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SEPARATING TURBULENT BOUNDARY LAYERS

W.H. SCHOFIELD

AERONAUTICAL REREARCH LABORATORIES
FISHERMAN'S BEND, VIC. 3207 AUSTRALIA

SUMMARY. Two dimensional turbulent boundary layer separation is considered. It is shown that the Schofield and Perry defect law can describe detached profiles as accurately as it can describe attached profiles if the origin (for the similarity) is shifted from the wall out to the zero velocity position in the detached flow. A similarity description is proposed for the reversed flow so that the entire detached flow can be accurately described by two similarity relations. The extended validity of the Schofield & Perry defect law implies a unique progression of mean velocity profiles up to and through separation. Good experimental support for this result is presented. Experimental evidence also supports the proposition that boundary layers detach with a universal mean profile shape. A comparison of this result with other separation theories leads to the slightly broader conclusion that separating layers in moving equilibrium not only detach with the same mean profile shape but detach at the same local pressure gradient.

1. INTRODUCTION

Turbulent boundary layer separation is usually responsible for setting an upper limit to the performance of aerodynamic devices. After separation the performance of a device is determined mainly by the separated flow. Thus to be able to describe and predict separating and separated flow is a major aim of fluid mechanics research.

Although the topic is an old one there has been little progress in analytical work, partially because the experimental data that existed were limited and of poor quality. Recently however some high quality measurements of separated flows have been published. The problems to be addressed are now: to find simple, universal, similarity relations to describe separating and separated flows and to devise a simple universal separation criterion. These two problems are the subject of new proposals presented in this paper. They could form the basis of a simple prediction method for separating and separated flows.

2. SIMILARITY RELATIONS IN SEPARATING LAYERS

2.1 Similarity Before Detachment

The logarithmic law of the wall is valid in most two dimensional turbulent wall layers. This was established by Coles & Hirst (1968) where it was shown that even Stratford's (1959) near separating layers had small logarithmic regions. Recently Simpson et al. (1977, 1980) showed that the logarithmic region persists in separating layers until the wall flow contains instantaneous flow reversals. This validity probably extends to reattaching profiles, see Schofield (1983a). Two parameter descriptions of adverse pressure gradient layers have been traditionally based on the velocity scale $U_\tau (=(\tau_o/\rho)^{\frac{1}{2}}$, where τ_o is the wall shear and ρ the fluid density) and a total layer thickness. However at separation U_τ becomes zero and these profile descriptions become meaningless.

Schofield and Perry (1972) suggested that a better similarity scale for boundary layers in adverse pressure gradient flow was U_s related to the maximum shear stress in the layer rather than the wall shear stress. The similarity defect law based on $U_m (=(\tau_m/\rho)^{\frac{1}{2}}$, where τ_m is the maximum shear stress in the layer) gives good descriptions of attached profiles (see Schofield (1981)) for the outer 90 - 95% of a layer, with an expression for the mean velocity (u) of

$$\frac{U_1 - u}{U_s} = 1 - 0.4(^Y/_B)^{\frac{1}{2}} - 0.6 \sin (^{\pi Y}/_{2B}) \qquad (1)$$

where $U_s = 8\ (B/L)^{\frac{1}{2}}\ U_m$, $B = 2.86\ \delta^*\ U_1/U_s$, L the distance from the wall to τ_m, U_1 the free stream velocity, δ^* the displacement thickness. Near the wall, equation (1) can be expressed as

$$\frac{u}{U_1} = 0.47 \left\{\frac{U_s}{U_1}\right\}^{3/2} (^Y/_{\delta^*})^{\frac{1}{2}} + 1 - U_s/U_1. \qquad (2)$$

Perry and Schofield (1973) used equation (2) to find U_s/U_1 from a profile by adapting the methodology introduced by Clauser (1954) to find U_τ/U_1 from the logarithmic law.

2.2 Proposed Similarity for Separated Flow

The velocity scale used in Schofield and Perry similarity is related to the maximum shear stress which does not disappear or reverse its direction during flow detachment. There is, therefore, no theoretical reason why it should not describe the forward flowing part of a separated flow. Back flow near the wall is probably strongly influenced by downstream conditions and is therefore unlikely to scale on the same parameters; it would form the wall matching condition for a detached profile replacing the usual law of the wall in attached flow.

