A REVIEW OF SCALE EFFECTS IN UNSTEADY AERODYNAMICS

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Abstract

The importance of scale effects is recognised generally in steady aerodynamics but is often ignored in unsteady aerodynamics. An attempt is made to remedy this situation by the compilation of a review of information on the influence of Reynolds number from a wide range of unsteady aerodynamic tests, with particular reference to wing flows. The unsteady tests considered are buffet and buffeting, dynamic tests of aerofoils and wings, pressure measurements, oscillatory control surface derivatives, and stability derivatives.

The review suggests that for the usual model conditions with fixed transition, scale effects are small for fully attached or well separated flows, but large close to incipient separation. In contrast, with free transition scale effects can be large for both attached and separated flows. Much more research is needed into the magnitude of scale effects on unsteady flows at transonic speeds.

Introduction

A comprehensive review of the problems of boundary layer simulation and control in wind tunnels is now available(1). This includes a review of boundary layer simulation procedures, a simulation/extrapolation methodology and a discussion of the physical aspects of boundary layer separation and the associated research requirements. However the emphasis is primarily on steady measurements, although there is some brief discussion of scale effects on buffet onset. Further evidence about scale effects on steady measurements is provided for combat aircraft by Peckham and Woodward(2) and for both combat and transport aircraft at transonic speeds by Haines(3).

The present paper provides a supplement to these references by reviewing the comparable evidence regarding scale effects on unsteady measurements, with particular reference to wing flows. This evidence is severely limited but it is enumerated here both to stimulate discussion and to ensure that the possibility of significant scale effects is considered when planning wind-tunnel and flight-test programmes for unsteady measurements. In preparing this brief review some evidence has had to be discarded due to uncertain aeroelastic effects.

Origin of scale effects and implications for unsteady aerodynamics

Scale effects as between measurements on models and aircraft in flight may be attributed to two inter-related causes which are discussed. Then options for investigating scale effects, and the character of scale effects are considered.

Origin of scale effects

Failure to achieve full scale Reynolds number

The common and generally recognised cause of scale effects is the inability of a wind-tunnel test to reproduce the full scale Reynolds number. The Reynolds number (based on an appropriate reference length) such as the aerodynamic mean chord $\bar{\bar{c}}$, or a boundary layer momentum thickness, θ , represents the ratio of the inertia forces in the fluid to the viscous forces. Based on the aerodynamic mean chord of a wing, the Reynolds number is typically in the range of only 10^6 to 10^7 for a model in a conventional wind tunnel, compared to 10^7 to 10^8 for an aircraft in flight. [The corresponding Reynolds number for a helicopter blade in flight would be between 4×10^6 to 6×10^6].

For fully turbulent local flows Reynolds number determines the thickness of attached boundary layers, the conditions for separation and the thickness of separated shear layers. Fig 1a shows an aerofoil at a high angle of incidence having a flow separation at about mid-chord for a low Reynolds number. The changes in boundary layer thickness as the Reynolds number is increased (Fig 1b) are large on the upper surface (with adverse pressure gradients) because of changes in separation position. The changes in boundary-layer thickness with Reynolds number are much smaller on the lower surface (with favourable pressure gradients and attached boundary layers). In this example the changes in separation position on the upper surface affect the overall circulation about the aerofoil and the pressure distribution on both surfaces. Hence according to Elsenaar(4) there are two types of Reynolds number effects. The first type are direct effects, due to variations in boundary layer thickness with a fixed pressure distribution. The second type are indirect effects, due to changes in pressure distribution caused by changes in boundary layer displacement thickness and wake effects. Fig 1c illustrates how both types of Reynolds number effect might be identified from steady pressure distributions.

Failure to achieve full scale transition position

The less familiar cause of scale effects is the failure of a model test to reproduce the position of boundary layer transition, x_t , appropriate to full scale. This short-coming can create scale effects even when the Reynolds number of the tunnel test duplicates the full scale value. For this condition often the transition position on the model will be further forward, either because of surface roughness or because of flow unsteadiness in the wind tunnel absent in flight. With the incorrect transition position, the attached boundary layer thickness will be incorrect, conditions at separation will be incorrect (separation may be advanced or delayed according to the details of the problem) and the thickness of the separated shear layers will be incorrect (Fig 2). With varying transition position, changes with Reynolds number are thus unlikely to be smooth and monotonic, particularly in the range from 10^6 to 10^7. Generally the failure to fix transition at an appropriate point on a wind tunnel model is probably more serious than the failure to reproduce the correct Reynolds number.

Possible methods for the investigation of scale effects

With two inter-related causes for scale effects (the incorrect transition position and the incorrect turbulent boundary layer thickness) model experiments might investigate the sensitivity of particular measurements by three possible methods. The objective is to be able to extrapolate from measurements on a model (say at $R\bar{\bar{c}} = 3 \times 10^6$) to predict the performance of an aircraft (say at $R\bar{\bar{c}} = 30 \times 10^6$). For transonic speeds boundary layer thicknesses and shock positions must be correctly represented.

The three methods are:

(1) Variations in transition fixed position at constant Reynolds number,

(2) Variations in Reynolds number with fixed transition,

(3) Variations in transition position combined with variations in Reynolds number.

The Reynolds number may be increased by increasing the model scale, or by increasing the free stream density at constant Mach number (as in a conventional wind tunnel) or by lowering the total temperature (as in a cryogenic wind tunnel). Method (1) is generally inconvenient but is exploited in some investigations. Only the transition position is being varied so that extrapolation to full scale is difficult. For Method 1 [unlike Methods (2) and (3)] the measurements have the same precision for every transition position. Two examples may be cited. It is fairly common practice at transonic speeds to vary the transition position (forced by roughness at constant Reynolds number) upstream of the shock, to provide a varying value of $R\theta$ there, as discussed by Haines[3]. An unusual and elegant application of this method was included *en passant* in Ashill's drag measurements on a large swept panel model[5]. Here transition could be controlled at constant Reynolds number by the injection of air along the leading-edge of a swept wing. [The unit Reynolds number was also varied for some tests].

Method (2) is exploited widely in pressurised wind tunnels, such as the RAE 8ft x 8ft Tunnel, but hitherto has been little used in the low speed RAE 5 m tunnel (possibly due to the difficulties of fixing transition at high lift condition at low speeds) or in the new cryogenic facilities. With only one parameter varied (Reynolds number), extrapolation to full scale should be possible, even if the measurements are not always monotonic.

