

Turbulent boundary layer under a transient change in pressure gradients

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ABSTRACT

The response of turbulent boundary layers (TBLs) to unsteady pressure gradients (UPGs) is relevant to a wide range of aerodynamic and hydrodynamic applications involving varying flow conditions. While existing studies have primarily focused on steady or periodically varying pressure gradients, the transient response of TBLs following abrupt pressure gradient changes remain largely unexplored. The present study experimentally investigates the evolution of a TBL subjected to transient changes in spatial pressure gradients using planar particle image velocimetry (PIV). Experiments were conducted in a recirculating water tunnel, where a NACA 0012 airfoil was employed to impose favourable to adverse pressure gradient (FAPG) distributions. Two opposite one-way UPG forcing scenarios were examined through controlled pitch-down and pitch-up motions of the airfoil. Three transition rates were considered to assess the influence of UPG forcing dynamic strength. Phase-averaged streamwise velocity statistics were analysed during and after the transient forcing and compared with the corresponding steady-state results to characterize the TBL response and subsequent recovery behaviour. The results show that the boundary layer response depends on both temporal and spatial history effects. In the upstream favourable pressure gradient (FPG) region, the flow responds relatively rapidly to the imposed forcing and approaches the equivalent steady state shortly after the transition. In contrast, delayed adjustment becomes increasingly pronounced downstream under adverse pressure gradient (APG) conditions. Due to accumulated temporal and spatial history effects, an inverse response is observed at far downstream locations, where the transient flow behaviour temporarily opposes the expected steady-state trend. Comparison among different transition rates demonstrates that slower transitions allow the boundary layer to adapt more progressively to the evolving pressure gradient condition, resulting in smaller deviations from the equivalent steady state and faster subsequent recovery. For a rapid transition, the recovery time is shown to depend strongly on the final pressure gradient distribution. While a sequence of weaker FAPGs with relatively mild spatial variation leads to a plateau in recovery time, stronger FAPGs intensifies non-equilibrium effects and prolong the recovery process towards the final steady state.

1. Introduction

Turbulent boundary layers (TBLs) subjected to pressure gradients are ubiquitous in aerodynamic and hydrodynamic applications, including airfoil flows, turbomachinery, and offshore structures. Understanding the response of TBLs to pressure gradients is essential for accurately predicting and modelling unsteady turbulent flows, thereby improving the performance and efficiency of engineering systems. While extensive research has investigated the effects of pressure gradients under steady conditions, many practical applications involve pressure gradients that vary in both time and space. These variations, arising from mechanical motions or environmental disturbances, lead to more complex flow behaviour. However, due to the challenges associated with simulating such conditions experimentally and numerically, studies of TBLs under unsteady pressure gradients (UPGs) remain limited.

Under steady conditions, deviations of TBL behaviour from the canonical zero pressure gradient (ZPG) case depend on the sign (favourable or adverse), magnitude, and spatial distribution of the imposed pressure gradients. A favourable pressure gradient (FPG) extends the logarithmic region, weakens the wake region, and suppresses turbulence (Harun et al., 2013); in sufficiently strong cases, it may even induce laminarization (Ichimiya et al., 1998). In contrast, an adverse pressure gradient (APG) results in a thinner log region, an enlarged wake region, and energized large-scale structures (Monty et al., 2011); when sufficiently strong, it can lead to flow separation (Na & Moin, 1998). For spatially varying pressure gradients, however, these behaviours do not directly apply. Instead, the flow response is dominated by the cumulative influence of upstream conditions (Vinuesa et al., 2017), and rapid spatial variations often generate internal boundary layers associated with peaks in turbulent stresses (Parthasarathy & Saxton-Fox, 2023).