To test these ideas recent detailed results taken in separating layers by Simpson et al. (1977, 1981) Perry and Fairlie (1975), Schofield (1983a) and Seddon (1967) were analysed. As only the forward flowing portion of the layer was to be described by the Schofield and Perry similarity a new ordinate (Y_D) was used which has its origin at u = 0 in the detached flow rather than at the wall. Typical half power plots of detached profiles are shown in figure 1. In general the velocity ratios (U_s/U_1) so determined exceed 1 in detached flow. Using the velocity ratios determined in the half power plots the profiles can be plotted on Schofield and Perry co-ordinates, see figure 2. The data correlate well with the Schofield and Perry similarity relation except near $Y_D = 0$. This is the region where the outer flow is matched to the wall flow (in this case the reversed flow) and the deviation from equation (1) is similar to that observed in attached flow (see Perry and Schofield (1973)); thus these profiles are not different in this respect from attached profiles. Complete sets of data from the six experiments are presented in Schofield (1983b) and are similar to those shown in figure 2.

2.3 Reversed Flow Similarity

It can be argued that the back flow may be determined by a number of factors and this makes it difficult to formulate simple similarity scales. Firstly the back flow could be considered a wall flow with scales U_τ, ν/U_τ. Simpson et al. (1981) showed that these scales did not correlate their data; they also tried unsuccessfully several wall-wake correlation schemes involving the outer flow variables U_1, δ. As the outer flow has been shown here to scale with U_s and B_D, these were tried on a range of data but gave hopeless results.

Schofield (1983a) showed that the size of the separation bubble in a boundary layer under a shock wave was greatly affected by downstream conditions. Simpson et al. (1977, 1981) found that downstream conditions affected the level of back flow in separated regions that did not reattach. These considerations suggest that back flow is a complex region in which both wall and outer flow variables are important, the action of both being modified by dynamic and continuity constraints imposed on the flow from downstream. The resulting flow appears to scale on its own local variables; the maximum back flow velocity (U_N) and its distance from the wall were suggested by Simpson et al. (1981). These parameters give a fair correlation of data but a better correlation can be obtained by using the total back flow thickness (D) as shown in figure 3.

3. SEPARATION CRITERIA

If a mean velocity profile is described by equation 1 and we integrate across the layer to get expressions for the displacement/momentum thickness we can show (Schofield 1983b) that

$$\frac{\delta^*}{\theta} = H = \frac{1}{1-0.58(U_s/U_1)} \pm 10\% \qquad (3)$$

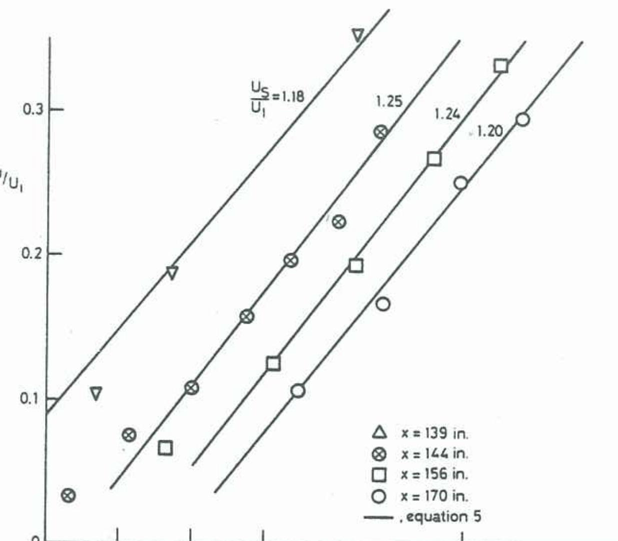

Figure 1. Half Power Distributions. Data of Simpson et. al (1981).

