



Miniature vortex generator control of turbulent boundary layers

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Miniature vortex generators (MVGs) are a promising passive flow control technique for viscous drag reduction by producing large-scale vortical motions that manipulate turbulence structures in turbulent boundary layers (TBLs) without significant device drag. This study conducts hot-wire anemometry experiments to investigate the influence of the Reynolds number and the ratio of MVG height h to TBL thickness δ_0 (MVG height ratio h/δ_0) on turbulence structures. Experiments encompass two MVG height ratios, $h/\delta_0 = 0.09, 0.18$, friction Reynolds numbers ranging from $Re_\tau = 400$ to 2000 and measure the velocity information at various downstream stations. Spectral analysis confirms the MVG-induced vortices amplify large-scale structures in the outer region, sustaining up to 100 times the MVG height downstream. The MVGs are also found to attenuate turbulence energy across a wide range of turbulence structures below the amplification location in the logarithmic region, connected with the MVG-induced spanwise motion. Increasing the friction Reynolds number from $Re_\tau = 400$ to 900 or doubling the MVG height ratio causes the amplified structures to develop into longer motions and move away from the wall, while increasing the turbulence energy attenuation proportion to the log region. Moreover, the energy attenuation amplitude of large-scale structures in the near-wall region increases with a larger MVG height ratio but decreases with increasing Reynolds numbers. The findings indicate that, at friction Reynolds numbers $Re_\tau \geq 900$, MVGs induce spanwise motions that attenuate near-wall structures and modulate large-scale outer motions. The present configuration does not yield a global viscous drag reduction, but the turbulence modulation trends suggest the potential for viscous drag reduction when the MVG configurations are optimised to enhance favourable buffer-layer spanwise motions.

Key words: turbulence control, vortex interactions, turbulent boundary layers

1. Introduction

Controlling wall-bounded turbulent flows is an active area of research (Adrian 2007; Hutchins & Marusic 2007a; Marusic *et al.* 2010; Barkley *et al.* 2015), due to its practical importance. For example, in the turbulent boundary layer (TBL) class of wall-bounded turbulent flows investigated in this study, TBL control devices are used to improve transport speed and fuel efficiency via reducing viscous drag in engineering applications, such as flows over aircraft wings and ship hulls (Chung *et al.* 2021). Control strategies include passive techniques that introduce perturbation without additional energy input (Corke & Thomas 2018), such as riblets and large-eddy breakup devices (LEBUs). Existing passive control devices increase device drag (a type of form drag), such that it is challenging to achieve a reduction in total drag, i.e. viscous plus device drag from control devices (García-Mayoral & Jiménez 2011; Park *et al.* 2011; Saravi & Cheng 2013; Chin *et al.* 2017). Active flow control is an alternative approach, which requires additional energy input, such as plasma/blowing–suction walls (Antonia *et al.* 1988; Djenidi, Kamruzzaman & Dostal 2019). Active control strategies incur negligible device drag and reduce total drag. Under certain conditions, the power saving from the total drag reduction covers the energy input, leading to positive net power savings. For instance, plasma actuation has demonstrated substantial net power savings, achieving friction drag reductions of up to 70 % (Thomas, Corke & Duong 2023), while wall oscillation techniques have similarly provided net energy benefits, with drag reductions of up to 25 % (Chandran *et al.* 2023). Despite these examples, the energy requirements of most active methods remain a barrier to practical application (Corke & Thomas 2018). In addition, they often need complicated control systems to work well under different flow conditions (Corke & Thomas 2018).

Motivated by the challenges involved in active and passive flow control techniques, theoretical, numerical and experimental studies have been performed over the past decade to gain a better understanding of the contributions of the small- and large-eddy motions towards viscous drag (Hutchins & Marusic 2007a; Marusic *et al.* 2010; Mathis *et al.* 2013; Chandran, Monty & Marusic 2020; Chung *et al.* 2021). Near-wall structures, comprising quasistreamwise vortices and low-speed streaks within the viscous sublayer, buffer and lower logarithmic layers, are generated through a self-sustaining cycle, in which vortices create streaks by lifting and redistributing momentum. The streaks undergo instability and disturbance amplification, and the resulting motions generate new vortices that restart the cycle (Robinson 1991; Jiménez & Pinelli 1999; Schoppa & Hussain 2002). Large-scale motions consist of streamwise-aligned hairpin eddies with a length scale of the order of δ , while superstructures in TBLs extend up to 20δ (Adrian 2007; Hutchins & Marusic 2007a). The large-scale structures, including hairpin-shaped structures and superstructures, have modulation effects on the small-scale structures in the near-wall region, which account for the majority of the total viscous drag (Hutchins & Marusic 2007b; Mathis, Hutchins & Marusic 2009; Agostini & Leschziner 2018). Hence, attenuating either near-wall small-scale structures or large-scale structures in the outer region could lead to viscous drag reduction (Agostini & Leschziner 2018). This has underpinned the design of flow control devices to reduce viscous drag, particularly in the field of passive control strategies, which includes LEBUs that attenuate large-scale motions in the outer region far downstream, although they still induce considerable device drag (Perlin, Dowling & Ceccio 2016).

Miniature vortex generators (MVGs) are a promising approach for passive flow control without significantly increasing device drag (Lin 2002). The MVG technique comprises a spanwise-aligned MVG array consisting of two blades vertically mounted on a wall and positioned at a certain ‘attack angle’ to the flow. The ‘miniature’ of MVG refers to the low

ratio of MVG height h to boundary layer thickness δ . The MVGs are typically defined as $h/\delta_0 \leq 0.2$ (Lin 1999), where δ_0 is the boundary layer thickness at the MVG location. In contrast, devices with ratios $h/\delta_0 \geq 0.5$ are classified as vortex generators (VGs), and those with ratios $0.2 < h/\delta_0 < 0.5$ are referred to as low-profile VGs (Chan & Chin 2022). The MVG height ratio is one of the most important parameters correlating with the strength and size of the MVG-induced vortex (Lin 2002; Godard & Stanislas 2006).

The MVGs were first introduced to reduce form drag caused by flow separation in laminar and TBL flows, when a fluid moves over a bluff body, such as when air flows over aerofoils (Lin *et al.* 1994). Optimised MVG configurations can substantially reduce form drag in aerofoil applications, such that total drag (including viscous and device drag) is halved (Godard & Stanislas 2006). When MVGs are applied to road vehicles, where the total drag is dominated by viscous drag, the total drag reduction can still reach up to 10 % (Sudin *et al.* 2014). The MVGs have also been used to reduce viscous drag in transitional boundary layers by delaying the flow from transition to turbulence (Fransson & Talamelli 2012; Shahinfar *et al.* 2013). The proposed mechanism is that MVGs impose large-scale vortical motions and incur long high- and low-speed streaks, which can stabilise the Tollmien–Schlichting wave formation and delay the turbulence formation by prolonging the transition progress (Shahinfar *et al.* 2013). The MVG-induced streaks propagate downstream as far as 700 times the MVG height, and the high-speed streaks can reduce turbulence intensity by stabilising the developing turbulence in the near-wall region (Fransson & Talamelli 2012). A configuration with two consecutive MVG arrays delays transition by over 3000 times the MVG height, achieving up to 65 % total drag reduction over a 4 m reference length, compared with the smooth-wall case without MVGs (Sattarzadeh *et al.* 2014).

The turbulence structures and velocity fluctuation amplitudes in TBLs differ from those in transitional boundary layers (Schlichting & Gersten 2016; Lee & Jiang 2019), indicating that the effects of MVG-induced vortices may differ from that in transitional boundary layers. Therefore, it is necessary to explore the MVG effects in TBL flows, particularly in turbulence structure manipulations. In a related study, Lögdberg *et al.* (2009) conducted an experiment on VGs in TBLs ($h/\delta_0 > 0.2$), focusing on vortex evolution for flow separation. They found that a VG-induced streamwise vortex developed in the near-wall region at a friction Reynolds number $Re_\tau \approx 3000$. Since their study, understanding of turbulence structures has advanced considerably (Jiménez 2018; Marusic & Monty 2019). Based on these advances, Chan & Chin (2022) explored MVG control effects on turbulence motions in TBL flows using a large-eddy simulation (LES) approach. Their results suggest that the MVG-induced motions interrupt the near-wall cycle structures dominating the near-wall region of a flat plat TBL. Although the spanwise-averaged drag is nearly the same as that of a smooth wall, there is a LES study that reported a local drag reduction in the spanwise direction, particularly in the upwash region (Chan & Chin 2022).

