Advances in Hypersonic Exploration Capability—Wind Tunnel to Flight Reynolds Number

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In the past, the limited Reynolds number capability of hypersonic facilities has prevented reliable extrapolation of data to flight Reynolds numbers. Recent results on a hypersonic cruise aircraft configuration obtained at Mach 8 in the Cornell Aeronautical Laboratory Hypersonic Shock Tunnel over a Reynolds number range from a completely laminar boundary-layer to a predominately turbulent one are presented. The significant factors which can affect extrapolation of wind-tunnel data at subscale Reynolds numbers to flight values are identified. The capability for predicting turbulent flight Reynolds number data from wind-tunnel data under laminar and transitional boundary-layer conditions are shown.

Introduction

THE basic aim of complete configuration wind-tunnel tests is to determine the full-scale aerodynamic performance of the particular concept. In the past, a major problem in the study of efficient hypersonic airbreathing aircraft resulted from the limited Reynolds number capability of hypersonic wind tunnels. The nature of the problem presented by this limitation is shown in Fig. 1. Because of the relatively low Reynolds numbers then available on realistic configurations, the boundary layers over a small subscale test models were mostly laminar and transitional, whereas, over full-scale aircraft (typically 100 m long), a turbulent boundary layer will cover all but a small area of the vehicle near the wing and tail leading edges and the fuselage nose. This difference in wind-tunnel and flight Reynolds numbers, of course, has always existed at lower speeds, but the problem has been overcome by adding small roughness elements to the model which artificially produce a turbulent boundary layer. At hypersonic speeds, however, usable boundary-layer trips have not been developed.[1,2] Because of the inability to develop a predominantly turbulent boundary layer over test models at hypersonic speeds, the viscous effects, not only on skin friction, but also on other important aerodynamic parameters, listed in Table 1, that affect flight performance could not be determined. As a result, reliable extrapolation of full-scale aerodynamics from wind-tunnel results could not be made.

Table 1 Aerodynamic parameters

PARAMETERS AFFECTING FLIGHT EXTRAPOLATIONS OF $(L/D)_{max}$	
FRICTION DRAG	C_{D_F}
PRESSURE DRAG	C_{D_P}
LIFT CURVE SLOPE	C_{L_α}
DRAG DUE TO LIFT	C_{D_L}
CONTROL EFFECTIVENESS	ΔC_m ΔC_L ΔC_D

Shock Tunnel

In the meantime, several developments have occurred to increase the range of available Reynolds numbers. These developments include modification to existing conventional tunnels and improvement in shock tunnel capabilities. In particular, the Cornell Aeronautical Laboratory Hypersonic Shock Tunnel[3] has been extremely useful in studying high Reynolds number effects. As shown in Fig. 2, by operating this tunnel at low stagnation temperatures (sufficient to avoid air liquefaction) and high pressures, full-scale Reynolds numbers are available. All tests were conducted in completely unsaturated air where the lowest test static temperature was 71°K, thus, all data were taken well outside the supersaturated region as defined by Daum.[4] Under these conditions, model boundary layers are predominantly turbulent without forced transition. On the other end of its Reynolds number range, the tunnel provides completely laminar mode boundary layers. The Cornell Aeronautical Laboratory Hypersonic Shock Tunnel, then, provides the unique opportunity to study hypersonic viscous effects on aerodynamic performance over the complete boundary-layer spectrum.

Test Configuration

Taking advantage of this opportunity, a study has been carried out on the model shown in Fig. 3. The configuration is representative of current ideas for a Mach 6, hypersonic

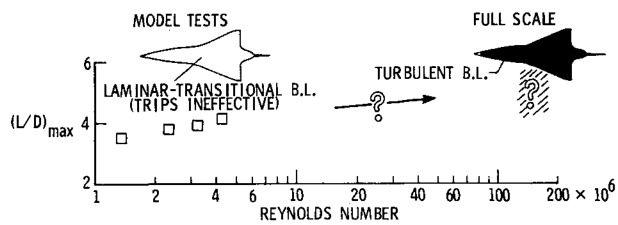

Fig. 1 Hypersonic wind-tunnel extrapolation capability in the mid-60's.