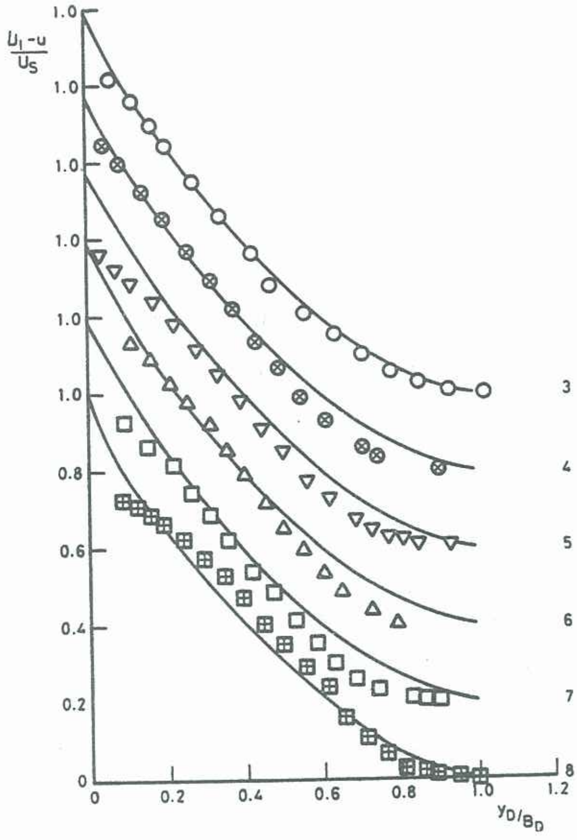

Figure 2. Mean Velocity Similarity for Separated flow. Data of Schofield (1983a).

where the ± 10% allows for the uncertainty in the Schofield and Perry similarity description of profiles near y (and y_D) = 0. The equation should apply to detached layers for that part of the layer in which $y_D > 0$. Figure 4 shows that a wide range of attached and detached profiles follow the H, H_D - U_s/U_1 locus of equation 3 however this evidence does not necessarily imply that detachment occurs in all layers at the same position on the locus.

Before we can consider separation or detachment criteria we need to consider what is meant by separation or detachment, as lack of agreement over the meaning of these terms bedevils work in this field. At a recent colloquium on separating flow (Simpson (1981)) definitions of turbulent detachment states involving time dependent measurements, were agreed on. The detachment states were related to the percentage of time the flow near the wall was in back flow. The definitions are: incipient detachment is the condition of 1% back flow ($\gamma_p = 0.99$), intermittent transitory detachment is the condition of 20% back flow ($\gamma_p = 0.8$) and transitory detachment is the condition of 50% back flow ($\gamma_p = 0.5$). Detachment was defined as $C_f = 0$.[1] Thus the positions of detachment and transitory detachment must be very close unless the magnitude of the wall stress near detachment differs markedly during the upstream and downstream flow phases and this is most unlikely. These definitions are appealing as they are precise and employ a measure of intermittent flow reversal (γ_p) which reflects the nature of separation. There are however, obvious difficulties in using γ_p; to experimentally measure γ_p requires sophisticated instrumentation. From a prediction point of view present calculation methods could not hope to accurately predict γ_p but their ability to accurately predict mean flow development is fairly good and is rapidly improving. For these reasons we

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1 Separation is defined as the entire detachment process.

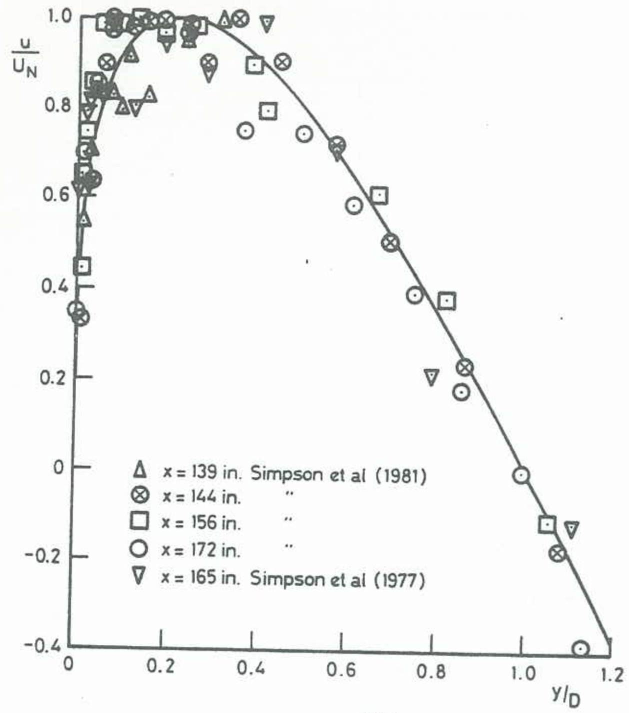

Figure 3. Back Flow Similarity.

