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S. Beguet, J. Perraud, M. Forte, J.P. Brazier. Modeling of Transverse Gaps Effects on Boundary-Layer Transition. *Journal of Aircraft*, 2018, 54 (2), pp.794-801. 10.2514/1.C033647 . hal-01835768

HAL Id: hal-01835768

<https://hal.science/hal-01835768>

Submitted on 11 Jul 2018

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Modeling of transverse gaps effects on boundary-layer transition¹

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Delaying laminar-turbulent transition is considered a crucial issue with respect to the reduction of airplanes environmental impact, allowing to reduce skin friction drag and thus, fuel consumption. As part of this thematic, boundary-layer destabilizing effects of surface imperfections – assembly gaps, steps, rivets, waviness, holes – have been investigated by ONERA scientists for many years. Experimental, numerical and theoretical works provided fruitful results partly described in this paper, which especially focuses on gaps effects. Geometrical triggering criteria were searched and found to reproduce transition at a realistic chord percentage on reduced scale models. More recently, predicting the impact of gaps on laminar flow transition was also studied so as to provide a numerical tool for defining tolerances compatible with Natural Laminar Flow (NLF) airfoils. A specific model based on a ΔN approach has been developed to quantify the transition displacement caused by transverse gaps with a rectangular section. Detailed experimental studies which recently contributed to its validation are also presented in this paper.

¹ Published online by AIAA Journal of Aircraft, with permission, copyright ONERA 2016.
<http://dx.doi.org/10.2514/1.C033647>

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Nomenclature

b	gap width, mm
b^*	gap width in the streamwise direction, mm
c	chord, mm
$H_i = \frac{\delta_1}{\theta}$	incompressible shape factor
h	gap depth, mm
N_{peak}	local N-factor peak at the gap location
ΔN_{far}	N-factor shift downstream of the gap location
N_T	N-factor for which transition occurs
P	stagnation pressure, bar
Re_b	Reynolds number based on b and on the local external flow velocity
Re_{θ_g}	Reynolds number based on θ_g and on the local external flow velocity
T	stagnation temperature, K
Tu	free-stream turbulence level
U_∞	upstream velocity, m.s ⁻¹
u_g	local external velocity at the gap location, m.s ⁻¹
x	streamwise coordinate, mm
x_g	gap location, mm
x_T	transition location, mm
α	streamwise wavenumber
β	angle of attack (or AoA), degree
δ_{1g}	boundary-layer displacement thickness at the gap location, on a smooth profile (no gap), mm
ϕ	sweep angle, degree
ν	kinematic viscosity of the fluid, m ² .s ⁻¹
θ_g	boundary-layer momentum thickness at the gap location, on a smooth profile, mm
ω	angular frequency, s ⁻¹

I. Introduction

Considering the continuously increasing demand in air transport, a major effort is required so that pollutant emissions do not meet the same trend. Reducing harmful emissions has risen among the main goals of the International Civil Aviation Organisation (ICAO). As less drag reduces fuel consumption, numerous investigations aim at diminishing skin friction drag, which usually represents between 30 % and 80 % of the total airplane drag. Active and passive flow control devices have been developed for years to this end. They generally exploit the rather large difference in skin friction drag which exists between laminar and turbulent boundary-layers (a turbulent boundary-layer induces much more skin friction than a laminar one). Among them, optimizing airfoil shapes is considered as a natural passive way of extending the laminar boundary-layer region and falls in the Natural Laminar Flow (NLF) category. From the late 1930's, different countries conducted flight tests to observe pressure gradient effects, sweep or yaw angle effects on the laminar-turbulent transition position as part of NLF investigations. Smaller scale experiments were also carried out in wind-tunnels, but they all highlighted how difficult it was to reproduce real flight conditions: high Reynolds numbers, pressure conditions, noise level, including instrumentation troubles and small geometric details. This last point has been interesting ONERA scientists for many years. At the beginning, surface imperfections were studied to define triggering criteria in order to artificially induce the transition at a realistic chord percentage on models at laboratory scale. Recently, their destabilizing impact was also investigated to take it into account during the airfoil design process.