When UPGs are introduced, the complexity of the flow increases further. In addition to the magnitude and spatial variation of the pressure gradient, the TBL evolution depends on the type of forcing (periodic or transient) and time scale of unsteadiness, making it significantly more difficult to characterize. Under UPGs, the TBL does not have sufficient time to adjust to the imposed conditions, and its response is governed by memory and inertia. As a result, the flow often exhibits delayed and non-equilibrium behaviour compared to the equivalent steady pressure gradient impositions (Covert & Lorber, 1984; Parthasarathy & Saxton-Fox, 2025). Meanwhile, time-averaged velocity and turbulence levels under periodic modulation have been reported to be relatively unaffected by the freestream unsteadiness (Brereton et al., 1990), highlighting the importance of phase-averaged analysis. Furthermore, Covert & Lorber (1984) showed that the flow response to UPGs is sensitive to the rate of change, especially under strong pressure gradients. It has also been observed that unsteady effects tend to shift away from the wall as the time scale of imposed forcing increases (Ambrogio et al., 2022). Given that our understanding of pressure gradient effects remain incomplete, disentangling unsteadiness from pressure gradient is challenging. The present study seeks to provide some insights into unsteady effects by experimentally examining two opposite

one-way transient UPG forcing scenarios at three different rates of change.

Existing studies of TBLs under UPGs have primarily focused on the flow response during the period of pressure gradient variation, with limited attention given to the subsequent adjustment towards a new equilibrium. In particular, the time scale required for a TBL to recover to steady state following a rapid change remains unclear. The objective of this study is therefore to report on the TBL behaviour during and after a transient change in spatial pressure gradients, with emphasis on the streamwise velocity statistics and the associated recovery behaviour.

2. Experimental setup

The experiments were conducted in the Recirculating Water Tunnel at the University of Southampton using planar particle image velocimetry (PIV) technique. A schematic of the experimental setup is shown in Fig. 1(a). The facility has an 8.1 m long and 1.2 m wide test section, with optical access provided through glass walls. The water depth was maintained at 0.58 m throughout the experiments, with a freestream velocity of $U_\infty = 0.3$ m/s. To impose the pressure gradient, a NACA 0012 airfoil with a span of 1 m a chord length (c) of 0.3 m was mounted 5 m downstream of the tunnel inlet and 0.24 m above the tunnel floor. This height corresponds to approximately twice the boundary layer thickness (δ_0) in the absence of the airfoil. The friction Reynolds number based on δ_0 was $Re_\tau \approx 1400$. Transient pressure gradient variations were generated by controlling the airfoil pitch angle (α) using a belt-driven motion system coupled with bell-crank mechanisms at both ends.

The flow was seeded with 50 μm Polyamide particles and illuminated by two iLA 5150 LPS v3 high-power double-pulsed LED sources in the streamwise-wall-normal plane. The flow field under the airfoil was captured using three 4 MP Phantom CMOS cameras equipped with Nikon 105 mm lenses. The cameras were arranged in a triangular configuration, with the lower two cameras