are forced into using mean flow parameters. However it does seem possible that γ_p may be uniquely related to the mean flow profile shape and therefore a universal detachment criterion may be possible using Schofield and Perry similarity as follows. Figure 5 shows wall flow reversal measurement (γ_p) by Simpson et al. (1981) and the corresponding velocity scale ratios (U_s/U_1) for the mean flow, both plotted as functions of flow length, x. If the relationship between γ_p and U_s/U_1 shown in this figure apply in all two dimensional separating layers then the detachment stages will occur at fixed values of U_s/U_1 and therefore at approximately constant values of H. However there are no other separating data containing (relevant) intermittency measurements and hence these proposals cannot be tested further. It is however possible to test the most important condition of transitory detachment through the concommitant detachment criterion, $\overline{C_f} = 0$.

Figure 6 shows the H versus U_s/U_1 relation (equation 3) and the data points for Simpson et al.'s (1981) experiment. The correlation with the relation is as good after detachment as before detachment. Also shown in the figure is the skin friction distribution which is consistent with detachment ($\overline{C_f} = 0$) near the position of $\gamma_p = 0.5$ which occurs at $U_s/U_1 = 1.18$ from figure 5. Detachment data for other separating flows are broadly consistent with these results in that firstly, nearly all the data whether attached or detached show good agreement with equation 3. Secondly, detached profiles[1] first appear on the H versus U_s/U_1 trajectories with values of U_s/U_1 between 1.1 to 1.2. All skin friction distributions can be plausibly extrapolated to zero at or near $U_s/U_1 = 1.18$ (see Schofield (1983b) where H = 3.2.

3.1 Discussion

The proposition is then, that boundary layers approaching separation do so along a unique H - U_s/U_1 locus and that detachment occurs at a set point on this locus corresponding to H = 3.2. That detachment occurs at a universal value of H was an early idea in boundary layer theory and has been used by practical designers for a long time. It was Clauser in 1956 who initially attacked the view that a boundary layer could separate at a set value of H. He showed that H depended on both U_τ and pressure gradient and could be greatly increased by a rough wall. He implied that a rough wall would bring on detachment at a different value of H than on a smooth wall. However the data he used to support his argument was confined to zero pressure gradient flow. Adverse pressure gradient flow is quite different in that the effect of U_τ on profile shape is very small (see Schofield 1981) and thus rough wall layers approaching detachment show behaviour similar to the smooth wall layers (see Schofield 1983b).

[1]Detachment being determined in most cases with surface flow visualisation tests and/or negative velocities near the wall in the mean velocity profiles.

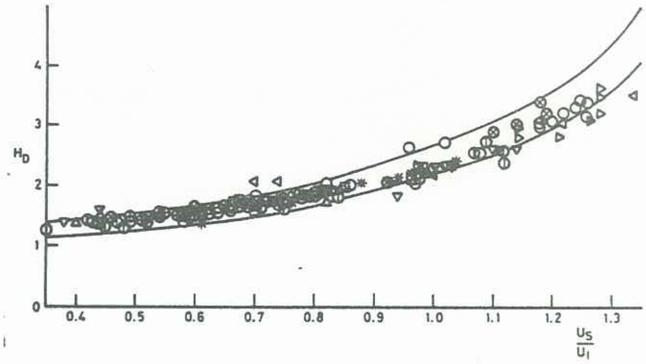

Figure 4. Shape Factor versus Velocity Ratio. Attached and Detached Profiles.