From the view of induced flow structures, generating large-scale streamwise vortices (LSSVs) using control devices has emerged as an effective strategy for viscous drag reduction in TBL flows. This concept was originally proposed by Schoppa & Hussain (1998) in the context of direct numerical simulations for turbulent channel flows. They introduced LSSVs through two approaches: (i) counter-rotating vortex forcing in the outer region; and (ii) spanwise wall-jet forcing on the wall. Both methods induce strong spanwise motions and achieved drag reductions of up to 20 % and 50 %, respectively. This strategy is employed in active flow control methods using plasma actuators, which generate near-wall jets that effectively suppress quasistreamwise vortices in TBLs. For instance, Cheng *et al.* (2021) demonstrated global drag reductions up to 26 % by inducing spanwise arrays of LSSVs, while Duong, Corke & Thomas (2021) achieved over 60 % global drag reduction

using pulsed-direct-current plasma actuators. Cheng *et al.* (2021) suggested that the global drag reduction is associated with the lifting of low-speed fluid in the upwash region and the LSSV-induced spanwise motions between upwash and downwash regions. The lifted low-speed fluid reduces near-wall streamwise velocity gradients, thereby reducing drag, while the induced spanwise motions weaken wall-normal vorticity and disrupt the streak transient growth mechanism, consistent with the viscous drag reduction strategy proposed by Schoppa & Hussain (1998). Both studies found decreases in streamwise and spanwise turbulence intensities, as well as reductions in turbulence production near the wall, confirming the effectiveness of LSSVs for viscous drag reduction. This strategy highlights the potential of MVG-induced streamwise vortical structures for drag reduction in TBLs.

The modulation of near-wall flow disturbance by MVGs and the local drag reduction observed in the upwash motions associated with the MVG-induced LSSVs indicates that the MVGs can be explored for TBL flow control (Cheng *et al.* 2021; Chan & Chin 2022). However, due to the high computational cost of LES, only one LES experiment was performed by Chan & Chin (2022) and the friction Reynolds number was limited to $Re_\tau = 950$. Therefore, the effects of important parameters on the outer-region turbulence structures remain unclear, particularly the influence of the MVG height ratio and the effects at higher friction Reynolds numbers, $Re_\tau > 950$. According to the wall shear stress model proposed by Marusic *et al.* (2021), small-scale structures dominate the contribution to the total shear stress, whereas large-scale structures account for up to 30 %. Therefore, it is important to characterise how MVGs modulate turbulence structures.

In this study, we perform a series of experiments on MVGs in TBLs to gain understanding of how the MVG height ratio and the Reynolds number affect turbulence structures. We test two height ratios, $h/\delta_0 = 0.09$ and 0.18 , and a range of Reynolds numbers from $Re_\tau = 400$ – 2000 for zero pressure gradient (ZPG) MVG-modified TBLs, and measure the downstream flow fields at various stations. We use a recently proposed friction velocity determination method (Kong *et al.* 2024) to derive the inner-scaling turbulence structures, which are not directly available from experimental measurements. We find the MVGs attenuate an increasing proportion of turbulence energy as Reynolds number increases, which implies the MVGs have the potential to control turbulence structures in TBLs.

2. Experimental set-up

2.1. Wind tunnel

The ZPG MVG-modified TBL experiments are performed in the closed-loop wind tunnel at the University of Adelaide. The airflow goes through three layers of meshes and one layer of honeycomb grid, which can maintain a low turbulence level of approximately 0.5 %. A working section is attached to the wind tunnel, having a length of 2 m and a rectangular cross-sectional area of $0.5 \times 0.3 \text{ m}^2$. A 1.9 m-long aluminium flat plate is mounted on the bottom floor of the working section. The sidewalls are adjustable to compensate for the boundary layer growth to maintain ZPG. A tripping device of 36-grit sandpaper of length 100 mm is mounted at the leading edge to ensure flows develop to TBLs.

2.2. The MVG configurations

The schematic of the MVG and reference TBL measurement settings is shown in figure 1. The Cartesian coordinates x , y and z correspond to the streamwise, wall-normal and spanwise directions, respectively. The coordinate system is chosen with the origin at the leading edge centreline of the aluminium flat plate. The effectiveness of vane-type MVGs in

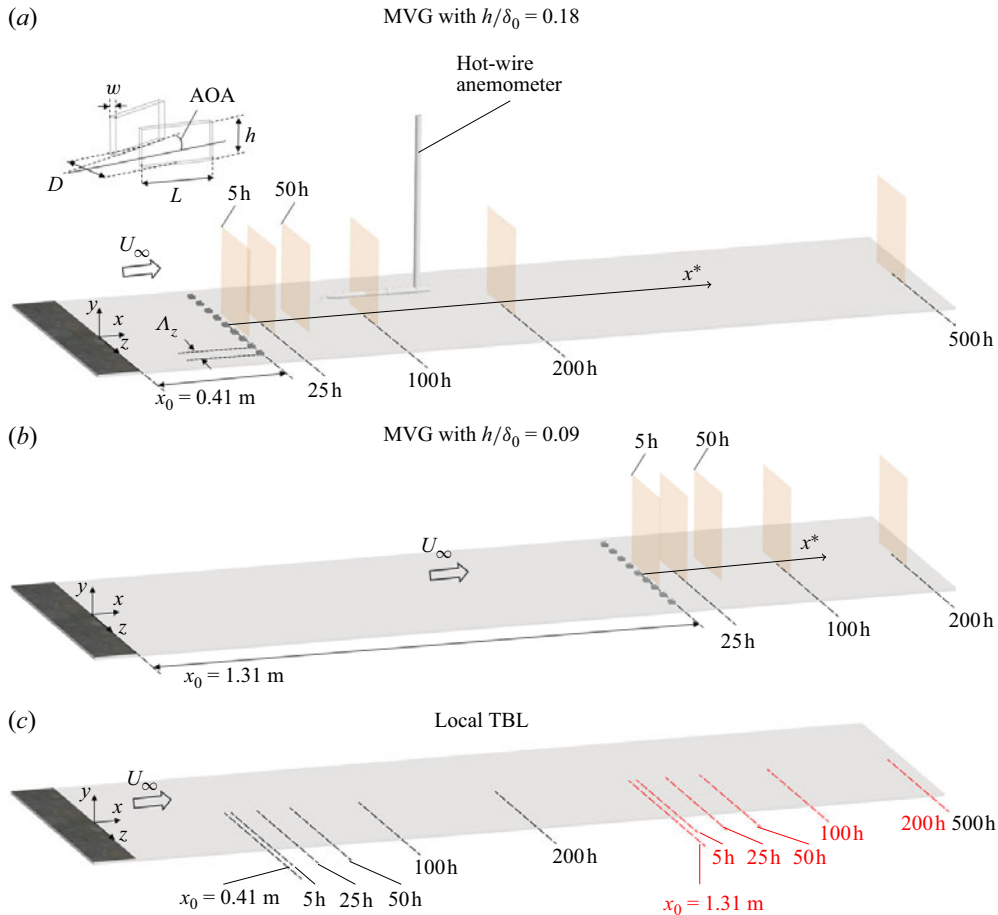


Figure 1. Schematic views of the MVG configuration and experimental set-up for MVG (a,b) and reference TBLs (c). The value of x_0 for the two MVG height ratios is defined from the trailing edge of the tripping device to the trailing edge of MVG blades. Measurement yz -planes downstream the MVG devices are denoted as the planes at $x^* = x - x_0 = 5h, 25, 50, 100, 200$ and $500h$. At each streamwise station, six linear-spaced spanwise velocity profiles are measured at $z = 0-0.5\Lambda_z$. The reference TBL results are measured over a flat plate at corresponding streamwise stations of the MVG result, in which the black and red annotations denote the streamwise stations scaled by the two MVG placements $x_0 = 0.41$ m and 1.31 m, respectively.

maximising circulation amplitude for flow-separation control has been extensively studied, focusing on optimising geometric parameters such as blade aspect ratio, L/h , angle of attack (AOA), spanwise distance between MVG pairs, D , and spanwise wavelength of MVG pairs, Λ_z (Pearcey 1961; Godard & Stanislas 2006). The AOA intensifies the circulation of MVG-induced vortices, enhancing flow control as it increases; however, AOAs exceeding 18° can cause excessive instability in transition control applications. Consequently, an optimal AOA range of $15^\circ-18^\circ$ is recommended, aligning with studies on flow separation and transition control (Pauley & Eaton 1988; Godard & Stanislas 2006; Sattarzadeh & Fransson 2015). The blade aspect ratio, L/h , has a minimal effect on vortex circulation amplitude, with a suggested value of 2.5 (Pearcey 1961). For spanwise wavelength, configurations with $\Lambda_z/h = 10$ and $\Lambda_z/D = 4$ are recommended to achieve a long effective distance range while effectively suppressing flow separation (Pearcey 1961). Furthermore, Fransson & Talamelli (2012) and Shahinfar *et al.* (2013) advocate for spanwise wavelength

Case	Flow conditions					MVG geometries				
	x_0 (m)	U_∞ (m s ⁻¹)	$Re_{\tau 0}$	h/δ_0	h (mm)	AOA(°)	Λ_z/h	L/h	D/h	w/h
MVG ₄₀₀ ¹⁸	0.41	7.4	400	0.18	3	15	10	2.5	2.5	0.25
MVG ₉₀₀ ¹⁸	0.41	20	940	0.18	—	—	...	—	—	—
MVG ₆₀₀ ⁰⁹	1.31	7.4	650	0.09	—	—	...	—	—	—
MVG ₉₀₀ ⁰⁹	1.31	11	900	0.09	—	—	...	—	—	—
MVG ₁₆₀₀ ⁰⁹	1.31	20	1600	0.09	—	—	...	—	—	—

Table 1. Experimental conditions and MVG configurations. Here δ_0 is the boundary layer thickness at $x = x_0$.

ratios of $\Lambda_z/D = 4\text{--}5$ for MVG pairs to establish an effective vortex pattern across the entire spanwise length. Lower Λ_z/D ratios can lead to vortex collisions and ejection from the wall, whereas higher Λ_z/D ratios result in MVG-induced vortices developing individually without covering the full wavelength, thereby diminishing their effectiveness.

