



Extrapolating wind-tunnel data to full-scale Reynolds number Part 2: Procedures

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EXTRAPOLATING WIND-TUNNEL DATA TO FULL-SCALE REYNOLDS NUMBER Part 2: Procedures

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EXTRAPOLATING WIND-TUNNEL DATA TO FULL-SCALE REYNOLDS NUMBER Part 2: Procedures

1. INTRODUCTION

Dynamic similarity and its application to wind-tunnel testing at Reynolds numbers below full scale are fully discussed in Part 1¹. The present Data Item is concerned with the practical application of the concepts, described in Reference 1, to wind-tunnel testing in the transonic speed range, particularly as applied to typical transport aircraft configurations where the flow over substantial regions on the wing may be regarded as quasi two-dimensional under normal operating conditions. Normally this is the case for aspect ratios ≥ 4 approximately.

Particular attention is drawn in Reference 1 to the difficulties encountered in transonic wind-tunnel testing, where changes in Reynolds number often lead to substantial and rapid changes in the flow external to the boundary layer (“indirect Reynolds-number effects”^{1,2,3}) rather than comparatively small and gradual changes (“direct Reynolds-number effects”^{1,2,3}). Indirect Reynolds-number effects are particularly associated with separation originating near to the shock/boundary layer interaction and separation originating near a highly-loaded trailing edge. Interaction between these two separations is also of major importance.

Pearcey^{1,4} divided such interactions into two main classes. In the first of these there is no significant separation near the trailing edge until, with increasing lift coefficient or Mach number, a shock-induced separation bubble extends rearwards and eventually bursts. In the second class, a separation originates at the trailing edge and extends further forwards with increasing lift coefficient or Mach number, until it interferes with the development of the shock-induced separation bubble. Both of these classes are a major cause of indirect Reynolds-number effects. They are also complex and can be difficult to predict using computational fluid dynamics (CFD) methods, particularly in the case of separation emanating from a smooth surface in the absence of a shock wave. Furthermore, in wind-tunnel tests at Reynolds numbers lower than the full-scale value, such separations and interactions are prone to occur at a lower C_L for a given M and a lower M for a given C_L than is the case at full scale.

Where only **direct Reynolds-number effects** are involved, CFD is frequently used to extrapolate wind-tunnel results to higher Reynolds numbers. For example, where wind-tunnel tests have been made with natural transition, a CFD method can be run at the Reynolds numbers and transition locations corresponding to both test and full-scale (where transition usually occurs near the leading edge), in order to provide a basis for extrapolation. In this case the transition location on the model must be determined using, for example, the techniques described in Reference 6. An alternative method is to use a suitable technique to fix transition* at a location corresponding to the full-scale case†. CFD calculations are made, with this transition location, at both the test- and full-scale Reynolds numbers. The difference between the results of the two calculations is then used to extrapolate the wind-tunnel test results. Any CFD method used for this extrapolation must incorporate boundary-layer modelling capable of predicting trends due to Reynolds-number variation with sufficient accuracy. Where the dominating Reynolds-number effects are quasi two-dimensional (as is frequently the case on the high aspect ratio wing of a transport aircraft⁷) it is possible to employ a two-dimensional CFD code (e.g. VGK^{5‡}) to perform such extrapolation. Because of its ready availability, extensive use of VGK is made in this Data Item, for the purposes of illustration.

* Suitable techniques that may be used to fix transition include a surface roughness strip (transition strip), a discrete surface irregularity, such as a thin wire, or local air jets. In this Data Item the use of a surface roughness strip is assumed.

† Generally different transition locations will be required on upper and lower surfaces. In the case of a wing, a spanwise variation in transition location may also be required.

‡ In VGK, a potential flow calculation is coupled with an integral boundary-layer method and transition location is explicitly specified by the user. This specified transition location is overridden by VGK if the local skin-friction coefficient becomes less than 2×10^{-6} (see Reference 5). Where a two-dimensional CFD method is used for a swept wing, calculations are made at selected spanwise locations for the aerofoil profile and freestream Mach number component normal to the sweep direction and at a Reynolds number based on velocity and chord in this direction.

It is important to note that wind-tunnel tests are usually necessary, even if only direct Reynolds-number effects are significant, because CFD modelling may not estimate absolute values to the required accuracy. For example, in many CFD codes (including VGK) employing integral boundary-layer methods, transition is modelled by assuming an instantaneous change from laminar to turbulent flow, while retaining continuity in momentum thickness. In the real flow the transition region may be of significant extent¹. However, such CFD codes may still be employed to predict trends with sufficient accuracy to guide the extrapolation of wind-tunnel results.

When **indirect Reynolds-number effects** are present in wind-tunnel tests, the use of simple CFD extrapolations of wind-tunnel data is precluded, even if indirect Reynolds-number effects are absent at full scale. In this case the wind-tunnel data are first extrapolated to a Reynolds number (Re_C) above which indirect Reynolds-number effects are of small significance. CFD is then used to extrapolate from Re_C to full-scale Reynolds-number.

Estimation of Re_C requires a thorough understanding of the nature of the particular flow under investigation. Also, factors which influence the development of separations associated with indirect Reynolds-number effects should be systematically varied in the test to permit extrapolation of wind-tunnel data to conditions obtaining at Re_C . Where the Reynolds-number range available in the wind-tunnel tests is restricted, this variation is achieved by manipulating the boundary-layer thickness at a critical location (such as the shock location or the trailing edge) by fixing transition on the wind-tunnel model at a location downstream of that corresponding to the full-scale flow. This procedure, known as “*aft fixing*”, has the effect of thinning the boundary layer at the selected location, thus simulating the effect of a higher Reynolds number. Suitable “*simulation criteria*” must then be used to relate this apparent increase in Reynolds number to the chosen transition location.

