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Leading Edge — Trailing Edge Airfoil Interactions

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Leading Edge – Trailing Edge Airfoil Interactions

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Abstract

Computational aerodynamics predictions of airfoil drag and maximum lift continue to be a challenge to aerodynamicists, even using large computer programs. The reliable calculation of the drag break and maximum lift, including the effects of Reynolds number, are simply not developed to the stage where they can be used routinely in aerodynamic design. This is especially troubling in the case of multidisciplinary design optimization, where thousands of calculations are made, accurate sensitivities to geometry changes are required, and the results are not clearly visible during the process. This paper provides a survey of various airfoil results and of parametric studies of boundary layer solutions that illustrate the strong connection between boundary layer development at the trailing edge and the details of the viscous flow near the leading edge for many critical cases. With the exception of work by Cebeci and co-workers, this problem has largely been ignored in computational research, although it is well known by the experimental aerodynamics community.

Introduction

Airfoil aerodynamics continues to present computational challenges, even for apparently simple subsonic cases. The difficulty is the accurate prediction of drag and the prediction of maximum lift trends with Reynolds number. Repeatedly, experts discover that the drag, in particular the sudden break associated with the onset of separation, is difficult to predict. Figure 1 illustrates the problem, and is taken from work by Cebeci, et al.[1] He has been studying this problem for many years. The work illustrated by Fig. 1 also shows a corresponding problem in obtaining reliable experimental data. Of particular interest here, Cebeci, et al,[1,2] have found the results of their predictions to be extremely sensitive to transition details and transition location when it comes to the prediction of maximum lift and drag.

For many airfoils of interest, at the angles of attack where the boundary layer separation starts to occur at the trailing edge, the pressure distribution around the leading edge will demonstrate a distinct suction peak. Figure 2 provides an example of the inviscid computational prediction of a pressure distribution corresponding to a condition studied by Cebeci.[1] This peak and subsequent rapid recompression will lead to transition to turbulent flow. Frequently, the initially laminar flow separates before transition occurs, resulting in a laminar separated flow that quickly undergoes transition to turbulent flow and subsequent flow reattachment—a separation bubble. Downstream of the bubble the thin viscous shear layer near the surface appears to be a normal turbulent boundary layer. Thus, the boundary layer is initially laminar, and then transitions to turbulent flow. Turbulent flow separation may eventually occur at some point far downstream, initially at the trailing edge, and then moving progressively forward in the classic trailing edge separation stall. The airfoil drag is directly connected to the boundary layer properties and separation location.

The details of the development of the boundary layer change as the angle of attack is increased. The transition location, existence and size of a separation bubble, and downstream turbulent flow separation all demonstrate a systematic evolution from fully attached flow to separated flow. Historically, the primary interest in laminar separation bubbles has been to predict when the leading edge separation bubble will burst, producing a sudden separation over the entire upper surface of the airfoil, with an accompanying dramatic loss in lift. However, the laminar/turbulent transition and any separation bubble plays a key role in airfoil drag and maximum lift well before the bubble bursts. Figure 3 illustrates the problem being studied. For many cases, the boundary layer state at the trailing edge may be strongly influenced by the initial conditions required for the turbulent boundary layer definition.

The assertion that the type and location of the transition is important is not exactly a revelation. The proper modeling of the boundary layer, often using artificial roughness to define the transition location, is major consideration in wind tunnel testing. The adjustment of the results to project the aerodynamic characteristics (drag and maximum lift in particular) to full scale Reynolds numbers is one of the oldest and most important problems in aerodynamics.

The subject problem examined here attracted my attention some twenty years ago, when the initial computer programs developed to include viscous effects in the prediction of transonic flow over the new supercritical airfoils be-

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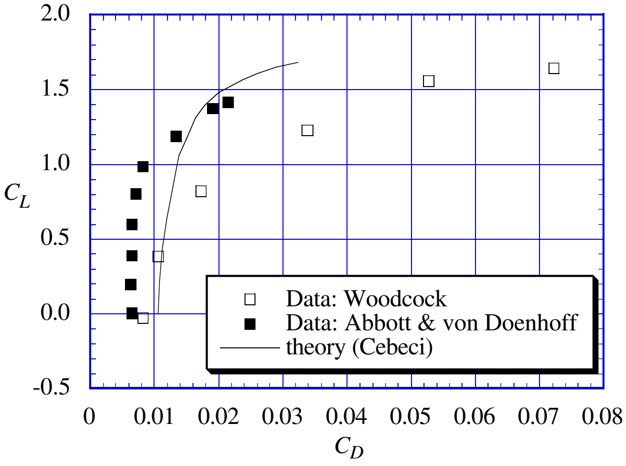

Figure 1. Drag polar computed by Cebeci, et al.[1], illustrating the continuing difficulty in computing drag.

