



Selection of roughness bands to induce boundary-layer transition in wind-tunnel testing

**Associated software: ecrit1
ecrit2**



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SELECTION OF ROUGHNESS BANDS TO INDUCE BOUNDARY-LAYER TRANSITION IN WIND-TUNNEL TESTING

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SELECTION OF ROUGHNESS BANDS TO INDUCE BOUNDARY-LAYER TRANSITION IN WIND-TUNNEL TESTING

1. INTRODUCTION

In wind-tunnel testing, transition fixing is primarily employed to provide a boundary layer that is more representative of the full-scale condition (usually fully turbulent on a swept wing) when a test is conducted at a lower Reynolds number. In transonic wind-tunnel testing there may be particular requirements for appropriate boundary-layer representation at critical regions such as the expected shock-wave location, or near a highly-loaded wing trailing edge, where separation may be expected^{1,2,3,4}. In this case aft-fixing is employed, in which boundary-layer transition is artificially induced upstream of the location at which natural transition occurs in the wind-tunnel test but downstream of the anticipated full-scale location².

Transition-fixing devices are therefore used in wind-tunnel testing to establish transition at a well-defined position, without causing unrepresentative flow disturbance external to the boundary layer. The device should be easy to apply in a consistent manner and effective over a reasonable range of test conditions. The drag penalty, reflected as an increase in boundary-layer momentum thickness at the device location, should be kept as small as possible and should be accountable.

Transition devices may be sub classified as active or passive. Active devices, such as local surface heating/cooling⁵ or pulsed suction/jets⁶ may be used to induce (or delay) boundary-layer transition. Passive devices use surface protuberances, such as grit applied in a narrow band, which produce sufficient local turbulence to cause boundary-layer transition upstream of the natural transition location.

In principle, active devices give a measure of control, which permits some accommodation of a range of local boundary-layer and freestream conditions. They are, however, physically difficult to implement and practical considerations dictate deployment at a single location, or a very restricted number of locations. These factors severely restrict their application to wind-tunnel testing in general and pose particular difficulties when aft-fixing² is employed, as this usually requires boundary-layer transition to be fixed at a number of different locations on the model surface during the course of a test campaign. Thus, passive devices are more commonly used in wind-tunnel testing and a brief review of such devices is given in this Item, followed by a detailed analysis of the considerations relating to selection of bands of randomly-distributed roughness elements (*e.g.* bands of randomly-distributed sand, carborundum, or ballotini particles), which are commonly used to achieve artificial boundary-layer transition.

This Data Item is accompanied by two programs to aid calculation of the required roughness height in distributed-roughness transition bands. The first of these, *ecrit1* (Appendix A) calculates the roughness height required to induce transition on a flat plate with zero freestream pressure gradient. It can be used for transition bands near the fuselage nose and on the horizontal and vertical tail surfaces and also for preliminary assessment wing-transition-band requirements (Section 6.4.1). The second program, *ecrit2* (Appendix B), provides a more accurate assessment of wing-transition-band requirements based on local flow conditions at the transition-band location (Section 6.4.2).

2. NOTATION

A_E	frontal area of roughness particle
a	a constant in incompressible flow or a function of freestream Mach number in compressible flow (Section 6.4.1)
C_{DE}	drag coefficient of individual roughness element
$C_{d_{band}}$	Local drag coefficient of roughness band
c	chord length of aerofoil or flat plate
$\bar{c}$	wing mean chord
e	protuberance height
M_∞	freestream Mach number
N	distribution density of roughness particles in transition band
$Re_{\bar{c}}$	Reynolds number based on wing mean chord $\left(= \frac{U_\infty \bar{c}}{\nu_\infty} \right)$
Re_e	Reynolds number based on protuberance height $\left(= \frac{U_\infty e}{\nu_\infty} \right)$
Re_x	Reynolds number based on distance from leading edge $\left(= \frac{U_\infty x}{\nu_\infty} \right)$
U_∞	freestream speed
ω	width of transition band
x	distance from leading edge, measured in freestream direction
$\Delta\theta$	local increase in boundary momentum thickness caused by transition band
δ^*	boundary layer displacement thickness
ν_∞	freestream kinematic viscosity

3. TRANSITION MECHANISMS

3.1 Natural Transition

Natural transition from laminar to turbulent flow in a boundary layer may be caused by several mechanisms, which are reviewed in Reference 1. The main mechanisms are:

- (a) **2-D instability** in which Tollmien-Schlichting (T-S) waves, normal to the stream direction and initiated by a very small disturbance, become unstable, leading to transition;
- (b) **Crossflow instability**, which, on swept wings, causes the development of stationary co-rotating streamwise vortices within the boundary layer;
- (c) **Görtler vortices**, which are a set of counter-rotating vortices that form on a concave surface, such as the cove area on the under surface of a cambered wing;
- (d) **Leading-edge contamination** on a swept wing, in which turbulence, originating in the fuselage boundary layer, migrates along the wing leading edge.

