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# Comparison of Conventional and Adaptive Wall Wind Tunnel Results with Regard to Reynolds Number Effects

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## Introduction

Studies of the CAST 10-2/DOA2 airfoil commenced in the early seventies with the verification of the design in tests in the 1 x 1 Meter Transonic Wind Tunnel Göttingen (TWG) [1]. Part of these studies were devoted to the investigation of viscous effects, i.e., the influence of the state and condition of the boundary layer, on the flow development. Viscous conditions were varied by changing the Reynolds number itself, although in a very limited range, and transition location; it was found that the flow development on this airfoil was very sensitive to changes in the viscous conditions [1]. This led to an investigation of the airfoil under contract in the Lockheed Compressible Flow Wind Tunnel (CFWT) at Reynolds numbers up to $Re = 30 \times 10^6$ and fixed and free transition [2] and, finally, to tests in the slotted 0.3-m Transonic Cryogenic Wind Tunnel of NASA Langley (0.3-mTCT) within a NASA/DFVLR cooperation. The objective of the latter series of experiments was twofold: to determine the effect of Reynolds number on the flow about a certain class of transonic airfoils characterized by extreme rear adverse pressure gradients, thus susceptible to rear separation, and to study the influence of the Reynolds number on the model-wind-tunnel system, i.e., on wall interference, be it sidewall or top and bottom wall induced, in conventional partly open wind tunnels. Here, two different size models having chords of $c = 76$ mm and $c = 152$ mm, respectively, were investigated. The results of these studies were summarized at the AGARD Symposium on Wind Tunnels and Testing Techniques in Cesme, Turkey, 1983 [3].

The continuation of the CAST 10-2/DOA2 airfoil studies in the adaptive wall TCT and the adaptive wall ONERA/CERT T2 - ONERA joined the NASA/DFVLR airfoil study program in 1983 - provided the opportunity to confirm or reject the postulations of the previous analysis [3] of viscous effects on airfoil flow and wall interference. In the following, we will revisit the results obtained in the conventional wind tunnels and compare them to the adaptive wall data. In the discussion, we will frequently refer to the Cesme paper [3] which is, therefore, attached for easy access (see page 47).

## Sidewall Interference Effects

It was shown in [3] that the sidewall or sidewall boundary layer development may have a pronounced effect on the non-linearity of the lift curves, Fig. 5 of [3]: only a small deviation from a linear lift variation with angle of attack occurred for the large chord, small aspect ratio TCT model, while the small chord TCT and the CFWT airfoil models with their substantially higher aspect ratios showed a very pronounced non-linear increase in lift. It was concluded that sidewall interference effects suppress the non-linear lift increase as a result of the influence on the upper surface shock which assumes a more foreward position due to the interaction of the airfoil flow field with the sidewall boundary layer, Fig. 6 of [3].

Let us now turn to the investigation in the adaptive wall wind tunnel (TCT only) where lift interference effects are substantially reduced: Figure 1 shows the lift curves measured in the slotted TCT with the two different size CAST 10-2 models mentioned above and the lift curve obtained in the adaptive wall TCT with a 180 mm chord model. Remarkable is firstly the large difference in angle of attack for a given lift coefficient but close agreement in maximum lift for the Mach number of $M_\infty = 0.73$ considered here. In order to compare the linearity of the lift development with incidence, the lift curves were shifted to match in the lower incidence range, Figure 2. One observes a close agreement between the non-linear behavior of lift measured in the adaptive TCT and the slotted TCT with the smaller model, despite the smaller aspect ratio in case of the former. Considering the maximum non-linear lift, $\Delta C_{LL}$, as function of the aspect ratio in Figure 3, one tends to conclude that even at an aspect ratio of 1.8 - as existed in the adaptive wall test - sidewall interference effects are minor. This is somewhat surprising since it was previously inferred from a number of experimental results that aspect ratios of $AR > 2$ were required for sidewall effects to be negligible [4]. It is quite possible that (horizontal) wall adaptation is here of influence; however, this is a matter for further research. Concerning the influence of the Reynolds number on sidewall interference, the reader is again referred to [3] where it was concluded that the interference becomes slightly more severe at higher Reynolds numbers.