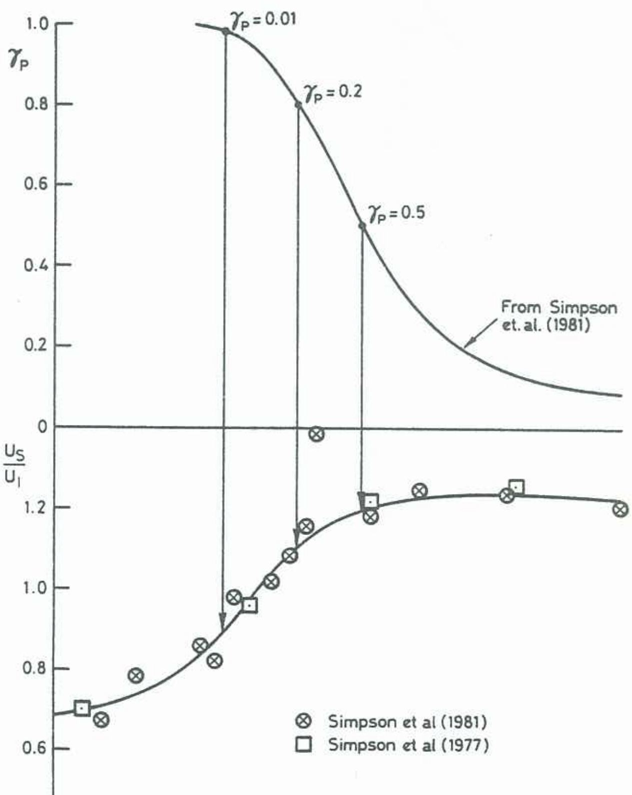

Figure 5. Intermittant Flow Reversal and Velocity Ratio Distributions.

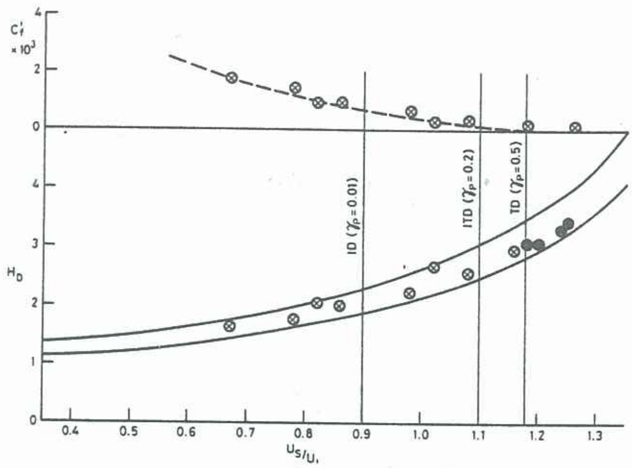

Figure 6. Mean Flow Separation Parameters. Data of Simpson et. al (1981).

The present proposal implies a universal separation profile and in this it is similar to Coles' (1956) account of separation. Simpson et al. (1977) and Schofield (1981) both assumed that the separation process involved a contraction of the logarithmic law down to the wall with a corresponding extension of the half power law towards the wall. For the detachment condition, $C_f' = 0$, the Schofield and Perry equations (see Schofield and Perry (1972)) imply that the half power law extends to the wall which for zero mean velocity at the wall requires $U_s = U_1$. Thus the argument gives $U_s/U_1 = 1$ as the detachment condition rather than $U_s/U_1 = 1.18$ as suggested above. There are however two weaknesses in this argument.. Firstly it takes no account of the viscous sublayer which is important when considering velocities near the wall. Secondly the argument uses the Schofield and Perry observation that the logarithmic and half power regions join at a point of tangency. This condition does not appear to apply to separating layers (see Schofield 1983b). For these reasons the result predicted by Simpson et al. and Schofield can only be a first approximation.

Finally if we compare these proposals with the theoretical limit for detaching equilibrium layers[1] (Schofield (1981)) we can learn something of the separating behaviour of layers in moving equilibrium. Figure 7 shows this theoretical limit for detachment as a line of $C_f' = 0$ on axes of inverse velocity ratio (U_1/U_s) and pressure gradient strength $(-m)$*. In figure 7a the positions of observed equilibrium layers near detachment have been plotted and it seems reasonable that boundary layers separating in moving equilibrium would pass through the position of these equilibrium layers. The separating layers already considered in this work were re-analysed as moving equilibrium layers and their locii up to detachment were found to be very similar to the line passing through the equilibrium layers; one example is shown in figure 7b. The trajectories cross the detachment line near $U_s/U_1 = 1.18$ and are thus consistent with the above work. The trajectories also imply that the local pressure gradient decreases as detachment is approached and that the layers detach with the same local pressure ($m \simeq -0.2$). The first point is supported by empirical observation (Simpson et al. (1981), Perry and Fairlie (1975) and Schofield (1983a)) and arises from the interaction between sheared and unsheared flow during separation. The second point is a new result.