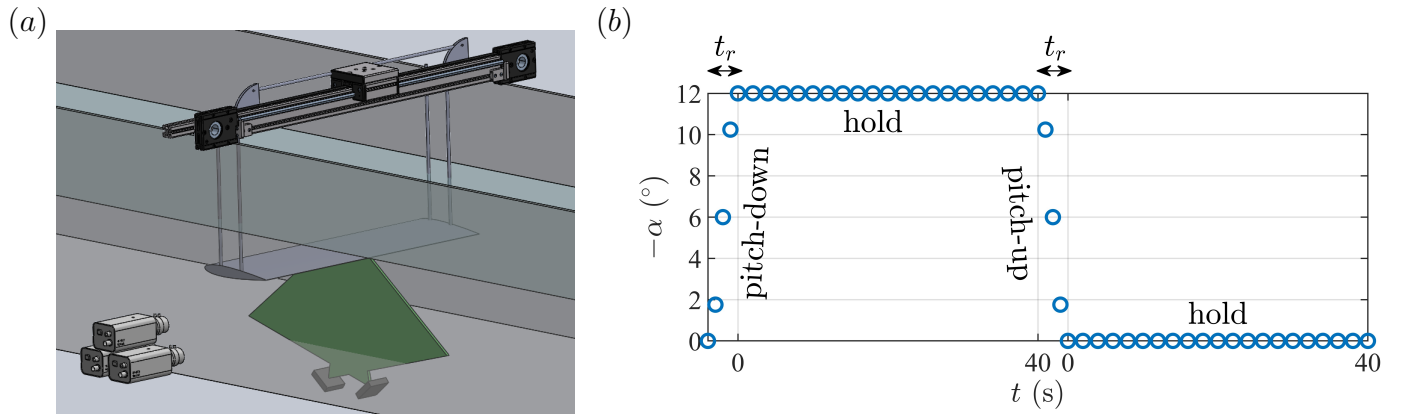


Figure 1. (a) Schematic of the experimental setup. (b) Airfoil pitch angle (α) during one motion cycle.

recording the boundary layer region and the upper camera recording the outer region. The image resolution is $85 \mu\text{m}/\text{pixel}$ for the lower cameras and $133 \mu\text{m}/\text{pixel}$ for the upper camera.

Two opposite one-way forcing scenarios were considered via: a pitch-down motion (α from 0° to -12°) and a pitch-up motion (α from -12° to 0°), each followed by a constant-angle holding period of 40 s ($\approx 100\delta_0/U_\infty$) to allow the boundary layer to approach a steady state. The variation of pitch angle during one motion cycle is shown in Fig. 1(b). Note that $t = 0 \text{ s}$ is defined as the end of the transition, i.e., the beginning of the holding period. To avoid abrupt acceleration and deceleration, the pitch motion was prescribed using a half-sinusoidal trajectory over a finite ramp time (t_r). Three ramp times, $t_r = 1, 2$, and 4 s , were examined to investigate the effects of the UPG forcing time scale. The unsteadiness was characterized using the reduced frequency, k , defined as

$$k = \frac{L_{PG}/U_\infty}{t_r} \quad (1)$$

where L_{PG} is the characteristic length, taken here as the chord length, c , representing the extent of the imposed spatial pressure gradients. The three ramp times therefore correspond to $k = 1, 0.5$, and 0.25 , respectively. For each case, 400 motion cycles were performed to obtain phase-averaged statistics. PIV image acquisition rates of $4, 2$, and 1 Hz were used for $1, 2$, and 4 s ramp cases, respectively, resolving five phases during the transition. Corresponding steady-state flow fields at those phases were also measured as baseline reference cases.

PIV image pairs were acquired using LaVision Davis 10 software and processed using an open source Python framework PIVtools (Taylor et al., 2025). A final interrogation window size of 16×32 with 50% overlap (62.5% for the upper camera) resulted in a velocity vector spacing of 0.68 mm in the wall-normal (y) direction and 1.35 mm in the streamwise (x) direction.

3. Results

3.1. Steady FAPGs

The five equally spaced phases during the pressure gradient transition correspond to $\alpha = 0^\circ, -1.8^\circ, -6^\circ, -10.2^\circ$, and -12° . Fig. 2(a) presents the spatial distributions of the steady-state pressure coefficient, C_P , at these phases. The pressure coefficient was evaluated using Bernoulli's equation along a streamline outside the boundary layer. The distributions of corresponding pressure gradient are shown in Fig. 2(b) in terms of the acceleration parameter, $K = \nu/U_e^2 \text{ d}U_e/\text{d}x$, where U_e is the local velocity at the boundary layer edge. As expected, a sequence of favourable to adverse pressure gradients (FAPGs) is generated below the airfoil. As the pitch angle becomes more negative, the overall strength of the FAPG increases, while the transition from FPG to APG shifts slightly upstream from $x/c = 0.4$ to 0.28 .