## Lift Interference

It was shown in [3], see, e.g., Figs. 14 and 15, that the influence of the Reynolds number on lift interference is negligible at lift coefficients prior to maximum lift so that for these conditions true Reynolds number effects on the flow about the airfoil could be exposed. Here, we want to confirm this observation utilizing the adaptive wall interference free wind tunnel results. To proceed, let us first consider the lift curves for the various model-wind-tunnel configurations at the (nominal) Mach number of $M_\infty = 0.765$, Figure 4: The data for the large chord model in the slotted TCT exhibit the lowest lift curve slope while the adaptive wall TCT shows the highest slope reflecting the range of lift interference encountered for the model-wind-tunnel configurations considered in this test series. Note, that even for the small model in the slotted TCT with a test section height to chord ratio of $H/c = 8$, wall interference is still substantial. The deviations in lift indicate that in order to determine the influence of the Reynolds number on lift for the various configurations, it is necessary to suitably correct the data either by theory or empirically. Here, a simple procedure was employed, Figure 5: for given freestream conditions, here $M_\infty = 0.765$, $Re = 10\times10^6$, transition fixed, a lift coefficient was selected in the range of interest, here $C_L = 0.55$, and the angles of attack necessary to generate this lift coefficient in the various model-tunnel systems was noted. For these angles of attack the Reynolds number dependence of lift for free and fixed transition was then plotted, Figure 6. One observes that for fixed transition and at high Reynolds numbers, where the movement of the transition point with increasing Reynolds number has ceased, the data of the adapted TCT fall within the band of results previously established (Fig. 15a of [3]). The ONERA T2 data follow this band only up to a Reynolds number of about $20\times10^6$, then drop abruptly below the data band but still follow the trend given by the data band as the Reynolds number is further increased; this behavior seems unrealistic and must be checked.

The adaptive wall data of TCT and T2 confirm the conclusion that Reynolds number effects on lift interference are negligible, i.e., the wall characteristics are not changed by viscous effects to a degree noticeable in the Reynolds number dependence of lift prior to maximum lift. Note, that the considerable difference in the lift dependence between the various model-wind-tunnel configurations at low Reynolds numbers and free transition reflects the different model/wind tunnel environments; from the very late onset of the rapid transition point movement as Reynolds number is increased, indicated by the late drop in lift coefficient, one may conclude that the ONERA/CERT T2 adaptive wall tunnel is a very low turbulence facility.

The dependence of the pressure distribution on Reynolds number corresponding to the data points of the adaptive wall TCT measurements is, for completeness sake, depicted in Figure 7.

## Maximum Lift and Drag Rise (Blockage Interference)

It was shown in [3], Fig. 11 and 12, that very pronounced differences existed in the Reynolds number dependence of maximum lift and the drag-rise Mach number between the various model-wind-tunnel configurations. From an analysis of the results it was concluded that this was essentually due to the influence of the Reynolds number on the characteristics of partially open test section walls responsible for blockage interference. It was, furthermore, judged that perforated walls were more sensitive to Reynolds number changes than slotted ones.

Again, the results from the adaptive wall wind tunnels, which are essentially interference free, are well suited to confirm or reject the above conclusions. For this reason we have depicted in Figure 8 for a (nominal) Mach number of $M_\infty = 0.765$ maximum lift for the various model-wind-tunnel configurations, including the adaptive wall tunnels TCT and T2, as function of the Reynolds number. Considering only the gradient of the maximum lift curves which is a measure of the viscous effects on wall interference (here essentially blockage interference), one observes that there is a large deviation from the "interference free" gradient in case of the perforated wind tunnels TWG and CFWT, but only minor discrepancies for the slotted TCT, independent of model size. (The large deviation in the level of max. lift between the facilities considered is, of course, also an influence mainly of blockage interference.)

For a better comparison of the gradients of the maximum-lift curves, these curves were shifted parallel to intersect the interference free results at a Reynolds number of $Re = 4 \times 10^6$, Figure 9. Clearly indicated is the considerably stronger Reynolds number dependence of the perforated tunnels TWG and CFWT and the slotted tunnel TWB compared to the interference free results. The larger gradients in the Reynolds number dependence confirm the conclusion of [3], namely that the diminishing viscous effects with increasing Reynolds number raise the effective open area ratio of the walls thus reducing the effective freestream Mach number which results, in turn, in higher maximum lift. The slotted-TCT results are fairly close to the interference free data, exhibit, however somewhat lower gradients in the Reynolds number dependence. This means that the open area ratio reduces slightly with Reynolds number which might be due to the special design of the TCT slots. Still, the lower sensitivity of the characteristics of slotted walls to viscous changes is indicated by both the TWB and TCT results thus confirming the earlier conclusion.