For a typical transport aircraft configuration there are likely to be two situations in the transonic region where reliable prediction of full-scale behaviour from wind-tunnel tests is of particular importance. Firstly, the design cruise condition, where there may be local supersonic flow over the forward part of the wing upper surface and, further downstream, a return to local subsonic flow either with or without a weak shock. Secondly, near the buffet boundary, where there are likely to be relatively strong shocks and regions of separated flow.

At the design cruise condition, the problems to be addressed are the prediction of the increase in lift coefficient (at constant incidence) with increasing Reynolds number, together with accompanying changes in drag- and pitching-moment coefficients and the propensity of boundary-layer separation to extend upstream from the trailing edge.

Near the buffet boundary, interest lies in the increase in freestream Mach number or lift coefficient, beyond the design cruise condition, at which buffet onset may be expected.

The full-scale flow phenomena to be simulated vary according to the objectives of the test program. For example, the development of both shock-induced separation and separation from the trailing edge are particularly significant when investigating the buffet boundary. On the other hand, at cruise conditions, the influence of the boundary layer on shock position and strength and the thickness of the boundary layer near the trailing edge of a rear-loaded aerofoil will be important. Thus the choice of appropriate simulation criteria is complex, since it depends on the purpose of the test and, in a given test, more than one flow phenomenon may be involved.

The range of locations over which the use of aft fixing is effective is limited and may prevent the attainment of the boundary-layer thickness required to simulate conditions at or above Re_C . In this case the extrapolation will be subject to additional uncertainty. In spite of such limitations, however, methods based on the use of aft fixing frequently allow data obtained from wind-tunnel tests conducted at

Reynolds numbers significantly below full scale to be extrapolated to give full-scale predictions of useful accuracy. Such methods⁷ may also be used to extend the effective Reynolds-number range of a wind tunnel in which the facility exists to change the tunnel Reynolds number at constant Mach number (*e.g.* in a pressurised or cryogenic tunnel).

In this Data Item strategies are described for a number of test scenarios corresponding to the relative magnitudes of Re_C , the wind-tunnel Reynolds number and the full-scale Reynolds number. Methods are given to facilitate selection and use of suitable criteria that may be used to relate transition location to an effective Reynolds number greater than the nominal wind-tunnel Reynolds number.

2. NOTATION

A	location on curve of value measured at Re_A (see Sketch 3.2)
B	location on curve of value measured at Re_B (see Sketch 3.2)
B_{eff}	location on curve of value extrapolated to $Re_{B_{eff}}$ (see Sketch 3.4)
C	location on curve of measured values at Re_C (see Sketch 3.2)
C'	location on curve of CFD results at Re_C (see Section 8)
C_D	drag coefficient
C_L	lift coefficient
C_m	pitching moment coefficient
C_{m0}	pitching moment coefficient at zero lift
C_p	pressure coefficient
C_{pte}	pressure coefficient near trailing edge (upper surface)
c	chord length
c_f	local surface friction coefficient ($= \tau_w / (\rho u_e^2 / 2)$)
D	value at full-scale Reynolds number (see Sketch 3.2)
F	location on curve of value measured with $x_{trstrip} = x_{trf}$ at wind-tunnel Reynolds number (see Section 8)
F'	location on curve of CFD results with $x_{trstrip} = x_{trf}$ at wind-tunnel Reynolds number (see Section 8)
H_{i1}	boundary layer incompressible shape parameter immediately upstream of shock wave
l_b	length of separation bubble
M	Mach number
M_1	Mach number immediately upstream of shock wave
$M_{1buffet}$	Mach number immediately upstream of shock wave at buffet boundary
M_∞	freestream Mach number

Re	Reynolds number (based on model reference dimension (<i>e.g.</i> chord, c))
Re_A	minimum wind-tunnel Reynolds number
Re_B	maximum wind-tunnel Reynolds number
Re_{Beff}	maximum effective Reynolds number in aft-fixed test
Re_C	Reynolds number above which indirect Reynolds-number effects may be considered to be small
Re_{Ceff}	Re_C estimated using data from aft-fixed tests or CFD with transition specified at locations aft of full-scale location
Re_{Cf}	value of Re_C with transition at forward location corresponding to full scale
Re_{eff}	effective Reynolds number in aft-fixed test
Re_f	Re_{eff} corresponding to x_{trf}
$Re_{fullscale}$	full-scale Reynolds number
Re_{test}	test Reynolds number
$Re_{\theta 1}$	Reynolds number based on boundary-layer momentum thickness upstream of shock wave
T	location on curve of value measured with $x_{trstrip} = x_{trmax}$ at wind-tunnel Reynolds number (see Section 8)
T'	location on CFD curve with $x_{trstrip} = x_{trmax}$ at wind-tunnel Reynolds number (see Section 8)
T''	location of T' after CFD curve has been shifted to coincide with test results (see Section 8.8.5)
u	velocity in boundary layer, in x direction
u_e	velocity at edge of boundary layer, in x direction
$\bar{u}$	normalised velocity ($= u/u_e$)
X	particular parameter under investigation (see Section 8)
X_C	value of X at C
$X_{C'}$	value of X at C'
X_{Ccorr}	corrected value of X at C

X_{comp}	CFD estimation of X under full-scale conditions
X_F	value of X at F
$X_{F'}$	value of X at F'
X_{Fcorr}	corrected value of X at F
X_T	value of X at T
$X_{T'}$	value of X at T'
$X_{T''}$	value of X at T''
x	distance from leading edge of aerofoil or flat plate, measured along chord
x_{tr}	value of x at transition location
x_{trC}	value of $x_{trstrip}$ required to suppress indirect Reynolds-number effects (may be extrapolated value (see Section 8))
x_{trf}	value of $x_{trstrip}$ required to simulate full-scale flow according to chosen simulation criterion, i.e. giving $Re_{eff} = Re_{fullscale}$ (may be extrapolated value (see Section 8))
$x_{trfullscale}$	transition location at full scale
x_{trmax}	maximum permissible value of $x_{trstrip}$ if interference with upper-surface shock is to be avoided
$x_{trstrip}$	distance of transition strip downstream from leading edge
x_{ups}	value of x at position where upstream influence of shock wave is first encountered on an aerofoil
x_0	value of x at virtual origin of turbulent boundary layer
x_1	value of x immediately upstream of shock wave on an aerofoil
y	distance normal to surface
$\bar{y}$	normalised distance ($= y/\delta$)
α	incidence angle
ΔX	difference between CFD and test curves (see Sketch 8.10)
ΔX_C	$X_{C'} - X_C$