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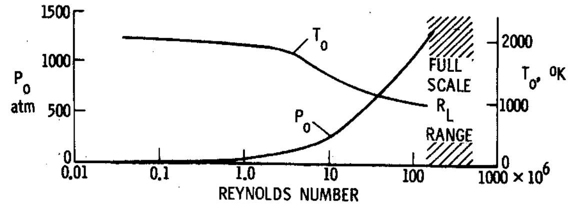

Fig. 2 Performance of the Cornell Aeronautical Laboratory Shock Tunnel at $M = 8$.

transport aircraft. The full-scale version would be nearly 100 m long and have about a 5000 naut mile range capability. The concept features a wide fuselage in relation to its height combined with strakes to improve the lifting capability of this predominant component. The fuselage is blended with the strakes and wing to reduce adverse component interference effects. The solid lines show the configuration tested. The vertical tail and propulsion system were eliminated during these tests. The test model was about $\frac{2}{3}$ m long or $\frac{1}{150}$ scale of the full-size flight vehicle. Additional model details may be found in Ref. 5. The investigation consisted of force tests over a Reynolds number range from about 0.5 million to 160 million, based on fuselage design length. Over this Reynolds number range, the Mach number varied from about 7.5 to 8.1.

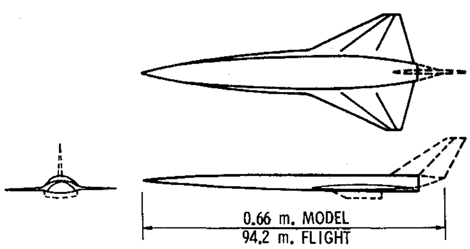

Fig. 3 Hypersonic test model.

Results and Discussion

The lift-to-drag ratio L/D as a function of Reynolds number is shown in Fig. 4. Notice that this is not a variation of the maximum L/D, but rather the L/D at an angle of attack of 3°. This is the angle of attack for maximum L/D at the highest test Reynolds number, and the model attitude is kept constant at this value for lower Reynolds numbers. Predictions of the data, assuming either an all laminar or an all turbulent boundary layer, are also shown. To obtain these predictions, inviscid theories (tangent cone on the fuselage, shock expansion on the strakes and wing) were applied to the isolated components through the computer program of Ref. 6. To these results skin friction C_F predictions given by the T' theory of Ref. 7, and Spalding-Chi theory of Ref. 8, were added. These theories were applied through the computer program of Ref. 6.

At the lowest Reynolds numbers, the model boundary layer is completely laminar. Transitional boundary-layer effects begin to emerge at Reynolds numbers of about 1.5–2 million. These effects predominate for about a decade in Reynolds number until the turbulent boundary layer exerts the major influence at Reynolds numbers between 15 and 20 million. This trend agrees with data obtained in the Cornell Aeronautical Laboratory Shock Tunnel on isolated cones and flat plates and from schlieren photographs of the present configuration. This is an interesting result for several reasons: 1) this range of Reynolds numbers is about the limit of conventional wind tunnels presently available and 2) if the turbulent boundary layer predominates at these Reynolds numbers in these facilities (there are indications they do and additional confirmation tests are planned), then flight extrapolations of wind-tunnel data can be made confidently since only small corrections will be required. The question then, is what performance parameters have major effects on these extrapolations.

Consider first the normal force C_N which is closely related to the lift force for low-drag configurations at low angles of attack. This parameter could be sensitive to the nature of the boundary layer through the viscous effects on lee-side flows and component interference, and at the lower Reynolds numbers through the boundary-layer displacement effects. In Fig. 5, the normal force is shown as functions of angle of attack for various Reynolds numbers over the test range. No viscous effects were included in the theoretical prediction of normal force. Although there may be some viscous effects at the lower Reynolds numbers, this effect is very small. In any event, at Reynolds numbers above 10 million, there are no noticeable viscous effects at all. This result is further borne out in Fig. 6 where the C_N at an angle of attack of 3° is essentially independent of Reynolds number. This result implies that if viscous effects change the local characteristics of lee-side flows and component interference, their over-all effect is negligible for this configuration, and the normal force parameter may be neglected in the extrapolation process.

Next consider the axial-force coefficient C_A. This parameter is, of course, strongly affected by viscous effects on skin-friction and boundary-layer displacement effects. The large variation of C_A with Reynolds number is shown in Figs. 7 and 8. Most of the change in C_A is probably due to skin-friction changes as boundary-layer displacement effects would be ex-

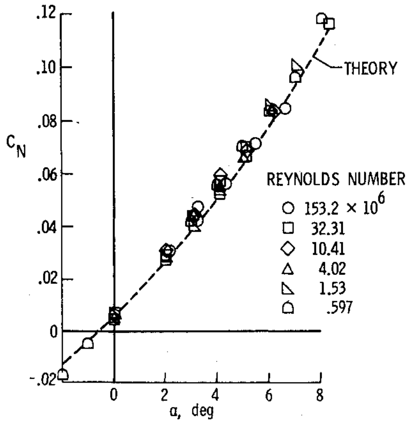

Fig. 5 Variation of normal-force coefficient with angle of attack at various Reynolds numbers, $M = 8$.

