Technical note

Generalized Coles’ law and outer layer conformal mapping

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ABSTRACT

The time-averaged velocity profile of a turbulent boundary layer can be predicted by combining its different trends in the inner and outer regions in a single law of the wake. A new non-dimensional coordinate system that projects the time-averaged velocity profiles of the inner and the outer regions on the same non-dimensional plane is introduced, leading to a unified treatment for the mixing region. In this coordinate system, various laws of the wake are shown to be the same but a constant. The non-dimensionalization is tested on a specific law of the wake, in which the closure coefficients are regressed from wind tunnel measurements and direct numerical simulations of turbulent boundary layers under zero-pressure gradient, over a good range of boundary layer thickness based Reynolds numbers. This data fit produced profiles within 2% of the reference values. This is of practical use to numerical modellers for generating boundary layer inflow profiles.

Keywords: Boundary layer model, law of the wake, scaling law, turbulent boundary layer, wake parameter

1 Introduction

The zero-pressure gradient boundary layer is an established test case for improved near-wall velocity profile formulations for turbulent wall-bounded flows. Buschmann and Gad-el-Hak (2007) review the use of scaling laws for turbulent boundary layers, demonstrating that a universally applicable functional is lacking, with neither power law nor logarithmic behaviours being ruled out. Under certain conditions, the boundary layer inner region is described by a logarithmic profile by von Kármán (1954). Its outer region is described by a defect velocity approach. Coles (1956) combined these two analytical descriptions into a single formulation, the law of the wake. Following this approach, several variants of this law have been published by Moses (1964), Finley et al. (1966), Granville (1976), Dean (1976), Lewkowicz (1982), Guo and Julien (2003), Guo et al. (2005), and Yang (2009).

The state of the art in the law of the wake raises two issues. First, how do the above-mentioned formulations compare with each other, and, second, why does the law of the wake not remove the presence of two concurrent length scales in the velocity profile, namely the boundary layer thickness \( \delta \) in the outer region, with its corresponding free-stream velocity scale \( u_\infty \), and the viscous length scale \( \mu/u_t \) in the inner region, with its corresponding friction velocity \( u_t \), with \( \mu \) the laminar viscosity. This research addresses both issues by introducing a novel scaling for the outer layer \( (\gamma, \alpha) \), where the defect velocity region and the logarithmic portion of the profile are projected on an unied non-dimensional reference system. The scaling depends on the value of the von Kármán parameter \( k \) and the smooth wall parameter \( B \). Krogstad et al. (1992) determined \( k \) and \( B \) empirically by regressing measured velocity profiles. Following their approach, this work presents regressed values of \( k \) and \( B \), and of the wake parameter \( \Pi \) over the boundary layer thickness-based Reynolds number range of \( 145 \leq R \leq 13030 \), where \( R = \delta u_t/\nu \). These give velocity profiles, by the law of the wake of Finley et al. (1966), within \( \pm 2\% \) of the measurements.
2 Unifying the laws of the wake

2.1 Classical formulations

Based on the existence of a region of overlap between the inner region of the turbulent boundary layer, described by the law of the wall

\[ u^+ = f(y^+) \]  \hspace{1cm} (1)

and its outer region, described by the velocity defect law

\[ 1 - \frac{u}{u_\infty} = f(\eta) \]  \hspace{1cm} (2)

Coles (1956) proposed the additive function

\[ u^+ = k^{-1} \ln y^+ + B + \Pi k^{-1} f(\eta) \]  \hspace{1cm} (3)

where \( u^+ = u/u_* \), \( y^+ = y/u_* \), and \( \eta = y/\delta \), where \( y \) is the wall-normal distance, and \( \Pi \) the wake parameter determined by

\[ \Pi = 0.5k(u_\infty^+ - k^{-1} \ln R - B) \]  \hspace{1cm} (4)

where \( R = \delta u_*/\nu \) is the non-dimensional boundary layer thickness and \( u_\infty^+ = u_\infty/u_* \) the normalized free-stream velocity. Commonly used formulations for the velocity defect law are reported in Table 1.