δ	boundary-layer thickness
δ_1^*	boundary-layer displacement thickness immediately upstream of shock wave
θ	momentum thickness of boundary layer
θ_{lam}	momentum thickness of laminar boundary layer
θ_{te}	momentum thickness of boundary layer at trailing edge
θ_{tr}	momentum thickness of boundary layer at transition
θ_{turb}	momentum thickness of turbulent boundary layer
θ_1	momentum thickness of boundary layer immediately upstream of shock wave
ρ	density
τ_w	shear stress at surface

3. EXTRAPOLATION METHODS

The methods by which successful extrapolation may be achieved are influenced by the characteristics of the available wind tunnel. In Reference 7 two main methods are described:

The *Reynolds-number “sweep”**; this is possible only if the stagnation pressure and/or temperature in the tunnel can be varied (see Section 3.1).

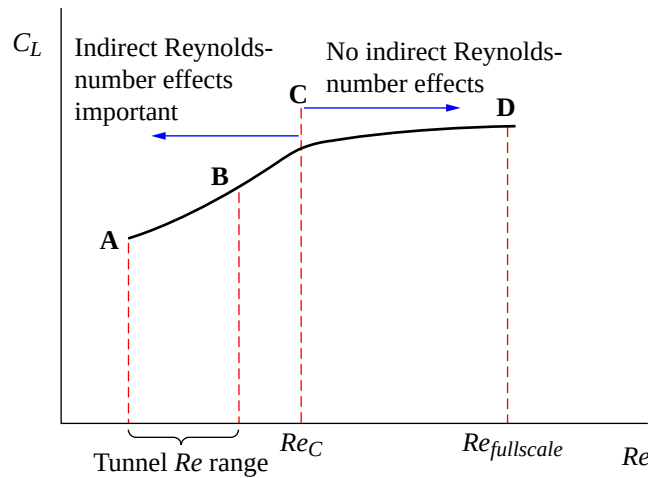
The *transition-location “sweep”*; this is the only option when stagnation conditions in the tunnel are essentially fixed (e.g. in an “atmospheric” tunnel) (see Section 3.2).

Of these methods, the first is the simpler and, for this reason, it is discussed first.

3.1 Extrapolation from Results Obtained for Several Reynolds Numbers (Reynolds-Number Sweep)

Sketch 3.1 shows, schematically, the variation of C_L with Reynolds number for a typical transport configuration at a constant transonic Mach number and incidence. Below Re_C significant indirect Reynolds-number effects occur, causing the form of the variation to differ from that above Re_C , where the effect of a change in Reynolds number on any separation is gradual and systematic, since only direct Reynolds-number effects are present. This makes it difficult to extrapolate to full-scale Reynolds number using measurements taken in the Reynolds-number range that is available in the wind tunnel (A to B in Sketch 3.1).

* “Sweep” is used here to refer to a systematic series of tests, conducted at selected values of the qualifying parameter (e.g. Reynolds number). When used in this sense, it has no connection with wing sweep.

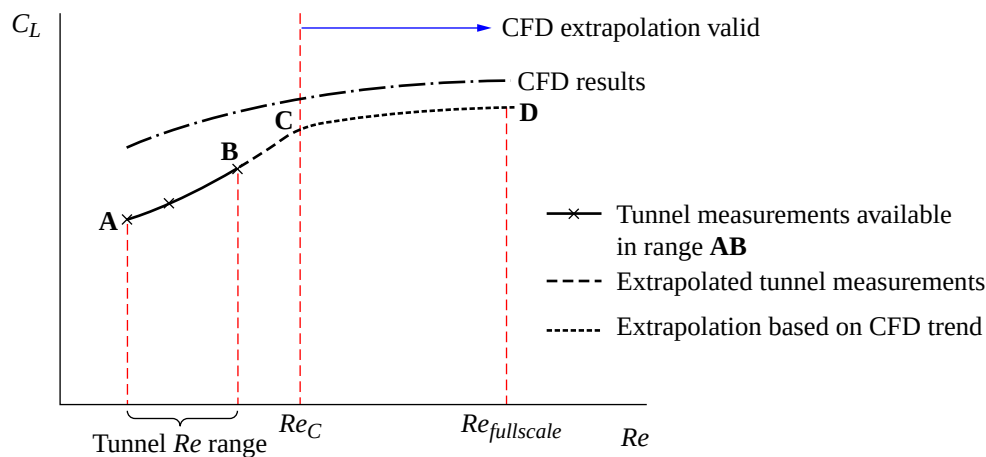


Sketch 3.1 Schematic variation of C_L with Re for a typical transport configuration at constant transonic Mach number and incidence

In Sketch 3.1, C_L is chosen as the dependent variable purely for the purpose of illustration and the form of the variation is not necessarily representative. It should be noted that such curves may not show an easily identifiable discontinuity at **C**, nor will the curve **AC**, where indirect Reynolds-number effects occur, be necessarily smooth and monotonic. The relative positions of points **B**, **C** and **D**, shown in Sketch 3.1, represent only one of a number of possibilities. Alternative scenarios are discussed in Section 5.

In the region **C** to **D** (Sketch 3.1), trends established using CFD codes, or theoretical methods, may be used to extrapolate wind-tunnel results to full scale since, even when the absolute accuracy of such predictions is inadequate, incremental values may be predicted with sufficient precision. Methods of suitable accuracy, which have the capability of predicting flows having no separation, or only restricted regions of separation, are available for this purpose (*e.g.* Reference 5 for aerofoils).

