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Laminar-Turbulent Transition in Free Shear Layers

Anthony Demetriades*
Montana State University, Bozeman, Mont.
Paul J. Ortwerth†
Air Force Weapons Laboratory, Albuquerque, N. Mex.
and
William M. Moeny‡
Tetra Corporation, Albuquerque, N. Mex.

Abstract

A STUDY has been performed to derive a threshold criterion for the existence of turbulence in a shear layer, and to see if such a threshold is useful in predicting transition onset in such a flow. This approach has already given satisfactory results in wake flows.[1] As in the latter case, the present work[2] is based on the existence of a minimum turbulence Reynolds number, and derives numerical results by utilizing established magnitudes of turbulence properties in the turbulent shear layer. Transition Reynolds numbers are predicted as a function of speed ratio, total temperature ratio, and Mach number jumps across the layer. New experiments are described in which free shear-layer transition was measured and, within an observed unit Reynolds-number effect, was found to parallel the predictions quite well.

Contents

In Ref. 1 it was shown that if a minimum or threshold turbulence Reynolds number $Re_{\Lambda 0}$ is necessary to maintain turbulence in a wake, then a transition Reynolds number can be computed that agrees satisfactorily with experimental data. In the present work similar results are sought for the two-dimensional free shear layer separating two streams of velocity u_1 and u_2, respectively. The layer is uniquely defined by the speed ratio $\lambda \equiv (u_1 - u_2)/(u_1 + u_2)$, the "fast" side Mach number M_1 and the total temperature ratio T_{01}/T_{02}. Such a layer is first considered to be fully turbulent and a computation is made of the turbulence Reynolds number Re_Λ along its dividing streamline. The magnitude of the velocity fluctuation u' is obtained from experimental measurements correlated by Ortwerth and Shine,[3] while the kinematic viscosity ν is taken by combining the shear-layer velocity profile with the Crocco relation. The integral scale Λ is assumed to bear a simple geometric relation to the flow width, as already discussed for other free turbulent flows in Ref. 1. One thus obtains Re_Λ explicitly in terms of the M_1, λ, and T_{01}/T_{02}, and it is found that Re_Λ increases monotonically downstream of the flow origin.

It is then argued that 1) a minimum value of $Re_{\Lambda 0}$ of Re_Λ is necessary to maintain the turbulence and 2) there exists a number of theoretical and experimental sources putting $Re_{\Lambda 0}$ in the 10-20 range. These sources include gradient diffusion modeling[4] and simple dissipation energy balance (Ref. 5, p. 185); similar thresholds on Re_Λ appear when turbulent and laminar dissipation rates are equated, or when the eddy viscosity decreases to the laminar viscosity value.[6,7] That $Re_{\Lambda 0}$ is of the order of 15 is also supported by experiments on grid turbulence decay[8-10] and by transition data given by Ref. 1.

For the shear layer, the adoption of such a minimum (or threshold) $Re_{\Lambda 0}$ means that turbulence cannot exist upstream of a point or zone, whose distance ξ_T from the turbulent flow origin depends on M_1, λ, and T_{01}/T_{02}. A necessary condition for transition is therefore generated with ξ_T as the distance from the turbulent origin where Re_Λ, computed as indicated earlier, reaches the threshold value $Re_{\Lambda 0}$. The paper next indicates how ξ_T can be exchanged for the distance X_T from the origin of the laminar flow. A transition Reynolds number is thus produced, based on the "fast side" properties and X_T:

$$Re_{XT} = \left(\frac{Re_\Lambda}{CC'}\right)^2 \frac{1}{\Gamma^2 G^2} \left(\frac{T_{\rm dsl}}{T_1}\right)^{2(k+1)} \left(\frac{\lambda+1}{\lambda}\right)^2 \qquad (1)$$

where C relates the scale Λ to the flow width; C' is an experimentally determined factor in the magnitude of u'; $T_{\rm dsl}$ and T_1 the dividing streamline and "fast-side" temperatures, respectively; and k the temperature-viscosity exponent. The functions Γ and G depend on M_1, T_{01}/T_{02}, and λ, and are related to the variations of u' and the flow width along the shear layer. The quantity $(Re_{\Lambda 0}/CC')^2$ basically contains all those factors for which precise theoretical or experimental information is still unavailable. If this quantity is expressed as C'' then Eq. (1) can be plotted as in Fig. 1 without knowledge of these factors. The figure indicates that transition moves aft as λ decreases, and as M_1 and the "slow side" stagnation temperature T_{02} increase.