In 1966, Nenni & Gluyas [1] conducted flight tests and suggested experimental criteria about steps and gaps effects on transition triggering. According to their results, a transverse gap would not significantly affect transition for $Re_b = \frac{U_\infty b}{\nu} < 15000$, with U_∞ the upstream flow velocity, ν its kinematic viscosity and b the gap width. Even if this criterion remains a usual reference, it is worth mentioning that the community agreed to rather use the local velocity at the gap position u_g instead of the upstream velocity U_∞ . As the very heart of this kind of study concerns unstable processes taking place inside the boundary-layer, this local point of view indeed should make more sense.

Gaps always cause flow re-circulation, most often limited to the gap extent. Various flow

topologies may be encountered depending on the aspect ratio h/b (where h is the gap depth). In 1982, they were identified by Sinha [2] (see Fig. 1) who showed, among others, that a gap becomes equivalent to a succession of two opposite steps for $h/b < 0.1$,

case (a). Very deep gaps also contain complex combinations of vortices (d), while in the range 0.1 to 1.5 the cavity flow is dominated by a main vortex (b) with possible secondary ones in the corners (c). Such configurations may present several stability behaviors. For this reason,

gaps influence on transition remains poorly documented while various investigations were carried out about steps, humps, and waviness (for example, see ref. [3]).

Fig. 1 Vortices categories according to Sinha's criteria [2]

The present paper covers more than thirty years of ONERA researches about the influence of gaps on transition. All the results described in this paper are part of the accumulated ONERA database, until now only available in ONERA internal reports written in French. References and details are registered in Tables 1 and 2. This article mainly aims at disseminating this knowledge through the community, in the light of experimental metrology, theoretical tools and computational methods for stability analysis evolutions. Its first part deals with gaps considered as a geometrical mean of artificially triggering transition at a realistic chord percentage in wind-tunnel experiments. Several experimental campaigns are described in order to get a better understanding of the way the triggering criteria were obtained. The second part concerns configurations for which transition occurs downstream of the gap location: in such cases, the transition location may be progressively moved toward the leading edge depending on several parameter changes. An appropriate ΔN model is proposed, based on both experimental and numerical recent investigations.

Table 1 Experimental ONERA database on transverse gaps effects

Date	Ref	Authors	Model	AoA β	Sweep ϕ	Metrology / Tools
1982	[4]	M. Olive A. Blanchard	Flat-plate	$-1^\circ/-6^\circ$	0°	Hot-wire
2001	[14]	A. Séraudie J. Perraud	ONERA-D	$-1^\circ/-6^\circ$	$0^\circ/60^\circ$	Pitot probe
2001	[15]	J. Perraud A. Séraudie	OALT25	$-0.15^\circ/0.5^\circ$	0°	Pitot probe
2010	[5]	A. Séraudie	ONERA-D	-8°	$0^\circ/60^\circ$	Hot-wire
2012	[6]	L. Gentili M. Forte	ONERA-D	-8°	$0^\circ/60^\circ$	Hot-wire
2014	[18]	S. Beguet M. Forte	ONERA-D	$0^\circ/1^\circ$	0°	Hot-wire

Table 2 Numerical ONERA database on transverse gaps effects

Date	Ref	Authors	Model	AoA β	Sweep ϕ	Metrology / Tools
1997	[11]	J. Perraud	Flat-plate	0°	0°	Laminar Navier-Stokes local linear stability PSE
2010	[17]	J.-Ph. Brazier	ONERA-D	-8°	$1^\circ/60^\circ$	RANS local linear stability
2011	[16]	J. Perraud	Flat-plate	0°	0°	Laminar Navier-Stoke local linear stability
2014	[18]	S. Beguet J. Perraud	ONERA-D	$0^\circ/1^\circ$	0°	Laminar Navier-Stoke local linear stability

II. Transition triggering criteria

Boundary-layer transition dependence on turbulence level and Reynolds number may prevent relevant comparisons between wind-tunnel experiments and flight tests. Adapted obstacles were thus sized to artificially trigger transition at the same location on models as in full scale conditions. Attention was especially paid on momentum thickness continuity in order to follow the natural