Method (3) is exercised whenever wind tunnel tests are made with free transition and varying Reynolds number. With two parameters varied simultaneously it is much more difficult to extrapolate to full scale and changes with Reynolds number are unlikely to be smooth and monotonic. [Morkovin once proposed the term 'uncontrolled transition' for this method]. It is unfortunate that many tests in unsteady aerodynamics are made with free transition. This is particularly unfortunate when tests are made on NACA 0012 aerofoils, for which the static aerodynamic characteristics are known to be sensitive to variations in Reynolds number[6]. This practice has aroused concern[7]. The overall suitability of these three methods for time-dependent experiments must now be considered.

A special requirement for unsteady experiments is that the free stream flow without model motion should be as steady as possible. In practice for model tests this means that the flow unsteadiness must be low[8] and that transition should be at a fixed point. Free transition is itself essentially an unsteady phenomenon, characterised by intermittency in both space and time. During a model test it is undesirable that the position of transition should vary during a motion cycle (due say to the oscillation of a control or the bending of a wing), if such variations do not occur at full scale.

Method 3 thus appears excluded *a priori* from most model experiments in unsteady aerodynamics, (although it forms an important constituent of the methodology of boundary layer simulation recommended for steady aerodynamic measurements[1]). However, at full scale there may be situations where transition will vary during a motion cycle. An example occurs in the motion of a helicopter rotor blade. Full scale Reynolds numbers range from 4×10^6 to 6×10^6 and, as these can be reached on rotor blades with chords of say 100 mm, in the ARA two-dimensional tunnel, most aerofoil tests there are made with free transition. When transition does vary during a cycle large dynamic effects may be caused, eg the amplitude-limited single-degree-of-freedom flutter observed in Ashill's measurements on the swept panel model[6],[9].

In contrast Methods 1 and 2 both effectively offer fixed transition positions during a motion cycle and might therefore be considered equally suited to unsteady experiments. Despite this conclusion other factors must be considered when comparing the advantages of Methods 1 and 2. Method 2 has a variation in Reynolds number which has intrinsic advantages for all kinds of unsteady experiments. Two examples may be cited. For buffeting measurements in a conventional wind tunnel the variation in density (at constant velocity) allows a variation in aerodynamic damping at constant frequency parameter which is essential for valid extrapolation to full scale conditions[10]. For the measurement of oscillatory pressures the variation in density provides an indication of the accuracy of the measurements. Unfortunately Method 2 may give effects due to varying static aeroelastic distortion. Despite this difficulty Method 2 is preferred over both Methods 1 and 3 for experiments in time-dependent aerodynamics in conventional tunnels. In cryogenic wind tunnels Method 2 offers a direct indication of changes due to variations in Reynolds number[11]. This is because when the Mach number and total pressure are held constant, Reynolds number may be increased by lowering the total temperature. Then the kinetic pressure, and thence the static aeroelastic distortion should remain constant.

General character of scale effects

If Method 2 is adopted (ie transition is fixed and Reynolds number varied), a tentative attempt may be made to infer the general character of scale effects. For simplicity this discussion assumes that the effects of static aeroelastic distortion are small, or negligible, compared to the scale effect and that there is no tunnel interference.

Fig 3a reproduces the sketch (Fig 1a) of the flow on a conventional aerofoil at low and high Reynolds numbers at Mach number M and a high angle of incidence α giving separations on the upper surface. Generally direct scale effects will be comparatively small on the lower surface, where the boundary layers are thin at both Reynolds numbers, due to the strong favourable pressure gradient. In contrast, direct scale effects will be larger on the upper surface, due to the rear separation, provoked by the strong adverse pressure gradient. In addition there will be indirect scale effects on both surfaces due to the change in circulation produced by the movement in the separation position. Note that the magnitude of indirect scale effects will depend on whether the comparisons are made at constant angle of incidence (as here) or at constant lift coefficient. If comparisons are made at constant lift coefficient indirect scale effects will be different, at least for aerofoils. This is illustrated by some recent measurements of trailing-edge pressure divergence indicative of trailing-edge separation[12]. The changes with Reynolds number are much larger when comparisons are made at constant angles of incidence (Fig 3b) than they are when made at constant lift coefficient (Fig 3c). For a wing there is the additional complication of variations in the spanwise lift distribution.

For a transonic flow with a shock induced separation, Green suggested[13] that if the local momentum thickness Reynolds number exceeds a certain critical value (somewhere between $R\theta = 10^3$ and 10^4) subsequent increases in Reynolds number should produce monotonic and favourable scale effects, such that the onset of flow separation should be further downstream. There is evidence that this hypothesis is correct[3].

As shown in Fig 3a, local scale effects would be comparatively small for attached flow regions, very large near separation and large for the area of separated flow (for this is appreciably different in size). These remarks relate to the local flow at a particular Mach number and angle of incidence, but can be generalised, as suggested below.

With regard to the wider issues of the overall effects of variations in Reynolds number on the aerodynamic performance of an aircraft wing, a sensitive indication should be given by contours (in the M-C_L domain) for onset, light, moderate and heavy buffeting. These are the dynamic wing buffeting criteria[14],[15]. As an illustration, Fig 4 shows such criteria for a 45° swept wing with fixed transition[16], but corresponding contours could be drawn for all wings.

With regard to steady measurements (Fig 4a), say of the drag coefficient or lateral static derivatives, scale effects should be small for attached flow regions (below the buffet onset contour), very large for small separations between buffet onset and light buffeting and small again when the flow is very well separated (heavy buffeting). This last would be consistent with Townsend's suggestion[17] that because of the large length scales of well separated flow structures, changes due to variations in Reynolds number are unimportant. Between the heavy and moderate buffeting contours it is plausible to suggest that scale effects for steady flows are medium, and from the moderate to light buffeting contours that scale effects are large.

Unsteady experiments of all types are more difficult and often inherently less accurate than steady measurements. Hence it is reasonable to expect that scale effects will generally be lost within the experimental scatter for attached flow regions (below buffet onset) and for well separated flow regions at or above heavy buffeting). Thus it is plausible to expect that observed scale effects will be medium between the buffet onset and moderate buffeting and small between moderate buffeting and heavy buffeting (Fig 4b). Plainly the region near buffet onset will be sensitive to scale effects in unsteady aerodynamics.