In the present study, the metal MVG blades are spanwise arranged as a total of 13 pairs of MVGs and affixed on the flat aluminium plate at streamwise locations, x_0 . Consistent with the LES study by Chan & Chin (2022), the rectangular vane-type MVG blades have dimensions of height $h = 3$ mm, thickness of $w = 0.75$ mm and length of $L = 7.5$ mm, resulting in a blade aspect ratio $L/h = 2.5$, as recommended by Pearcey (1961). The blades are arranged with an AOA of 15° . The spanwise distance between the centroids of MVG blades within a single pair is $D = 7.5$ mm, and the spanwise wavelength between MVG pairs $\Lambda_z = 30$ mm. These configurations adhere to the recommended ratios of $\Lambda_z/D = 4$ and $\Lambda_z/h = 10$ as suggested by Pearcey (1961) and Sattarzadeh & Fransson (2015), ensuring effective vortex formation and flow control performance.

The MVG experiments are performed by placing the MVG array at two streamwise locations, $x_0 = 0.41$ m and 1.31 m. Two MVG-TBL measurements are operated at two free stream velocities $U_\infty = 7.4$ and 20 m s⁻¹ at two MVG locations. Note that an additional MVG experiment is performed for the Reynolds number matching purpose by operating a moderate free stream velocity $U_\infty = 11$ m s⁻¹ with the MVGs arranged at $x_0 = 1.31$ m. The boundary layer thickness δ is the distance from the wall to the position based on 99 % of the free stream velocity. For the front and back MVG locations, the MVG height ratios are $h/\delta_0 \approx 0.18$ and 0.09 , respectively, where the higher $h/\delta_0 \approx 0.18$ is similar to those used by Chan & Chin (2022). The friction Reynolds numbers at the MVG locations vary from 400 to 1600 in the five sets of experiments to investigate the Reynolds number effects at the MVG placement. A summary of the flow condition detail and the MVG dimensions are found in table 1. Note that the superscript and subscript of the case name are referred to as the values of the MVG height ratio and the friction Reynolds number. For example, the case of MVG₄₀₀¹⁸ represents conditions at $Re_\tau = 400$ and $h/\delta_0 \approx 0.18$, similar to those of the LES study (Chan & Chin 2022).

2.3. Measurement grid set-up

The wall-normal and spanwise flow fields (yz -plane) are measured at several streamwise stations downstream of the MVG array, as shown in figure 1(a,b). For each yz -plane, we conduct six linear-spaced spanwise velocity profile measurements at $z/\Lambda_z = 0\text{--}0.5$, enough to characterise the spanwise-varied TBLs downstream of the MVGs and obtain the spanwise- and temporal-averaged profiles (also referred to as ‘global profiles’) with a

low uncertainty level of $< 3.5\%$ at each yz -plane (Kong *et al.* 2024). The study by Kong *et al.* (2024) provides evidence that six spanwise locations are sufficient for the MVG configuration used in our work. Six yz -planes are measured at $x^*/h = 5, 25, 50, 100, 200$ and 500 , where x^* is the streamwise distance from the trailing edge of the MVG array, $x^* = x - x_0$. For the cases with $h/\delta_0 = 0.09$, the MVGs are placed farther downstream at $x_0 = 1.31$ m and the streamwise measurement station is limited to $x^*/h \leq 200$ due to the length limitation of the test section. The wall-normal velocity profiles are taken from the near-wall position $y \approx 0.2$ mm to $y \approx 1.5\delta$ with varying measurement points of 30–50. Hence, the total number of grid points varies from 180–300 (6×30 – 6×50) for different streamwise stations.

2.4. Traverse system

The two-dimensional traverse system comprises horizontal and vertical sliding platforms equipped with two optical linear encoders and driven by microstepper motors, which can perform horizontal and vertical traverses of the sensor probe accurate to 5 and 0.5 μm , respectively. For each wall-normal velocity profile measurement, the wall distance of the sensor probe is determined using a digital microscope. The study of Kong *et al.* (2024) gives the details of the method determining wall distance. The accuracy of the wall distance is ≤ 8 μm , and the influence of the wall distance error on the U_τ estimation is reported to be negligible (Kong *et al.* 2024).

2.5. Velocity measurement

The velocity information is measured using hot-wire anemometry (HWA). Our in-house constant temperature anemometer is based on the design by Perry (1982), and identical to the Melbourne University Constant Temperature Anemometer that has been used by Marusic *et al.* (2013), Squire *et al.* (2016) and Kevin *et al.* (2017). The HWA uses a single-wire boundary-type probe with sensor filaments of platinum–wollaston wires and a filament length of $l = 0.5$ mm. The HWA system signal is sampled using a National Instrument data acquisition board (NI9234) with frequency $f_s = 51\,200$ Hz and a minimum duration $T = 120$ s. The viscous sampling time and sampling duration satisfy $t^+ = 1/f_s(U_\tau^2/\nu) < 1$ and $TU_\infty > 20\,000\delta$ to temporally resolve all high-energy velocity fluctuation and encompass several hundreds of the large-scale events (Hutchins & Marusic 2007a; Hutchins *et al.* 2009). The spatial resolution correlates with the inner-scaled sensor length, $l^+ = lU_\tau/\nu$, which varies from 10 to 25 for the five data sets. The inner-scaled sensor length of $l^+ \leq 25$ indicates that the measurements do not experience significant spatial attenuation (e.g. the error of the inner peak amplitude of turbulence intensity is $\lesssim 10\%$ (Hutchins *et al.* 2009)). For the mean statistics analysis, U and u' denote the time-averaged velocity signal and the velocity fluctuation in the streamwise direction, respectively. Here $\langle U \rangle$ and $\langle u' \rangle$ denote the corresponding spanwise-averaged quantities over half of the spanwise distance of MVG pairs, $z = 0 - \Lambda_z/2$. The superscript $+$ indicates the scaling of inner units, for example, $U^+ = U/U_\tau$ and $y^+ = y/l_v$, where $l_v = \nu/U_\tau$ is the viscous length scaling.

The velocity measurement processes are automatic and take approximately 10–20 hr for different yz -planes. The calibration is performed every 5 hr of measurement by placing a Pitot tube 10 mm above the hot-wire probe into the free stream flow. The free stream velocity is measured using a Pitot tube with an electronic barometer (220DD Baratron, MKS). The flow temperature is monitored by a calibrated RTD-type thermocouple (Pt1000). The calibration profile is determined by fitting a fourth-order polynomial curve onto the pressure and HWA signals. The intermediate calibration profile is then computed

Case	x (m)	x^*/h	x^*/δ_0	U_∞ (ms ⁻¹)	U_τ (ms ⁻¹)	Re_τ	$1000c_f$	δ (mm)	θ (mm)	δ^* (mm)	H
TBL ₄₀₀	0.425	5	0.8	7.4	0.3359	411	4.00	18.6	2.3	3.4	1.478
	0.485	25	4.0	7.4	0.3324	415	3.97	18.9	2.3	3.3	1.461
	0.560	50	8.1	7.4	0.3318	438	3.94	20.0	2.3	3.4	1.465
	0.710	100	16.1	7.4	0.3258	476	3.80	22.2	2.7	3.9	1.457
	1.010	200	32.3	7.4	0.3178	567	3.62	30.2	3.3	4.7	1.443
	1.910	500	80.6	7.4	0.3047	754	3.37	37.5	4.8	6.7	1.407
TBL ₁₀₀₀	0.425	5	0.8	20	0.8094	987	3.27	18.5	2.3	3.2	1.393
	0.485	25	4.1	20	0.8045	1002	3.23	18.9	2.3	3.1	1.373
	0.560	50	8.1	20	0.8021	1051	3.20	19.9	2.3	3.2	1.378
	0.710	100	16.2	20	0.7875	1149	3.08	22.1	2.6	3.7	1.390
	1.010	200	32.4	20	0.7701	1351	2.95	26.6	3.2	4.4	1.388
	1.910	500	81.1	20	0.7370	1800	2.72	37.0	4.5	6.2	1.380
TBL ₆₀₀	1.325	5	0.5	7.4	0.3097	668	3.49	32.7	4.0	5.7	1.429
	1.385	25	2.3	7.4	0.3105	679	3.45	33.1	4.1	5.9	1.433
	1.460	50	4.6	7.4	0.3094	703	3.44	34.4	4.2	6.0	1.426
	1.610	100	9.2	7.4	0.3052	716	3.44	35.6	4.3	6.1	1.419
	1.910	200	18.3	7.4	0.3047	754	3.37	37.5	4.8	6.7	1.407
TBL ₉₀₀	1.325	5	0.5	11	0.4388	923	3.25	31.9	3.8	5.4	1.406
	1.385	25	2.4	11	0.4373	934	3.22	32.4	3.9	5.5	1.407
	1.460	50	4.7	11	0.4367	970	3.17	33.7	4.1	5.8	1.409
	1.610	100	9.4	11	0.4342	998	3.19	34.9	4.2	5.9	1.400
	1.910	200	18.8	11	0.4246	1044	3.18	37.3	4.5	6.2	1.390
TBL ₁₆₀₀	1.325	5	0.5	20	0.7556	1606	2.84	32.2	3.8	5.3	1.379
	1.385	25	2.3	20	0.7477	1589	2.82	32.2	3.9	5.4	1.386
	1.460	50	4.7	20	0.7497	1615	2.83	32.7	4.0	5.5	1.379
	1.610	100	9.3	20	0.7598	1697	2.87	33.9	4.0	5.4	1.363
	1.910	200	18.6	20	0.7370	1800	2.72	37.0	4.5	6.2	1.380

