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A NEW SCALING FOR ADVERSE PRESSURE GRADIENT TUBULENT BOUNDARY LAYERS

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Abstract A new scaling for strong adverse pressure gradient (APG) turbulent boundary layers (TBL) is presented. The new scaling is applied to both the author's unsteady and steady APG TBL experiments as well as several previously published studies. The scaling is shown to provide a remarkable collapse of the mean velocity profiles in each case. The new scaling is motivated by the recognition that the physics of the strong APG TBL is dominated by the inflectional instability of an embedded shear layer within the boundary layer. The implications of the scaling on the physics of strong APG TBL flows is also discussed.

SUMMARY

Based on an experimental investigation of unsteady APG TBL as described in reference [1], it was found that the local flow physics is dominated by the inflectional instability of an embedded shear layer within the boundary layer. In particular, throughout the unsteady cycle of imposed external pressure variation, the turbulence intensity peak tracks with the wall-normal location of the velocity profile inflection point and the Q2 and Q4 Reynolds stresses are equal at the inflection point. The Q2 Reynolds stress is greatest on the high speed side of the inflection point and Q4 Reynolds stresses are greatest on the low speed side (see Figure1). These aspects are consistent with the formation of an embedded free shear layer.

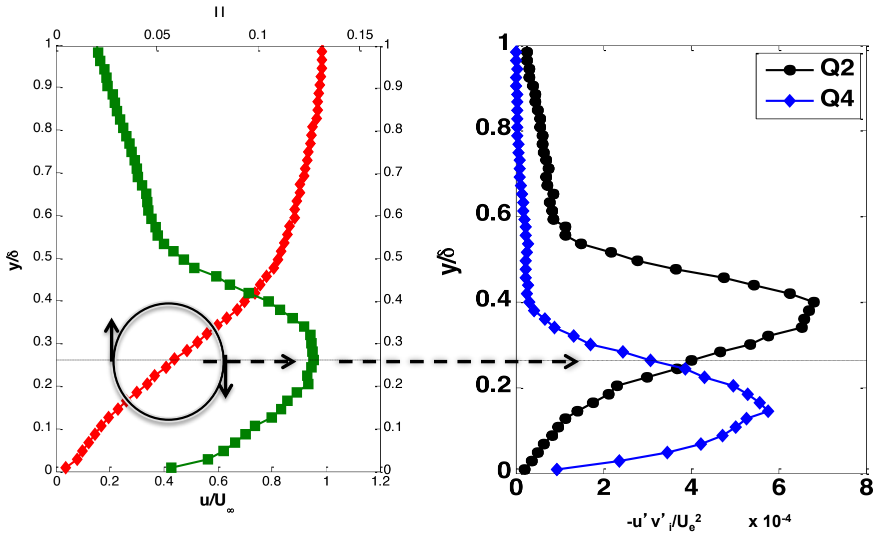

Figure 1. Sample phase-average unsteady APG TBL measurements showing that the maximum of the turbulence intensity profile tracks the phase-averaged velocity inflection point with Q2 Reynolds stress dominant above and Q4 Reynolds stress dominant below.

In the full paper we show that the formation of an embedded shear layer with associated inflectional instability mechanism is also a generic feature of *steady* APG TBL for sufficiently large wake pressure gradient parameter Π(x). Based upon these experimental results we implement a scaling based on free shear layer paramters. In partibular, the length scale is given by the maximum vorticity thickness,

$$\delta_\omega \equiv \left(U_e - \bar{U}\right)_{IP} / \left(d\bar{U}/dy\right)_{IP} = U_d)_{IP} / \left(d\bar{U}/dy\right)_{IP} \qquad (1)$$

while the velocity scale is given by,

$$\left(U_e - \bar{U}\right)_{IP} = U_d)_{IP} \qquad (2)$$

where subscript IP denotes the quantity is to be evaluated at the inflection point. Based upon this scaling the following similarity varables are utilized,

$$Y^* \equiv \frac{y - y_{IP}}{\delta_\omega}, \quad U^* \equiv \frac{U_e - \bar{U}}{U_d)_{IP}}, \quad u^*_{RMS} \equiv \frac{\sqrt{\overline{u^2}}}{U_d)_{IP}} \qquad (3)$$

As an example of the ability of this scaling to collapse strong APG TBL mean velocity profiles, Figure 2 presents two examples taken from the experimental data sets compiled by Kline, Coles and Hirst (2). The flows are indicted in the figure with the unscaled profiles shown at the top and the scaled version at the bottom. As is evident, the scaling works remarkably well with the only deviations noted occurring in the near-wall region.