The differences between steady and unsteady tests implied by Figs 4a and 4b takes no account of effects of frequency parameter, which are known to be important for certain separated flows. However, the evidence available for the variation of scale effects with frequency parameter is limited and still awaits careful investigations. Hence no particular range of frequency parameter can be assigned to Fig 4b.

This simplified and tentative view of the character of overall scale effects in time-dependent experiments, inferred from the physics of scale effects in steady flow (Fig 3a) is generally consistent with the detailed review of the different types of experiments which follows.

Review of different types of unsteady experiments

Comments are given on the magnitude of scale effects on the many different types of unsteady experiments, and how these results compare with the tentative classification suggested in Fig 4b. Fig 4 is itself derived from the boundaries for onset, light, moderate and heavy buffeting. Hence the first question addressed is the magnitude of scale effects on buffet and buffeting. Possibly these are the most important and difficult questions in unsteady aerodynamics.

Buffet is defined as the excitation (generally random) due to separated flow; buffeting is defined as the corresponding response of a structure[18]. The response may be in structural modes (such as wing first bending or fin torsion) but may be also in rigid body modes appropriate to aircraft handling characteristics both in flight and wind tunnel tests[19]. It is convenient initially to discuss the large volume of evidence about scale effect on buffet onset and then to discuss the limited evidence for scale effects on the severity of buffeting.

There is another reason for considering buffet and buffeting before other types of experiment. When buffet and buffeting problems are discussed it is assumed usually that the unsteady flows are independent of any small surface motions, ie all surfaces are assumed to be rigid. In contrast all the other types of unsteady aerodynamic experiments involve moving surfaces, eg dynamic tests of aerofoils and wings, unsteady pressures due to rapid control movements or stability derivatives. For brevity only unsteady flows associated with rigid surfaces are discussed here. Unsteady flows caused by moving surfaces are discussed elsewhere[20].

Buffet onset and incipient separation

Buffet onset generally correlates closely with the first local occurrence of incipient separation. Hence the type of incipient separation determines the character and magnitude of the scale effects. This may be illustrated with respect to scale effects on aerofoils (Fig 5).

Thin aerofoils (say less than 6%) in subsonic flow have a separation bubble close to the leading-edge, which extends progressively downstream towards the trailing edge as the angle of incidence increases. Scale effects are small with a very sharp leading-edge (rarely used) but much larger with a round leading-edge. Here scale effects are critically dependent upon the state of the relatively thin boundary layer between the leading-edge attachment line and the separation position (Fig 5a). With fully turbulent boundary layers separation is delayed as Reynolds number increases, ie scale effects are large and favourable.

In contrast, for thick aerofoils (say greater than 8%) in subsonic flow, with a trailing edge separation, scale effects are somewhat smaller because the boundary layer is usually turbulent and relatively thick at the trailing edge, even before separation extends upstream as incidence increases (Fig 5b). It should be noted that on a thick aerofoil, even at low Reynolds numbers with free transition, adverse pressure gradients should ensure boundary layer transition well upstream of separation.

For transonic speeds giving shock induced separation, two different classes of flow were identified by Pearcey et al[21]. For conventional sections, having relatively small rear loadings, the reattachment point downstream of separation moves very rapidly with increasing incidence from the shock to the trailing edge: this is classed as a Type A flow (Fig 5c). For Type A flows scale effects are normally considered relatively small for tests made with fixed transition. For more advanced sections, having relatively large rear loadings, with increasing incidence the shock induced separation bubble extends slowly downstream, while the separation from the trailing edge moves slowly upstream: this is classed as a Type B flow (Fig 5d). It is considered generally that for Class B flows scale effects can be large.

These generalisations for aerofoils may be extended to give some guidance for thin swept wings which represent the configuration of greatest importance for aircraft design. For low subsonic speeds, most moderately swept wings have a swept bubble type leading-edge separation, which extends progressively (inboard, outboard or downstream depending upon the thickness and camber distributions) as the angle of incidence increases (Fig 6a). By analogy with thin aerofoils, scale effects on buffet onset would be expected to be relatively large at subsonic speeds. This inference is confirmed by most experiments presented by Mabey[15]. However scale effects on wings are generally somewhat smaller than on the corresponding aerofoil. Fig 6b shows an interesting example of the variation of the incidence for onset with Reynolds number for a subsonic flow at $M = 0.3$ on an unswept wing with an NPL 9510 section[22]. This is a particularly important experiment because the measurements are made in a cryogenic wind tunnel. Here the aeroelastic effects are thought to be negligible because there is no apparent variation with kinetic pressure, q. With free transition the buffet onset boundary first increases from about $\alpha = 8°$ at $Rc = 0.7 \times 10^6$ to about $\alpha = 14°$ at $Rc = 4 \times 10^6$ (a favourable scale effect) and then falls as R increases to 18×10^6. Subsequent comparative measurements with transition fixed close to the leading-edge have given virtually identical results. These measurements have not yet been explained and this indicates the difficulty of correctly forecasting scale effects from isolated measurements at a single Reynolds number.

For transonic speeds most moderately swept wings have shock induced separations, with Type A or Type B flows (Fig 6c and 6d). By analogy with aerofoils, scale effects should be relatively small for Type A flows, but large for Type B flows. Fig 6e shows an interesting example of transonic flow on a high aspect ratio wing with $\Lambda = 25°$. For these tests[23] transition was fixed close to the leading-edge. As seen in Fig 6e at $M = 0.80$, for instance, Type A flow was thought to occur at high Reynolds number (above 15×10^6) whereas two different forms of Type B flow were observed at lower Reynolds number. These changes would make considerable differences to the buffet excitation close to buffet onset which excites wing bending and also to the pressures generated by wing motions in the torsional mode which excite "wing buzz".

For more highly swept wings (say $\Lambda > 55°$) the swept bubble type separation is replaced by a vortex, which has a characteristic pattern in sur-face oil flow studies. For highly swept wings with sharp leading edges, scale effects are commonly regarded as being small, because separation is fixed at the leading-edge. Nevertheless significant scale effects were observed between wind tunnel and flight measurements of steady and fluctuating pressures on the prototype of the Concorde aircraft, which has a sharp leading-edge.

For highly swept wings with round leading-edges the separation point is not fixed. Hence for these wings, for conditions near buffet onset, scale effects are generally very large, both within the Reynolds number range of wind tunnels and even in flight experiments. Thus on the F106B aircraft (with a 60° delta wing) the vortex core moves outboard and becomes smaller as Reynolds number increases[25].