It was shown in [3] that there also existed differences in the dependence of the drag-rise Mach number on Reynolds number between the various model-wind-tunnel systems considered, Fig. 12 of [3]; these differences have the same cause, namely the influence of the Reynolds number on wall characteristics. Determining the maximum lift at the drag-rise Mach number and plotting this parameter as function of the Reynolds number should, it was postulated, therefore lead to the correct maximum lift dependence on viscous effects. Comparing the latter results with the interference free data in Figure 10 indicates that this approach comes close to reality with only minor disagreement in gradient and level of the Reynolds number dependence. Nevertheless, the conclusions of [3] are essentially confirmed.

## Conclusions

A comparison of results from conventional and adaptive wall wind tunnels with regard to Reynolds number effects has been carried out. The special objective of this comparison was to confirm or reject earlier conclusions, solely based on conventional wind tunnel results, concerning the influence of viscous effects on the characteristics of partially open wind tunnel walls, hence wall interference. The following postulations could be confirmed:

- Certain classes of supercritical airfoils exhibit a non-linear increase in lift which is, at least in part, related to viscous-inviscid interactions on the airfoil. This non-linear lift characteristic can erroneously be suppressed by sidewall interference effects in addition to being affected by changes in Reynolds number. Adaptive walls seem to relieve the influence of sidewall interference.
- The degree of (horizontal) wall interference effects can be significantly affected by changes in Reynolds number, thus appearing as "true" Reynolds number effects.
- Perforated wall characteristics seem much more susceptible to viscous changes than the characteristics of slotted walls; here, blockage interference may be most severely influenced by viscous changes.
- "Real" Reynolds number effects are present on the CAST 10-2/DOA2 airfoil; they have been shown to be appreciable also by the adaptive wall wind tunnel tests.

## References

[1] Stanewsky, E. and Zimmer, H., "Development and wind tunnel test of three supercritical airfoils for transport aircraft", Z. Flugwiss. 23 (1975), Heft 7/8, pp. 246-256.

[2] Stanewsky, E., "Interaction between the outer inviscid flow and the boundary layer on transonic airfoils", Z. Flugwiss. Weltraumforsch. 7 (1983), Heft 4, pp. 242-252 (also see Ph. D. Thesis, Technical University Berlin (D83), 1981).

[3] Stanewsky, E., Demurie, F., Ray, E.J. and Johnson, C.B., "High Reynolds number tests of the CAST-10-2/DOA 2 transonic airfoil at ambient and cryogenic temperature conditions", AGARD-CP-348, 1983, pp. 10-1 to 10-13 (see page 47 in this CP).

[4] Ganzer, U., Stanewsky, E. and Ziemann, J., "Sidewall effects on airfoil tests", AIAA Journal, Vol. 22, No. 2, Feb. 1984, pp. 297-299.