The defect laws by Coles (1956), Coles’ polynomial defect law reported by White (1991), and the defect laws by Lewkowicz (1982) and Finley et al. (1966) satisfy

\[ u = u_\infty \text{ at } y = \delta \]  \hspace{1cm} (10)

The defect laws by Lewkowicz (1982), Moses (1964), and Finley et al. (1966) satisfy

\[ \frac{\partial u}{\partial y} = 0 \text{ at } y = \delta \]  \hspace{1cm} (11)

In an actual turbulent boundary layer, the mean velocity profile approaches Eqs. (10) and (11) asymptotically, with a rate that is strongly influenced by the free-stream turbulence level (Gostelow 2009). It is an established practice to define \( \delta \) in experiments at about 0.99\( u_\infty \) and to neglect the small velocity defect above it. For instance, Granville (1976) used 0.9969\( u_\infty \) and 0.998\( u_\infty \) for fitting his law of the wake to the experimental data. The same simplification is adopted in the data fitting of Section 3, by which the velocity defect above a reference \( \delta \) is set to zero and \( \delta \) is taken to match a desired finite input value.

2.2 Conformal mapping approach

Let the solution of

\[ \frac{\partial u^+}{\partial y^+} = (ky^+)^{-1} \]  \hspace{1cm} (12)

with \( u^+ \) defined by Eqs. (3) and (9), be \( y_{\text{crit}}^+ \). Substituting Eq. (12) into Eq. (3) and using \( f(\eta) \) from Eq. (9), then

\[ y_{\text{crit}}^+ = \frac{R(\Pi+1/6)}{\Pi+1/4} \]  \hspace{1cm} (13)

where \( y_{\text{crit}}^+ \) is the point where the distance of Eq. (3) from the logarithmic law of the wall \( u^+ = k^{-1} \ln y^+ + B \) is maximum (Jones et al. 2001). Its physical meaning may be expressed as the location where the effect of the dominant outer layer mixing over that of the inner layer driven viscous dissipation is a maximum. In other words, the mean velocity profile at \( y_{\text{crit}}^+ \) is essentially determined by the convective processes in the outer layer and the influence of viscosity is weak.

Consider the transformation

\[ \left( \frac{y}{y_{\text{crit}}} \right)^* = u^+ - k^{-1} \ln y_{\text{crit}}^+ \]  \hspace{1cm} (14)

For \( u^* \) to be real, \( y_{\text{crit}}^+ > 0 \). Imposing \( y_{\text{crit}}^+ > 0 \) in Eq. (13) gives \( \Pi > -1/6 \). Equation (3), expressed in terms of the new variables \( (y^*, u^*) \) from Eq. (14), with \( f(\eta) \) from Eq. (9), is

\[ u^* = \frac{1}{k} \ln y^* + B + \frac{2(\Pi+1/6)^2}{k(\Pi+1/4)^2} y^{*2}(3-2y^*) \]  \hspace{1cm} (15)

Using Eqs. (3) and (6) in Eq. (12), the root of the latter is \( y_{\text{crit}}^+ = R \). Substituting this in Eq. (14) and then Eq. (14) in Eq. (3) with Eq. (6) results in

\[ u^* = k^{-1} \ln y^* + B + 2\Pi k^{-1}(y^*)^2(3-2y^*) \]  \hspace{1cm} (16)

Similarly, substituting Eqs. (3) and (8) in Eq. (12) gives \( y_{\text{crit}}^+ = R(\Pi+1/12) \). Substituting this in Eq. (14) and then Eq. (14) in Eq. (3) with Eq. (8), this becomes

\[ u^* = \frac{1}{k} \ln y^* + B + \frac{2\Pi^3}{(\Pi+1/12)^2} y^{*2}(3-2y^*) \]  \hspace{1cm} (17)

Comparing Eqs. (15), (16), and (17), the transformation of Eq. (14) is seen to project the laws of the wake of Coles, Moses, White (1991), and the defect laws by Lewkowicz, Moses, and Finley et al. (1966) into Eq. (3) and using f(\( \eta \)) from Eq. (9), then

\[ y_{\text{crit}}^+ = \frac{R(\Pi+1/6)}{\Pi+1/4} \]  \hspace{1cm} (13)

where \( y_{\text{crit}}^+ \) is the point where the distance of Eq. (3) from the logarithmic law of the wall \( u^+ = k^{-1} \ln y^+ + B \) is maximum (Jones et al. 2001). Its physical meaning may be expressed as the location where the effect of the dominant outer layer mixing over that of the inner layer driven viscous dissipation is a maximum. In other words, the mean velocity profile at \( y_{\text{crit}}^+ \) is essentially determined by the convective processes in the outer layer and the influence of viscosity is weak.