All the above mechanisms result in a turbulent boundary-layer flow, which, in the case of mechanisms (a) to (c), becomes fully developed downstream of a transition region¹. For typical swept-wing aircraft, at full-scale Reynolds number, mechanism (d) frequently dominates and the boundary layer on the wing is then completely turbulent. At lower Reynolds numbers, typical of many wind-tunnel tests, mechanism (d) does not trigger transition on such aircraft configurations. Under these circumstances transition may be fixed, by artificial means, upstream of the natural transition location, in order to simulate full-scale behaviour (see References 1 to 4).

The transition location is also influenced by the flow external to the boundary layer. A favourable pressure gradient (*i.e.* one in which pressure reduces in the flow direction at the outer edge of the boundary layer) delays transition, while an adverse pressure gradient causes early transition. Turbulence and acoustic disturbances in the external flow both cause early transition.

3.2 Bypass Transition

Even when flow disturbances in a laminar boundary layer (caused, for example by freestream turbulence, acoustic noise or surface irregularities) are very weak, they become unstable at a critical Reynolds number and are then magnified, leading to “natural” transition in which a fully-turbulent boundary layer forms downstream of a transition region¹. The “receptivity” mechanisms by which external disturbances are assimilated into the boundary layer and influence transition are complex, but slight changes in an already small disturbance level can have a noticeable effect on transition location.

Transition can be fixed upstream of the natural transition location by deliberately introducing a strong disturbance. This is known as “bypass transition”, in the sense that the high-amplitude disturbance interact with the “natural mechanism”, such as T-S wave instability, introducing additional instability mechanisms that lead to early transition.

Large disturbances may be introduced by a number of devices, which may be sub-classified into active devices, which typically require electrical or pneumatic actuation, and passive devices, which require no such external stimulus. Typical disturbance sources are:

Active devices:

- Acoustic noise, driven by loudspeakers,
- Pulsed jets introduced at a solid surface.

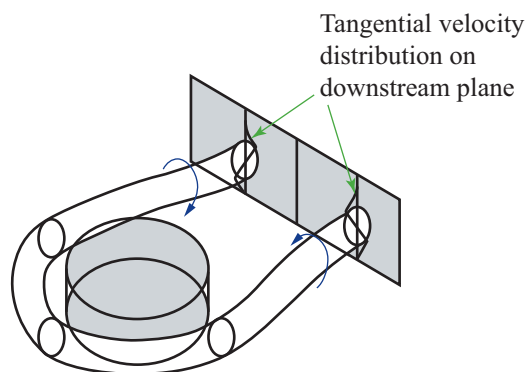
Passive devices:

- Freestream turbulence, which may be increased by the use of upstream wire grids,
- Surface mounted devices, including surface roughness.

Although all these devices have been the subject of investigation, passive surface-mounted devices offer relatively easy control over transition location and are easily implemented. Passive surface mounted devices are, therefore, the most frequently used in wind-tunnel testing and only transition-fixing devices of this type are considered further in this Item.

3.2.1 Example of bypass transition caused by wake of a single roughness particle

In Reference 10 it is shown that a roughness element generates a horseshoe vortex in the boundary layer, leading to a pair of counter-rotating vortices in the wake (Sketch 3.1), together with secondary vortices, not shown in Sketch 3.1.



Sketch 3.1 Vortex system produced by a cylindrical roughness element (from Reference 10)

These vortices interact with irregularities, such as T-S waves, causing early destabilisation. They thus bypass normal transition mechanisms such as the natural development of instability, *e.g.* that predicted by the Orr-Sommerfeld equation¹ for T-S waves.