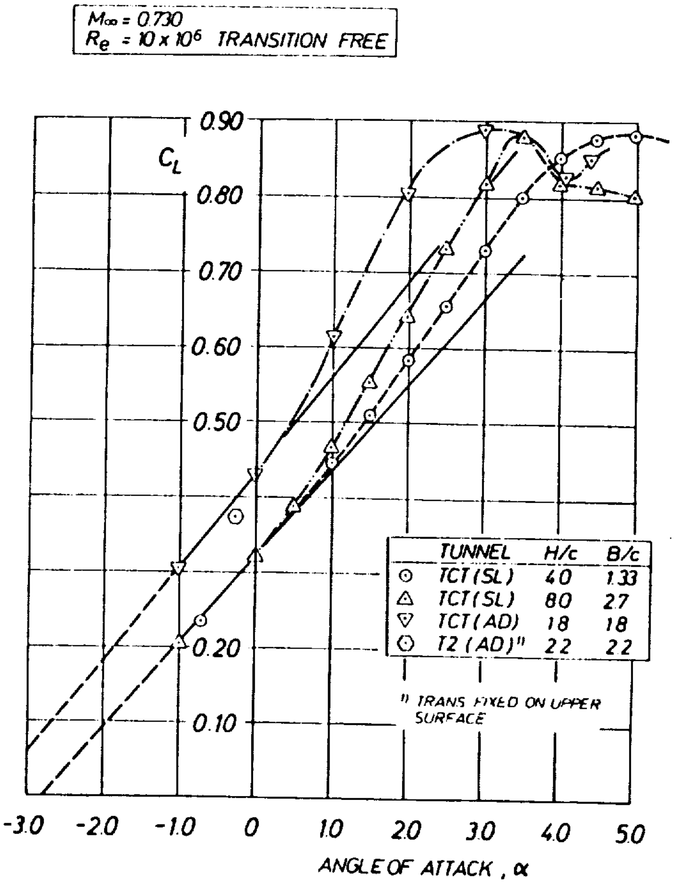

Figure 1: Lift curves obtained in conventional and adaptive wall wind tunnels

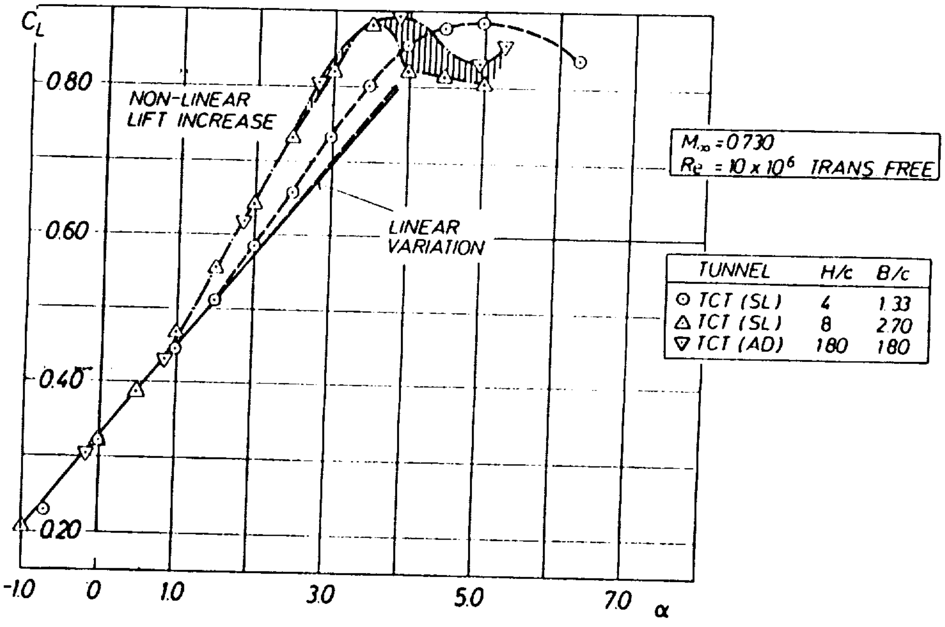

Figure 2: Lift curves of Fig. 1 shifted to match in the lower incidence range

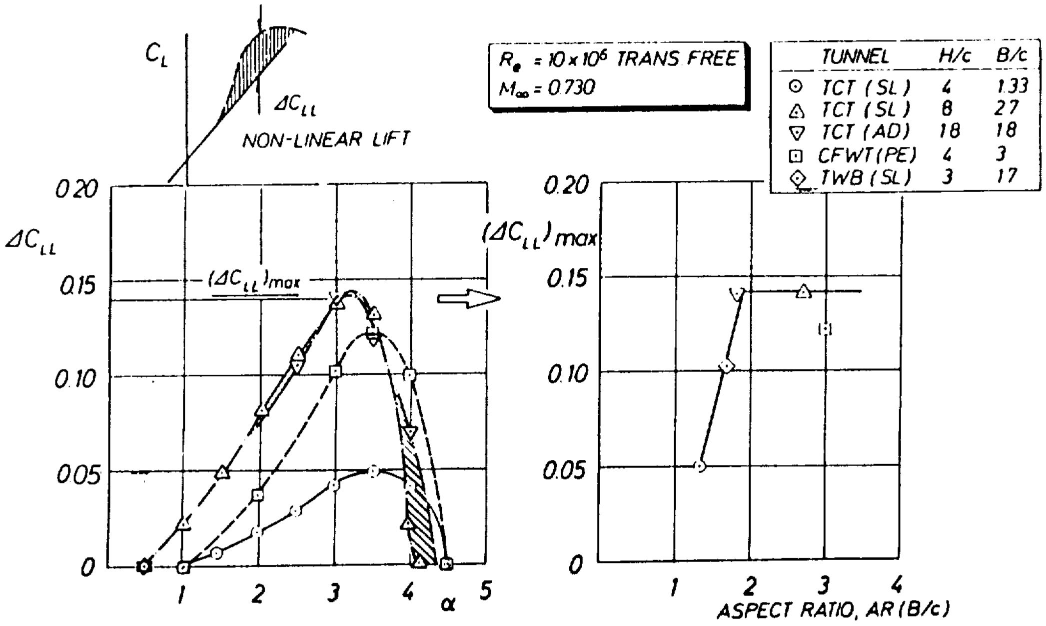

Figure 3: Effect of aspect ratio on the deviation from lift linearity