Fig. 3 shows the mean streamwise velocity (U) profiles at five streamwise locations: $x/c = 0, 0.25$,

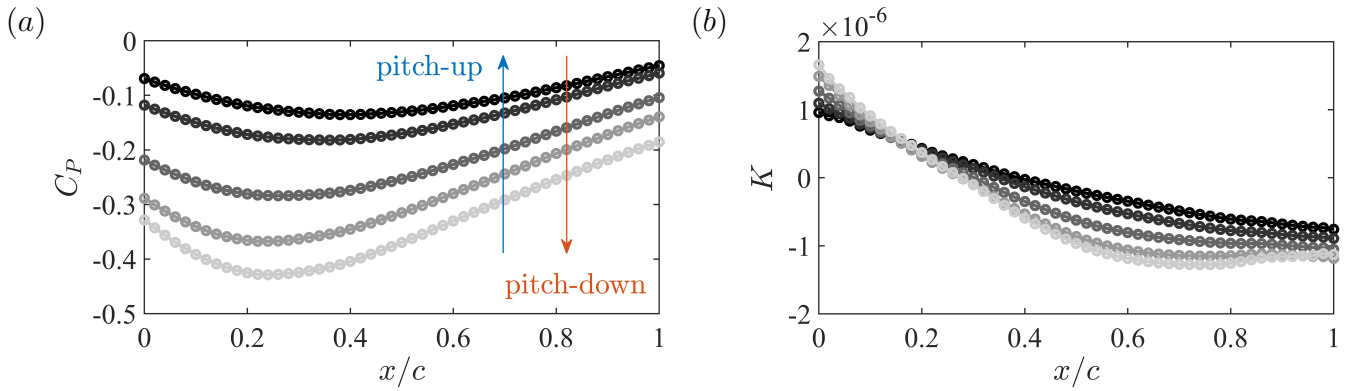


Figure 2. (a) Distributions of steady-state pressure coefficient (C_P) at five phases during the transition. Lighter greys correspond to negatively larger pitch angles. (b) Distributions of corresponding pressure gradient in terms of the acceleration parameter, K .

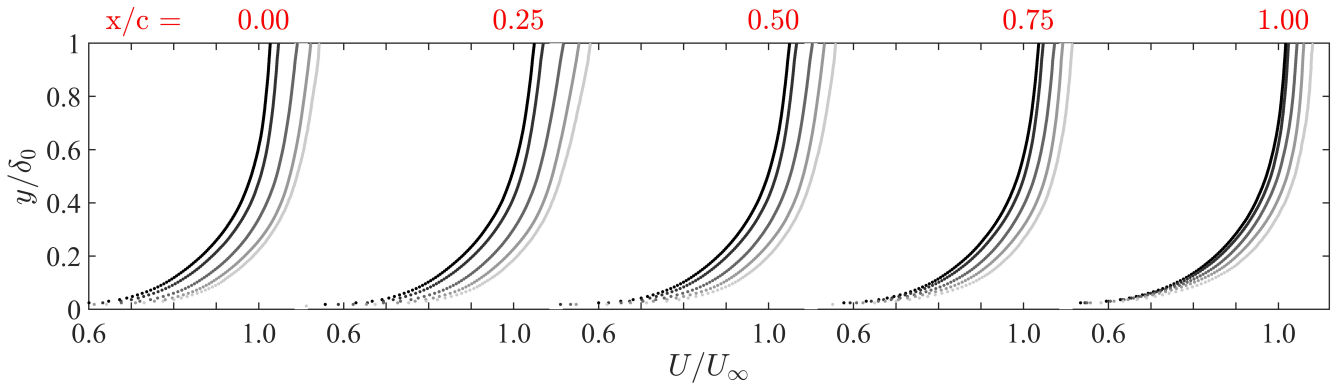


Figure 3. Mean streamwise velocity (U) profiles at five streamwise locations. Lighter greys correspond to negatively larger pitch angles (stronger FAPGs).

0.5, 0.75, and 1. The flow accelerates within the FPG region and then decelerates under the APG region. Larger negative pitch angles introduce stronger FPG (higher K) near the leading edge ($x/c = 0$), resulting in greater flow acceleration. Owing to the stronger upstream acceleration, the flow remains more accelerated throughout the downstream APG region ($x/c > 0.4$) compared with cases at smaller pitch angles, while the differences gradually diminish under the influence of enhanced local APG.