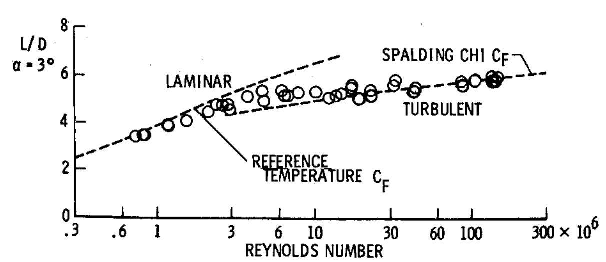

Fig. 4 Variation of lift-drag ratio at 3° angle of attack with Reynolds number, $M = 8$.

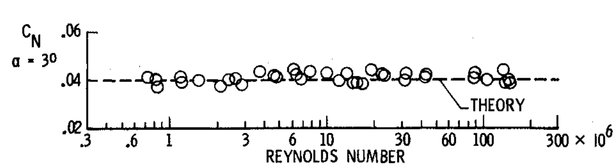

Fig. 6 Variation of normal-force coefficient at 3° angle of attack with Reynolds number, $M = 8$.

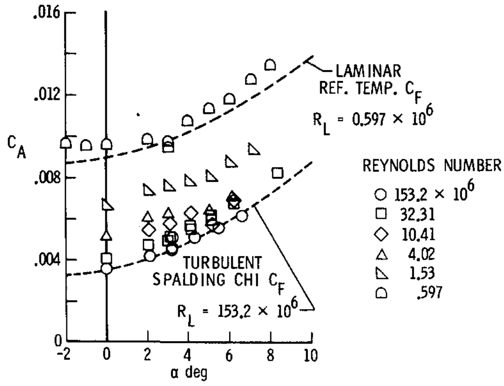

Fig. 7 Variation of axial-force coefficient with angle of attack at various Reynolds numbers, M = 8.

pected to be confined to the very low Reynolds numbers. The skin friction then, as it has always been, is a strong factor in extrapolations of wind-tunnel results to flight Reynolds numbers. It should be noted that the turbulent predictions for this blended wing-body configuration are superior to the laminar predictions.

The drag-due-to-lift parameter $\partial C_D/\partial C_L^2$ is the last one that will be considered. This parameter again would be most affected by viscous effects on both lee-side flows and component interference. The variation of $\partial C_D/\partial C_L^2$ with Reynolds number is shown in Fig. 9. The slight increase with Reynolds number is approximately the same as the predicted trend which accounts for the effect of small variations in the tunnel Mach number with Reynolds number. For all practical purposes, Reynolds number has no effect on $\partial C_D/\partial C_L^2$ which indicates again, as with the normal force, that over-all viscous effects on lee-side flows and component interference are negligible for this configuration. Considerations of the drag-due-to-lift parameter in hypersonic wind-tunnel data extrapolation are therefore not required.

Of the parameters considered then, only the viscous effects on skin friction need be accounted for in correcting subscale hypersonic wind-tunnel data to flight values. Let us examine now how accurately we can predict the data at the highest Reynolds number by making these viscous corrections to the data at lower Reynolds numbers. The correction simply amounts to replacing the skin friction in the data at lower Reynolds numbers with the turbulent skin friction at the high Reynolds number. For our estimates of the laminar skin friction, we used the T' method, and the Spalding-Chi method for the turbulent skin friction. The total axial-force coefficient to which these skin-friction corrections were made was obtained from a mean fairing through the data as shown in the top of Fig. 10. The percent errors in predicting constant angle of attack (3°), values of C_L, C_D, and L/D at the

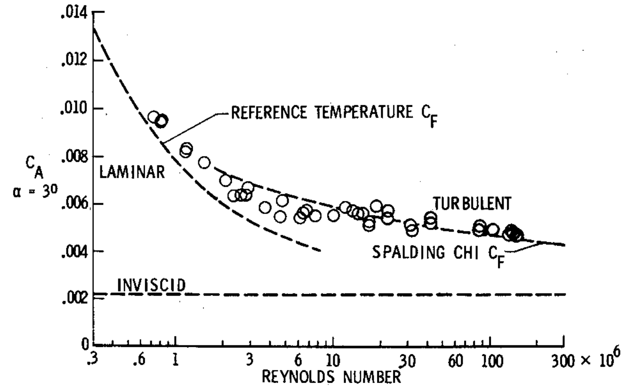

Fig. 8 Variation of axial-force coefficient at 3° angle of attack with Reynolds number, M = 8.