Fig. 2 Experimental data obtained at ONERA about "right tripping" limits in 2D configurations.

boundary-layer development. In 1982, Olive & Blanchard [4] first focused on gaps triggering ability, as a response to new technical needs linked to cryogenic wind-tunnel technology. Their works particularly aimed at obtaining what they called the "right tripping" curve: dimensionless geometric parameters of gaps which are required to trigger transition at the imperfection location, without over-thickening the boundary-layer. This last remark really matters because an over-thickening of the boundary-layer would not allow to reproduce real flow features (for instance it would imply more drag). Experiments were conducted in a subsonic open-return wind-tunnel, over a flat-plate equipped with a super-elliptical leading edge. Gaps of various dimensions and shapes, parallel to the leading edge, were tested using a removable insert. Hot-wire measurements provided information on the nature of the boundary-layer at several locations, whereas boundary-layer parameters (such as the displacement thickness, the momentum thickness and the shape factor) were computed. Olive & Blanchard finally obtained a single "right tripping" curve for the two pressure gradients they tested (slightly negative or zero). Their data are compared to more recent ones in Fig. 2.

These other points were obtained by Séraudie [5] and Gentili & Forte [6] at ambient temperature in a velocity range from 5 to 80 m/s (thus for unit Reynolds numbers between 300 000 and 5 millions),

on a different model (ONERA-D airfoil detailed in part III B 1) at several angles of attack (for more details, see Table 1). The h/b constant lines in Fig. 2 help relate the range of gaps tested to the topologies described in Fig. 1. Very deep gaps were not considered here while looking at efficient triggering conditions. According to Fig. 2, a "L-shaped" tendency emerges: dimensionless gap sizes respectively reach asymptotic values evaluated as $b/\delta_{1g} \geq 18$ and $h/\delta_{1g} \geq 2$, where δ_{1g} is the boundary-layer displacement thickness at the gap position for an equivalent smooth case. With regards to the large range of aerodynamic parameters, the unique qualitative evolution and the rather small dispersion are noticeable.

Fig. 3 Comparison of experimental data obtained at ONERA about "right tripping" limits in 2D and 3D configurations.

Similar studies were also conducted on swept wings. In this configuration, the gap width in the streamwise direction b^* ($b^* = b/\cos\phi$ with ϕ the sweep angle) was experimentally shown more relevant than the gap physical width b to characterize gaps triggering limits. Figure 3 compares two-dimensional data previously presented in Fig. 2 to their three-dimensional counterpart (see ref. [5] and [6]). While instability processes are totally different, corresponding to Tollmien-Schlichting waves in 2D, and to cross-flow instabilities in the 3D swept case, the asymptotic values appear to be quite similar for both configurations, with a number of 3D results located slightly below the 2D

trend.

Triggering criteria provide an easy way of dimensioning gaps to cause a realistic transition on models as well as an easy way of estimating an upper limit for NLF compatible tolerances. Laminar Navier-Stokes or boundary-layer computations of the smooth case provide the reference value δ_{1g} . Results must then be compared to the asymptots $b/\delta_{1g} = 18$ and $h/\delta_{1g} = 2$. For greater values, transition is known to be triggered at the gap location. It is also worth mentioning that this criterion highly contrasts with the original Nenni & Gluyas one which is based on upstream flow parameters and on the gap width, and which thus does not take into account local conditions as well as gap depth.

Even if this first part dealt with the triggering of transition at the roughness location, experiments also highlighted that gaps could affect transition location far downstream. Further investigations are described in the next part, where only 2D configurations are considered.

III. Gaps effects quantification in 2D cases

ONERA scientists developed a model in order to quantify the destabilizing effects of transverse gaps and contribute to answer the industrial demand concerning transition prediction and flow control.

After some comments about the stability tools which were used, this part focuses on the ΔN model description, from the mean flow calculation to the model definition and to its recent experimental validation.