3.2. Unsteady FAPGs

Taking the pitch-down case (α : 0° to -12°) with $k = 0.5$ as an example, Fig. 4 shows the evolution of the phase-averaged U during and after the transient pressure gradient change at five streamwise locations. For conciseness, only selected phases are presented to illustrate the TBL response: the initial state ($\alpha = 0^\circ$, light red), the midpoint of the transition ($\alpha = -6^\circ$, black), the end of the transition ($\alpha = -12^\circ$, $tU_\infty/\delta_0 = 0$, dark grey), 1 and 2 s after the transition ($\alpha = -12^\circ$, $tU_\infty/\delta_0 =$

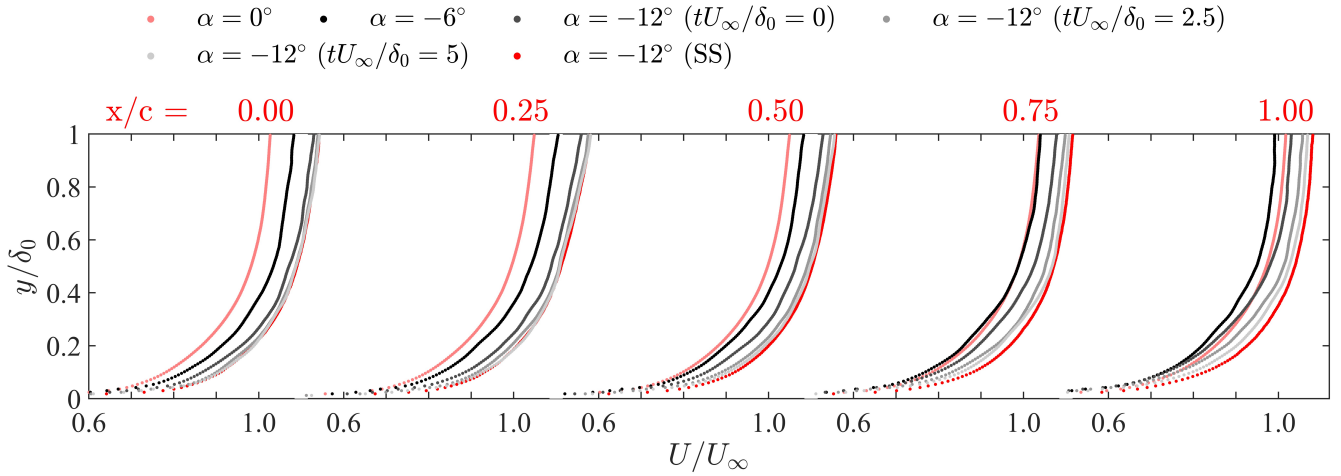


Figure 4. Evolution of phase-averaged streamwise velocity (U) profiles at five streamwise locations for the pitch-down case with $k = 0.5$.

2.5 and 5, lighter greys), and the final steady state ($\alpha = -12^\circ$, SS, red).

Within the FPG region ($x/c = 0$ and 0.25), the flow responds relatively rapidly to the imposed pressure gradient variation. Consequently, the velocity profile during the transient forcing closely follows the corresponding steady-state profiles, and the flow approaches the final steady state shortly. In contrast, the flow response becomes noticeably weaker in the downstream APG region, where a longer adjustment time is required before the flow recovers towards the steady-state condition. This delayed response becomes increasingly evident further downstream. At $x/c = 1$, a clear inverse response is observed. During the initial stage of the pitch-down motion (pitching from 0° to -6°), the flow decelerates despite the corresponding steady-state cases exhibiting acceleration (see Fig. 3). This behaviour indicates that the local flow does not respond solely to the instantaneous pressure gradient condition, but is instead strongly influenced by upstream and prior flow states. The delayed adjustment is therefore associated with both spatial and temporal history effects, which significantly prolong the equilibration process in the downstream region.

The observed TBL response to transient UPG forcing is qualitatively consistent across all investigated cases, although the degree of deviation from the equivalent steady state depends strongly on the rate of change. Fig. 5 presents contours of the streamwise velocity difference (ΔU) between the unsteady phase at the end of the pitch-down transition and the corresponding steady-state results. Comparison among the three k cases shows that faster transitions lead to larger deviations from the steady state throughout the field of view (FOV). In particular, the strongest discrepancies are concentrated in the downstream APG region ($x/c > 0.28$) close to the wall ($y/\delta_0 < 0.5$), where the flow is most strongly influenced by history effects and insufficient adjustment time.