In the absence of a suitable prediction method for transonic flows having more extensive separation, such extrapolation is not advisable below Re_C (Sketch 3.2). Thus alternative means must be employed to derive point **C** from wind-tunnel tests which have been performed at lower Reynolds numbers.



Sketch 3.2 Extrapolation methodology

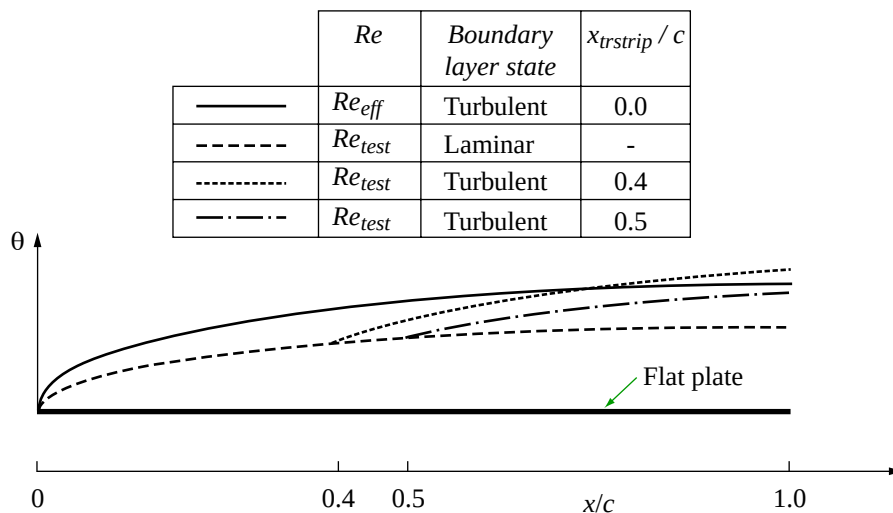
After Re_C has been determined (Sections 6 and 8.4), the portion **BC** of the curve may be obtained by directly extrapolating wind-tunnel measurements made in the region **AB** (although such extrapolation may be inaccurate, since indirect Reynolds-number effects may lead to a complex form for the curve in this region). This establishes point **C**. The full-scale result at **D** is obtained by applying the CFD trend to extrapolate from **C** to **D**. Where only a single wind-tunnel Reynolds number is available, the transition sweep method must be employed (Section 3.2).

In either case, the process depends on knowledge of Re_C , the determination of which is discussed in Sections 6 and 8.4.

3.2 Extrapolation from Results Obtained for Several Transition Locations (Transition Sweep)

If the Reynolds number in the wind tunnel cannot be varied independently of Mach number, an alternative means has to be found to establish the curve **AD** in Sketch 3.2. Essentially a means is required to manipulate the boundary-layer state at the test Reynolds number to reproduce flow features that occur at a higher Reynolds number. It will not be possible to reproduce the flow at this higher Reynolds number completely and a particular feature, or simulation criterion, must be selected. Control over the boundary-layer state may be exercised by moving the transition roughness strip from the position corresponding to full-scale transition (probably near the leading edge) to a point further aft. This is known as aft fixing. The effect of moving the transition location aft is to thin the turbulent boundary layer, thus simulating flow at a higher Reynolds number. This enables a chosen feature of the flow, at that higher Reynolds number, *e.g.* boundary layer momentum thickness at the wing trailing edge or shock wave location, to be matched.

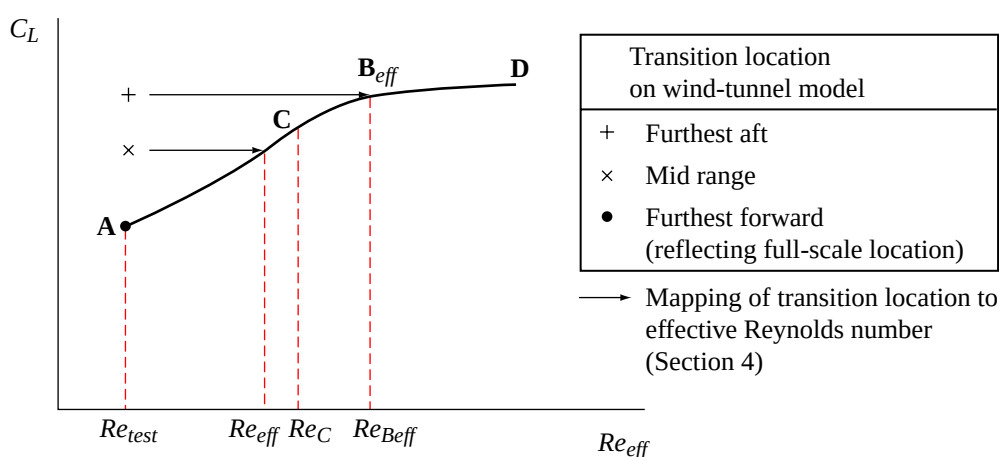
A particularly simple “flat-plate” simulation criterion⁷ may be used to establish a correlation between the location at which transition is fixed at the test Reynolds number and the correspondingly higher “effective” Reynolds number. In this criterion the trailing-edge momentum thickness on an aft-fixed flat plate, at the test Reynolds number, is matched to that on a plate with leading-edge transition at the higher effective Reynolds number. This is illustrated, schematically in Sketch 3.3, which shows both the turbulent boundary layer obtained at Re_{eff} , with transition at the leading edge of the plate, and boundary layers corresponding to the lower Reynolds number, Re_{test} , with artificial transition imposed at $x_{tristrip}/c = 0.4$ and 0.5 . For a transition location lying somewhere between $x_{tristrip}/c = 0.4$ and $x_{tristrip}/c = 0.5$, θ at the trailing edge of the plate is equal to that obtained at Re_{eff} with transition at the leading edge. Thus a correlation can be established between $x_{tristrip}/c$ and Re_{eff} , which will be applicable at the test Reynolds number, Re_{test} . In Section 4.1.1, a form of this correlation, established using simple boundary-layer theory and assuming instantaneous transition at the location of the transition strip, is presented (see also Appendix A).