The evaluation of C'' is of course needed if one wishes to compare the threshold expectations of Eq. (1) and the curves of Fig. 1 with experiments. In a qualitative sense, the present predictions are verified by the observations of Chapman et al.[11] that X_T increases as M_1 increases, and of Larson[12] regarding the effect of T_{01}/T_{02}. These references, however, involve separated laminar boundary layers which makes it difficult to define the flow origin, and thus also to quantify the X_T necessary for comparison with Eq. (1). It would be more appropriate to consider the shear-layer transition results reported by Birch and Keyes[13] and Crawford[14] in which the origin of the shear layer was experimentally well-defined. To add to this meager data base, a new experiment was done by the authors, resorting to the shock-crossing technique similar to that of Ref. 13. This experiment involved two consecutive two-dimensional deflections α_1 and α_2 of the Mach 8 stream of Wind-Tunnel B at the Arnold Engineering Development Center of the U. S. Air Force. Transition data were obtained by spark- and time-exposure shadow photography interpreted by visual and densitometric techniques. The transition data obtained are shown on Fig. 1 along with the data from Ref. 13. A similar comparison of the present theory with data is shown on Fig. 2. All data were cast in the coordinates of these figures by evaluating the C'' of Eq. (1) on the basis of

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*Professor, Mechanical Engineering. Associate Fellow AIAA.
†Chief, Pulsed Chemical Laser Section.
‡President. Member AIAA.

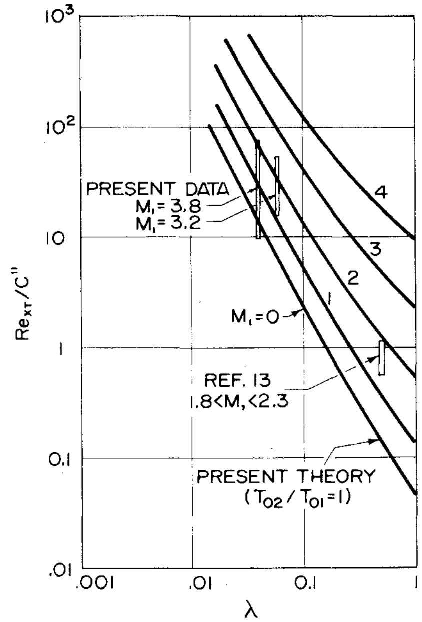

Fig. 1 Comparison of the theory with transition observations for adiabatic flow.

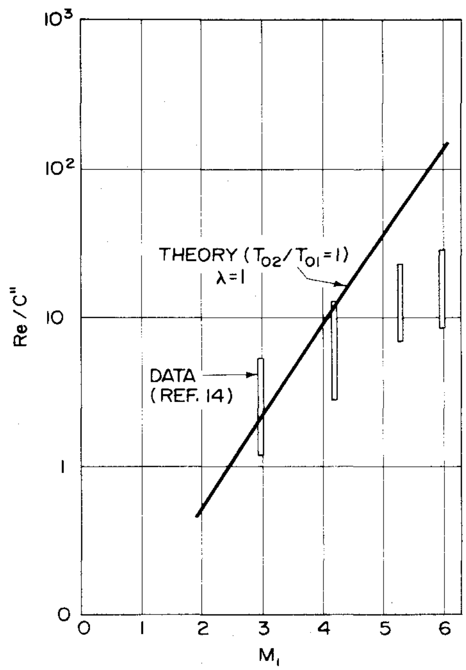

Fig. 2 Comparison of the theory with data on the effect of Mach number on shear-layer transition.

$Re_{\Lambda 0} = 15$ and the best available knowledge on C and C', by which $C \simeq 0.2$ and $C' \simeq 0.32$; C'' then becomes approximately 55,000.

It can be seen that there is qualitatively adequate agreement between the data and the present prediction of the transition threshold; for example, the rapid increase of Re_{XTR} with decreasing λ is verified, as is the increase of Re_{XTR} with increasing M_I. Quantitatively, however, the present approach overpredicts the transition Reynolds number, occasionally by a large factor. Furthermore, the transition Reynolds numbers reported in the present paper[2] as well as in Ref. 13 and 14 show an unmistakable dependence of Re_{XTR} on the unit Reynolds number Re'. The role of Re' in the transition process has been noted before for flows such as boundary layers, but its importance to free shear-layer transition has apparently not been appreciated. The data on Figs. 1 and 2 are shown as vertical bars along which Re' changes. The unit Reynolds number effect thus hinders, for the present, a more accurate comparison of Eq. (1) with transition data.

It should be noted that quantitative agreement is in anyway not expected here, since the present theoretical approach is based on a condition of necessity alone without an accompanying condition of sufficiency. As already pointed out in Ref. 1, the present theoretical threshold, like the minimum critical Reynolds number derived by stability theories, provides only guidelines on the functional dependence of the transition distance on the flow parameters. On the other hand, there is room in the present approach for including the effect of factors additional to λ, M_I, or T_{0I}/T_{02}, via the influence of such factors on the quantities appearing in Eq. (1). The paper concludes that there is sufficient similarity between this theory and the limited data available to warrant improved computations of Re_Λ in a shear layer; such an improvement should, of course, await more complete data on the variation of u' and Λ in the shear layer under a variety of conditions.

Acknowledgments

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