[1] Equilibrium layers are defined as layers of constant velocity ratio, U_s/U_1.

* m is the index of free stream velocity variation, $U_1 \propto x^m$.

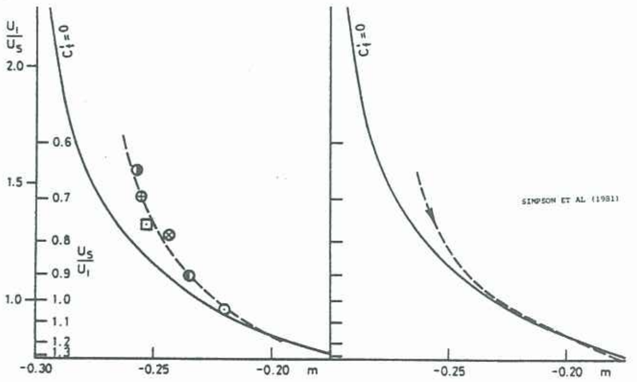

Figure 7. Equilibrium Layers near Separation.
(a) Observed Equilibrium Layers.
(b) Detachment Trajectory of Simpson et. al (1981).

4. CONCLUSIONS

1. The Schofield & Perry similarity for adverse pressure gradient boundary layers applies to detached flow as well as attached flow. The similarity applies only to the forward flowing portion of a detached layer and requires the origin to be moved from the wall to the zero mean velocity streamline in the flow.

2. Reversed boundary layer flow does not scale with forward flow similarity parameters, nor with wall variables. An improvement on the similarity parameters proposed for this region by Simpson et al. (1981) is to use the total back flow thickness as the length scale.

3. The validity of the Schofield and Perry defect law implies a unique progression of mean profile shapes up to and through separation. The progression follows the relation
H or $H_D = 1/(1-0.58\, U_s/U_1)$.

4. Turbulent boundary layers separating from surfaces of small curvature appear to detach with a universal mean velocity profile shape (defined by $U_s/U_1 = 1.18$) which has a shape factor of 3.2.

5. On co-ordinates of profile shape versus local pressure gradient, layers in moving equilibrium separate along trajectories that closely follow a line joining the positions of observed equilibrium layers near detachment. Layers which separate in moving equilibrium detach at the same local pressure gradient.

5. REFERENCES

Coles, D.E. (1956) J. Fluid Mech., Vol. 1, p. 191.
Coles, D.E. & Hirst, E.H. (1968) AFSOR-IFP Stanford Conf., Vol. II, Stanford Uni.
Clauser, F.H. (1954) J. Aero. Sci., Vol. 21, p. 91.
Perry, A.E. & Schofield, W.H. (1973) Phys. of Fluids, Vol. 16, p. 2068.
Perry, A.E. & Fairlie, B.D. (1975) J. Fluid Mech. Vol. 69, p. 657.
Sandborn, V.A. & Kline, S.J. (1961) J. Basic Eng., Trans. ASME, Vol. 83, p. 317.
Schofield, W.H. (1981) J. Fluid Mech. Vol. 113, p. 91.
Schofield, W.H. (1983a) Aero. Res. Labs., M.E. Rept. 161.
Schofield, W.H. (1983b) Aero. Res. Labs., M.E. Rept. 162.
Schofield, W.H. & Perry, A.E. (1972) Aero. Res. Labs., M.E. Rept. 134.
Seddon, J. (1967) ARC R. & M. No. 3502.
Stratford, B.S. (1959) J. Fluid Mech., Vol. 5, p. 1 & p. 17.
Simpson, R.L., Strickland, J.H. & Barr, P.W. (1977) J. Fluid Mech., Vol. 79, p. 553.
Simpson, R.L. (1981) J. Fluids, Eng., Trans. A.S.M.E., Vol. 103, p. 521.
Simpson, R.L., Chew, Y.T. & Shivaprasad, B.G. (1981) J. Fluid Mech., Vol. 113, p. 23.