Sketch 3.3 Reynolds-number mapping using the flat-plate simulation criterion

The mapping process is illustrated schematically in Sketch 3.4, where results, at a constant wind-tunnel Reynolds number, are shown for three different transition locations. The values determined for mid and aft transition points are mapped onto higher effective Reynolds numbers, Re_{eff} and Re_{Beff} , using the criterion illustrated in Sketch 3.3 (or another suitable criterion). In this illustration, the maximum effective Reynolds number, Re_{Beff} , lies above the point C. However an estimate of Re_C is still required (see Sections 6 and 8.4) in order to have confidence that B_{eff} lies within the region where CFD may be used as an extrapolation tool.

The flat-plate criterion, used here for the purpose of illustration, fails to take account of important features, such as the influence of local shock waves on the boundary layer. A variety of criteria may be used, the choice of which depends on the flow feature judged to be of critical importance. The mapping processes relating to common criteria are discussed in Section 4.



Sketch 3.4 Mapping transition aft-fixing location to effective Reynolds number

3.2.1 Limitations of aft fixing

The extent to which aft fixing is effective is limited. An obvious limitation is that the transition roughness strip must be located upstream of the point of natural transition on a wind-tunnel model. Natural transition may be caused by a variety of mechanisms (see Reference 1), including laminar separation prior to the roughness strip. It is also necessary that the roughness height in the strip is sufficient to cause transition, that there is no subsequent re-laminarisation and that the roughness height is low enough to avoid undue thickening of the local boundary layer. Guidance on suitable roughness characteristics to adopt is given in References 7, 8 and 9. During preliminary testing it is necessary to confirm that transition fixing has, in fact, been successful (see Section 7.2). The roughness strip should be situated well upstream of the shock⁷. In some circumstances, it may be possible to reduce the distance between the roughness strip and shock to 0.1c but a minimum separation of 0.15c is recommended for general use⁷. Also the roughness strip must not be so far forward as to influence supercritical flow development⁷ and care must be taken to avoid fixing transition in the region of a strong suction peak near the wing leading edge⁷. If the peak is immediately ahead of the roughness strip, there may be a significant interference between the expansion waves emanating from the region and the forward facing step introduced by the roughness strip. This can have very significant effects on the local pressure distribution. Situating the strip in the strong adverse pressure gradient immediately downstream of the suction peak may lead to boundary-layer thickening and possible adverse effects such as the promotion of trailing-edge separation.

4. SIMULATION CRITERIA FOR A TRANSITION SWEEP

In Section 3.2 the criterion chosen to map transition location to Re_{eff} is the simple flat-plate criterion⁷. This is, however, only one of a number of criteria which may be chosen and the appropriate criterion differs according to the nature of the flow being investigated and the purpose of the test.

The aim of the AGARD WG09 methodology⁷ is to manipulate the boundary layer in the wind-tunnel test (usually by aft fixing) to produce a match to a key flow feature which occurs at full-scale Reynolds number. Where this is not possible, the development of the chosen flow feature is examined up to the highest Re_{eff} attainable under the constraints of Section 3.2.1, in order to provide a basis for extrapolation.

The feature that is chosen defines the particular simulation criterion for the test and must be selected in the light of a sound knowledge of the physical properties of the flow. Generally the selection of a particular simulation criterion is the result of compromise and alternative criteria lead to different mapping relationships between the transition location and Re_{eff} . For this reason it is generally prudent to utilise more than one simulation criterion. The problem becomes more acute when Re_{Beff} is substantially lower than Re_C , because the influence of indirect Reynolds-number effects makes extrapolation from Re_{Beff} to Re_C very unreliable.

Criteria may be based on simple concepts, as is the case with the flat-plate criterion, or they may be derived from known empirical information, or from CFD calculation. In the last case the range of applicability may be limited since, not only may the code be incapable of correct representation of the indirect Reynolds-number effects (see Section 1 and Reference 1), it may also fail to produce converged solutions if these effects are severe.

In Table 4.1 the criteria presented are based on the two-dimensional flow over a flat plate or an aerofoil. For aircraft having wings of high aspect ratio, where much of the flow is of a quasi two-dimensional nature, such an approach proves acceptable, provided any three-dimensional effects are similar in the aft-fixed test case and the corresponding case at Re_{eff} to which it is mapped. If this is so, the three-dimensional effects will largely cancel and a mapping based on a two-dimensional criterion will be approximately valid.

In this Section the use of aft-fixing on the upper surface is discussed in detail and examples are given of several different criteria. The choice of criterion will depend on the particular flow feature of primary importance and the purpose of the test. The use of each criterion is discussed both in this Section and in Section 8.10, where specific test objectives are considered.

Although the discussion here relates mainly to the upper surface, the transition location on the lower surface is also important and should be chosen to minimise the influence on the upper-surface flow. This is discussed further in Section 8.2.

TABLE 4.1 Classification of simulation criteria *

Type I Match boundary layer for a simple flow to provide a Reynolds-number scaling independent of a particular test configuration.	Type II Match a feature relating to the external flow in the test configuration to give adequate simulation of indirect Reynolds-number effects.	Type III Match a local boundary-layer feature in the test configuration to allow assessment of direct Reynolds-number effects.
Specific criterion: I a. Match momentum thickness at trailing edge of flat plate.	Specific criteria: II a. Match shock-wave position. II b. Match shock-wave strength (taken as Mach Number immediately upstream of shock <i>i.e.</i> M_1).	Specific criteria: III a. Match momentum or displacement thickness at trailing edge of aerofoil (applicable to both upper and lower surfaces). III b. Match shape factor at important location. III c. Match extent of shock upstream influence. III d. Match shock-induced separation bubble length.
Note: The flat-plate criterion is very simple to apply and can be effective ⁷ when used to derive Re_{eff} . It is not applicable when shock-induced separation is dominant but is useful when predicting drag or onset of separation near the trailing edge.	Note: Type II criteria are used to account better for indirect Reynolds-number effects. Some mismatch usually remains; <i>e.g.</i> it may not be possible to match both shock strength and position simultaneously.	Notes: i. Type III criteria are used to match local boundary-layer conditions at the shock wave or other important locations. ii. Particular problems may exist when extensive shock-induced and trailing-edge separations are present.