Table 2. Boundary layer condition detail of the ZPG smooth-wall TBL (referred to local TBL). The reference local station $x^*/h = (x - x_0)/h$ is scaled with $x_0 = 0.41$ m and 1.31 m for the two cases of TBL₄₀₀, 1000 and the three cases of TBL₆₀₀, 900, 1600, respectively.

by interpolating the precalibration and postcalibration profiles obtained before and after each 5 hr measurement to correct the temperature drift if required (Talluru *et al.* 2014).

2.6. The ZPG smooth-wall flow

The ZPG smooth-wall TBL developed over the aluminium flat plate without the MVGs is used as the reference flow to characterise the MVG effects. The wall-normal velocity profile measurements are performed at the consistent local streamwise stations and free stream velocities to the MVG measurement and referred to as ‘local TBL’, as shown in figure 1. The boundary layer parameters of the local TBL are summarised in table 2.

2.7. Friction velocity determination

The friction velocity is $U_\tau = \sqrt{\tau_w/\rho}$, where τ_w is the wall shear stress and ρ is the fluid density. For the local TBL results, the friction velocity is determined by the composite method, which has been used in experimental studies (Chauhan, Monkewitz & Nagib 2009; Rodríguez-López *et al.* 2015; Kong *et al.* 2023). For the MVG measurements, the present study determines the friction velocities for the global velocity profiles by applying the inner2 method to investigate the inner-scaled global statistics. The inner2 method utilises the Musker function, incorporating a bump function to fit with the drifting

Case	Symbol	x^*/h	x^*/δ_0	U_τ (m s ⁻¹)	Re_τ	$1000c_f$	δ (mm)	θ (mm)	δ^* (mm)	H	h^+
MVG ¹⁸ ₄₀₀		5	0.8	0.3609	405	4.66	17.0	2.0	3.0	1.520	71.4
		25	4.0	0.3492	423	4.34	18.3	2.2	3.2	1.455	69.2
		50	8.1	0.3410	453	4.19	20.1	2.4	3.5	1.453	67.5
		100	16.1	0.3327	491	3.95	22.4	2.7	4.0	1.451	65.8
		200	32.3	0.3255	582	3.81	27.1	3.3	4.7	1.426	64.4
		500	80.6	0.3108	816	3.49	39.8	4.8	6.7	1.405	61.5
MVG ¹⁸ ₉₀₀		5	0.8	0.8439	980	3.62	17.6	2.0	2.9	1.432	167.0
		25	4.0	0.8333	1045	3.50	19.0	2.3	3.1	1.392	164.9
		50	8.1	0.8122	1081	3.33	20.2	2.4	3.3	1.384	160.1
		100	16.2	0.7939	1192	3.20	22.8	2.7	3.8	1.383	157.1
		200	32.4	0.7834	1420	3.08	27.5	3.2	4.3	1.360	155.0
		500	81.1	0.7416	1924	2.77	39.4	4.5	6.0	1.346	146.8
MVG ⁰⁹ ₆₀₀		5	0.5	0.3315	691	3.94	31.6	3.8	5.5	1.454	65.6
		25	2.3	0.3235	695	3.76	32.6	3.9	5.6	1.426	64.0
		50	4.6	0.3178	704	3.62	33.6	4.1	5.8	1.423	62.9
		100	9.2	0.3123	734	3.49	35.6	4.3	6.1	1.419	61.8
		200	18.3	0.3071	779	3.39	38.5	4.7	6.7	1.419	60.8
MVG ⁰⁹ ₉₀₀		5	0.5	0.4647	920	3.48	30.0	3.6	5.2	1.424	92.0
		25	2.4	0.4591	931	3.42	30.7	3.8	5.3	1.413	90.9
		50	4.7	0.4553	937	3.38	31.2	3.8	5.4	1.405	90.1
		100	9.4	0.4504	989	3.29	33.3	4.0	5.6	1.392	89.1
		200	18.8	0.4413	1075	3.17	36.9	4.4	6.1	1.384	87.3
MVG ⁰⁹ ₁₆₀₀		5	0.5	0.7922	1645	3.12	31.5	3.7	5.1	1.390	156.8
		25	2.3	0.7819	1701	3.06	33.0	3.9	5.3	1.372	154.7
		50	4.7	0.7753	1703	2.98	33.3	3.9	5.3	1.363	153.4
		100	9.3	0.7595	1725	2.89	34.4	4.1	5.6	1.366	150.3
		200	18.6	0.7434	1849	2.77	37.7	4.5	6.1	1.365	147.1

Table 3. Boundary layer condition detail of the five MVG experiments.

buffer layer of MVG-modified TBLs. The procedure of the inner2 method is provided in [Appendix A](#) (see detail in Kong *et al.* (2024)). The friction velocity and boundary layer condition of a total of 27 global profiles are summarised in [table 3](#). The global friction drag coefficient c_f for the MVG measurements in [table 3](#) is nearly identical to the local TBL results in [table 2](#) for all five experiments. Specifically, there is a maximum increase of approximately 15 % immediately downstream of the MVG device, with deviations of less than 3 % for $x^*/h \geq 50$. This finding is consistent with the LES MVG study by Chan & Chin (2022).

3. Results

3.1. Mean flow characteristics

The contours and the spanwise profiles of the mean streamwise velocity scaled with the free stream velocity, U_∞ , for the five yz -planes of MVG¹⁸₄₀₀ at $x^*/h = 5$ –500 are illustrated in [figure 2](#). Results are shown for MVG¹⁸₄₀₀ only, as the five sets of experimental data show similar developments for the contours of mean streamwise velocity and velocity fluctuation. At the near-wake station, $x^*/h = 5$, a velocity deficit region is observed behind the MVG blade ([figure 2a](#)), which indicates the primary vortex induced by the