A. Numerical prediction

1. Theoretical overview

Amplification of small amplitude disturbances, such as Tollmien-Schlichting waves in 2D flows, may be predicted by way of linear stability theory. The subclass of local linear stability theory is presently the most often used approach for transport aircraft design, solving the Orr-Sommerfeld equation for viscous boundary layer flow. In local linear stability theory, disturbances are expressed as $d' = \hat{d}(y) \exp[i(\alpha x - \omega t)]$, with an amplitude $\hat{d}$ depending only on the normal coordinate y . This ansatz allows to reduce the problem to an ordinary differential equation for the amplitude function

$\hat{d}$. A further simplification consists in using spatial theory, by which the frequency ω is real and the wavenumber α complex. The term $\exp(-\text{Im}(\alpha))$, with $\text{Im}(\alpha)$ being the imaginary part of α , then describes the amplitude growth of a disturbance at a given angular frequency $\omega = 2\pi f$. Because we often encounter exponential growth, it is convenient to consider the logarithm of the amplification rate and to introduce a so-called N-factor as

$$N_f(x) = \int_{x_0}^x -\text{Im}(\alpha) dx \quad (1)$$

where x_0 is the most upstream position for which the considered frequency is amplified for the first time. Finally, because there is no a priori knowledge of the frequency causing transition, the N-factor is defined by taking the maximum over frequency :

$$N(x) = \max_f (N_f(x)) \quad (2)$$

In 1956, Smith and Gamberoni [7] and Van Ingen [8] based their well-known e^N prediction method for laminar-turbulent transition, depending on the N-factor amplification and on the upstream level of perturbations. As long as $N(x)$ remains smaller than a limit value N_T , the boundary-layer is laminar. Non-linear mechanisms, rapidly leading to the birth of turbulent spots, start at the transition point. It is worth noting that the validity of this spatial approach was shown in case of rapidly evolving flows, in case of thin separation bubbles, by comparing $-\text{Im}(\alpha)$ values taken from local linear stability analyses with Direct Numerical Simulation results (see Gruber and Bestek [9] for a separation bubble, and Edelmann and Rist [10] in the case of a forward-facing step). In case of deep gaps, acoustics may play a role as well as other types of instabilities. The use of global stability analysis could be explored in such configurations.

2. Empirical ΔN model

An appropriate N-factor modification may properly model the destabilizing effects of the studied imperfections, and this is the ΔN approach main principle. In a first phase, steady

laminar Navier-Stokes computations were undertaken using the ONERA code elsA, to compute the mean flow on a flat plate with a rectangular gap downstream of the leading edge. Care was taken to ensure a precise computation of the velocity profile by selecting a second order Roe scheme

with low artificial dissipation. The test case of the flat plate boundary-layer was exploited to ensure that mesh definition and numerical options were correctly chosen, so that the incompressible shape factor H_i is correct to the second decimal point. Parameters explored in this study are the gap width b ($15000 < Re_b < 40000$), the gap location characterized by a momentum thickness Reynolds number ($300 \leq Re_{\theta_g} \leq 800$), and the aspect ratio ($0.2 \leq h/b \leq 0.7$). Both Re_b and Re_{θ_g} are local parameters based on the flow velocity and momentum thickness at the gap location, but on a smooth case without any gap.

In order to facilitate comparisons of the results, and post-treatment, the gap location (upstream edge x_g) was kept constant at $x_g = 0.8$ m. The flat-plate leading edge was placed at a distance upstream of the gap such that the desired boundary-layer thickness, characterized by Re_{θ_g} , could be obtained at the gap location.

The flow Mach number was set to 0.3 in order to accelerate convergence and avoid the use of the low speed pre-conditioning in the Navier-Stokes solver. Flow topologies in this range of parameters present one or two contra-rotating, stationary, transverse vortices trapped inside the gap (cases b, c of Fig. 1). The boundary-layer profiles were extracted from the flow field following the determination of the boundary-layer upper limit, as in ref. [13].