The type and magnitude of scale effects on highly swept wings with round leading-edges which occur near buffet onset may be inferred from observations at constant Reynolds number of $Rc = 3 \times 10^6$ on a wing with 55° leading-edge sweep[25]. Transition is fixed at the leading edge on the port wing, which thus should give an indication of the wing flow at much higher Reynolds numbers. Transition is free on the starboard wing, and illustrates some interesting features of flow at low Reynolds numbers which are probably not typical of flows at much higher Reynolds numbers. No buffeting measurements were made on the model, but buffet onset on both wings can be inferred from tests on many other models with similar types of surface flow patterns. Fig 7 shows an unusual set of surface flow studies for M = 0.80 with the original interpretation[25]. For $\alpha = 2.2°$, $C_L = 0.12$, (Fig 7a) on the port wing the flow is fully attached, as would be expected. However, on the starboard wing there is already a small laminar separation bubble near the leading-edge (outboard of 0.75 semi-span) followed by turbulent re-attachment. In-board of this laminar separation turbulent wedges extended from imperfections in the leading edge through the attached laminar flow region, clearly marking the main transition front. This condition should be just after buffet onset on the starboard wing, with no buffeting on the port wing.

For $\alpha = 4.3°$, $C_L = 0.25$, (Fig 7b) on the port wing outboard of about 0.67 semi span there is a region of strong spanwise flow, which is consistent with an array of small vortices, lying chordwise. The excitation from such an array of small vortices would be at such high frequencies that the wing first bending mode probably is not excited. Hence it should be a conservative assumption that this condition represents buffet onset on the port wing. In contrast, on the corresponding, outboard area on the starboard wing there is now a single, primary vortex. Experience suggests that this vortex would certainly produce pressure fluctuations at a sufficiently low frequency to excite the wing first bending mode, and create light buffeting (this may be inferred after a careful study of separation patterns and buffeting contours). Inboard of this vortex there is a laminar separation bubble followed by turbulent reattachment. This bubble is a low Reynolds number feature of the flow which may have little relevance to full scale flows. If the inferences made here are accepted, the failure to fix transition would have lowered the buffet onset from a C_L of just above 0.25 to only 0.12. An increase of 0.13 in C_L for buffet onset between wind tunnel and flight tests in quite common for highly swept wings, even with fixed transition (see Ref 15) and this makes accurate predictions quite difficult.

It is interesting to note that although similar differences between the port and starboard wing flows persist even at $\alpha = 6.5°$ ($C_L = 0.37$, not illustrated here) there are few differences in the flow at $\alpha = 8.6°$, $C_L = 0.48$ (Fig 7c). These differences are confined to the area of secondary separation. There are no differences at higher angles of incidence. In view of the closeness of the separation line to the leading-edge for $\alpha > 8.6°$, it would be reasonable to assume that scale effects should be small for this condition, corresponding with moderate buffeting. Taken together, Figs 5,6 and 7 provide general, albeit somewhat simplified, guidance on the character of scale effects on buffet onset over a wide range of wings, and thus provide a reference for typical flight/tunnel comparisons.

Many recent wind tunnel measurements with fixed transition at higher Reynolds numbers have been compared with more precise flight measurements, but often such comparisons are good for one aircraft but poor for another, without any certain explanation for the difference. The most comprehensive tunnel/flight comparison currently available[26] relates to the F 1-11 TACT aircraft, with wings swept 26° and 36° at M = 0.80 and 0.90. These comparisons show no significant scale effect on buffet onset, within the wind-tunnel test range of 7×10^6 to 14×10^6 and flight measurements at 25×10^6. For the wind-tunnel tests transition was fixed at about $x/\sqrt{c} = 0.10$, rather than x/c = constant (as is usual practice). Thus the roughness band was further downstream relative to the local chord at the wing tip than at the wing root. This places the roughness band at an approximately constant % of the local chord upstream of the swept shock on the wing at transonic speeds. This unusual choice of roughness position may contribute fortuitously to the good simulation of full scale conditions achieved in these tests.

Severity of buffet and buffeting

The severity of buffet (excitation) and buffeting (response) depends on how the separations develop after buffet onset. It is reasonable to suggest that where the separations develop differently as Reynolds number varies (say as indicated by variations in steady forces or surface flow visualisation) the buffet excitation also is likely to vary. However, only a few direct comparisons of this type are currently available. Here we will refer briefly to the extensive comparisons[26] for the F 1-11 TACT aircraft (which is very stiff compared say, to a large transport aircraft). The data generally show excellent correlation of pressure fluctuation measurements on models and aircraft except in the regions of shock waves and near separation onset boundaries. It is expected that Reynolds number and static aeroelastic distortion are the most important effects. Static aeroelastic distortion should have a larger effect at a spanwise station $\eta = 0.910$ than at $\eta = 0.744$ or $\eta = 0.578$.

These effects are illustrated in Fig 8, which shows some typical comparisons of $C_{p_{rms}}$ versus incidence for $M = 0.80$ and $\Lambda = 26°$. The difference between the wind tunnel ($\overline{Rc} = 14 \times 10^6$) and flight measurements ($Rc = 25 \times 10^6$) are generally small, except at $x/c = 0.06$ on all three sections (where adverse scale effects are observed, the shock moving upstream at the higher Reynolds number). A similar adverse scale effect was observed between the wind tunnel measurements at $\overline{Rc} = 7 \times 10^6$ and 14×10^6. Here the effects of static aeroelasticity were eliminated by comparing measurements on steel and aluminium models having the same static aeroelastic distortion because the ratio (model stiffness/kinetic pressure) is the same. It is curious that this adverse scale effect for $x/c = 0.06$ does not continue in the flight measurements for $\eta = 0.744$. Perhaps this local scale effect occurs only within the wind tunnel test, because $x/c = 0.06$ is just upstream of the roughness band. Ref 26 suggests that scale effects on the aircraft are small within the range from $\overline{Rc} = 25 \times 10^6$ to 40×10^6, at least for $\eta = 0.744$.

