



Extrapolating wind-tunnel data to full-scale Reynolds number Part 3: Example (ii) Comparison of extrapolated low-Reynolds-number lift measurements on the F4 wing/body with high-Reynolds-number measurements



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EXTRAPOLATING WIND-TUNNEL DATA TO FULL-SCALE REYNOLDS NUMBER Part 3: Example (ii) Comparison of extrapolated low-Reynolds-number lift measurements on the F4 wing/body with high-Reynolds-number measurements

1. INTRODUCTION

References 1 and 2 describe the problems involved in extrapolating low-Reynolds-number wind-tunnel tests to high (full-scale) Reynolds number. Problems are often caused by the presence of local separations, which may be very sensitive to Reynolds number, originating on highly-loaded regions of a wing near a shock wave or the trailing edge. Reynolds-number sensitivity caused by such separations is an *indirect* Reynolds-number effect¹ in contrast to the *direct* Reynolds-number effect¹ caused by changes in the condition of an attached boundary layer.

Indirect Reynolds-number effects are difficult to model and therefore the use of CFD for the extrapolation of isolated low-Reynolds-number wind-tunnel measurements is generally unsatisfactory. In Reference 2 two methods are described by which additional low-Reynolds-number test data may be used to obtain a more satisfactory extrapolation to high Reynolds number.

In the first of these methods, the *Reynolds-number sweep*², additional tests are made at different (but still low) Reynolds numbers, to permit initial extrapolation of the experimental data to a Reynolds number at which indirect Reynolds-number effects are no longer significant. CFD may then be used to extrapolate further from this point to the required full-scale Reynolds number. This method is clearly only applicable where the wind-tunnel facility used permits variation of Reynolds number (*e.g.* by changing stagnation pressure) over a sufficient range.

The second method, the *transition sweep*², relies on the simulation of airflow at high Reynolds number by fixing boundary-layer transition on the wing surfaces downstream of the locations anticipated at full scale; a process known as *aft fixing*². Transition fixing is achieved, for example, by means of bands containing distributed roughness. Systematic variation of the transition location on the upper (and if necessary also the lower) wing surface then provides sufficient experimental data to permit extrapolation (at the test Reynolds number) to target transition locations at which indirect Reynolds-number effects are expected to be insignificant. An example showing how these target transition locations are established is given in Reference 3. CFD is then used to extrapolate from this point to the desired full-scale Reynolds number and transition locations, in a manner similar to the Reynolds-number sweep method. It should be noted that the target transition locations may not be realisable in practice. For example, a transition location downstream of that at which natural transition occurs may be required to eliminate indirect Reynolds-number effects. However, provided the CFD method used for the final extrapolation allows calculation of the flow with transition imposed at the required location, this does not present a problem.

In order to demonstrate and assess the two methods, an example is required for which test results are available for Reynolds numbers typical of full scale as well as the lower Reynolds numbers typical of many wind-tunnel tests. Although the availability of suitable data sets is very limited, one example of direct relevance to both the Reynolds-number and transition-sweep methods was found, although this is restricted to lift measurements at one fixed incidence angle. This example relates to the F4 wing/body combination, which has been tested in both low-Reynolds-number^{4,5} and high-Reynolds-number⁶ facilities.

In Reference 3, the BVGK aerofoil code^{7,8} is used for the F4 wing/body combination to determine appropriate transition location limits on both upper and lower wing surfaces. The extrapolation procedures described here call on this previous analysis and are also based on two-dimensional calculations using

BVGK. Following the methods described in Appendices A and B, these 2D calculations, made at typical sections on the wing, are then used to estimate changes in the performance of the three-dimensional wing/body combination.

The analysis presented is constrained by the availability of both experimental data and CFD methods. This document does not, therefore, seek to define a proscriptive procedure either for designing wind-tunnel tests or for subsequent interpretation of the results of such tests. It does, however, illustrate that useful extrapolation can be achieved using simple, easy-to-use, methods. A thorough understanding of the physical features of the flow under investigation and intelligent interpretation of CFD results is essential for successful interpretation of the results.

