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Transition from Laminar to Turbulent Flow in Separated Shear Layers

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Nomenclature

c = airfoil chord
L = streamwise distance from separation to transition
ℓ = unit of length
M = Mach number
Re = Reynolds number
s = wetted length from stagnation point to boundary-layer separation
T' = relative turbulence intensity in freestream
U = velocity
ν = kinematic viscosity

Subscripts

c = based on length c
L = based on length L
s = based on local value at separation
∞ = based on freestream conditions

Introduction

When a laminar boundary layer separates from a solid boundary, the free shear layer may undergo transition to the turbulent state and the turbulent layer may subsequently reattach to the solid boundary. In such cases, the region of separation is referred to as a separation bubble. Laminar-to-turbulent boundary-layer transition on many practical aerodynamic and hydrodynamic configurations occurs by this process. Therefore, there is interest in both the prediction of laminar separation and the streamwise distance from separation to transition. The location of separation may be predicted by semiempirical criteria or by various computer codes written for calculating laminar boundary-layer characteristics. This Note concerns the streamwise length from separation to "transition," denoted by L or a Reynolds number $(U/\nu)_s L = Re_{sL}$. Because transition lengths in separation bubbles are relatively short compared to, for example, airfoil chord, authors writing on this subject usually have not made a distinction between the beginning and end of transition.

There have been proposals for methods of predicting Re_{sL}. Several of the semiempirical types are briefly reviewed in Ref. 1, where new data from subsonic wind tunnel experiments are presented. References 2 and 3 discuss separation bubbles and describe efforts at predicting transition based upon the e^n approach, whereby an unstable shear layer is assumed to undergo transition through the amplification of Tollmein-Schlichting waves. Reference 4 is a recent analysis of the problem of computing the flow in the bubble region. The present Note shows that a feature of the transition phenomenon hidden in the data of Ref. 1 and apparently not recognized in earlier investigations should be considered in future work.

Technical Discussion

The purpose of this Note is to point out a rather strong factor that seems to have been generally overlooked in the context of transition over separation bubbles or other free shear layers. This factor, which is commonly called the unit Reynolds number Re/ℓ or (U/ν), is shown in this Note to exert an influence very similar to its usual effect on the transition of bounded shear layers (see, e.g., Refs. 5–7).

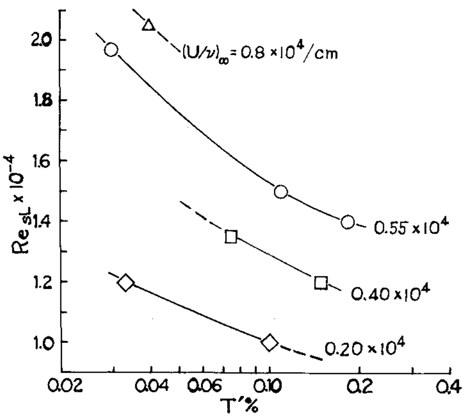

Fig. 1 Experimental data of Ref. 1 recast to indicate the relationship of Re_{sL} and T' when Re/ℓ is constant.

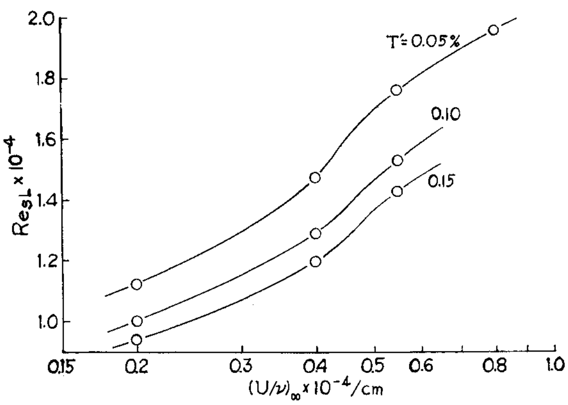

Fig. 2 The influence of Re/ℓ upon Re_{sL} in the subsonic separation-bubble flows of Ref. 1.