In summary, although there are significant local differences between model measurements at $\overline{Rc} = 7 \times 10^6$ and 14×10^6 there are only small differences between model measurements at $\overline{Rc} = 14 \times 10^6$ and flight measurements at $\overline{Rc} = 25 \times 10^6$ and 40×10^6. This illustrates the difficulty of attempting to extrapolate with measurements available at only a few Reynolds numbers. No other comparisons as comprehensive as these are available elsewhere.

The discussion of scale effects on the local buffet excitation is relatively easy compared with the more difficult question of scale effects on buffeting. The difficulty arises because the buffeting (response) is determined not only by the excitation, but by the total damping in the structural mode. The total damping often includes significant aerodynamic damping. Thus in both flight and ordinary wind tunnel tests variations in Reynolds number involve variations in kinetic pressure and total damping. [This is frequently ignored in the presentation of both flight and wind tunnel tests]. Faced with this difficulty, the only practical way to isolate genuine scale effects is to compute the buffet excitation parameter, $\sqrt{nG(n)}$, in every mode.

$$\sqrt{nG(n)} = \frac{2}{\sqrt{\pi}} \cdot \frac{m\ddot{z}}{qS} \cdot \zeta^{\frac{1}{2}} \qquad (1)$$

with m = generalised mass in mode with respect to motion at tip,
$\ddot{z}$ = rms tip acceleration in mode,
q = kinetic pressure,
S = reference area,
ζ = total damping - as ratio to critical damping.

In the few experiments where careful comparisons have been made between the buffet excitation parameter in flight and wind tunnel tests(14),(27) scale effects are comparatively small, except in the region of buffet onset.

It is appropriate to close this section with a discussion of the advantages of cryogenic wind tunnels when assessing the magnitude of scale effects on the severity of buffeting according to equation (1). Kilgore et al showed that the cryogenic wind tunnel offers two great advantages for steady and unsteady model tests(11).

(1) A wide range of Reynolds number can be covered on a single model at constant kinetic pressure (and hence constant static aeroelastic distortion).

(2) Reynolds number may be held constant while kinetic pressure is varied, thus giving constant scale effects and varying static aeroelastic distortion.

In addition, cryogenic tunnels possess a special advantage for buffeting tests(28) on ordinary wind tunnel models. As compared to conventional wind tunnels, in cryogenic tunnels at the same total pressure and Mach number, aerodynamic damping is large relative to structural damping, as in flight. This makes extrapolation from wind tunnels to flight (using equation 1) much easier.

Currently only Boyden of NASA Langley has exploited these advantages of cryogenic wind tunnels for buffeting tests(22). His published measurements suggest that on a 65° delta wing with sharp leading-edges there are no Reynolds number effects, although there are significant effects of both static aeroelastic distortion and of frequency parameter. Also for the low aspect ratio unswept wing with an NPL 9510 section shown in Fig 6b (deliberately selected because of its sensitivity to scale effects) Reynolds number effects on the severity of buffeting are small with both free and fixed transition, according to a preliminary analysis of the comparative tests.

Periodic flows on rigid aerofoils at transonic speeds

On rigid aerofoils and wings there is an important class of periodic flows which can occur over a narrow Mach number range at transonic speeds. These periodic flows have interesting scale effects, radically different for fixed and free transition. They will be illustrated primarily with respect to measurements on a rigid 14% thick biconvex wing(29).

Fig 9 illustrates the types of flow which can occur at $\alpha = 0°$ with fixed transition. The region of periodic flow (from $M = 0.82$ to 0.86) is characterised by large amplitude shock oscillations which occur with 180° phase difference between the upper and lower surfaces. (For the 14% thick wing the shock motion is classified(30) as Tijdeman Type B but Type A and C shock motions may occur with lower or higher thickness/chord ratios or with different wing sections). With transition fixed close to the leading-edge the narrow range of Mach number within which periodic flow occurs is independent of Reynolds number from about $Rc = 0.5 \times 10^6$ to $Rc = 7 \times 10^6$. Similar results are observed with transition fixed upstream of the shock (at $x_k/c = 0.43$). Accordingly scale effects are judged small with turbulent boundary layer/shock interactions.

The boundaries for periodic flow with free transition (Fig 10a) are radically different from those with fixed transition and illustrate the dangers of testing with free transition. At the lowest Reynolds number, $Rc = 1 \times 10^6$, the periodic flow extends from M = 0.80 to 0.88. As the Reynolds number increases the Mach number range for periodic flow becomes progressively smaller, until it disappears very suddenly at a Reynolds number of 3.4×10^6 and then re-appears at Reynolds number of 4.8×10^6. Other tests[31] indicate that an increase in boundary layer thickness (achieved by varying roughness heights) will reduce the region of periodic flow with both laminar or turbulent boundary layers. Hence the reduction in the region of periodic flow with the increases in Reynolds number may reasonably be attributed to an increase in the thickness of the boundary layer at the shock. The increase in boundary layer thickness is caused by the forward movement of transition, either in an attached boundary layer, or in a separated shear layer.

The disappearance of the periodic flow over the Reynolds number range from 3.6×10^6 to 4.8×10^6 was unexpected. However an explanation can be offered. The periodic flow involves large chordwise movements of the shock, from about $x/c = 0.55$ to 0.75, on opposite surfaces of the aerofoil (Fig 10b). Within this region of the aerofoil, the hypothesis is made that the boundary layer is in the same state (ie either fully laminar or fully turbulent), for otherwise the intermittency characteristic of a transition region would surely seriously inhibit the development of periodic shear layers and shock movements. The intermittency of the transition region is determined by the rate of growth and decay of turbulent spots within the laminar boundary layer. This process varies both in time and in space. Based on this assumption the intermittency of the transition region could interrupt the large chordwise movements of the shock and destroy the two-dimensionality of the motion inferred from the shadowgraph and the oil flow pictures.

According to this hypothesis, the sudden collapse of the periodic flow (at $Rc = 3.3 \times 10^6$) corresponds with the onset of transition, at a local Reynolds number, R_{x_t} at $x/c = 0.75$. As shown in Fig 18b this gives:

$$R_{x_t} = 3.3 \times 10^6 \times 0.75 = 2.7 \times 10^6 \quad (2)$$

The re-establishment of the periodic flow (at Rc 4.8×10^6) corresponds with the completion of transition, R_{x_T}, at $x/c = 0.55$, where

$$R_{x_T} = 4.8 \times 10^6 \times 0.55 = 2.7 \times 10^6 \quad (3)$$

The agreement between equations (2) and (3) both confirms the hypothesis and indicates that the boundary layer transition is sudden, as the direct result of the shock wave/boundary layer interaction, and probably associated with separation. This is, of course, in complete contrast to the more gradual transition process observed on flat plates or slender cones, where there is no shock and where the pressure gradient is small[32].