2. NOTATION

A	aspect ratio ($= b^2/S$)
b	wing span
C_L	overall lift coefficient
C_{Ldist}	overall lift coefficient at which the spanwise load distribution is estimated (from FP calculations in this example, (Appendix A))
$\bar{C}_{Ldistb}$	mean body lift coefficient corresponding to C_{Ldist} (Appendix A)
$\bar{C}_{Ldistn}$	($n = 1, 2$ or 3) mean lift coefficient (predicted from FP calculations in this example) on region, n , of the wing corresponding to C_{Ldist} (Appendix A)
$\bar{C}_{Leb}$	mean body lift coefficient for equivalent wing (Appendix A)
$\bar{C}_{Len}$	($n = 1, 2$ or 3) mean lift coefficient on region, n , of the equivalent wing (Appendix A)
C_{Lext}	extrapolated overall lift coefficient
C_{Lext1}	extrapolated overall lift coefficient before downwash correction
C_{Lmatch}	C_L at which BVGK and experimental data are matched (Section 4)
C_l	lift coefficient of local two-dimensional wing section, based on c and local velocity in streamwise direction
C_{len}	($n = 1, 2$ or 3) lift coefficient on equivalent wing for two-dimensional section normal to $\Lambda_{0.5}$ line, based on c_{en} and velocity component normal to $\Lambda_{0.5}$ line (Appendix A)
c	chord of local section in line-of-flight direction
$\bar{c}$	mean chord ($= b/S$)
c_{en}	($n = 1, 2$ or 3) local chord of equivalent wing normal to $\Lambda_{0.5}$ line, used for BVGK calculations
M_{LFn}	($n = 1, 2$ or 3) local line-of-flight Mach number ($= M_\infty + \Delta M_n$)

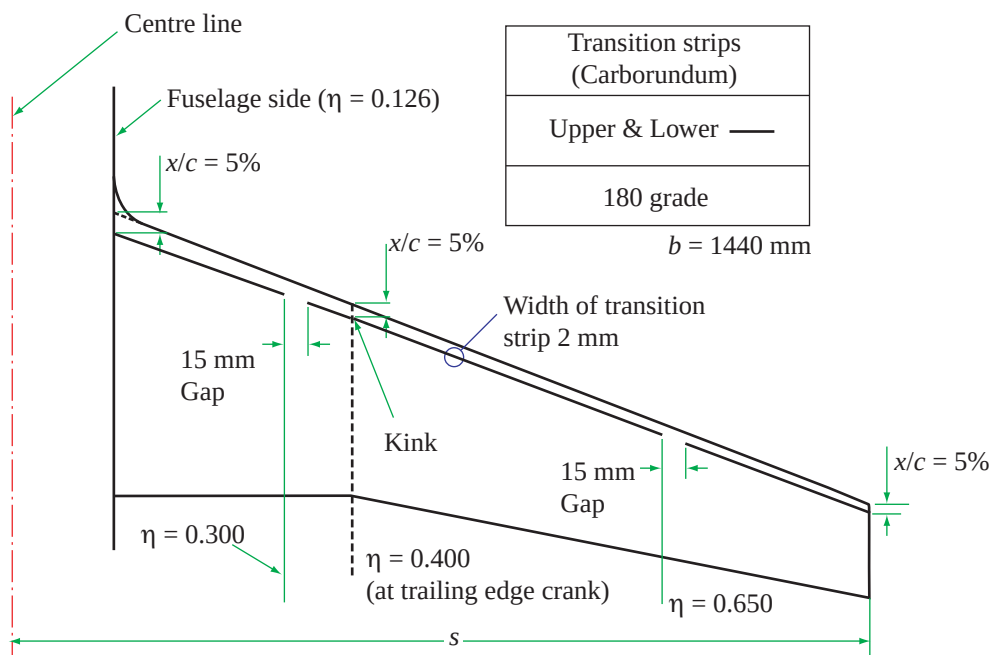
M_{2Dn}	($n = 1, 2$ or 3) Mach number used for BVGK calculation
M_∞	freestream Mach number
q	dynamic pressure
Re_C	Reynolds number above which indirect Reynolds number effects become insignificant
Re_{LFn}	($n = 1, 2$ or 3) Reynolds number based on local line-of-flight approach velocity and chord
Re_{en}	($n = 1, 2$ or 3) Reynolds number used for BVGK calculation on section of equivalent wing
Re_{match}	value of Re_∞ at which BVGK estimate and experimental data are matched (Section 4)
Re_∞	Reynolds number based on freestream velocity and $\bar{c}$
S	wing area
S_b	half-body reference area (Sketch A1.1)
S_{eb}	half-body reference area of equivalent wing (Sketch A1.3)
S_{en}	($n = 1, 2$ or 3) area of equivalent wing region (Sketch A1.3)
S_n	($n = 1, 2$ or 3) area of wing region (Sketch A1.1)
s	wing semi span ($= b/2$)
s'	semi-span of exposed part of wing (Sketch A1.3)
T_s	wind-tunnel stagnation temperature
x	coordinate measured downstream in direction of freestream (origin at wing leading edge)
x_{trl}	transition location on lower surface
x_{tru}	transition location on upper surface
y	coordinate measured from body axis in spanwise direction
α	incidence
α_{en}	($n = 1, 2$ or 3) incidence at 2D section, normal to $\Lambda_{0.5}$ line of equivalent wing (Appendix A)
ΔC_L	difference in lift coefficient between experiment and BVGK estimate
ΔM_n	($n = 1, 2$ or 3) correction to M_∞ for local body influence
$\Delta \alpha_v$	increment in wing incidence due to additional lift after extrapolation
η	y/s