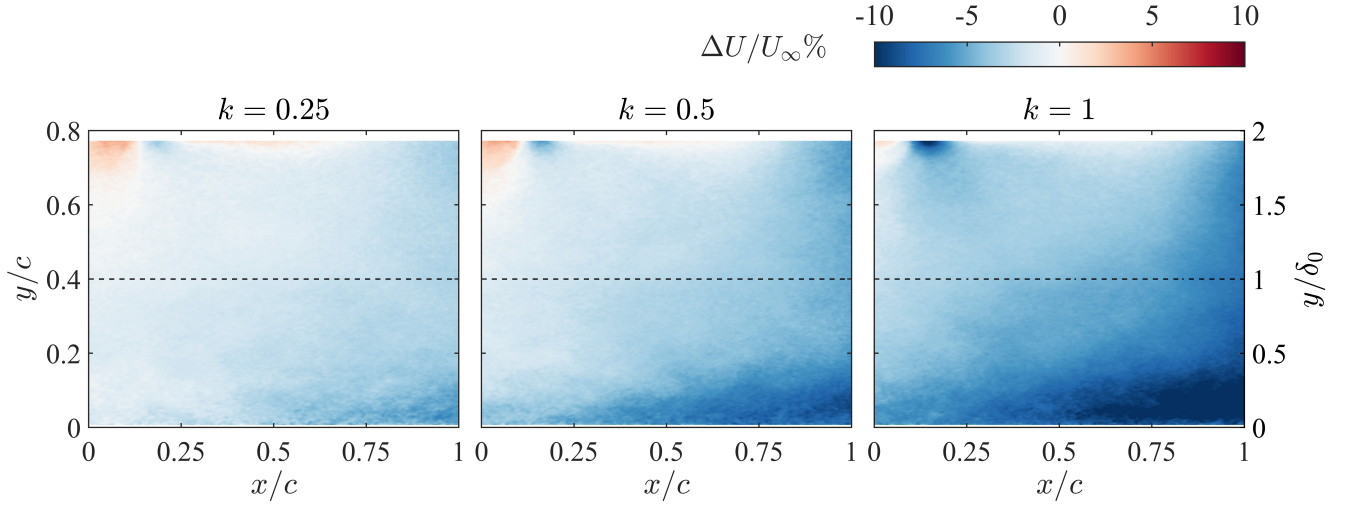


Figure 5. Contours of streamwise velocity difference (ΔU) between the phase at the end of the pitch-down transition and the corresponding steady-state condition.