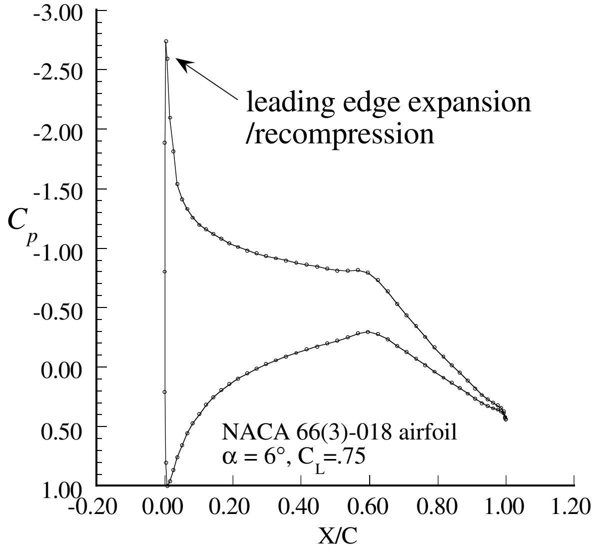

Figure 2. Typical inviscid pressure distribution at start of drag polar break.

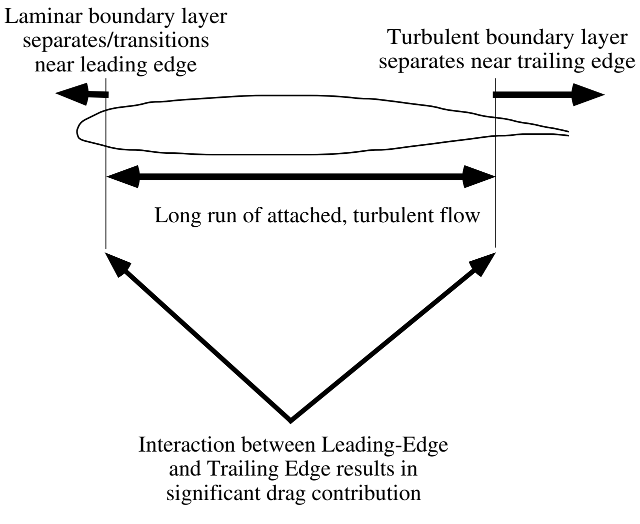

Figure 3. Leading-edge-trailing edge interaction sketch showing the concept basis.

came available.[3,4] They didn't account for the initial laminar flow, and the starting conditions for the boundary layer calculations appeared to be completely unimportant. Nevertheless, they got "good" results.

Curiously, current efforts to predict drag and maximum lift employing large computer programs are not being used to investigate the essential physics of the problem. The focus in this paper is an examination of a variety of evidence that has been reported in other forums, but when collected provides a useful theme for the study of airfoil aerodynamics. We also use simple model problems and attached boundary layer calculations to gain computational insight into the mechanisms connecting the flow at the front and rear of the airfoil. Most current methods have become either extremely complicated, representing a myriad of effects in an interaction solution, or employ a nearly complete set of viscous flow equations to obtain a solution to the entire flowfield at once. In either case, it's difficult to isolate and understand particular aspects of the aerodynamics. Simple boundary layer calculations can be used to understand the connection, or "interaction" between the leading edge boundary layer development and the eventual state of the boundary layer at the trailing edge. We call this "leading edge – trailing edge interaction" .

Brief Surveys of Related Investigations

Reynolds Number Effects

The Reynolds number scaling problem is one of the classic problems of aerodynamics. The standard view was that increasing Reynolds number improved the aerodynamic properties of airplanes. The problem is how to simulate flight Reynolds number when ground test capability requires testing at Reynolds numbers below full scale values. This involves two different considerations. The first consideration is the question of how to simulate the full scale Reynolds number by the use of transition strips, or even whether to use them at all. The second problem is how to adjust wind tunnel data to full scale conditions.

