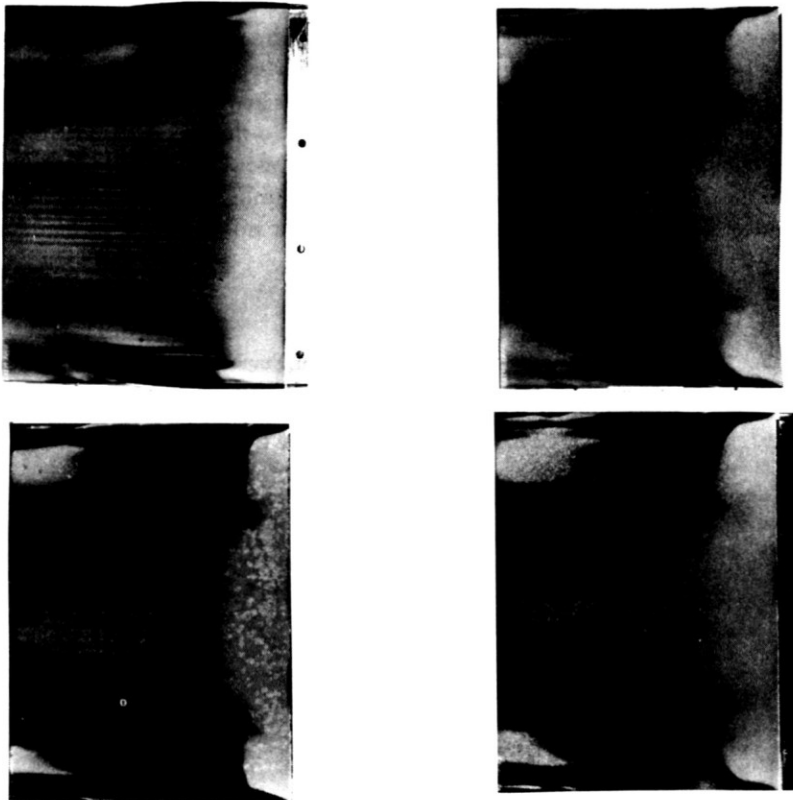


Fig. 5. Sublimation technique.

models. Therefore, the existence of leading-edge irregularities cannot explain the presence of a regular pattern of flow perturbations at reattachment. It is most probably a fundamental boundary-layer instability which in these tests is triggered by the leading-edge irregularities.

It is recognized that additional investigations remain to be done to determine exactly where the perturbations start to be regularly distributed. Without such information, it is impossible for example to evaluate the effect of the flow curvature in relation to Görtler's theory.<sup>4</sup>

## CONCLUSIONS

The flow perturbations extend, after reattachment, into the full thickness of the boundary layer with a maximum intensity of pitot-pressure variations occurring at about mid-height, both in the laminar and turbulent portions of the boundary layer. These variations vanish at the outer edge of the boundary layer and have their maximum amplitude in the transition region.

Although the existence of a regular pattern of flow perturbations could not be explained by the presence of leading-edge irregularities, it appears that the boundary-layer instability was triggered by these irregularities. No relation existed between the spacing (i.e., the wavelength) of the flow perturbations and the distribution of leading-edge irregularities. However, the amplitude of the perturbations was approximately proportional to the size of these irregularities. By extrapolation of the results it is concluded that a two-dimensional flow might be obtained within one percent (in  $\Delta P_p$ ) at reattachment, if the leading-edge thickness were constant to within  $\frac{1}{2}$  to 1 micron, assuming no other effect such as the influence of possible irregularities in the air flow upstream of the models.

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## DISCUSSIONS

*Discussor:* R. Legendre, ONERA

Indique que les longueurs d'ondes des perturbations détectées par le Professeur Favre à Marseille étaient d'un ordre de grandeur nettement supérieur à l'épaisseur de la couche limite.

Les longueurs d'ondes observées par l'auteur font penser qu'il existait des tourbillons longitudinaux alternés qu'il serait utile de révéler par visualisation ou d'après les indications de la prise statique d'une sonde de Prandtl très fine.

*Author's reply to discussion:*

La longueur d'onde des perturbations détectées par le Professeur Favre à Marseille est de l'ordre de 10 à 50 mm (d'après les Figures 13 et 17 du rapport Agard No. 278) tandis que la couche limite a une épaisseur de l'ordre de 30 mm. Dans la présente étude, la longueur d'onde est nettement plus faible (2 à 5 mm) mais la couche limite est également beaucoup plus mince (2 à 3 mm). Il en résulte donc que les rapports entre longueur d'onde et épaisseur de couche-limite sont très voisins dans les deux études.

Aucune tentative n'a été faite pour détecter la présence de tourbillons alternés longitudinaux dans la couche-limite. La suggestion de M. Legendre, d'utiliser une sonde statique, est certainement très bonne dans les conditions de nos essais.