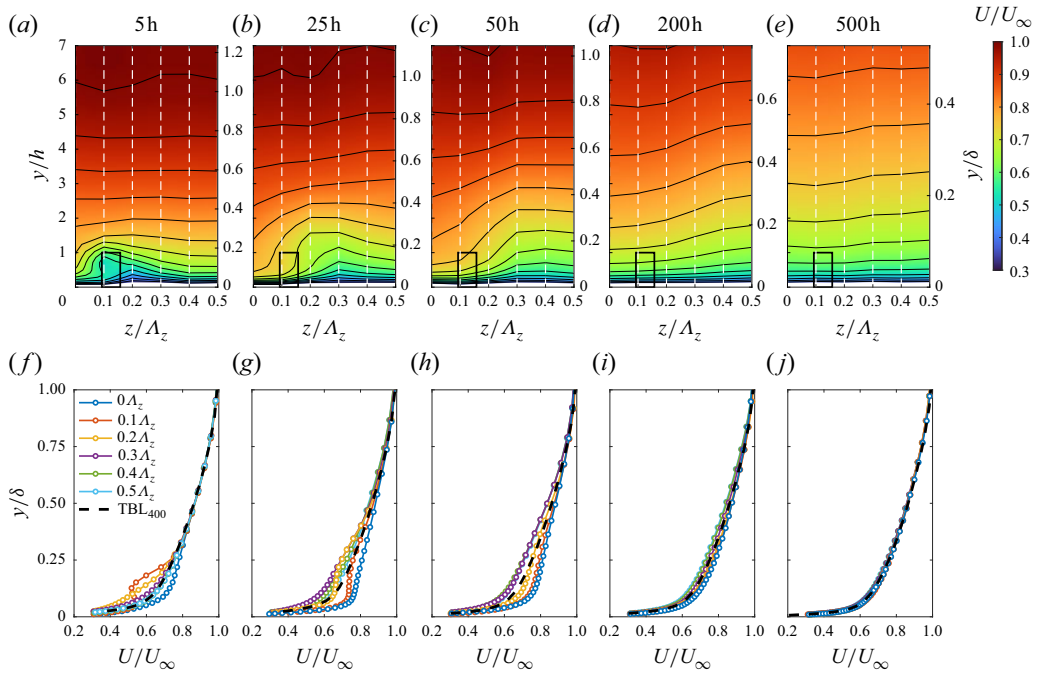


Figure 2. Contours (a–e) and spanwise profiles (f–j) of the mean streamwise velocity of MVG_{400}^{18} at $x^*/h = 5, 25, 50, 200$ and 500 (as marked). The y -axes of the outer-scaled streamwise velocity contours are normalised by the MVG height h (a–e) and the boundary layer thickness δ (f–j), which can show the MVG influences near the MVG blades and the entire boundary layers, respectively. The contour level is $U/U_\infty = [0.3 : 0.05 : 0.95, 0.99]$. The white dashed line in contours indicates the spanwise velocity profile positions. The black box indicates the projection area of the MVG blade in the streamwise direction. The black dashed line is the local TBL velocity profile of TBL_{400} , plotted against the outer-scaled wall-normal position.

MVGs (Yao *et al.* 2002; Chan & Chin 2022). The velocity defect effect is constrained to the near-wall region, $y/h < 3$, which is consistent with the numerical result of Chan & Chin (2022). In addition, when comparing the spanwise profiles of the MVG case with the TBL case at $x^*/h = 5$, only the spanwise region of $z/\Lambda_z = 0-0.3$ ($z/h = 0-3$) is affected by the MVGs. This result indicates that the MVG influence is limited to $y/h < 3$ and $0 < z/h < 3$ for each pair of the MVGs at the near-wake station under the specific MVG configuration studied.

For the downstream flow development, the low-momentum region shifts from $z/\Lambda_z = 0.2$ to 0.5 (figure 2b–e), as seen as in the velocity deficit observed at $y/\delta = 0.25$ (figure 2g–j). The outcome is due to the self-induction mechanism and is consistent with numerical and experimental results (Löfdberg *et al.* 2009; Chan & Chin 2022). In figures 2(c) and 2(h), the high- and low-momentum regions are formed at $z/\Lambda_z = 0-0.1$ and $z/\Lambda_z = 0.3-0.5$, respectively, which indicates that the MVG-induced vortex expands in the spanwise direction, covering the entire wavelength $z/\Lambda_z = 0-0.5$ at $x^*/h = 50$. The high- and low-momentum regions are less pronounced for farther downstream stations, and the MVG influence becomes negligible at $x^*/h \geq 200$ (figures 2d, and 2i). The spanwise profiles of the MVG case collapse with the local TBL, which indicate that the MVG-modified TBL may have reached equilibrium and behave almost similarly to the smooth-wall TBL at $x^*/h = 500$ (figure 2j).

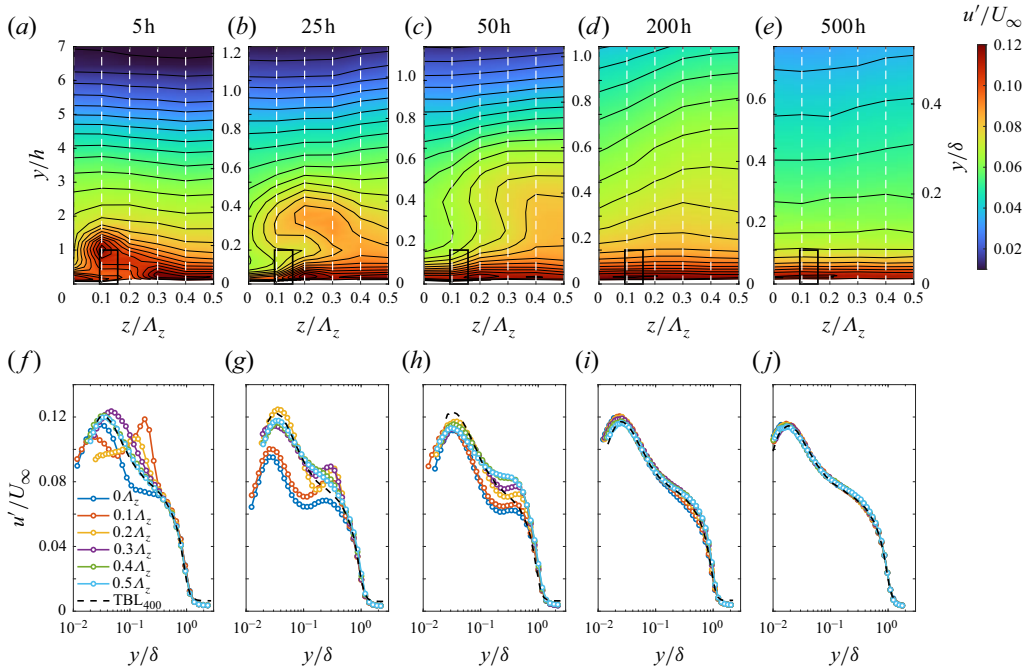


Figure 3. Contours (a–e) and spanwise profiles (f–j) of velocity fluctuation of MVG_{400}^{18} at $x^*/h = 5, 25, 50, 200$ and 500 (as marked). The y-axis normalisation is similar to figure 2. The contour level is $u'/U_\infty = [0.005 : 0.12]$. The white dash-line in contours indicates the spanwise velocity profile positions. The black box indicates the projection area of the MVG blade in the streamwise direction. The black dash-line is the local TBL result, referring to figure 2.

The contours and spanwise profiles of the velocity fluctuation (u') of MVG_{400}^{18} at $x^*/h = 5$ – 500 scaled with the free stream velocity (U_∞) are illustrated in figure 3. At the near-wake station of $x^*/h = 5$, turbulence intensity is amplified from the inside tip of MVG blades at $z/\Lambda_z = 0.1$ and $y/h = 1$ (figures 3a and 3f). At downstream stations of $x^*/h = 25$ – 50 , the MVG-induced turbulence intensity shifts away from the wall and spanwise towards the centre of two MVG pairs, as shown in figures 3(b,c) and 3(g,h), which is consistent with the lift-up mechanism of the MVG-induced vortex (Landahl 1980). The downwash motion reduces the turbulence intensity in the logarithmic region for $z/\Lambda_z = 0$ – 0.1 at $x^*/h = 25$ at $y/\delta \approx 0.2$. In contrast, the upwash region exhibits increased turbulence intensity in the logarithmic region, which aligns with observations from spanwise-jet-induced streamwise vortices (Yao, Chen & Hussain 2018; Cheng *et al.* 2021). This behaviour suggests that the streamwise vortices advect near-wall turbulence and quasistreamwise vortices upward into the outer region, thereby supporting the proposed drag reduction mechanism that near-wall turbulence transferred away from the wall reduces skin friction (Tardu 2001). A slight spanwise variation of the turbulence fluctuation in the outer region of $y/\delta = 0.4$ at $x^*/h = 200$ (figures 3d and 3i). The spanwise profiles of the velocity fluctuation show a good agreement in the spanwise direction (figures 3e and 3j), which further supports the notion that the MVG influence may have dissipated for the turbulence intensity at $x^*/h = 500$.

The turbulence intensity reduction in the log region is analysed in relation to the secondary flows observed from the LES MVG result of Chan & Chin (2022). The streamwise velocity fluctuation maps are compared with the LES MVG result at $x^*/h =$