Two sensors, based on shear and on vorticity, were used to define this limit. Care was taken to include the cavity region in the boundary-layer. The profiles are expressed in term of wall normal distance, hence the integral quantities show jumps at both edges of the gap, and the shape factor increases drastically within the gap width (Fig. 4).

The boundary-layer profiles were then used as input data for a local, linear stability calculation using the ONERA code CASTET, to produce the N-factor curves.

Figure 5(a) shows envelope curves of Tollmien-Schlichting N-factors obtained for several gaps such that $Re_{\theta_g} = 300$, in which case a large peak may exist at the gap location. When Re_{θ_g} is increased to 800 (Fig. 5(b)), the local response is reduced while the N-factor curve jump past the gap may become more important.

From the results of a parametric study, it was shown that the N-factor modification induced by a gap results in the superposition of two components represented in Fig. 6(a): on one hand, N_{peak}

Fig. 4 Example of computed shape factor

Fig. 5 Linear stability calculations examples in presence of gaps.

which represents a drastic amplification just past the roughness and may induce transition onset at the gap position and, on the other hand, ΔN_{far} which represents a shift from the natural N-factor curve and which may induce a progressive upwind move of the transition position.

As part of this data modeling, Fig. 6(a) shows that ΔN_{far} adds up to the smooth case N-factor curve, whereas N_{peak} does not.

Fig. 6 Perraud's model [16]. Linear stability results and model definition

Such a difference is justified by linear stability theory which

shows that there are two different frequency ranges of Tollmien-Schlichting waves. First, a range of lower frequency Tollmien-Schlichting waves which are amplified over a wide chordwise extent, including the gap. Second, there are Tollmien-Schlichting waves with higher frequencies (and shorter wavelength) which are only amplified within the gap length.

Figure 6(b) supports this remark by showing the emergence of high frequencies within the gap. Unstable frequencies ranging between 1 kHz and 3 kHz start gaining amplitude upstream of the gap location, are further amplified in the gap region, and pursue their evolution at a higher N-factor level past the gap. In parallel, higher frequencies ranging around 4 kHz arise inside the gap and are strongly damped just after.

The Re_b and Re_{θ_g} dependencies are consistent with complementary experimental observations which emphasized the gap position influence – taken into account in θ_g – and confirmed the gap width influence [14, 15]. Concerning gap depth, computations showed an evolution of the results up to an aspect ratio $h/b = 0.2$, and a slow variation of mean flow parameters in the range $0.2 < h/b < 0.7$. Deeper gaps proved difficult to treat, due to convergence issues with the laminar Navier-Stokes solver. Further analysis assumes that $h/b > 0.2$ without considering gap depth effects.

The model proposed here assumes that a small gap on a flat plate will induce a pressure gradient perturbation resulting in a perturbation of the base N-factor curve. On a profile, the shape-induced pressure gradient will result in a modified smooth wall N-factor, to which the perturbation caused by a gap may then be added.

As all these simulations were done at Mach 0.3, the uncoupled regime observed in this domain may be questionable at larger velocities. This point would necessitate additional simulations.

Figure 7 shows values of N_{peak} function of both gap width and location through the two parameters Re_b and Re_{θ_g} . These variations were expressed with a rather simple model, given by equations (3) and (4).

$$N_{peak} = 0.0001(Re_b/Re_{\theta_g}) + 0.000209 Re_b - 0.00793 Re_{\theta_g} + 4.97 \quad (3)$$

$$\Delta N_{far} = 0.0086(Re_b/Re_{\theta_g}) + 0.000035 Re_b - 0.0025 Re_{\theta_g} + 2.244 \quad (4)$$

This model is of low order to avoid rapid variations at its limits. It may be used within the range of parameters specified earlier.

Fig. 7 N_{peak} model and data points issued from stability computations

In order to explore the link between this N_{peak} model and the triggering model of Olive & Blanchard [4], a simple analysis may be proposed, assuming a Blasius boundary-layer over a flat

plate (for which $Re_\theta = 0.664\sqrt{Re_x}$), a transition N-factor of 7, and instant transition when N_{peak} given by eq. (3) reaches a value of 7. It is assumed here that the gap depth is larger than required by both criteria ($h/b > 0.2$).