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Comparing Eqs. (15), (16), and (17), the transformation of Eq. (14) is seen to project the laws of the wake of Coles, Moses,

Table 1 Classical velocity defect laws

| Reference          | \( f(\eta) \)                             | Equations |
|--------------------|-------------------------------------------|-----------|
| Coles (1956)       | \( 1 - \cos(\pi\eta) \)                   | (5)       |
| Coles’ polynomial  | \( 2\eta^2(3-2\eta) \)                     | (6)       |
| (White 1991)       |                                           |           |
| Lewkowicz (1982)   | \( 2(3\eta^2-2\eta^3) - \eta(3\Pi)^{-1} \) | (7)       |
| Moses (1964)       | \( 2(3\eta^2-2\eta^3) - \eta(3\Pi)^{-1} \) | (8)       |
| Finley et al. (1966)| \( (\Pi^2 + 6)\eta^2 - (\Pi^2 + 4)\eta^3 \) | (9)       |
and Finley et al. so that, in \((y^*, u^*)\) coordinates, the three laws are identical but a constant. The form of the three laws is that of Coles equation (3), with \((y^*, u^*)\) in place of \(y^+, u^+, \) and \(y/\delta\).

Having determined a common functional in \((y^*, u^*)\) coordinates enables to see the three laws of the wake as belonging to the same class. It also enables to study what key elements make them different from each other. The three laws use different values of \(y^+_\text{crit}\). This suggests that in Coles’ law re-stated as Eq. (16), where \(y^+_\text{crit} = R\), the viscous effects on the mean velocity profile decrease monotonically to the boundary layer edge, at \(y^+ = R\), while momentum transport effects have the opposite trend. In Eq. (15), the re-statement of Finley et al.’s law, transport effects over viscous effects reach a maximum below the boundary layer edge, for instance, \(y^+_\text{crit} = 0\). In the re-stated Moses’ law of Eq. (17), this maximum occurs further down the boundary layer, for instance, at \(y^+_\text{crit} = 0.86R\) for \(P = 0.5\).

3 Validation

3.1 Predictions of outer layer velocity profile at various \(R\)

Equation (3), with \(f(\eta)\) from Eq. (9), was fitted to a range of streamwise velocity data (Spalart 1988, Erm and Joubert 1991, Österlund 1999, De Graaff and Eaton 2000) from turbulent boundary layers under zero pressure gradient over the range of \(145 \leq R \leq 13,030\). The values of \(u^+_\text{cr}\) and \(R\) are given by the above authors and are reported in Table 2. Note that \(k\), \(II\), and \(B\) are unknown parameters to be determined by regression, as by Krogstad et al. (1992).

Figure 1(a) shows the non-dimensional mean streamwise velocity defect \((1 - u/u_\infty)\) versus the non-dimensional wall distance \(\eta\). The symbols used are given in Table 2 and denote values from experiment and direct numerical simulation. An incremental vertical shift of \((1 - u/u_\infty) = 0.50\) was applied to all curves for clarity and the 0 label on the ordinate of Fig. 1(a) refers to the \(R = 145\) curve. The experimental data almost collapse on each fitted curve, suggesting that the curve fit has captured most of the \(u^+\) dependence on \(\delta, u_\infty, u_r,\) and \(R\).

The quality of the data fit was further investigated, similar to Buschmann and Gad-el-Hak (2007), by evaluating the fractional difference (FD), which is defined as

\[
FD = \frac{100k(u^+_a - u^+_e)}{\ln y^+_i} \tag{18}
\]

where \(u^+_a\) is the value given by Eq. (3), with \(f(\eta)\) from Eq. (9), and \(u^+_e\) is the corresponding measured value for a given \(y^+_i\) in a discretized velocity profile of \(N\) points. Buschmann and Gad-el-Hak (2007) computed FD for a range of exponential and logarithmic laws. Figure 1(b) shows FD from Eq. (3), with \(f(\eta)\) from Eq. (9), following Buschmann and Gad-el-Hak (2007).