η_{start}	lower limit of integration (Section A2)
η_{finish}	upper limit of integration (Section A2)
Λ_{max}	sweep angle at maximum local wing thickness
$\Lambda_{0.5}$	mid-chord sweep angle

3. AVAILABLE WIND-TUNNEL DATA

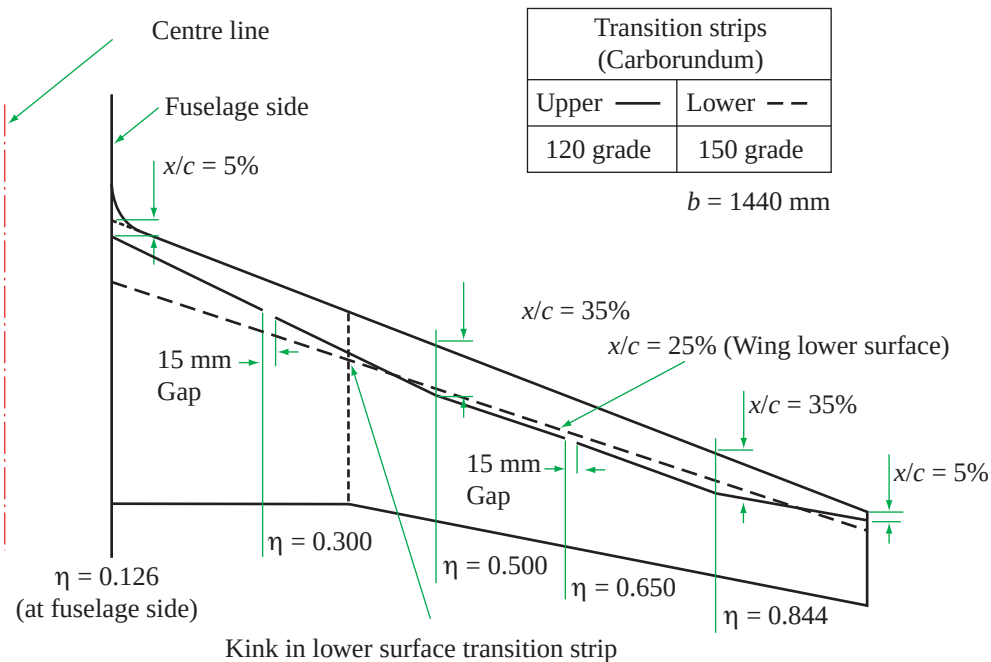
Reference 6 describes tests made on the F4 wing/body in the ETW tunnel at Reynolds numbers between 3.0×10^6 and 33.0×10^6 with free transition. Data are given for lift, drag and pitching moment. Additional data are given for tests made for Reynolds numbers between 3.0×10^6 and 8.45×10^6 , with transition bands at the locations shown in Sketch 3.1 and also for a single Reynolds number of 3.0×10^6 , for the transition band locations shown in Sketch 3.2.