Once the periodic flow is re-established (at $Rc = 4.8 \times 10^6$), further increases in Reynolds number slightly decrease the thickness of the turbulent boundary layer and hence slowly increase the Mach number range for periodic flow, until at $Rc = 7 \times 10^6$ periodic flow extends from M = 0.83 to 0.86. Hence this type of periodic flow could certainly occur at full scale Reynolds numbers as high as 10^8. The complete and misleading disappearance of the periodic flow over the Reynolds number range from $Rc = 3.3 \times 10^6$ to 4.8×10^6 (typical of model tests in many transonic tunnels) is a caution against attempting to simulate full-scale conditions more closely by tests with free transition at moderate Reynolds numbers at transonic speeds.

Conclusions and recommendations

The unsteady experiments reviewed here for rigid surfaces and elsewhere[20] for moving surfaces confirm the four principal suggestions advanced initially.

(1) With free transition scale effects can be very large and non-monotonic.

(2) With fixed transition scale effects are more likely to be monotonic and large effects are generally confined to the region close to the onset of flow separation.

This conclusion has important implications with respect to the prediction of any unsteady phenomenon involving separation, such as buffet onset or dynamic stall tests.

(3) Scale effects in unsteady transonic flow are of great importance and have been considered only briefly here. Other information exists but much more research (both theoretical and experimental) is essential, particularly with respect to the buffet onset boundaries of transport aircraft.

(4) A careful assessment must be made between the magnitude of direct and indirect scale effects. If comparisons are made at constant lift coefficient, indirect scale effects may be smaller, at least for aerofoils.

Overall the review reveals an unsatisfactory situation with regard to scale effects in both experimental and theoretical unsteady aerodynamics. It is recommended that unsteady experiments should be made with fixed transition and varying Reynolds number and/or with various fixed transition positions as recommended for steady experiments in Ref 1. A similar recommendation is made with respect to theoretical studies. For the few problems in time-dependent aerodynamics where computational fluid dynamics (CFD) does provide predictions, such predictions are presented generally for a comparison with a model experiment at a single, low Reynolds number (say 10^6). For such problems it is recommended that in addition predictions should be made always either with fully turbulent boundary layers at much lower and much higher Reynolds numbers (say 10^4, 10^5, 10^7, and 10^8) or at fixed Reynolds number with varying transition. Such theoretical studies might prove helpful in resolving many anomalies observed currently in experiments in time-dependent aerodynamics. Three important test cases, which might be studied theoretically are suggested elsewhere(20). These test cases have been considered already for a few limited Reynolds numbers and restricted transition positions(33),(34).

List of symbols

c, $\bar{c}$, $\bar{\bar{c}}$	local, mean and aerodynamic mean chords
C_L	lift coefficient
C_N	normal force coefficient
C_p, $C_{p_{rms}}$	steady and rms pressure coefficient
f	frequency (Hz)
$\sqrt{nG(n)}$	buffet excitation parameter in first wing bending mode (eqn 1)
M	free stream Mach number
m	generalised mass (eqn 1)
$q = \frac{1}{2}\rho U^2$	kinetic pressure
R	unit Reynolds number
S	exposed wing area (eqn 1)
U	free stream velocity
$x, y, z,$	co-ordinates (x streamwise)
x_t	boundary transition position (mean or onset)
x_T	completion of transition
xk	roughness position
$\ddot{z}$	tip acceleration (eqn 1)
α	incidence (°)
ζ	total damping (as a fraction of critical, eqn 1)
θ	boundary-layer momentum thickness
η	semi-span ratio
Λ	wing leading edge sweep
$\nu = \omega c/U$	frequency parameter based on appropriate length
$\omega = 2\pi f$	circular frequency (rad/s)

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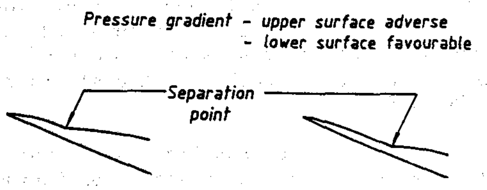
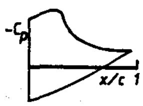
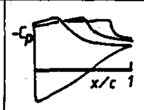
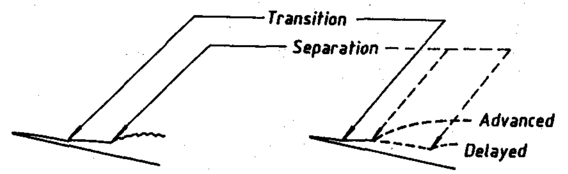


(a) Low Reynolds number *(b) High Reynolds number*

	DIRECT	INDIRECT
Pressure distributions	 Constant	 Variable
Circulation	Constant	Variable
Magnitude of scale effects on lift	Often small and predictable	Large and may be unpredictable

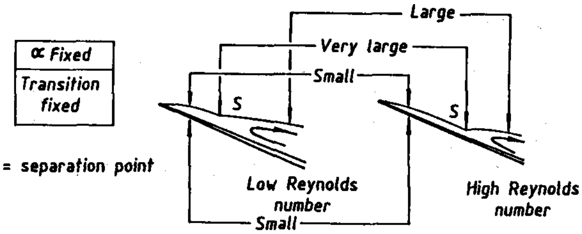
(c) Differences between direct and indirect effects

Fig. 1 Origin and nature of scale effects



(a) Correct *(b) Premature (due to roughness or free-stream flow unsteadiness)*

Fig. 2 Influence of transition position at full scale Reynolds number on aerofoil separation



(a) Local effects

Fig. 3 Scale effects on an aerofoil with separated flow (M, α, or C_L fixed)