Fig. 8 Link between Olive & Blanchard results and the N_{peak} model

This results in two rather simple equations expressing the limit width causing transition at a given x location, as plotted in Fig. 8. This figure shows a fairly good agreement between the two criteria, provided that the unit Reynolds number (expressed here in term of flow velocity, with $P = 1$ bar, $T = 300$ K) is large enough. Above 100 m/s, the two criteria are in fair agreement, but at 50 m/s the required width to trigger transition is larger with eq. (3), i.e. the computed N_{peak} value will be too small with regard to Olive & Blanchard criterion. It should be pointed out that the N_{peak} model was obtained based on Mach 0.3 laminar Navier-Stokes computations, with a flow velocity close to 100 m/s.

3. Practical terms

Focusing on practical aspects, the ΔN model is proving to be simple of use. Once computed the mean flow in the baseline case (without surface imperfection), the local parameters (velocity and momentum thickness) are enough to calculate N_{peak} . With this first value, the studied gap is

quickly known to trigger transition or not by comparing N_{peak} with the transitional N-factor N_T of the considered configuration. Such a point already makes this model an interesting tool for defining NLF tolerances. In case of a non-triggering gap, adding the corresponding ΔN_{far} to the baseline N-factor envelope curve allows to estimate the laminar-turbulent transition shift caused by the gap.

B. Experimental validation

1. Experimental setup and methodologies

While the N_{peak} model may quite simply be related to Olive & Blanchard criterion, experiments before 2011 did not allow to validate the ΔN_{far} model because the search of a "critical velocity", with

measurements done at a single location, could not detect a progressive move of the transition location. Additional experiments were required which took place in the subsonic open-return "TRIN1" wind-tunnel located in ONERA Toulouse premises. This wind-tunnel runs in ambient conditions at free-stream velocities from 10 to 80 m/s. Its low free-stream turbulence level ($7 \times 10^{-4} < Tu < 2.5 \times 10^{-3}$) is well-suited for transition and laminarity studies. A two-dimensional model based on an ONERA-D symmetric profile was mounted in its test section as described in Fig. 9(a). This airfoil has a chord length of 0.35 m and is equipped with a metallic insert in order to change gap dimensions at exactly $x_g/c = 10\%$.

Transition was detected by constant temperature hot-wire anemometry (CTA), but with two distinct approaches: in 2012 [6], measurements aimed at finding local velocity for which transition occurs (mentioned as "critical velocity" in this paper) by increasing free-stream velocity while keeping a fixed probe location, whereas in 2014 [18] they aimed at finding the location where transition occurs by translating the probe at a constant height above the wall for a fixed free-stream velocity. Both approaches are described with greater details in [19] and [20]. They both contribute to the validation database presented in this part. In practice, several methods can be used to localize the beginning of the laminar-turbulent transition: in both presented studies, transition is identified by a sudden increase in velocity fluctuations in the boundary-layer (corresponding to the birth of turbulent spots). Tested gaps are listed in Table 3.

Fig. 9 ONERA-D MODEL

Table 3 Gaps dimensions

Width, b (mm)	3	3	3	3	4	4	5	5
Depth, h (mm)	0.5	1	1.5	2	0.5	1	0.5	1
Aspect ratio, h/b	0.17	0.33	0.5	0.67	0.125	0.25	0.1	0.2

2. Transitional N -factor values

N_T values are required to numerically predict the transition location induced by gaps (using the ΔN model) before comparing it to measurements. It actually may be calculated from the free-stream turbulence level (Tu) of the working environment by using the Mack formula (expressed as $N_T = -8.43 - 2.4 \ln(Tu)$), but the way of obtaining Tu always induces discussions (mainly about the frequency integration range). For this reason, a more robust procedure based on the experimental database and linear stability analyses was preferred to deduce the N_T values in both presented studies. For a given smooth configuration, the experimental transition location was reported on the N -factor envelope curve provided by a local linear stability analysis. The N -factor reached at this location was then taken as N_T .