The F4 wing/body combination was also extensively tested in the ONERA-S2MA, the NLR-HST and the DERA-8ft $\times$ 8ft wind tunnels, in an AGARD test programme^{4,5}. Tests were made at Reynolds numbers up to 3.0×10^6 with transition fixed at the locations given in Sketch 3.3. Data are given for pressure distributions together with force and moment balance data for lift, drag and pitching moment.

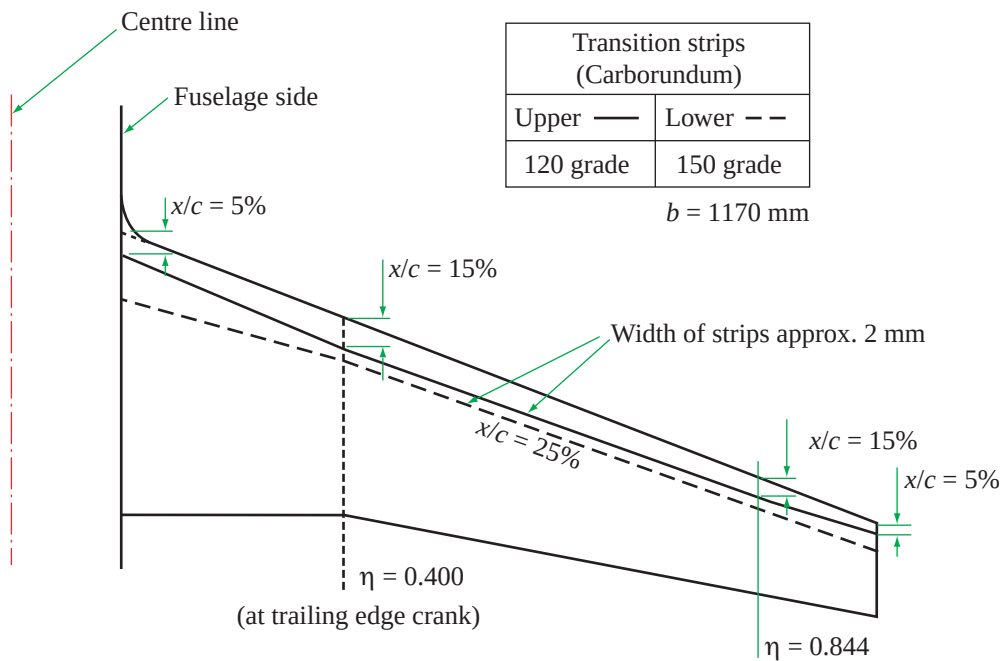


Sketch 3.1 Transition locations used in ETW tests: 5% - 5%* (from Reference 6)

* Here 5% - 5% denotes $x_{tru}/c = x_{trl}/c = 0.05$ on both upper and lower surfaces. (also see footnote on page 5).



Sketch 3.2 Alternative transition locations used in ETW tests: 35% - 25%* (from Reference 6)



Sketch 3.3 Transition locations used in ONERA, NLR and DERA tests: 15% - 25%* (from Reference 4)

* In this Item specification of transition locations is given in the form, e.g. 35% - 25%. This defines a transition "fix" on the upper surface at $x_{tru}/c = 0.35c$ in the region between the two kinks in the transition band (Sketch 3.2) and on the lower surface at $x_{trl}/c = 0.25c$.