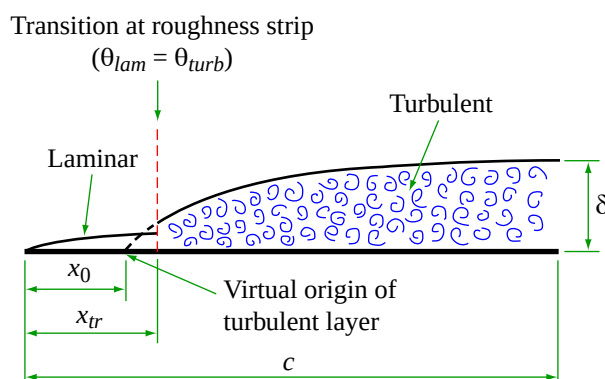
* In Reference 7, the terms “zero-level”, “first-order” and “second-order” are used to define types of simulation criteria. That usage is avoided in the present document since “first-order” and “second-order” have mathematical connotations that are inapplicable here. The correspondence between the two systems is shown below.

Present document	Type I	Type II	Type III
Reference 7 (page 101)	zero-level	first-order	second-order

4.1 Type I Criteria

4.1.1 The flat plate criterion (Type I a.)

The simple Type I criterion, the flat-plate criterion, is used as an example in Section 3.2. The criterion, described in Appendix A and Reference 7, is based on the assumption of an incompressible boundary layer. A suitable mapping, in which momentum thickness is matched at the trailing edge of the flat plate, may be obtained (Appendix A) from simple boundary-layer theory and empirical relationships for local surface friction coefficient¹⁰. This relates the transition location at the test Reynolds number, with aft fixing (Sketch 4.1), to Re_{eff} , corresponding to transition at the leading edge,



Sketch 4.1 Flat-plate criterion mapping function (vertical scale exaggerated)

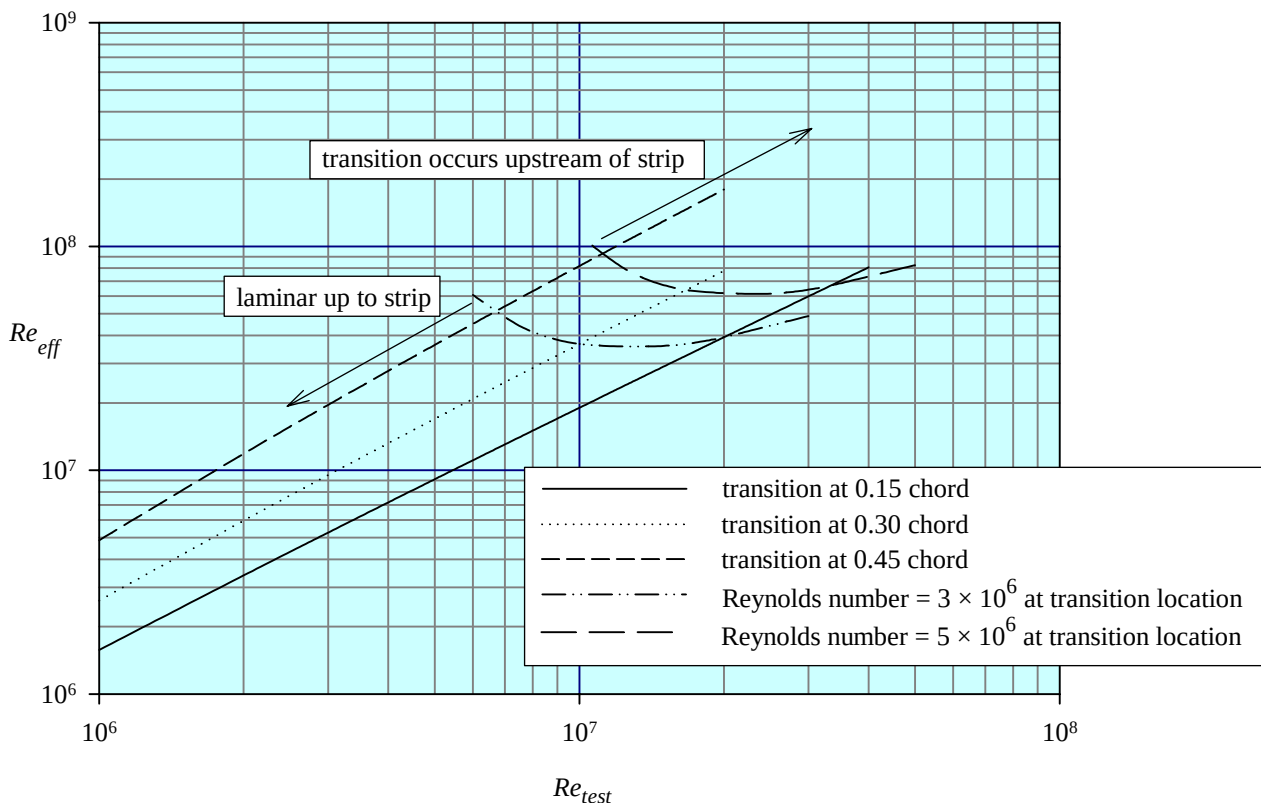
This mapping is defined (see Appendix A) by

$$\frac{x_0}{c} = \frac{x_{tr}}{c} - 41.58 Re_{test}^{-3/8} \left(\frac{x_{tr}}{c} \right)^{5/8} \quad (4.1)$$

and

$$\frac{Re_{eff}}{Re_{test}} = \left(1 - \frac{x_0}{c} \right)^{-4} = \left(1 - \frac{x_{tr}}{c} + 41.58 Re_{test}^{-3/8} \left(\frac{x_{tr}}{c} \right)^{5/8} \right)^{-4} \quad (4.2)$$