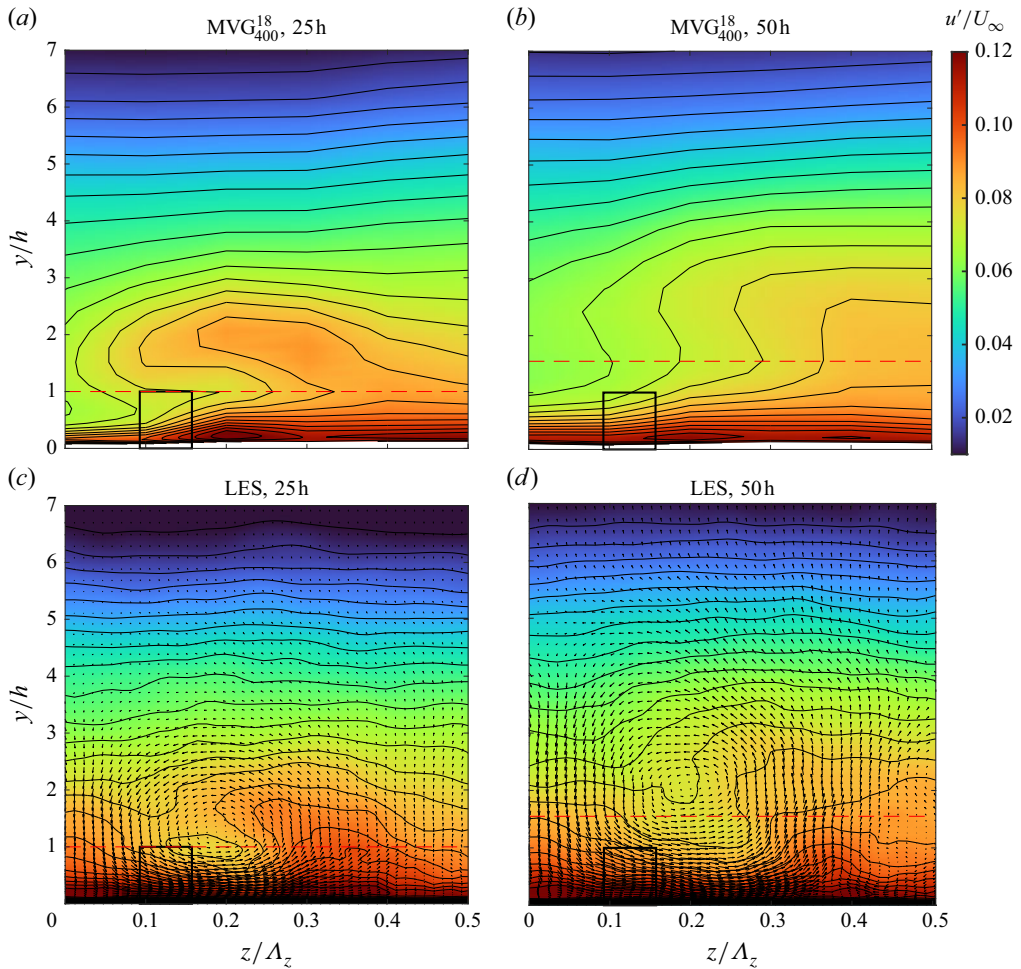


Figure 4. Contours of velocity fluctuation of MVG₄₀₀¹⁸ (a,b) and the LES MVG result by Chan & Chin (2022) (c,d) at $x^*/h = 25$ and 50. The y-axis normalisation and the contour level refer to figure 3. The black box indicates the projection area of the MVG blade in the streamwise direction. The red dashed line indicates the wall-normal location where velocity fluctuation is reduced near the wall. The secondary flow topology is denoted by the mean wall-normal and spanwise velocity vector map of the LES MVG result.

25 and 50 in figure 4. The near-wall attenuation effect aggregates near the MVG blade height ($y/h = 1$) at $x^*/h = 25$ for both experimental and LES results, denoted by the red dashed line. Farther downstream at $x^*/h = 50$, the attenuation location shifts upward to $y/h = 1.6$. The LES MVG results show that the turbulence intensity attenuation is primarily located in the downwash region of $z/\Delta_z = 0-0.2$, consistent with the experimental result. The vector field of the secondary flow induced by MVGs indicates that the turbulence intensity attenuation is associated with the spanwise motion below the MVG-induced streamwise vortices (figures 4c and 4d).

The MVG's influence on both the mean velocity and streamwise velocity fluctuation fields can be correlated by comparing the profiles in figures 2(f-j) and 3(f-j). The MVG effects appear in the inner layer ($y/\delta \leq 0.1$) behind the MVG blade ($z/\Delta_z = 0.1$) at the near-wake station ($x^*/h = 5$), where reductions in turbulence intensity and a velocity deficit are pronounced, as shown in figures 2(f) and 3(f). At the downstream

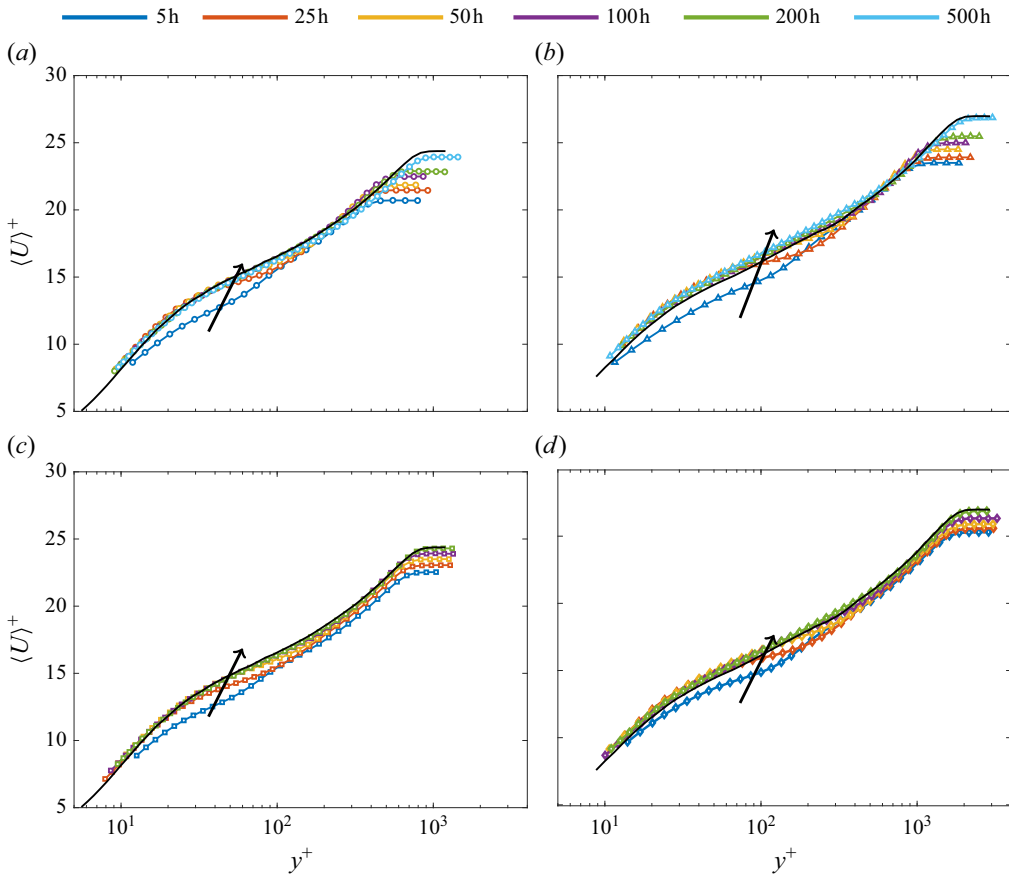


Figure 5. Inner-scaled mean velocity profiles for cases of MVG_{400}^{18} (a), MVG_{900}^{18} (b), MVG_{600}^{09} (c) and MVG_{1600}^{09} (d); black solid lines are the local TBL results of TBL_{400} and TBL_{1000} at $(x - x_0)/h = 500$ in table 2. The arrows indicate increasing x^*/h .

location of $x^*/h = 50$, the MVG-modified TBL develops into distinct downwash and upwash regions that span half the wavelength of an MVG pair. The downwash region shows increased momentum and reduced velocity fluctuations, while the upwash region is associated with a momentum deficit and velocity fluctuation amplification over $z/\Lambda_z = 0.2\text{--}0.5$, compared with the local TBL result (figures 2h and 3h). The result suggests that MVG primary vortex lifts low-momentum, highly fluctuating near-wall fluid into the outer flow in the upwash region, while the downwash region shows the opposite effect.

3.2. Global mean statistics

The global mean statistics of the MVG results are investigated to characterise the global MVG effects, including the global mean velocity and turbulence intensity. The global mean velocity profiles for the four cases of MVG_{400}^{18} , MVG_{900}^{18} , MVG_{600}^{09} and MVG_{1600}^{09} across the six streamwise stations of $x^*/h = 5\text{--}500$ are plotted with the corresponding local TBL results at the last downstream station, $x = 1.91$ m in figure 5. The global mean velocity profiles for each of the yz -cross-sectional planes are obtained by averaging the six spanwise profiles. In comparison with the local TBL result, there is a velocity defect in the log-law region at streamwise stations of $x^*/h \leq 25$ for the four MVG cases. This

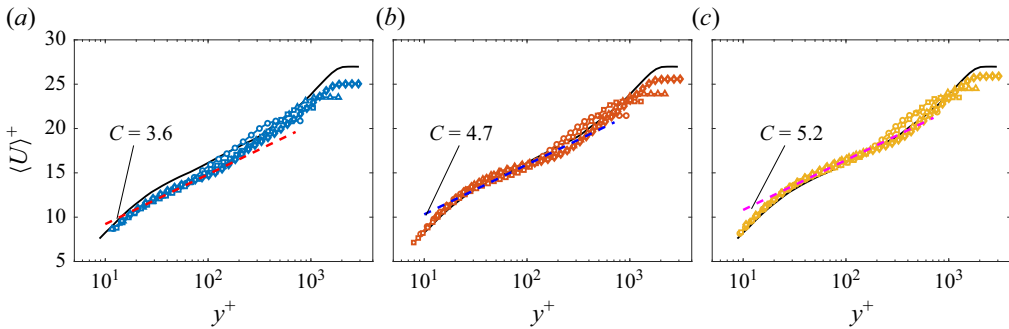


Figure 6. Inner-scaled mean velocity profiles of the four MVG cases in figure 5 at $x^* = 5$ h (a), 25 h (b) and 50 h (c); The four MVG cases are MVG_{400}^{18} ($\circ$), MVG_{900}^{18} (Δ), MVG_{600}^{09} ($\square$) and MVG_{1600}^{09} ($\diamond$). The black solid line refers to the local TBL of TBL_{1000} at $(x - x_0)/h = 500$.