3.1 Wind-tunnel Test Data suitable for Extrapolation using both Reynolds-number and Transition-location Sweep Methods: Variation of C_L with Re_∞ and Transition Location at Fixed α

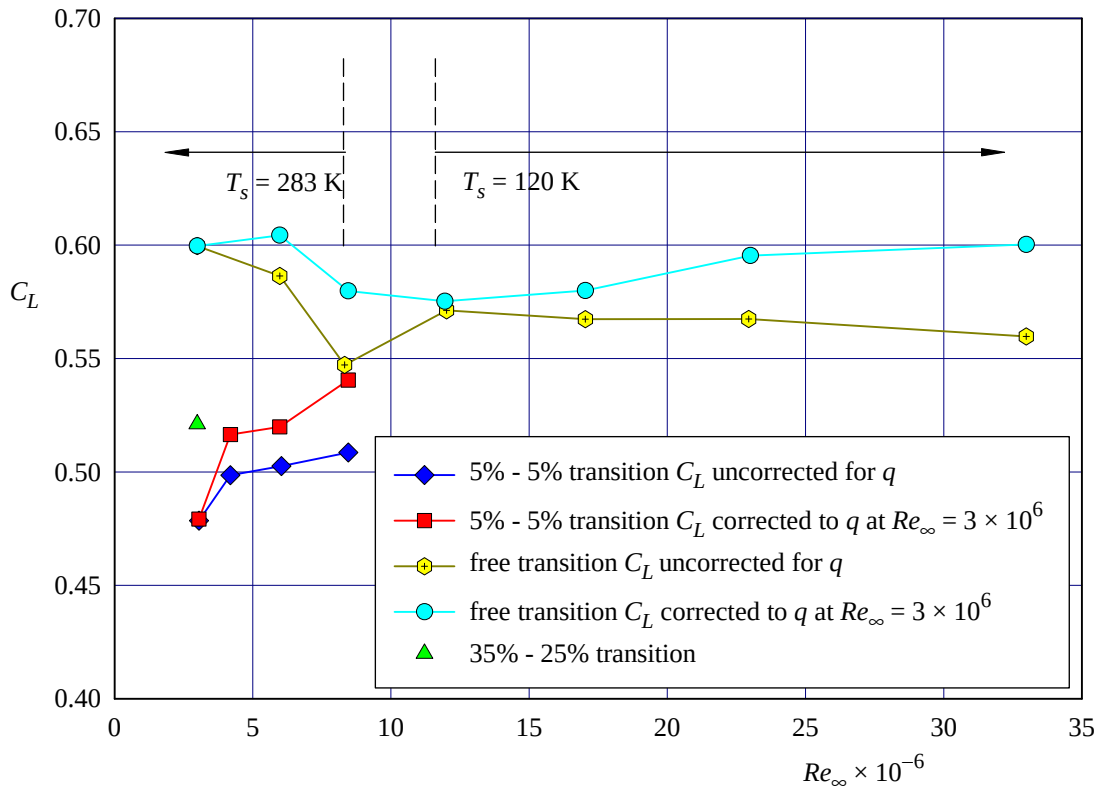
In order to demonstrate both the Reynolds-number sweep and transition-sweep extrapolation methods, outlined in Reference 2, low-Reynolds-number test data are required in which both Reynolds number and transition location are systematically varied, together with high-Reynolds-number data suitable for comparison with the extrapolated data. References 4 and 6 give a suitable set of data relating to the variation of C_L with Re_∞ and transition location at fixed α . Extrapolation of this data set is a severe test of the techniques as extrapolation at constant α rather than constant C_L is likely to involve substantial changes in, for example, shock-wave location in both the tests and the CFD calculations performed during extrapolation. In Reference 2 the difficulty of using these methods to extrapolate lift-curve slope is mentioned although, in the present example, only a single incidence is involved. Details of the wind-tunnel data used in this analysis are given in Sections 3.1.1 and 3.1.2.