The mapping is illustrated in Sketch 4.2, which also includes boundaries to indicate when local Reynolds number at the transition strip reaches 3×10^6 and 5×10^6 . At local Reynolds numbers below 3×10^6 it is likely that laminar conditions will be maintained up to the transition strip. Above 5×10^6 it is extremely likely that transition will occur upstream of the transition strip, thus nullifying the use of the strip. It must be remembered, however, that these values apply to the flow over a flat plate at zero incidence. In a wind-tunnel test on an aerofoil or an aircraft configuration, the actual values are likely to differ from those quoted for the flat plate because of the influence of the pressure distribution around the model under test, as well as compressibility effects. In any test using aft transition it is, therefore, essential to employ methods, such as those of Reference 6, to ensure that premature transition or separation has not taken place and that full transition is obtained downstream of the transition strip.



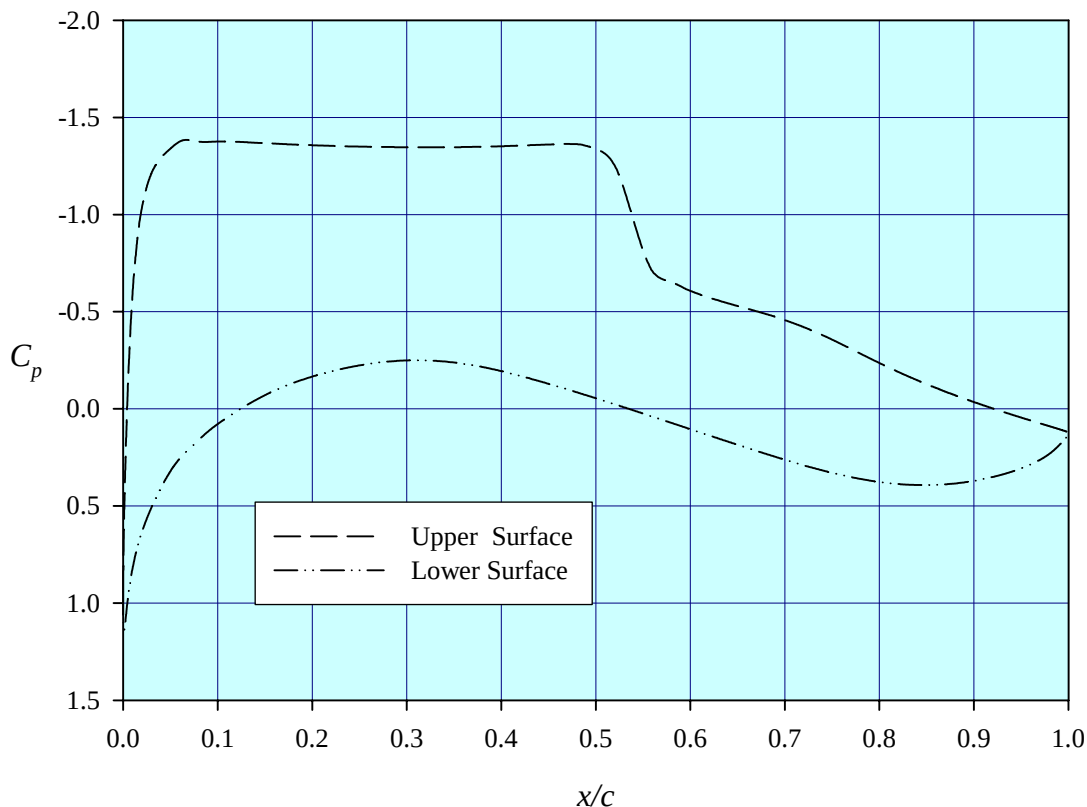
Sketch 4.2 Determination of Re_{eff} by matching θ at the trailing edge of a flat plate (flat-plate criterion)

In Reference 7 it is stated that, in spite of the very simple nature of the flat-plate criterion, it has proved effective in many cases. External pressure distribution and compressibility effects in the flow around a wing or aerofoil cause deviations from the basic flat-plate boundary layers that are, to some extent, similar when sufficiently downstream of the transition strip. Matching θ_{te} for the flat-plate flows therefore provides an approximate match between the boundary layers in the corresponding real flows, both at the trailing edge and for some distance upstream. This will be approximately true, even in the presence of a shock wave, provided shock-induced indirect Reynolds-number effects are not dominant and the transition strip location is not limited by proximity to the shock wave.

4.2 Type II Criteria

With Type II criteria, the aim is to match some flow feature external to the boundary layer. Shock position (Type II a.) or strength (Type II b.) are typical features which may be chosen. Shock position is matched in the following example.

Sketch 4.3 shows the pressure distribution (calculated using the VGK method) for an OAT15A aerofoil⁵ at a typical model-test Reynolds number. If constant incidence, rather than constant C_L , is specified, then the shock wave, shown in Sketch 4.3, moves significantly with change in either the Reynolds number or transition location.