4. ARTIFICIAL TRANSITION FIXING IN WIND-TUNNEL TESTING

4.1 Reasons for Fixing

- To establish transition in a low-Reynolds-number test at or near the transition location expected at high Reynolds numbers.
- To suppress unrepresentative shock-induced and/or trailing-edge separation in low-Reynolds-number tests at transonic Mach numbers^{1,2,3,4} by using aft fixing to match the full-scale boundary-layer characteristics at important locations on the wing². In this case the test transition location will differ substantially from that at full scale and suitable correction must be applied to the test results to allow for this.
- Reduce the complexity of wind-tunnel data analysis due to transition location drift during a test.

4.2 Requirements

- Fixing should be assured over a sufficient range of test conditions,
- The fix location should be precisely defined,
- The drag penalty caused by the device should be as small as possible and calculable,
- The device used should be easy to apply and repeatable.

5. TYPICAL SURFACE-MOUNTED DEVICES

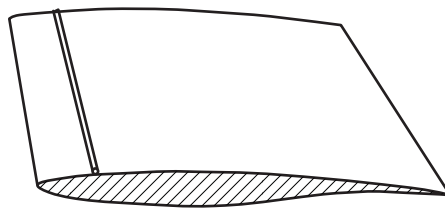
A protuberance associated with a passive device has a height that is small compared with the boundary-layer thickness but great enough to generate a disturbance in the boundary layer that is sufficient to trigger and sustain turbulence downstream of the device. Such a protuberance also causes an increase in boundary-layer momentum thickness, leading to an additional drag penalty.

The flow disturbance, produced by a device, is amplified (Section 3.2) leading to complete transition, which may occur immediately downstream of the device, or be delayed for some distance downstream. In either case a further distance may be required to obtain the fully-established turbulent boundary-layer profile.

Passive devices can be further sub-classified as continuous (*i.e.* unbroken in the spanwise direction) and distributed devices, which consist of discrete elements distributed in a narrow band along the span.

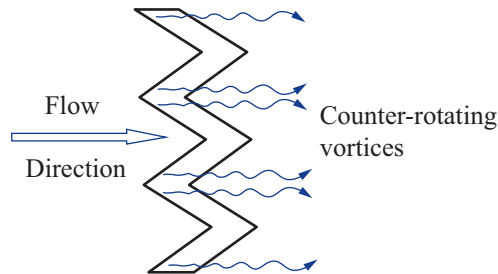
5.1 Continuous Devices

Sketch 5.1 shows a wire attached to the upper surface of an aerofoil as a continuous passive device to induce boundary-layer transition. Early transition is promoted by the wire wake and tests in incompressible flow⁷ indicate that complete transition is sustained when Re_e lies somewhere between 200 and 400 (where e is the height of the protuberance, *i.e.* the wire diameter). This device has the advantage that the wire dimensions are repeatable and can be closely controlled. Similar devices, such as a strip of rectangular cross-section may also be used.



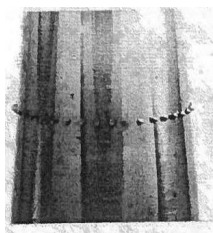
Sketch 5.1 Spanwise wire boundary-layer trip

Sketch 5.2 shows a zig-zag strip. This device causes transition by shedding pairs of streamwise counter-rotating vortices. According to Reference 8, for a given height of protuberance, the zig-zag strip is more effective than an equivalent straight strip of rectangular cross section, although it is more difficult to apply and gives a higher drag.

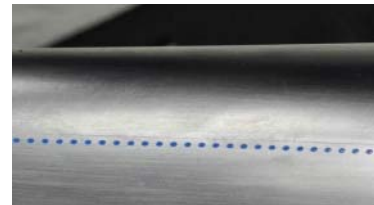


Sketch 5.2 Zig-zag strip

5.2 Distributed Devices



(a) Machined elements on cone
(from Reference 9)



(b) Cad Cut™ (Boeing disks) aeronautical
trip dots (Courtesy ARA Ltd)

Sketch 5.3 Examples of “single-row” distributed devices

The protuberances used in distributed devices, such as those shown in Sketch 5.3, will be expected to produce less drag than the equivalent continuous device but transition will not be achieved until the regions of turbulence produced by the individual elements have coalesced.

Dimensions of the elements in the “single-row” devices shown in Sketch 5.3 can be closely controlled. However, the machined elements (Sketch 5.3(a)) are difficult to manufacture and for this reason are of limited applicability. Cad-Cut™ dots, also known as Boeing disks, (Sketch 5.3(b)) are commercially available, of consistent geometry and easy to apply. They are available in a variety of thicknesses but are of relatively large diameter. In both cases these elements can be used in multiple rows but this may result in a transition band of high width.