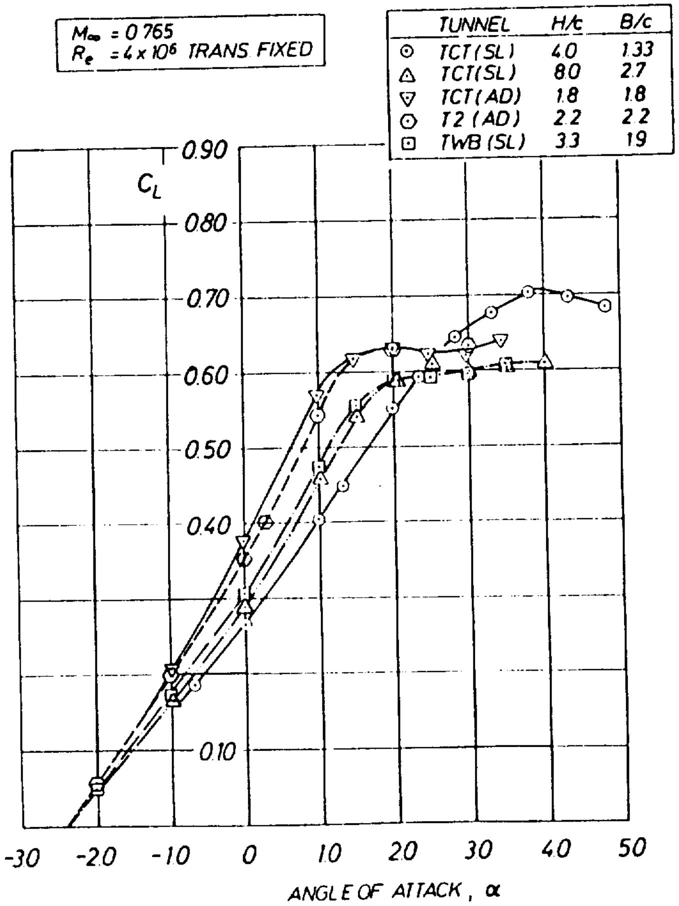

Figure 4: Lift curves for various model-wind-tunnel configurations

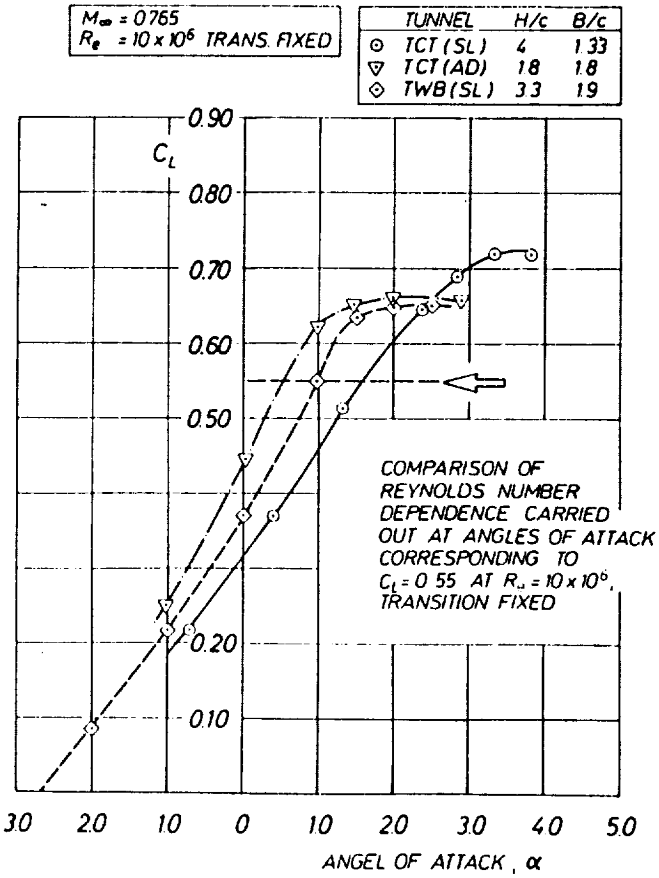

Figure 5: Selection of angles of attack to determine the Reynolds number dependence of lift for the various model-wind-tunnel systems