A fairly recent development has been the discovery that sometimes performance decreases with increasing Reynolds number. My first exposure to this possibility was the work on reducing DC-10 cruise drag reported by Lynch of Douglas.[5] He reported a case where cruise drag improvements predicted in wind tunnel tests failed to materialize in flight, and in fact performance deteriorated. He initially attributed this problem to Reynolds number effects associated with the flow expansion and subsequent recompression over the drooped ailerons. The hypothesis was that the expansion and recompression became much more pronounced as the boundary layer became thinner at flight Reynolds number, resulting in separation in flight due to the steeper adverse pressure gradient in the recompression, which did not occur in the wind tunnel. Later, after additional work, Lynch retracted this explanation, attributing it to differences between two dimensional and three dimensional flows.[6]

However, although the DC-10 example might not actually have been due to adverse increasing Reynolds number effects, other cases have arisen which definitely identified cases where performance decreased with increasing Reynolds number. The examples are for subsonic maximum lift. The best survey is by McMasters and Mack,[7] who describe the Boeing experience and draw on the work of Woodward, et al.[8] among others. Another discussion, in support of NASA Langley flight testing, is due to Yip, et al.[9] The McMasters and Mack paper should be added to the list of required reading for aerodynamicists. They document the progression of experience from the 1950s to the present. Figure 4 is a schematic of their story. The first important observation is that peaky airfoil distributions (the case of the 737) demonstrate larger scale effects than rooftop pressure distributions (the case of the 747).

Experience with more advanced airfoils used in the 767 resulted in the first experience at Boeing where the maximum lift decreased above a certain Reynolds number—one well below the flight value. This resulted in uncertainty in the extrapolation to flight Reynolds number and additional design work to at least maintain the maximum lift with increasing Reynolds number. More recently, the 777 work apparently followed a similar trend. Here the maximum lift initially increased, then showed minor increases with Reynolds number increases, and then started to decrease.*

The current explanation for this surprising behavior resides in the flow at the leading edge. At the lower Reynolds numbers the boundary layer is initially laminar, and then transitions in a classical two-dimensional sense. At higher Reynolds numbers the flow on the attachment line is initially turbulent, and this results in a thicker boundary layer that tends to separate more readily, leading to lower values of maximum lift. This explanation is originally due to Woodward, et al.[8] Finally, there is a suggestion that as the Reynolds number increases further, the strong favorable pressure gradient at the leading edge may cause the flow to relaminarize, with the effect that the maximum lift might start to increase again. Yip et al.[9] provide further discussion. Note that this explanation is fundamentally three dimensional. The leading edge must be swept. However, Mcmasters[7] says that Boeing has seen evidence that this reversal in maximum lift with Mach number has also been seen in two dimensional testing.

The key in this analysis is that it centers entirely around the flow at the leading edge. However, for the wings described above the separation and loss of lift actually begins at the trailing edge. The experimentalists' first concern is the risk associated with guaranteeing performance using results at Reynolds number below full scale. The problem is primarily being considered to answer the question of deciding how high the Reynolds number capability has to be in a new wind tunnel. The development of a new scaling methodology (and the related design methodology) to use low Reynolds number results cannot be relied upon to solve their problem.

Computational Progress

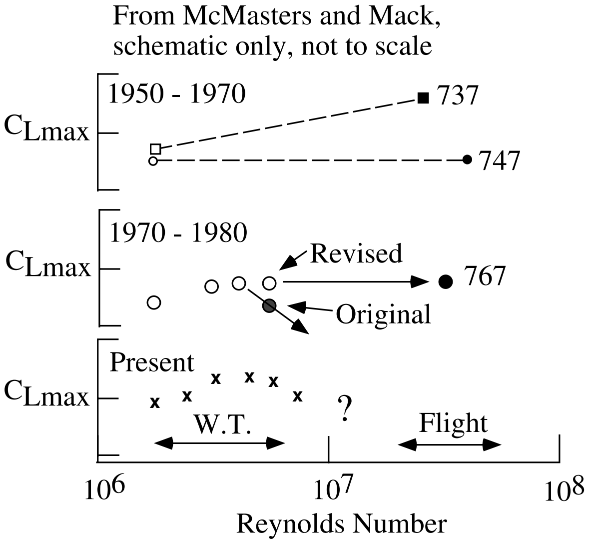

Figure 4. Boeing experience in tunnel to flight scaling (McMasters and Mack, Ref. 7)