3. Results supporting the ΔN model assumptions

Figure 10(a) represents critical Re_b values versus aspect ratios h/b for both experiments [5, 6]. Even if Re_b was first defined by Nenni & Gluyas as $Re_b = \frac{U_\infty b}{\nu}$, Re_b is here rather chosen as $Re_b = \frac{u_g b}{\nu}$, with u_g the external velocity taken at the gap location under critical conditions. According to this plot, critical Re_b becomes constant for aspect ratios higher than $h/b = 0.2$, and so becomes independent of h .

This asymptotic phenomenon can also be observed in Fig. 10(b) which represents examples of hot-wire voltage fluctuations along the chord for several gaps (and thus for several aspect ratios).

This confirms that h has a negligible effect on transition as long as $h > 0.2b$. All these test campaigns finally confirm the fact that the ΔN model (which does not take into account the gap depth) should be applicable for $h/b > 0.2$ and would loose in precision in case of shallow gaps not respecting this condition.

Fig. 10 Gap depth effects. h/b criterion verification [18]

Even if Re_b definitions remain significantly different, it is still worth commenting that the Nenni & Gluyas criterion [1] (which outlines that a transverse gap does not affect transition if $Re_b \leq 15000$) seems to underestimate the transition triggering capacity of the gap. This difference may come from many different parameters such as Mach number, pressure gradient or free-stream turbulence level which is much lower during flight tests (Nenni & Gluyas conditions) than in wind-tunnels, but this

Table 4 Transition locations (x_T/c) - Measurements versus numerical prediction

		30 m/s		40 m/s		50 m/s		60 m/s	
AoA	$b ; h$	Exp	Num	Exp	Num	Exp	Num	Exp	Num
$\beta = 0^\circ$	3 ; 1	69 %	63 %	63 %	62 %	59 %	58 %	41 %	58 %
	4 ; 1	66 %	62 %	61 %	61 %	10 %	57 %	10 %	57 %
$\beta = 1^\circ$	3 ; 1	20 %	15 %	×	×	×	×	×	×
	4 ; 1	15 %	14 %	×	×	×	×	×	×

remark also tends to support the fact that a local approach apparently makes more sense, as already noticed in Part II.

4. Results concerning the ΔN_{far} effect

In 2014 [18], successful results were found about the ΔN_{far} estimation. A visual example of numerical and experimental comparison is given in Fig. 11 for $\beta = 1^\circ$, $U_\infty = 30$ m/s and $b = 4$ mm. In this configuration, data perfectly match: the experiment gives $x_T/c = 0.15\%$ (see Fig. 11(a)) and computations (local linear stability calculation for the smooth case + ΔN model) give $x_T/c = 0.14\%$ (see Fig. 11(b)). In the other cases (see Table 4), measurements and numerical predictions generally differ from 1 to 6 % of chord, depending on gap geometries, pressure gradient and velocity.

Fig. 11 Numerical determination of transition location, $U_\infty = 30$ m/s, $\beta = 1^\circ$ and $b = 4$ mm [18]

Some particular results however remain to be discussed. The largest difference is obtained at $\beta = 0^\circ$ with the gap $b = 4 \text{ mm} / h = 1 \text{ mm}$, for $U_\infty = 50 \text{ m/s}$ and $U_\infty = 60 \text{ m/s}$. In these cases, transition directly occurs at the gap location whereas the model prediction finds it at $x/c = 57 \%$. According to the model definition, such a transition should have been caused by N_{peak} : this remark tends to support a possible under-estimation of N_{peak} (which did not exceed N_T as planned) rather than a ΔN_{far} failure.

The last significant difference is observed at $\beta = 0^\circ$ with the gap $b = 3 \text{ mm} / h = 1 \text{ mm}$, for $U_\infty = 60 \text{ m/s}$. In this case, the model

shows a long region with decreasing N-factors (see Fig. 12), resulting from a small negative pressure gradient. Such configuration is very different from the monotonically increasing flat plate N-factor curve, and this difference may explain the large error. Transition cannot be predicted using linear stability within this region, while non-linear mechanisms may play a role with N-factors above 6. Another point which may be raised is the validity of the assumption concerning the ΔN independence from pressure gradient, which may not be valid in this case. Further investigations would be needed to evaluate pressure gradient effects on N_{peak} and ΔN_{far} .