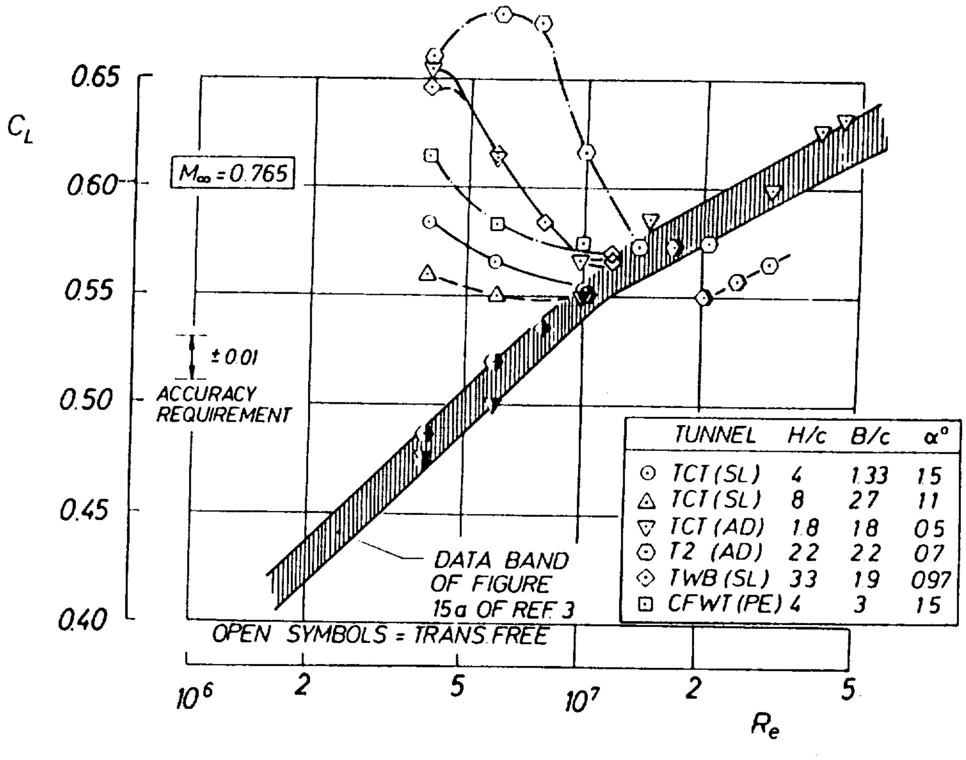

Figure 6: Effect of Reynolds number on lift

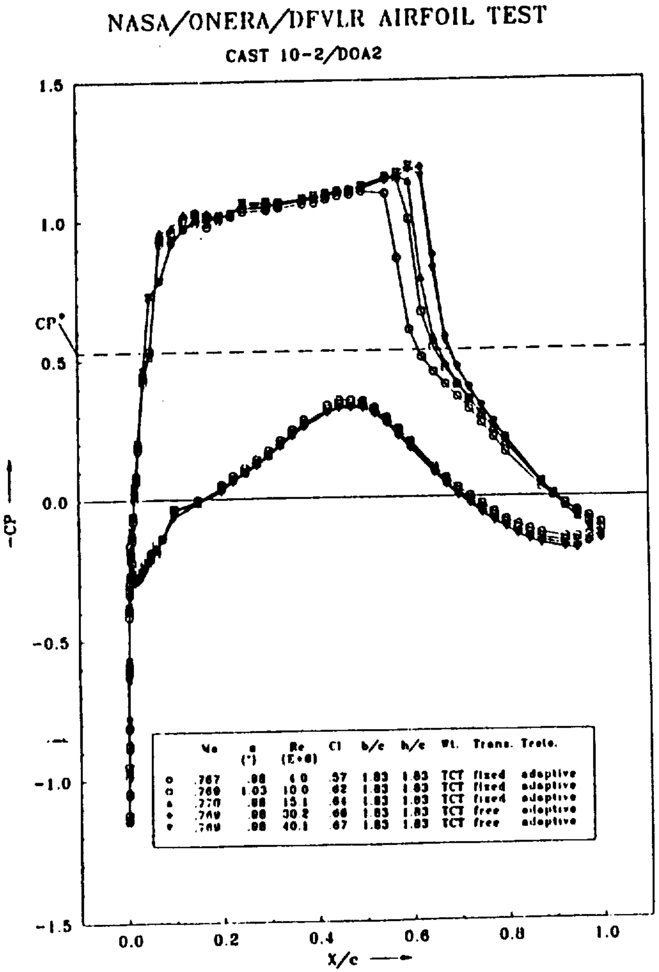

Figure 7: Reynolds number effect on the pressure