| \(R\) | \(u^+_\infty\) | \(II\) | \(k\) | Symbol |
|-------|-------------|------|-----|-------|
| 300   | 145         | 18.25| 0.253| 0.390 | ○    |
| 697   | 335         | 20.25| 0.227| 0.411 | *    |
| 1003  | 460         | 21.5 | 0.321| 0.415 | Δ    |
| 1430  | 640         | 22.4 | 0.308| 0.393 | •    |
| 2900  | 1192        | 24.33| 0.357| 0.390 | ▽    |
| 3654  | 1365        | 25.38| 0.575| 0.402 | ×    |
| 5200  | 2000        | 26   | 0.490| 0.406 | ▼    |
| 12,633| 4436        | 28.62| 0.635| 0.404 | □    |
| 13,000| 4770        | 28   | 0.484| 0.412 | ◊    |
| 22,845| 8000        | 30.15| 0.615| 0.407 | +    |
| 31,000| 13,030      | 30   | 0.383| 0.419 | ☆    |

Figure 1 Fitting velocity profiles to measurements over the range \(134 \leq R \leq 13,030\): (a) Profiles from experiment and direct numerical simulation in Table 2, lines by Eq. (9), (b) fractional difference FD between fitted and measured velocity profiles. Low \(R\), light grey lines; high \(R\), black lines, with line patterns as in (a). (c) Predicted velocity defect profiles. For symbols, see Table 2.
Over the range of $30 \leq y^+ \leq R$, over which $k$ and $II$ were optimized, Fig. 1(b) shows that the fitted velocity data are within $\pm 2\%$ of the measured values. Multiple crossings of the FD = 0 line indicate the absence of a systematic $u^+$ under-prediction or over-prediction over this $y^+$ range, for all Reynolds numbers tested $R$. If $y^+ < 30$, the law of the wake of Eq. (3), with $f(\eta)$ from Eq. (9), does not follow the experimental profile through the viscous sub-layer, where $u^+ = y^+$, which is a known feature of the von Kármán law of the wall. This gives a rising FD as $y^+ < 30$, as in most of the logarithmic laws reviewed by Buschmann and Gad-el-Hak (2007). In Fig. 1(b), the lighter curves denote the lower reference Reynolds numbers, as in Buschmann and Gad-el-Hak (2007). Over the range of $30 \leq y^+ \leq R$, there appears not to be a clear Reynolds number trend in the FD error from the even placement of all curves about the FD = 0 axis.

Figure 1(c) shows the fitted velocity profiles of Fig. 1(a) without the vertical shift. In this figure, the symbols of Table 2 label each curve by its reference Reynolds number. Plotting the velocity profiles in defect velocity form shows a good scaling of the outer region, where all curves collapse as $\eta \rightarrow 1$. The curves are shown to satisfy the boundary conditions of Eqs. (10) and (11) as $\eta \rightarrow 1$. At $\eta < 1$, the curves depart among each other, with the higher Reynolds number profiles having a more pronounced concavity and a correspondingly lower velocity defect.

Figure 2(a) shows the fitted wake parameter $II$ versus the free-stream Reynolds number, from the regression method by Krogstad et al. (1992). A least-squares linear regression is applied to $II$, from which its standard deviation is obtained. Assuming the differences in $II$ are normal, independent, with constant variance, the 50% confidence interval band for $II$ is plotted in Fig. 2(a). A positive correlation between $II$ and the free-stream Reynolds number is shown in Fig. 2(a). The width of the 50% confidence interval band is narrower than the regressed variation of $R$. If $y^+ > 30$, as obtained by regression. The significant standard deviation is computed from Eq. (13) using $\eta \rightarrow 1$ and the overlap regions, where the inner scaling of Eq. (1) and the outer scaling of Eq. (2) apply.

3.2 Velocity profiles in modified logarithmic coordinates

George and Castillo (1997) defined the limit of the overlap region and the outer boundary layer in terms of $(y^*, u^*)$ and $(y/\delta, u/\nu_{\infty})$. Rather than using two different scaling coordinates, time-averaged velocity measurements are here presented using the unified coordinate system $(y^*, u^*)$ from Eq. (14). Just like with $(y^+, u^+)$ and $(y/\delta, u/\nu_{\infty})$, the normalization $(y^*, u^*)$ aims to collapse the experimental velocity data on a single profile, without any zone restriction. $y^*_{crit}$ in Eq. (14) is univocally defined and is function of the wake parameter and the normalized boundary layer thickness. It is computed from Eq. (13) using $R$ from experiment and direct numerical simulation and using $II$ regressed following Krogstad et al. (1992).