So far we have described the problem using experimental observations. Computational fluid dynamics is also being used to study the same problems. Because of the presence of flow separation, most of the work is being done using so-called Navier-Stokes equations programs, which actually solve the Reynolds averaged equations subject to use of a turbulence model. Good examples include the work of Londenberg,[10] Rumsey and Vatsa,[11] Rogers,[12] and Anderson and Bonhaus.[13] Each of these papers provides good examples of computational research. However, in each case the focus eventually shifts to the evaluation of turbulence models. In each case, numerous calculations were done, and the results compared. Because the differences in the solutions mainly appear over the aft portion of the airfoil where separated flow exists, almost all the analysis of results was done for this region. The details at the leading edge were not examined, even though virtually all the experimental work points to the leading edge region as holding the key to accurate predictions (Cebeci's work excepted). The only Navier-Stokes analysis that focused on the leading edge was by by Pulliam some years ago.

In cases to date, the trends with Reynolds number were not particularly satisfactory, and the comparisons were implicit. Recently, Dominik[14] has presented results where Reynolds number trends were explicitly examined. He concluded that the Navier-Stokes code he was using did not do a good job of predicting trends with Reynolds number for maximum lift, even though several modern turbulence models were available. For the first recent time, he raised the issue of code capability to treat the flow around the leading edge in adequate detail, including the laminar separation bubble.

Note that many Navier-Stokes codes do not compute the integral properties aerodynamicists use to gain insight into the flow physics. Some codes handle transition poorly. It is unusual for the codes to include transition criteria. Improvements in both areas are required to help aerodynamicists investigate flow physics.

Although not currently popular, success in modeling high lift flow has been obtained using a viscous-inviscid interaction approach. Drela and Giles modeled the flowfield in

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* One wonders about surprises that might arise from trying to over-generalize the results being obtained in the NASA Langley 737 flight test program considering the difference in tunnel to flight scaling between the 737 and current Boeing designs.

terms of separate identifiable flow phenomena to produce an excellent method.[15,16] By explicitly addressing the separate physical phenomena, Drela has been able to explain many of the flow characteristics for these cases. The method has even been incorporated into a design and optimization methodology.[17]

Separation Bubble Studies

It is clear from the review so far that separation bubbles are important in the "leading edge - trailing edge" interaction phenomena. Many aerodynamicists have studied them, even though the computational community has not yet included them in the work associated with analyzing Navier-Stokes results.[18-22] Work continues in this area.[23,24] Most of the effort is associated with low Reynolds number aerodynamics. Not only is this an important area, but it is also possible to do experiments. Experimental investigation of separation bubbles at high Reynolds number is difficult because of the extremely small scale of the phenomena.

In practice, the key piece of information needed from the separation bubble analysis at high Reynolds number is the correct effective starting condition for the turbulent boundary layer. The increase in momentum thickness is the most important piece of information.

The LE–TE Interaction Flow Model

To conduct the initial study of the connection between the leading edge boundary layer and resulting trailing edge conditions, a series of simple pressure distributions are postulated, and the resulting drag, as computed from the Squire-Young formula, is then compared for a systematic variation in the initial conditions. The study is at this point a kind of poor man's version of the parametrics presented by Smith in his landmark paper.[25] Figure 5 provides details of the rooftop type pressure distribution used in the first part of the study. In this study the reference starting conditions are taken to be $\theta/L = 0.00004$, and $Re_\theta = 500$ at $x/L = .04$. The initial momentum thickness is then varied over a range from .5 to 40 times the reference condition, and the resulting variation in trailing edge boundary layer properties is investigated.

The second case uses an idealized peaky pressure distribution based on the real pressure distribution given in Fig. 2. The idealized case pressure distribution is shown in Fig. 6.