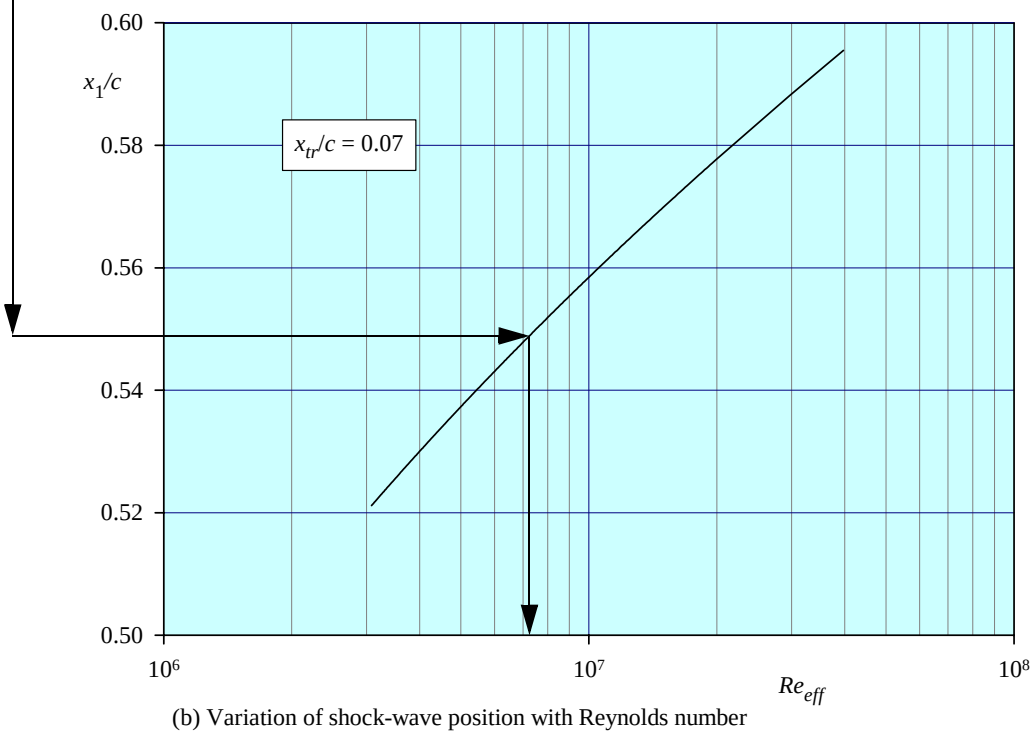
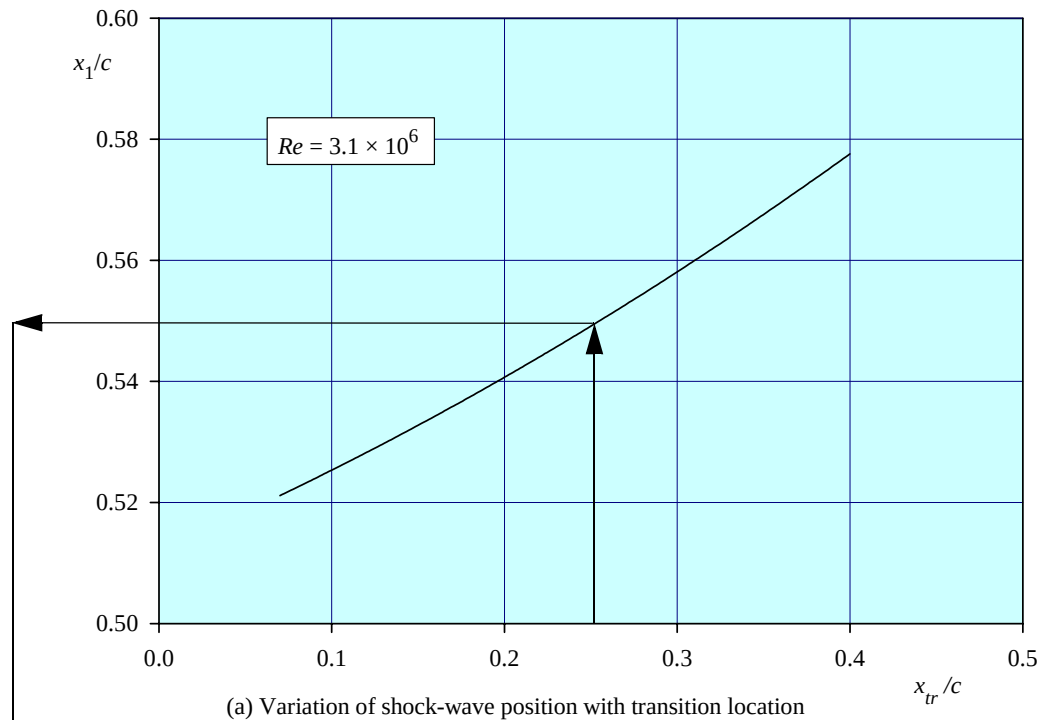


Sketch 4.3 Pressure distribution for OAT15A aerofoil ($\alpha = 2.525$ deg, $M_\infty = 0.724$, $Re = 3.1 \times 10^6$, $x_{tr}/c = 0.07$), derived using VGK

Here the appropriate mapping criterion is to regard a test at low Reynolds number, with aft-transition fixing, as equivalent to one at higher Reynolds number (the effective Reynolds number), with the same shock-wave location but with transition near the leading edge.

Sketch 4.4 shows how VGK may be used to achieve this mapping for the example case of an OAT15A aerofoil at $M_\infty = 0.724$ and $\alpha = 2.525$ deg. Sketch 4.4(a) shows the variation of shock-wave location (output, to the nearest grid point, by VGK) with transition position, for a typical wind-tunnel Reynolds number of 3.1×10^6 . Sketch 4.4(b) gives the corresponding variation of shock-wave location with Reynolds number, with transition location fixed near the leading edge ($x_{tr}/c = 0.07$). This was also estimated using VGK.

The arrows in Sketch 4.4 illustrate how a particular transition location may be associated with an equivalent effective Reynolds number. For example the point $x_{tr}/c = 0.26$ maps onto $Re_{eff} = 7.1 \times 10^6$. Sketch 4.5 shows the resulting variation of effective Reynolds number with transition location, obtained by this process.



**Sketch 4.4 Determination of Re_{eff} from predicted shock wave location
(OAT15A aerofoil at $\alpha = 2.525$ deg and $M_\infty = 0.724$), derived using VGK***

* In Sketch 4.4(b) $x_{tr}/c = 0.07$ is used rather than $x_{tr}/c = 0$ to avoid possible difficulties when forcing transition in the high pressure gradient at the nose