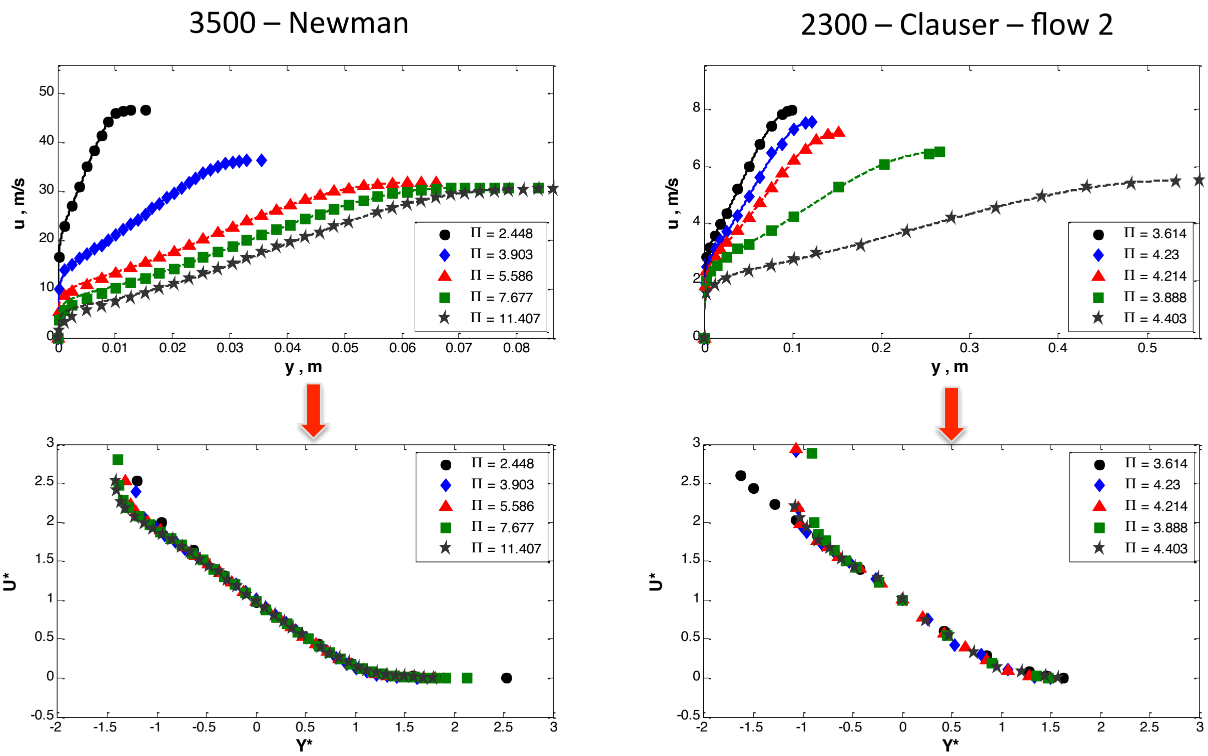

Figure 2. Example of the implementation of the new scaling for two APG TBL data sets from ref[2].

In the full paper we will present several additional examples of this scaling for both steady and unsteady APG TBL. In addition, the near-wall deviation from scaled behavior will be shown to be a unique function of pressure gradient wake parameter, Π(x). We will also demonstrate the ability of this scaling to collapse the turbulent stresses. Finally, the implications of the scaling on the flow physics of APG TBL in general will be addressed.

References

[1] Schatzman,, D. M., “A Study of Unsteady Turbulent Boundary Layer Separation Under Conditions Relevant to Helicopter Rotor Dynamics,” Ph.D dissertation, University of Notre Dame, 2011.

[2]. Kline, S. J., Coles, D. E., and Hirst, E. A., “Computation of Turbulent Boundary Layers-1968 AFOSR-IFP-Stanford Conference, Stanford University, 1968.