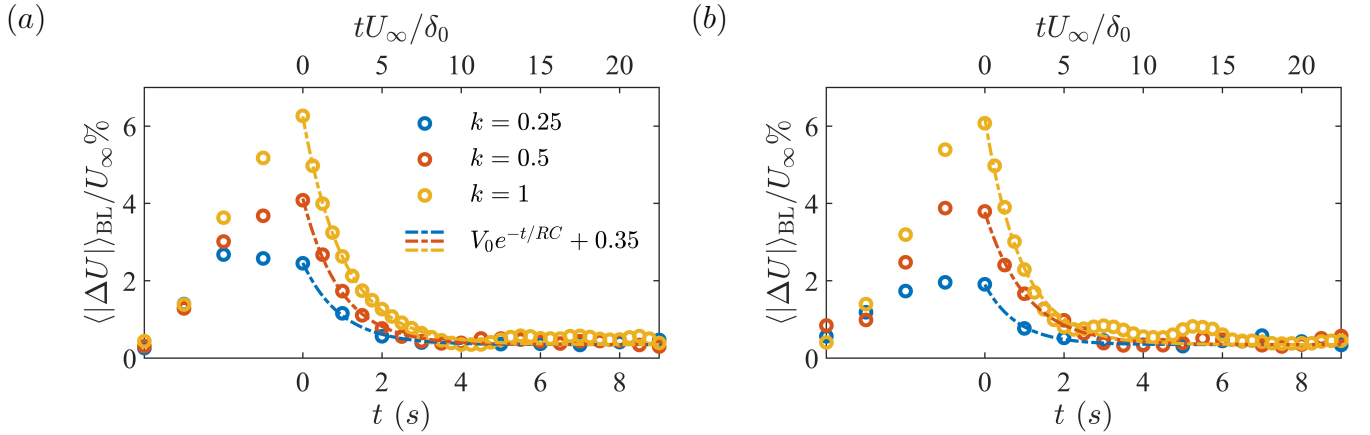


Figure 6. Variation of the spatially averaged streamwise velocity difference, ($\langle |\Delta U| \rangle_{BL}$), for (a) pitch-down and (b) pitch-up case.

3.3. Time of recovery

To quantify the deviation of the unsteady flow from the corresponding steady state, the spatial average of $|\Delta U|$ is evaluated within the region below $y = \delta_0$ (indicated by the black dashed line in Fig. 5), denoted as $\langle |\Delta U| \rangle_{BL}$. Fig. 6 shows the evolution of $\langle |\Delta U| \rangle_{BL}$ for both pitch-down and pitch-up scenarios, illustrating the responsiveness of the boundary layer to UPG forcing at different rates. At the same phase during the transition, or at the same elapsed time after the transition, cases with smaller k consistently exhibit smaller velocity differences. This indicates that slower transitions allow the boundary layer to adapt more progressively to the evolving pressure gradient condition, resulting in closer agreement with the corresponding steady state. As a consequence, slower transitions generally lead to faster recovery towards the final steady state.

To quantitatively assess the effect of UPG dynamic strength, a RC circuit equation,

$$\langle |\Delta U| \rangle_{\text{BL}} / U_\infty \% = V_0 e^{-t/RC} + 0.35 \quad (2)$$

is fitted to the holding period, as indicated by the dash-dotted lines in Fig. 6. The recovery time (t_c) is estimated as the time at which $\langle |\Delta U| \rangle_{\text{BL}} / U_\infty$ reaches 0.45%. The dynamic strength of the UPG forcing is characterized using the turbulent reduced frequency,

$$k_\tau = t_\tau / t_r \quad (3)$$

which is the ratio between the large turbulent time scale and the UPG forcing time scale (Momen & Bou-Zeid, 2017; Parthasarathy & Saxton-Fox, 2025). Here, t_τ is defined as δ / U_τ at the entry of the FOV ($x/c = 0$) prior to the transient forcing, where δ is the local boundary layer thickness and U_τ is the friction velocity. Physically, k_τ represents the ability of large turbulent structures to adjust to the imposed pressure gradient variation, with smaller k_τ corresponding to more responsive flow structures. Fig. 7 shows the recovery time normalized by $\overline{U}_e/c$ as a function of k_τ , where $\overline{U}_e$ is the spatially averaged boundary layer edge velocity across the FOV in the final steady state. This dimensionless quantity represents the number of flow-through times across the region of interest.

From the available data, the recovery behaviour depends on both the dynamic strength of the UPG forcing and the spatial pressure gradient distribution. At relatively small k_τ , the large-scale turbulent structures are able to respond to the pressure gradient variation with a time delay, which increases with increasing k_τ and becomes the dominant mechanism governing flow equilibration. As a result, the recovery time initially increases with k_τ for both pitch-down and pitch-up cases. At larger k_τ , however, the two forcing scenarios exhibit distinctly different trends. In the pitch-up case, where the FAPG weakens during the transition, the recovery time appears to approach a plateau. In contrast, in the pitch-down case, where the FAPG strengthens during the transition, the recovery time continues to increase with k_τ . Given that the magnitude of $\langle |\Delta U| \rangle_{\text{BL}}$ immediately after the fastest transition are comparable for the two forcing cases (see Fig. 6), the different recovery trends suggest that the subsequent adjustment process is strongly influenced by the final pressure gradient condition. Specifically, the stronger downstream APG and enhanced spatial