distribution, adaptive TCT tests

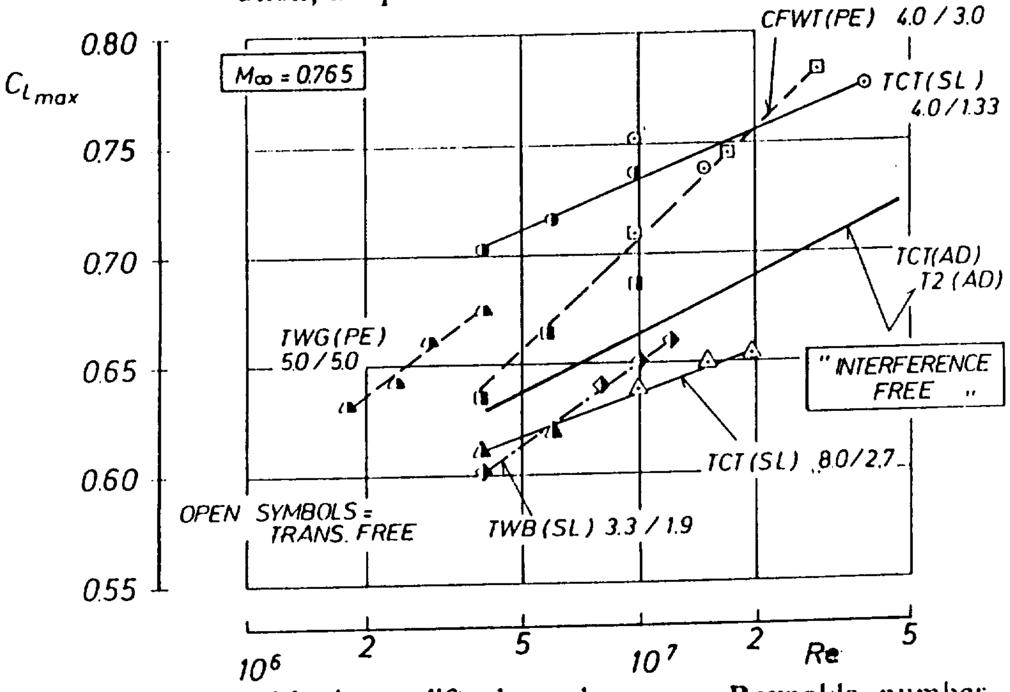

Figure 8: Maximum-lift dependence on Reynolds number for conventional and adaptive wall wind tunnels