3.1.1 ETW wind-tunnel test data (Reference 6)

Sketch 3.4 shows the variation of C_L with Re_∞ , measured in the tests of Reference 6. Results are given for free-transition tests and for the 5% - 5% transition locations, both without correction for model distortion due to dynamic pressure and with correction applied to normalise C_L values to the dynamic pressure appropriate to test conditions at $Re_\infty = 3.0 \times 10^6$. In these tests Re_∞ is increased from 3.0×10^6 to 8.45×10^6 by increasing stagnation pressure. To obtain the increase from $Re_\infty = 8.45 \times 10^6$ to 12.1×10^6 , stagnation temperature is reduced from 283K to 120K, and stagnation pressure returned to its original value. The further increase in Re_∞ from 12.1×10^6 to 33.0×10^6 is then again obtained by increasing the stagnation pressure. It is apparent that model distortion causes a marked unloading effect as stagnation pressure is increased and represents a significant pseudo Reynolds-number effect¹.

After correcting C_L for dynamic pressure, a strong Reynolds-number influence is still apparent at low Re_∞ for both the free-transition case and the 5% - 5% fix (Sketch 3.4), indicating the presence of indirect Reynolds-number effects. The identical value of C_L , with free transition, at $Re_\infty = 3.0 \times 10^6$ and 33.0×10^6 is coincidental. (In this case transition is uncontrolled and, although it occurs as far aft as possible, may interfere with the local flow in the region of the shock wave resulting in poor simulation of the high Reynolds-number flow by the low-Reynolds-number test.)

At $Re_\infty = 3.0 \times 10^6$, a single point is given for the 35% - 25% fix, which gives a higher C_L than that obtained with the 5% - 5% fix but lower than that obtained with free transition.



Sketch 3.4 Experimental variations of lift coefficient with Reynolds number for $M_\infty = 0.785$ and $\alpha = -0.28$ deg (from Reference 6)

3.1.2 AGARD wind-tunnel test data

Sketch 3.5 shows lift measurements for the F4 wing/body combination made in three wind tunnels, situated in the Netherlands, France and the United Kingdom and identified in Reference 5 as NLR-HST, ONERA-S2MA and DERA- 8ft $\times$ 8ft. The model is slightly smaller than that used in the ETW tests⁶ and 15% - 25% transition locations were used (Sketch 3.3). All tests were made at $Re_\infty = 3.0 \times 10^6$. Sketch 3.5 shows close agreement between the results obtained in the three tunnels at the incidence of -0.28 deg corresponding to the ETW results⁶ shown in Sketch 3.4. These results may therefore be interpolated to give the lift coefficient for a 15% - 25% fix at the test conditions corresponding to those of Sketch 3.4 ($M_\infty = 0.785$ and $\alpha = -0.28$ deg), which provides an additional data point for use in an extrapolation based on a transition sweep. Interpolation gives $C_L = 0.463$ at $\alpha = -0.28$ deg and $M_\infty = 0.785$.

Ideally all data would be obtained in a single wind-tunnel test series and the use of data derived from the separate AGARD test series introduces some uncertainties. One of these is that the kinks in the upper- and lower-surface transition bands are located at $\eta = 0.5$ in the ETW tests and at $\eta = 0.4$ in the AGARD tests (Sketch 3.2 and Sketch 3.3). A second uncertainty is that the ETW results are corrected for model distortion to a dynamic pressure corresponding to $Re_\infty = 3.0 \times 10^6$. There is, however, no guarantee that the model geometries at a dynamic pressure at $Re_\infty = 3.0 \times 10^6$ are identical in the ETW and AGARD tests, since distortion from the unloaded condition may differ in the two cases. This possible difference is ignored in the present analysis.