The Computational Method

The flow model concept described above has been investigated using a boundary layer computer program. The boundary layer is calculated using the classic Bradshaw method.[26] The method uses the turbulent kinetic energy equation, accounting for the inner portion of the boundary layer by matching to the law of the wall. It could be considered an ancestor of the currently popular Johnson-King turbulence model.[27] The particular computer code used is described in Bradshaw, et al.,[28] and is an extension of the two-dimensional compressible boundary layer code.[29]

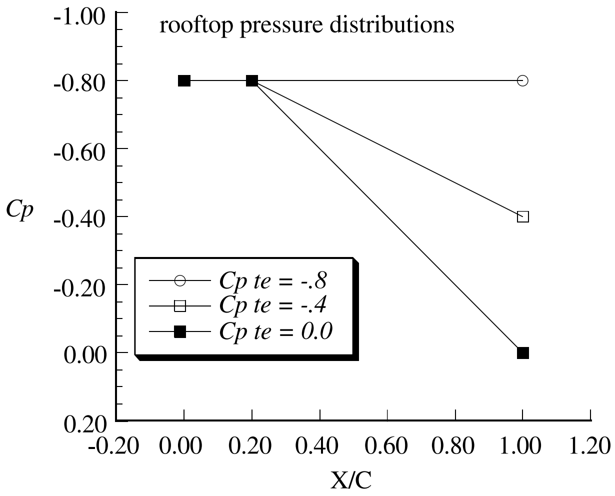


Figure 5, Model problem rooftop pressure distributions.

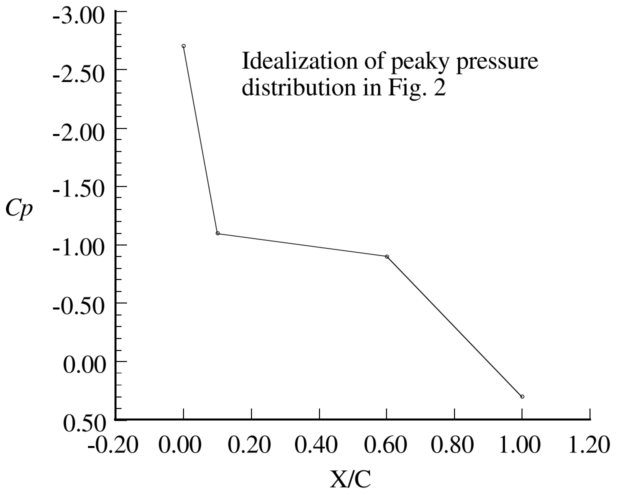


Figure 6. Model problem peaky pressure distribution.

This general class of methods has proven to be both accurate and reliable for the class of problems studied in this paper.[30] Calculations made using Green's lag entrainment method[31] produced virtually identical results.

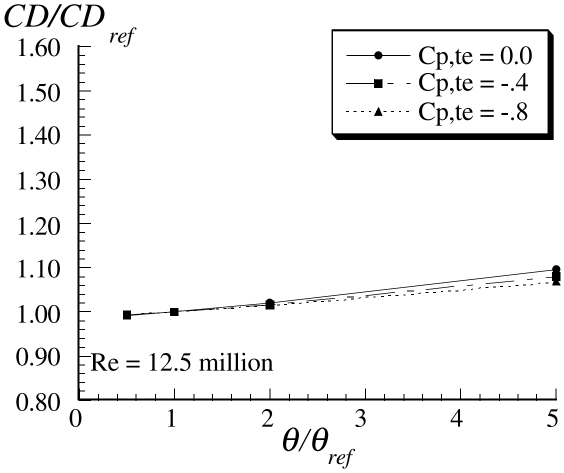
Although not currently popular in the literature, Bradshaw's method remains widely used in practice. This computational method provides an economical means of studying effects of varying pressure distribution, sweep, and taper on the boundary layer development. In particular, the trends rather than the absolute values of the various boundary layer properties are of primary interest in the present study. These trends, or gradients, would be completely consistent with results from more detailed and expensive calculations.

Model Problem Results

Figure 7 provides results for the rooftop model problem described above. Here the variation in drag, as computed by the Squire-Young Formula is presented normalized by the reference value, for a wide range of initial momentum thicknesses. Figure 7a shows the relative insensitivity of the results for minor variations in the initial momentum thickness. However, for large variations of the momentum thickness, as might be expected in the case of the laminar separation bubbles, Figure 7b shows the large effect on drag, even though the boundary layer has been attached for a long distance from the initial conditions. Figure 7b also illustrates how the effect is increased when the severity of the adverse pressure gradient is increased.