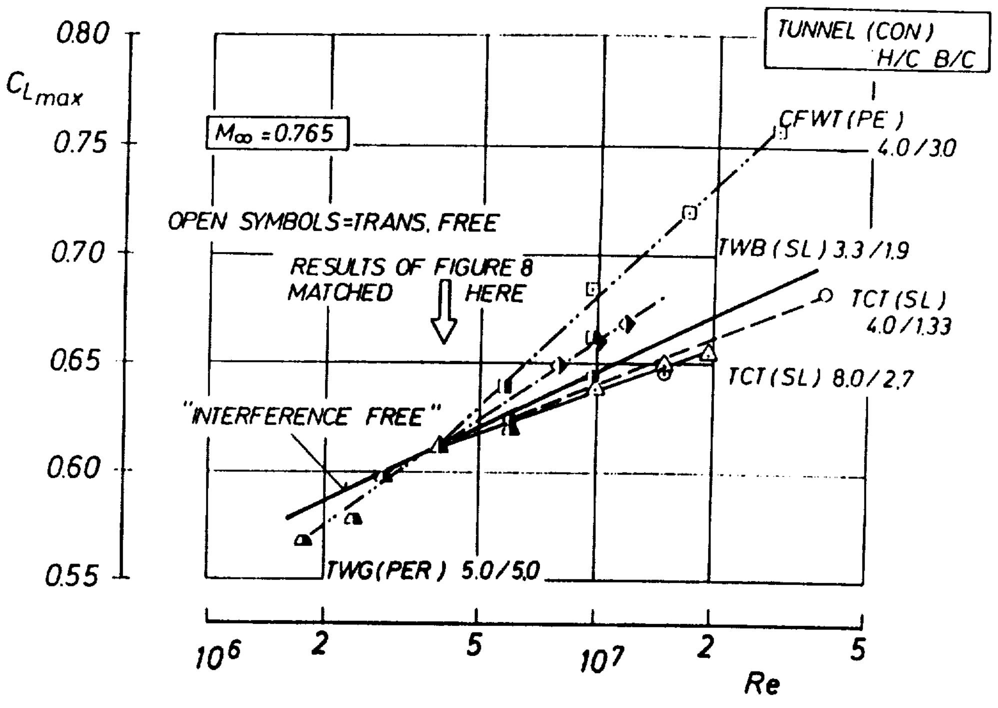

Figure 9: Maximum lift versus Reynolds number: Data of Fig. 8 shifted parallel to intersect interference free results at Re = $4\times10^6$

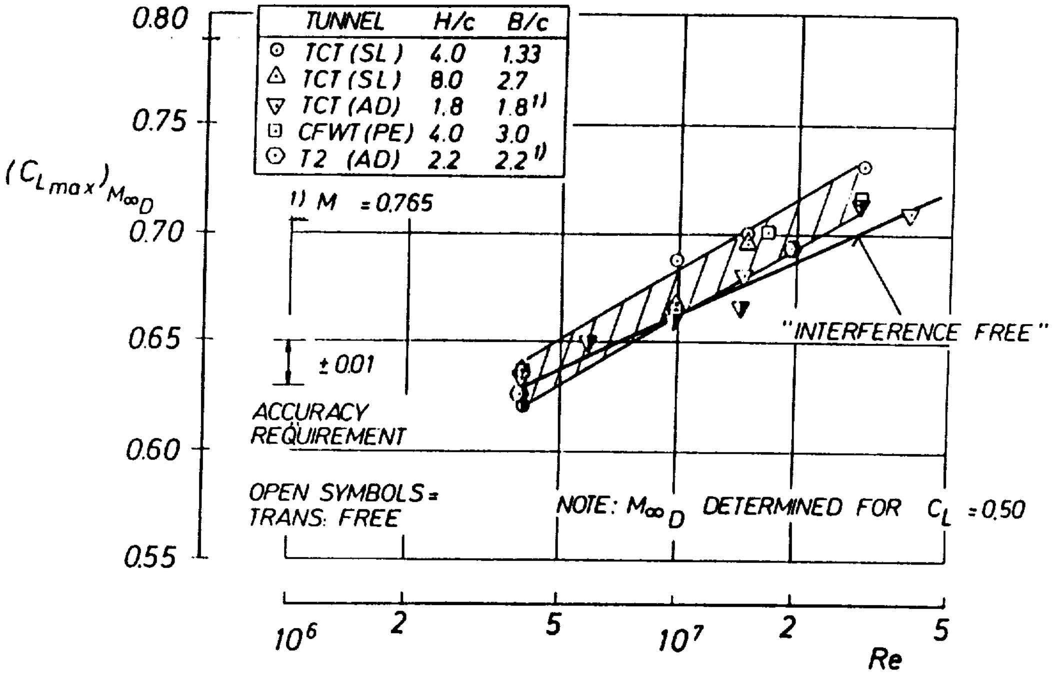

Figure 10: Effect of Reynolds number on the maximum lift at drag rise