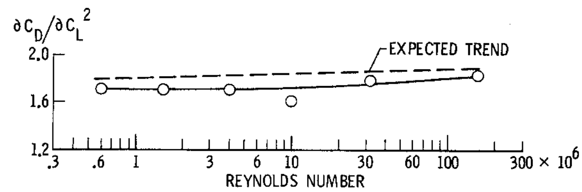

Fig. 9 Variation of drag due to lift with Reynolds number, M = 8.

highest Reynolds number are shown at the bottom. For the curves shown, the skin friction, at a given Reynolds number, was assumed either entirely laminar or entirely turbulent. At Reynolds numbers below about 1 million and above about 15 million, where this assumption is nearly correct, the predictions are in error less than 10%. In between, large potential errors result because a mixed boundary layer (partly laminar, partly transitional, partly turbulent) predominates. It is encouraging to note that if conventional tunnels can achieve a predominantly turbulent boundary layer at the upper limit of their capability (Reynolds numbers of about 20 million), full-scale Reynolds number predictions on the order of 5% or

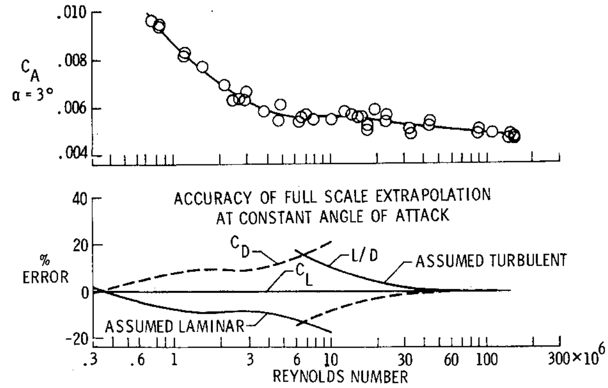

Fig. 10 Accuracy of extrapolation of performance characteristics at a constant angle of attack to full-scale Reynolds number.

less should be obtained assuming an all turbulent boundary layer. The accuracy of these predictions can be improved if the location of transition can be defined and the correct local skin-friction corrections are applied. The location of transition can be determined by using the phase-change-paint technique.

These results, of course, apply to the constant angle-of-attack case, and are not necessarily representative of the optimum, or $(L/D)_{max}$ case. Because of the higher drag at lower Reynolds numbers, the angle of attack for $(L/D)_{max}$ will be

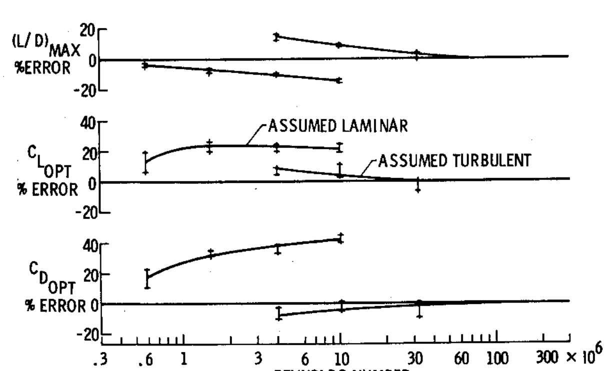

Fig. 11 Accuracy of extrapolations of optimum performance characteristics to full-scale Reynolds number.

higher at these test conditions than under full-scale Reynolds number conditions, and this optimum angle of attack will not be known a priori. We consider finally then, how accurately the optimum case can be predicted. The results are shown in Fig. 11.

Using the data at low Reynolds numbers (below 1 million), where the model boundary layer is laminar, the high Reynolds number value of $(L/D)_{max}$ is well predicted, but the optimum values of C_L and C_D are not. These errors are partly due to the inability to accurately predict skin friction on a complete configuration, particularly in the laminar region and partly due to the critical nature of the determination of the optimum C_L and C_D from faired data. The tick marks indicate likely errors from the fairing of present data. By correcting data in the Reynolds number range from 15 to 30 million, however, where the boundary layer is predominantly turbulent, adequate optimum performance values at the high Reynolds numbers can be predicted.

Concluding Remarks

Studies in the Cornell Aeronautical Laboratory Hypersonic Shock Tunnel, at Mach number 8, of a blended wing-body configuration, representative of a hypersonic transport vehicle, have shown that the factor that significantly affects extrapolation of hypersonic subscale Reynolds number data to flight Reynolds number values is the skin friction. If wind-tunnel data can be obtained at Reynolds numbers where the turbulent boundary layer predominates, simple turbulent skin-friction corrections to the data will allow good prediction of flight Reynolds number performance data. Further improvement should be possible by determining the location of transition and applying the correct local skin friction. The insignificance of the lift and drag-due-to-lift factors indicates that over-all viscous effects on both lee-side flows and component interference are secondary for the blended wing body used in this study. A different result may apply to discrete wing-body configuration types where the component interference effects may be more predominant. Furthermore, additional work is required to determine viscous effects on control effectiveness parameters over the Reynolds number range. An accurate knowledge of these parameters, of course, is required to predict reliable values of the trimmed performance at flight Reynolds numbers, and because of possible flow separation over controls, viscous effects on these parameters could be significant.

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