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By using the data in Fig. 6 of Ref. 1, values of Re_{sL} (R_ℓ in Ref. 1) may be tabulated for constant $Re_{\infty c}$ (R_c in Ref. 1) or for constant $(U/\nu)_\infty$ inasmuch as aifroil chord c was constant and equal to 25 cm. Corresponding values of relative freestream turbulence intensity T' may be extracted from Fig. 7 of Ref. 1. It is then possible to plot Figs. 1 and 2. Figure 1 shows the expected decrease of Re_{sL} as T' increases at constant $(U/\nu)_\infty$. Figure 2, obtained by reading Re_{sL} for a constant T' in Fig. 1, reveals the strong Re/ℓ effect, and it is very similar in slope to that sometimes found in wind-tunnel data. Straight lines fitted to the points have an average slope of approximately 0.4. It is interesting to note that, within the range of these data, the influence of Re/ℓ is roughly double that of T' in magnitude and opposite in direction. Emphasis must be given to the limited range of the data because the rates of change seen in Figs. 1 and 2 are not expected to continue indefinitely.

There has been much speculation about the inadequately understood unit Reynolds number phenomenon. Interest principally focuses on the absent length that could eliminate the dimensional feature of U/ν or a frequency term that would make U^2/ν dimensionless. It seems possible that the particular character of the disturbance that causes transition in a given case is the product of the combination of environmental factors present. These include both freestream and surface factors. The unit Reynolds number, or something related thereto, apparently is one of the environmental factors that can influence the disturbance, its growth, or the receptivity of the boundary layer to destabilization. On the basis of prior work, the discovery of an Re/ℓ effect in transition of free shear layers should not be surprising. Because of the limited data, the demonstration is not as complete as one would prefer. However, the results shown are thought to make a convincing statement.

Conclusions

It is remarked in Ref. 1 that Re_{sL} seemed to increase with T', apparently because of some unknown influence related to changes in the chord Reynolds number. It is further stated that, for a given value of T', multiple values of Re_{sL} can occur, suggesting that some characteristics of the freestream other than the turbulence intensity has a substantial effect on Re_{sL}. After the present analysis of the same data, it seems that appropriate, albeit tentative conclusions are that 1) increasing turbulence intensity had the expected effect of decreasing Re_{sL} when $(U/\nu)_\infty$ was held constant; 2) a strong Re/ℓ effect was evident, increasing $(U/\nu)_\infty$ and causing Re_{sL} to increase for constant T', as is also found in many studies of the transition of bounded shear layers; 3) the Re/ℓ effect should not be neglected in efforts to characterize the laminar-to-turbulent transition of the shear layer over separation bubbles; and 4) more experimental data are obviously needed for better verification of these tentative conclusions.

Acknowledgment

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Effects of Pitot Probe Shape on Measurement of Flow Turbulence

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Introduction

THE high-frequency response of semiconductor strain gage-type pressure transducers makes them an attractive alternative for flow turbulence investigations when high-quality optical access is unavailable for laser anemometer equipment or when flow temperature or erosion problems are too severe for hot-wire anemometry. Their ability to follow fluctuations in the total pressure has brought them into common usage for aircraft compressor intake instrumentation. Steenken[1] demonstrated that the spatial resolution of high-frequency turbulence is determined by transducer diameter, with the smaller probes providing a more accurate representation of the auto-power spectra at high frequencies. Grande and Oates[2] compared the output of this type of transducer with the output from a hot-wire anemometer in wind tunnel flows and found that both signals had essentially the same normalized power spectral density at frequencies up to 25 kHz.

This Note describes some of the effects of enclosing this type of transducer with various tip housings to improve its response for mean and fluctuating pressure measurements. Measurements taken with these probes and with a hot film anemometer along the centerline of a freejet provided a relationship between the fluctuation levels of freestream velocity and total pressure.

Experimental Approach

The experiments were conducted in a freejet from a 5.08-cm-diam nozzle with an 88.4 m/s mean velocity and a 0.2% turbulence intensity at the exit. The air supply was a 0.91-m square cross-section settling chamber pressurized by a centrifugal fan. A silicon diaphragm pressure transducer (Kulite model SCS-093-5), 2.36 mm in diameter and 25.4 mm long, was chosen as one of the smallest transducers to pro-

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