Fig. 12 N-factor envelope curve, $U_\infty = 60 \text{ m/s}$ at $\beta = 0^\circ$ [18]

Even if some points remain to be improved, ΔN_{far} can properly quantify the progressive effect

of gaps on transition which happens downstream of its location, in case of strictly increasing N -factor curves. As shown in this part, the first and only experimental campaign conducted in order to measure this effect provided very encouraging results.

Conclusion

This paper sums up activities conducted at different periods extending over more than thirty years of ONERA research dealing with the effect of transverse rectangular gaps on boundary-layer laminar-turbulent transition. Gaps were first investigated as a way to artificially trigger transition on wind-tunnel models during low Reynolds number tests without increasing the boundary-layer thickness. A triggering criterion was defined and confirmed after wind-tunnel tests in various conditions. On a two-dimensional wing (no sweep), the limits were expressed as $b/\delta_{1g} \geq 18$ and $h/\delta_{1g} \geq 2$. These results do not significantly differ for a three-dimensional (swept) wing although the very different nature of boundary-layer instabilities should be kept in mind to extrapolate from 2D to 3D. In contrast to the old Nenni & Gluyas criterion only function of Re_b , the Olive & Blanchard criterion (fig 2) also introduces the local flow properties at the gap location with the boundary-layer displacement thickness δ_{1g} .

Gaps effects on laminar-turbulent transition have been more recently investigated through both numerical and experimental studies which contributed to develop a specific ΔN model for low velocity 2D cases. Gaps were shown to contribute in two different ways: first, by amplifying the Tollmien-Schlichting waves already present upstream of the gap (ΔN_{far} effect), and second, by creating new instabilities only observed within the gap width (significant local effect, or N_{peak} effect). These two effects are quantified by formulas (3) and (4) depending on the gap width and the boundary-layer momentum thickness θ_g at the gap location. N_{peak} and ΔN_{far} provide a very simple way of predicting gaps effects, requiring at least a laminar Navier-Stokes computation (or a boundary-layer calculation) of the smooth case, and at worst (in case of non-triggering) a local linear stability analysis. Results of this model have been compared to the experimental database recently generated. One of the main difficulties lies in the fact that N_{peak} and ΔN_{far} empirical estimations result from numerical parametric studies on flat-plates with zero pressure gradient,

whereas comparative experiments were conducted with an airfoil model. Promising results tend to confirm the ΔN model relevancy (particularly for the downstream effect modeled by ΔN_{far}), but the pressure gradient effect needs to be further investigated. Also to be further explored are the effects of compressibility and the behavior of gaps with a larger depth ($h/b > 1$).

The link between the N_{peak} estimation and the Olive & Blanchard criterion was established for a Blasius boundary-layer with a number of hypotheses. Both of the L-shaped curve ($b/\delta_{1g} \geq 18$ and $h/\delta_{1g} \geq 2$) and the N_{peak} estimation (at large enough Reynolds number) provide a very easy way of predicting if a given gap may affect or trigger transition (they only require a laminar Navier-Stokes or a boundary-layer computation of the smooth case, and the gap dimensions). Together with the ΔN_{far} model, they may be used as a convenient way of determining tolerances compatible with NLF.

The present analysis is based on boundary-layer stability computations, assuming a dominant contribution of convective instabilities. Further analyses, taking into account global instabilities, are now under way at ONERA.

Acknowledgments

Part of this work has been undertaken within the Joint Technology Initiative "JTI Clean Sky", Smart Fixed Wing Aircraft Integrated Technology Demonstrator "SFWA-ITD" project (contract N° CSJU-GAM-SFWA-2008-001) financed by the 7th Framework Program of European Commission. The ΔN model was developed within the FLOWMAPI 2 contract supported by the French Délégation Générale à l'Armement (DGA).

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