This result illustrates why the initial viscous airfoil analysis programs were able to ignore the initial boundary layer characteristics. They were interested in essentially attached flow calculations, and the transonic airfoils of interest did not have pressure peaks/recompressions that led to laminar separations bubbles. However, for the case where laminar separation is present, the details of the leading edge viscous effects will show up at the trailing edge, resulting in a leading edge–trailing edge interaction phenomena that is crucial to the prediction of the drag.

The results of similar calculations for the idealized peaky case are shown in Fig. 8. They are compared to the rooftop calculations made for the recovery to freestream velocity. Now, we see that the sensitivity of the solution to the initial conditions is increased, being about double the previous values, illustrating precisely why the leading edge conditions increase in importance for cases near maximum lift and where the drag break starts to occur.



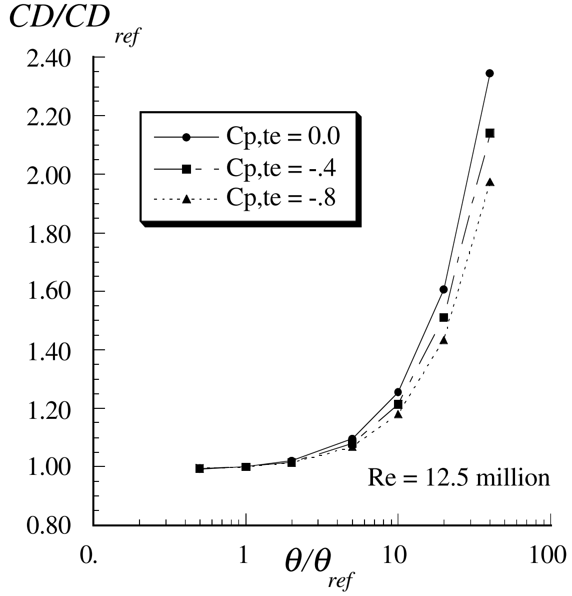
a) effects on drag over a "small" range of initial momentum thicknesses.

Figure 7. Results of the rooftop model problem

Conclusions

Several observations arise based on this work:

- As long as the boundary layer at the airfoil trailing edge is fully attached and not close to separating, the boundary layer development near the leading edge and the details of transition to turbulence providing initial conditions for the turbulent boundary layer development are not particularly important.



b) effects on drag over a large range of initial momentum thicknesses

Figure 7. Results of the rooftop model problem (concluded)

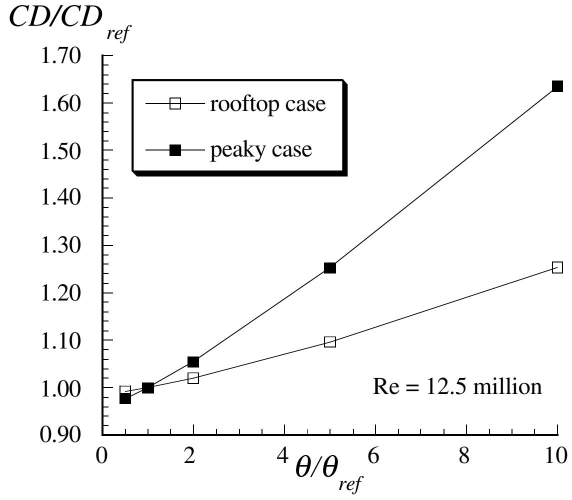


Figure 8. Results from the peaky model problem.

for the turbulent boundary layer development are not particularly important.

- The flow details in the laminar separation bubble and subsequent transition to an attached turbulent boundary layer flow near the leading edge of an airfoil are closely connected to the resulting drag of the airfoil when turbulent boundary layer separation occurs very close to the trailing edge, after a long run of attached flow.

- The computational community associated with Navier-Stokes solutions is not adequately addressing the flow field solution near the leading edge. Although the trailing edge and wake regions are also important, experimental evidence suggests that the leading edge details are equally important.

- Although difficult, experiments at moderately high Reynolds' numbers directed specifically toward the determination of the effective starting conditions for the attached turbulent boundary layer are required to identify precisely the Leading Edge – Trailing Edge interaction phenomena.

- The importance of the LE-TE interaction phenomena is known, but because of its competitive importance, major airframers are not revealing the full details of their understanding of the problem.

- Model problems can be used for insight.

Acknowledgements

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