Figure 2(b) shows the experimental velocity profiles in the logarithmic coordinates of Eq. (14). The projection shows an appreciable data collapse in the logarithmic profile region, over the range of $0.2 \leq y^* \leq 1.0$, above the viscous sub-layer that is not modelled by the law of the wake. Above $y^* = 1.0$, the velocity profiles asymptote to different values of the normalized free-stream velocity $u^*_\infty$ as in the conventional $(y^+, u^+)$ scaling (Buschmann and Gad-el-Hak 2007). However, the profiles about $y^* = 1.0$ are stacked parallel to one another, following essentially the same trend. This positive result derives from the new scaling $(y^*, u^*)$ that uses $R$ and $u^*_\infty$ as scaling parameters. Since $R = f(u_{\infty}/\nu, \delta)$ and $u^*_\infty = \nu_{\infty}/u_{\nu}$, these parameters embed both the inner and the outer scaling of Eqs. (1) and (2), upholding the fundamental notion of the classical inner, outer, and the overlap regions, where the inner scaling of Eq. (1) and the outer scaling of Eq. (2) apply.
Barenblatt et al. (2000), Chauhan et al. (2005) and Nagib and Chauhan (2008) proved that the values of $k$ and $B$ are Reynolds number dependent. As both are used to define $y^*_{{\text{crit}}}$ in Eq. (13), their Reynolds number dependence affects the data collapse. Still, the data fit shown in Figs. 1(a) and 2(b) by an appropriate regression of $k$ and $\Pi$ is useful for modelling boundary layers at Reynolds numbers commonly encountered in engineering practice.

4 Conclusions

A new non-dimensional coordinate system $(y^*, u^*)$ has been defined, which projects the time-averaged velocity profiles of the inner and outer regions of a turbulent boundary layer on the same non-dimensional plane. This enables a unified treatment of these two regions. The three laws of the wake considered herein are identical but a constant. This transformation highlights the commonality between these laws, offering a unified coordinate system in which their dependence on the common scaling parameter $y^*_{{\text{crit}}}$ was studied. A preliminary interpretation of the physical meaning of $y^*_{{\text{crit}}}$ is given, based on the known flow physics in the turbulent boundary layer outer region. Through conformal mapping, the variety of different analytical approximations for a turbulent velocity profile in the literature may be ordered, albeit this is currently limited to laws of the wake of logarithmic form. This may help the on-going search for a physics-based unified analytical description of the time-averaged turbulent boundary layer velocity profile.

The law of the wake of Finley et al. was used to regress experimental mean velocity profiles over a relatively wide Reynolds number range of $145 \leq R \leq 13,030$. By optimizing the law of the wake closure coefficients $k$ and $\Pi$ using an appropriate norm, the formulation shows to be a good fit to the measurements if $y^* \geq 30$, with an FD error of $\pm 2\%$ that is comparable to the previous work.

Tabulated values of $k$ and $\Pi$ enable the practical use of the fitted laws of the wake as input to computational fluid dynamic simulations at the test Reynolds numbers. The benefits of using this approach is that $R$ and $u'_w$, which are typically used in computational fluid dynamics to specify a desired wall-bounded inflow state, can be matched explicitly rather than by iteration. The correlations of the von Kármán constant and the wake parameter with the free-stream Reynolds number display a significant standard deviation for $k$. This requires attention if attempting to interpolate $k$ and $\Pi$ to obtain time-averaged velocity profiles at a Reynolds number different than these tested.

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Notation

| Symbol | Description |
|--------|-------------|
| $B$    | logarithmic law constant |
| $k$    | von Kármán constant |
| $N$    | number of points in experimental velocity profiles |
| $R$    | Reynolds number |
| $u$    | streamwise velocity component |
| $y$    | wall-normal distance |
| $\delta$ | boundary layer thickness |
| $\theta$ | momentum thickness |
| $\nu$ | kinematic viscosity |
| $\Pi$ | wake parameter |

Subscripts

| Subscript | Description |
|-----------|-------------|
| $a$       | analytical prediction |
| $\text{crit}$ | maximum difference value between log-law and law of the wake |
| $e$       | measured value |
| $\infty$  | free-stream value |

Superscripts

| Superscript | Description |
|-------------|-------------|
| $+$         | normalized value in wall units |
| $^*$        | normalized value by Eq. (14) |

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