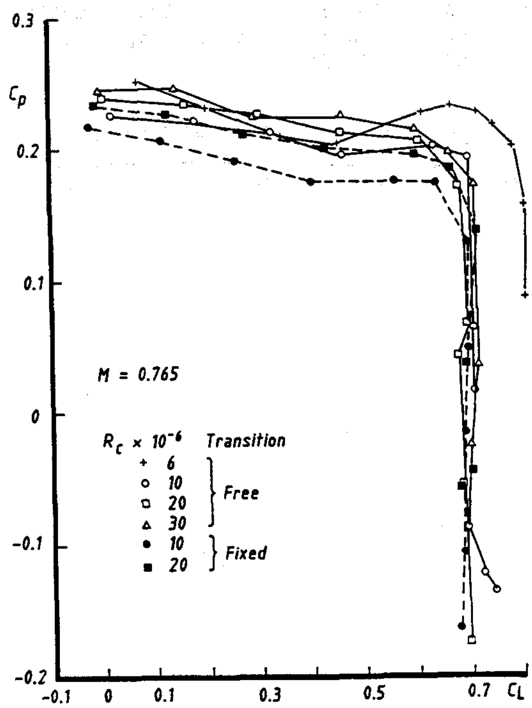


Fig. 3 (c) Scale effects on trailing-edge pressure coefficient at constant C_L (after Ref. 12)

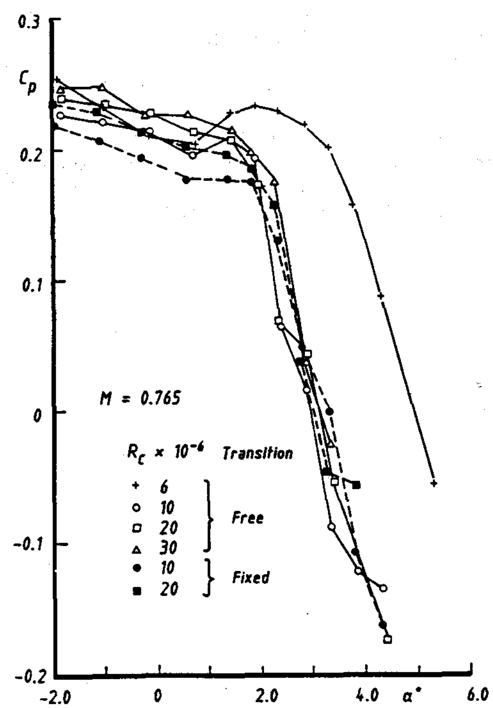


Fig. 3 (b) Scale effects on trailing-edge pressure coefficient at constant α (after Ref. 12)

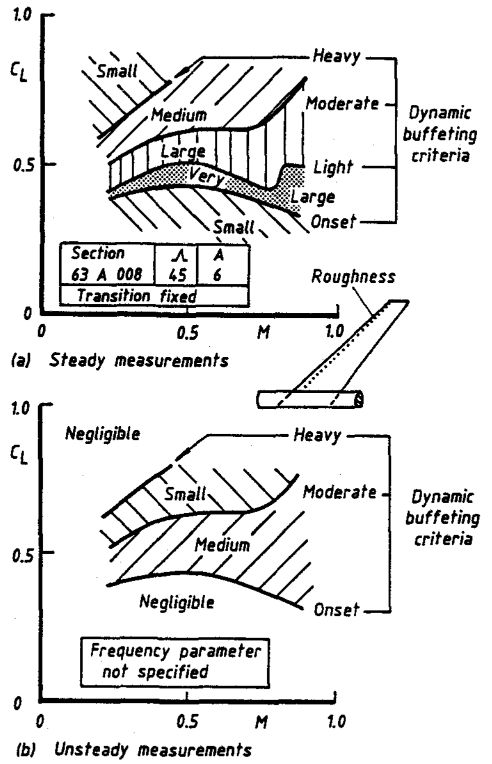


Fig.4 Tentative assessment on overall scale effects on a typical swept wing (after Ref.16)

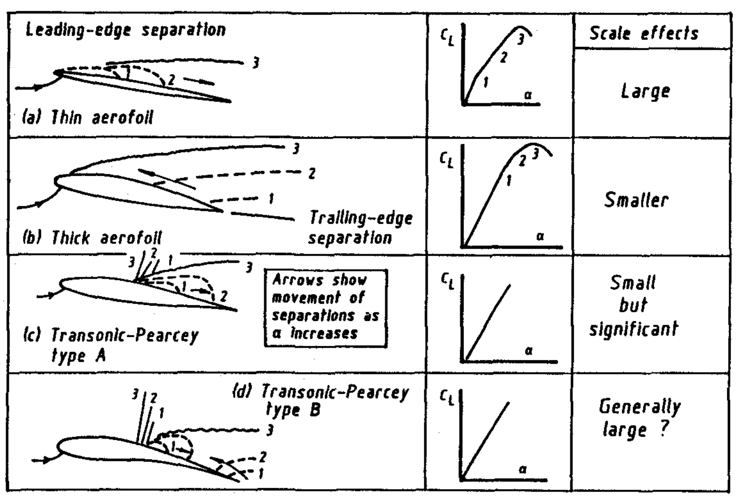


Fig.5 Types of flow separation and lift characteristics of aerofoils and typical scale effects