downward shift is often observed on rough-wall TBLs, and the shift amplitude is known as the roughness function, ΔU^+ , signalling an increase in wall drag (Chung *et al.* 2021). Note that evaluating ΔU^+ requires a well-defined logarithmic layer, which is absent near the MVGs at $x^*/h = 5$ and 25 due to the effects of MVGs and low Reynolds numbers. Here, ΔU^+ is estimated by locating the lowest intersection between a logarithmic profile with $\kappa = 0.41$ and the measured velocity data, thereby capturing the maximum velocity deficit caused by the MVGs. For our study, this log-region downshift is attributed to the velocity deficit occurring in the upwash motions by the MVG-induced primary vortex, as shown in figure 2(a). Similar velocity deficits due to upwash motions have been reported in standard VG studies (Lin 1999; Yao *et al.* 2002; Heffron, Williams & Avital 2021) and from other passive flow control studies that generate vortical motions, such as directional riblets (Koeltzsch, Dinkelacker & Grundmann 2002; Nugroho, Hutchins & Monty 2013; Kevin *et al.* 2017). Compared with the local TBL, the mean velocity profiles of MVG_{400}^{18} show that the ΔU^+ decreases along streamwise development and vanishes at $x^*/h \geq 50$. The four data sets show a similar trend in terms of decreasing ΔU^+ , which indicates the velocity defect in the global mean statistics is insensitive to the Reynolds number and MVG height ratio.

The global mean velocity profiles for all four MVG cases are plotted at three streamwise stations, $x^*/h = 5, 25$ and 50, in figure 6. The ΔU^+ variation is not plotted but is inferred from the differences in the intercept constant C of the logarithmic region between the MVG cases and the reference smooth-wall case, where C for the smooth-wall TBL is commonly reported as 5.2 (Hutchins & Marusic 2007b). The five different Reynolds number cases collapse to each other with uncertainties of $\Delta U^+ < \pm 1$ at the three locations. The log-law constant increases from $C = 3.6$ to 5.2 as the flow develops downstream, which agrees with the numerical result of the LES MVG study (Chan & Chin 2022). This further supports that the MVG-induced velocity defect of the global mean velocity profiles is independent of the Reynolds number and the MVG height ratio but, rather, is associated with the streamwise distance downstream of the MVGs.

The global turbulence characteristics of the MVG results are investigated to evaluate the MVG effects on controlling turbulence in figure 7. The global turbulence intensity ($\langle u'^2 \rangle$) is computed by averaging individual normal Reynolds stress ($u'u'$) at six spanwise locations, and normalised by the inner scaling of U_τ as $\langle u'^2 \rangle^+ = \langle u'^2 \rangle / U_\tau^2$. Figure 7 shows the global turbulence intensity with inner scaling for the four experimental cases at $x^*/h = 5$ –500. All streamwise stations show inner-layer peaks at $y^+ \approx 15$ for the four experimental cases. The magnitude of the peaks increases with streamwise development for the four data

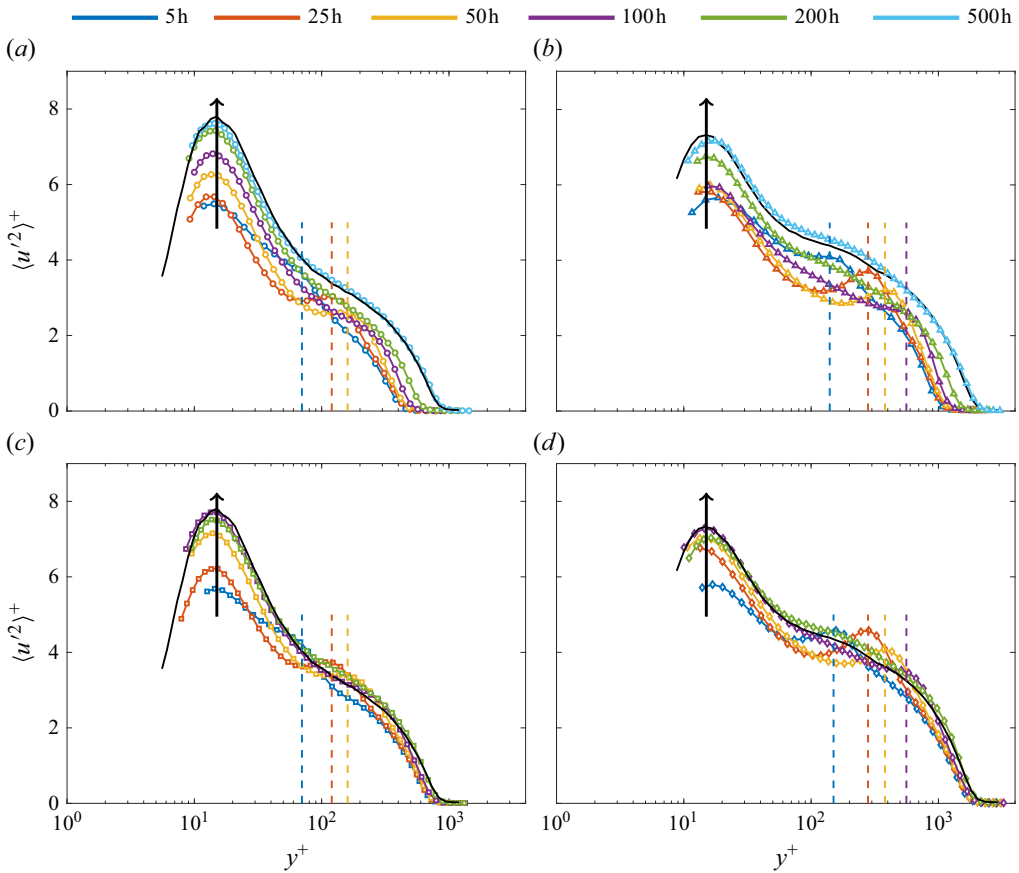


Figure 7. Inner-scaled turbulent intensity profiles for MVG_{400}^{18} (a), MVG_{900}^{18} (b), MVG_{600}^{09} (c) and MVG_{1600}^{09} (d); dash vertical lines indicate the outer humps induced by the MVGs. Colour code refers to the colour of $\times$ in table 1. Grey and black solid lines are the local TBL results referring to figure 5. The arrows indicate increasing x^*/h .

sets. For the downstream stations, $x^*/h = 5\text{--}25$, lower near-wall peaks are observed due to the turbulence intensity attenuation, which is caused by downwash motion that focuses on the centre area of the MVGs ($z/\Lambda_z = 0\text{--}0.1$). Such phenomena are also observed in other passive flow control studies, such as standard VGs and directional riblets (Kevin *et al.* 2017; Heffron *et al.* 2021).

For the near-wake station, $x^*/h = 5$, the profiles of MVG_{400}^{18} and MVG_{600}^{09} show a hump centring at $y^+ = 70$ (figures 7a and 7c), and the humps of MVG_{900}^{18} and MVG_{1600}^{09} become more pronounced, centring at $y^+ \approx 160$ (figures 7b and 7d), compared with the two low Re_τ cases. The hump location is consistent with the MVG blade height of h^+ , which further supports that the MVG blade tip induces velocity fluctuations. For the case MVG_{400}^{18} , as the streamwise flow develops from $x^*/h = 25\text{--}100$, the MVG-induced turbulence intensity becomes more pronounced and the hump shifts towards the outer layer from $y^+ = 120\text{--}220$ (figure 7a). In figure 8, the wall-normal distributions of MVG-induced velocity fluctuations for five MVG cases at four streamwise stations are compared with corresponding data from the LES study by Chan & Chin (2022). The profiles collapse, and the wall-normal hump location shifts towards the outer layer along the downstream development, which is associated with the path of the vortex propagation (Lögberg

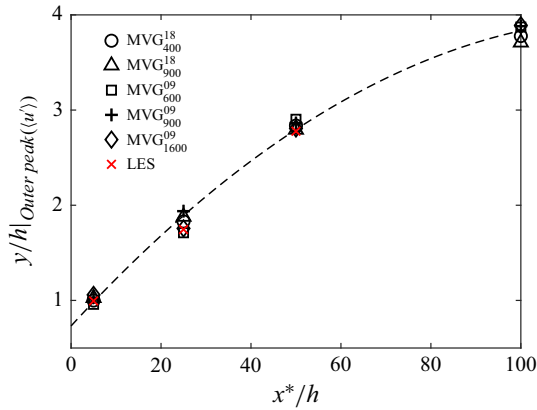


Figure 8. The wall-normal locations of the MVG-induced velocity fluctuation for five experimental data sets at $x^*/h = 5, 25, 50$ and 100 and the LES dataset from Chan & Chin (2022) at $x^*/h = 5, 25$ and 50 . The dashed line is the regression line for the experimental and LES results.

et al. 2009). This result indicates that the wall-normal propagation of the MVG-induced fluctuation is independent of the MVG height ratio and the Reynolds number.