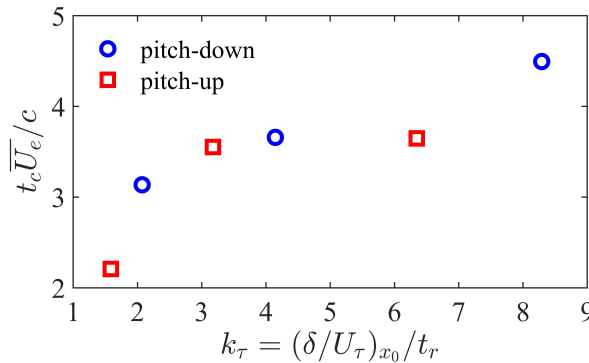


Figure 7. Time of recovery.

pressure gradient variation imposed during the pitch-down holding stage likely intensify non-equilibrium effects, thereby prolonging the recovery of the boundary layer towards its final steady state.

4. Conclusions

This study experimentally investigates the response of a turbulent boundary layer (TBL) to transient changes in spatial pressure gradients using planar particle image velocimetry. Two opposite one-way unsteady pressure gradient (UPG) forcing scenarios, generated through pitch-down and pitch-up motions of an airfoil, were examined at three different transition rates to assess the influence of UPG forcing dynamic strength on the boundary layer response. The subsequent holding period was also probed to investigate the recovery behaviour of the TBL towards the final equilibrium state.

The steady-state measurements show that the favourable to adverse pressure gradient (FAPG) distribution generated by the airfoil strengthens during pitch-down and weakens during pitch-up. During transient UPG forcing, the boundary layer flow responds relatively rapidly within the upstream FPG region, while delayed adjustment becomes increasingly pronounced further downstream under APG conditions. Due to accumulated temporal and spatial history effects, an inverse response is observed at far downstream locations during the transition, where the flow accelerates or decelerates despite the corresponding steady-state cases exhibiting the opposite behaviour.

Comparison among different transition rates demonstrates that slower transitions allowed the boundary layer to adapt more progressively to the evolving pressure gradient condition, resulting in smaller deviations from the equivalent steady state and faster subsequent recovery. The recovery time was estimated by fitting an RC circuit equation to the deviation of streamwise velocity from the final steady state during the holding period. The recovery behaviour was found to depend on both the dynamic strength of the UPG forcing, characterized by the turbulent reduced frequency (k_τ), and the final spatial distribution of pressure gradient. While the recovery time initially increases with k_τ for both UPG forcing cases, distinctly different behaviours are observed at larger k_τ . The pitch-up case exhibits an apparent plateau in recovery time, whereas the pitch-down case shows continuously increasing recovery time with increasing k_τ . These results suggest that stronger downstream APGs and enhanced spatial pressure gradient variations intensify non-equilibrium effects and prolong the adjustment process of the boundary layer.

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Nomenclature

c	Airfoil chord length [s]
C_P	Pressure coefficient
k	Reduced frequency
k_τ	Turbulent reduced frequency
K	Acceleration parameter
Re_τ	Friction Reynolds number
t	Time [s]
t_c	Recovery time [s]
t_r	Ramp time [s]
t_τ	Large turbulent time scale [s]
U	Mean streamwise velocity [m s^{-1}]
U_∞	Freestream velocity [m s^{-1}]
U_e	Boundary layer edge velocity [m s^{-1}]
U_τ	Friction velocity [m s^{-1}]
ΔU	Difference between unsteady and steady-state streamwise velocity [m s^{-1}]
x	Streamwise coordinate [m]
y	Wall-normal coordinate [m]
α	Pitch angle [$^\circ$]
δ	Boundary layer thickness [m]
δ_0	Reference boundary layer thickness without airfoil [m]
ν	Kinematic viscosity [$\text{m}^2 \text{s}^{-1}$]
APG	Adverse pressure gradient
FAPG	Favourable to adverse pressure gradient
FOV	Field of view
FPG	Favourable pressure gradient
PIV	Particle image velocimetry
TBL	Turbulent boundary layer
UPG	Unsteady pressure gradient
ZPG	Zero pressure gradient

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