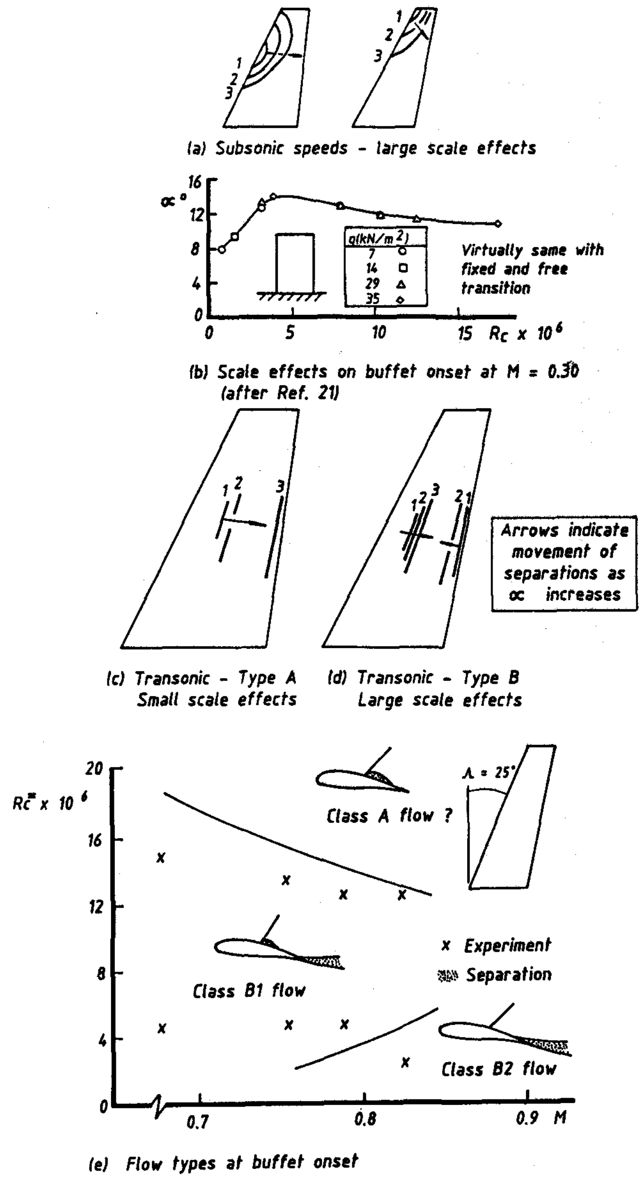


Fig.6 Types of flow separation on wings of low/ moderate sweep and corresponding scale effects

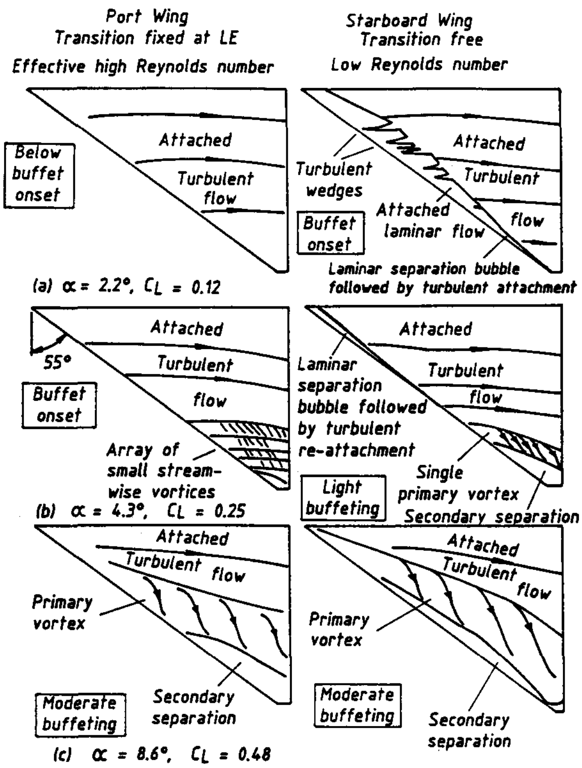


Fig.7 Typical inferred scale effects on highly swept wings. M = 0.80, $R_{\bar{c}}$ = 3 x 10⁶ (after Ref. 22 : 6% RAE 101 section)

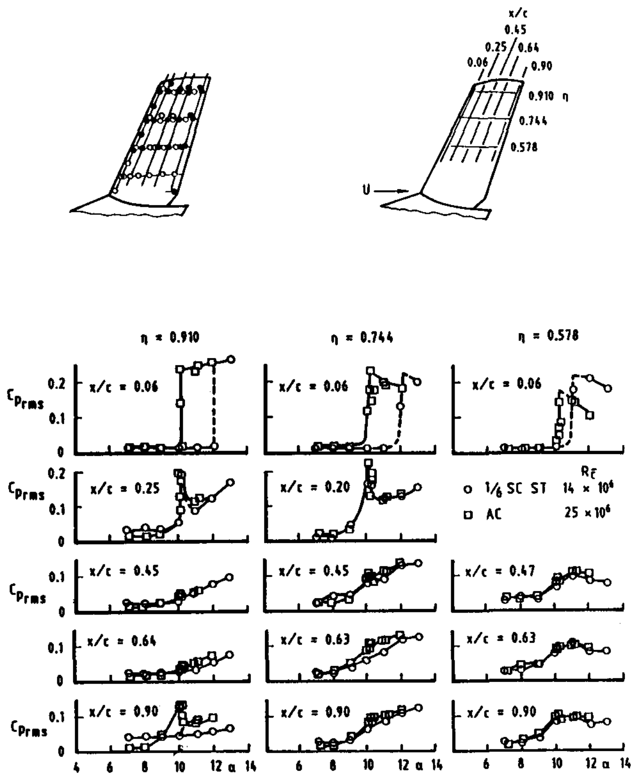


Fig.8 Correlation of pressure fluctuations on TACT 1/6 - scale models and aircraft. Λ = 26°, M = 0.80 (after Ref. 25)

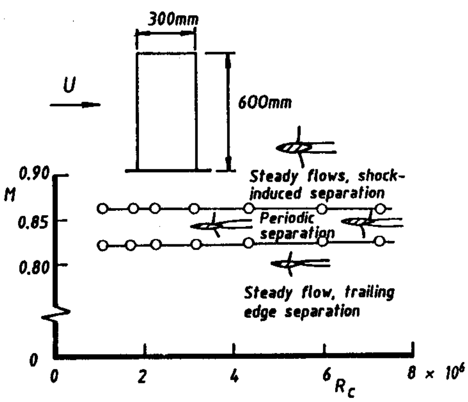


Fig.9 Flow domains for a 14% thick biconvex wing, α = 0°, transition fixed at $x_{t/c}$ = 0.02 (after Ref.29)

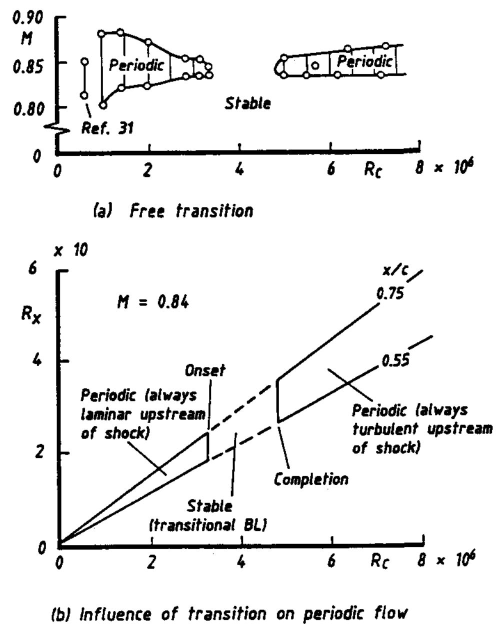


Fig.10 Boundaries for periodic flow, α = 0°, (after Ref. 29)