3.3. Spectral analysis

The energy spectral analysis presented in this section reveals the contribution of the turbulence intensity manipulation by MVGs from different length scales of turbulence structures. The premultiplied energy spectral maps of the streamwise velocity fluctuation, $k_x \phi_{uu}^+$, at $x^*/h = 5$ – 200 are analysed. The spatial energy spectra, ϕ_{uu} , of the streamwise velocity u are computed from the temporally sampled measurements using Taylor's hypothesis (Taylor 1938). The energy spectra are premultiplied by the streamwise wavenumber, k_x , and scaled by the friction velocity, U_τ . The streamwise wavenumber is defined as $k_x = 2\pi f/U_c$, where f is the frequency and the convection velocity, U_c , is approximated by the local mean streamwise velocity (Abbassi *et al.* 2017). This approximation may be less accurate for large scales near the wall (Del Álamo & Jiménez 2009), especially as MVG-induced streamwise vortices contradict Taylor's hypothesis. Nonetheless, it remains widely used in TBLs with secondary flows (Nugroho *et al.* 2013; Abbassi *et al.* 2017; Berk & Ganapathisubramani 2019; Xu, Zhong & Zhang 2019; Duong *et al.* 2021; Chan & Chin 2022). The premultiplied spectra are global statistics, found by spanwise averaging over six spectral maps across six spanwise locations of $z/\Lambda_z = 0$ – 0.5 . At each of the six spanwise locations, temporal measurements are converted into spatial spectra using the local mean velocity. The six resulting spectral maps are then averaged to yield the global premultiplied spectra (details of the spanwise averaging procedure are provided in Appendix B). The premultiplied energy spectral maps are plotted for the four MVG cases: MVG_{400}^{18} (figure 9a) and MVG_{600}^{09} (figure 9c) for two MVG height ratios $h/\delta_0 = 0.18$ and 0.09 , and MVG_{900}^{18} (figure 9b) and MVG_{1600}^{09} (figure 9d) at higher friction Reynolds numbers. These premultiplied spectra maps are plotted against the normalised streamwise wavelength, $\lambda_x^+ = (2\pi/k_x)/(\nu/U_\tau)$, to correlate the MVG energy manipulation with different length scales of motions. Note that the spectral maps at $x^*/h = 500$ are not presented, as the results at this x^*/h location collapse with the local TBL, consistent with the discussion related to figures 2 and 3.

The MVG effects on the TBL structures at a relatively low Reynolds number can be observed (figure 9a). At the near-wake station of $x^*/h = 5$, a near-wall peak is located at

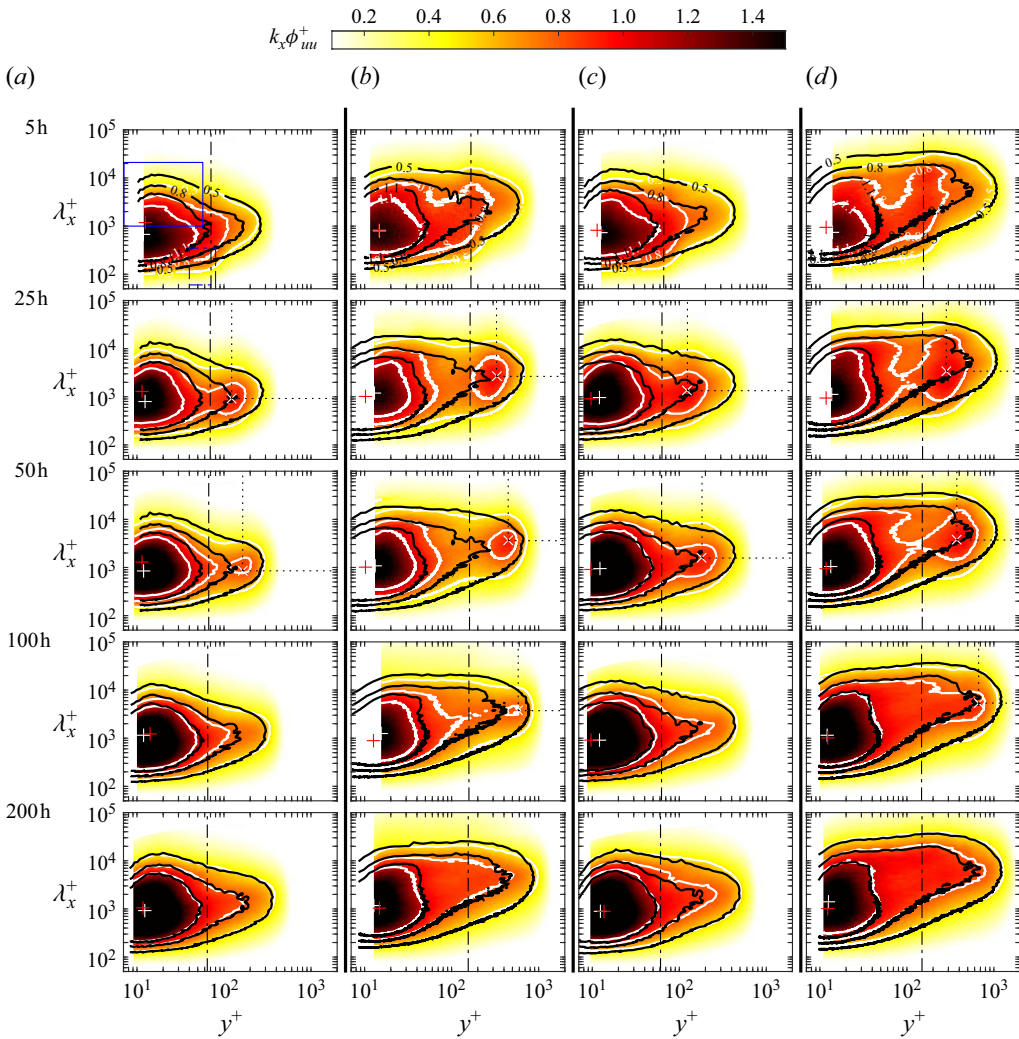


Figure 9. Premultiplied spectra contours for four experiments of MVG_{400}^{18} (a), MVG_{900}^{18} (b), MVG_{600}^{09} (c) and MVG_{1600}^{09} (d) at $x^*/h = 5\text{--}200$. The local TBL results of [table 2](#) are plotted with the MVG results at corresponding Re_τ . The white contour levels are $k_x \phi_{uu}^+ = [0.5, 0.8, 1.1]$ and the white symbol + denotes the near-wall peaks for the MVG results, while the corresponding local TBL results are denoted by the black contour and red +. The white symbol x denotes the identifiable outer peak for the MVG results, and the dashed line indicates the wall-normal location and the scaled wavelength of the outer peak. Vertical dash-dot lines are the locations of h^+ .

$\lambda_x^+ \approx 1000$ and $y^+ \approx 15$, similar to the local TBL result. Compared with the local TBL result, the MVG spectral map shows lower turbulence energy for structures of $\lambda_x^+ > 1000$ in the near-wall region (indicated by a blue solid box), consistent with the LES MVG study of Chan & Chin (2022). Note that similar results are observed in the other MVG cases in [figure 9\(b–d\)](#), though the blue box is not shown for simplicity. This outcome indicates that the MVG-induced vortices can disrupt the large-scale structures of $\lambda_x^+ > 1000$ in the near-wall region, resulting in turbulence energy reduction. In addition, there is an increase in turbulence energy for smaller-scale structures at $y^+ \approx h^+$ (highlighted by a blue dash-dot rectangle at $y^+ = 40\text{--}80$ and $\lambda_x^+ < 300$), compared with the local TBL result, aligning

with the turbulence intensity peak observed in [figure 7](#). This suggests that the small-scale structures are amplified close behind the MVGs.

The MVG long-distance effect can be observed by comparing the MVG and local TBL results at downstream stations, $x^*/h = 25$ – 200 ([figure 9a](#)). There is a growth in energy for length scales $\lambda_x^+ \approx 1000$ in the outer region, which develops into an outer peak, denoted by the symbol $\times$, at $x^*/h = 25$. Beyond $x^*/h = 25$, the outer peak decreases in turbulence energy as it shifts away from the wall and cannot be detected at $x^*/h \approx 100$, which is consistent with the outer humps observed in the turbulence intensity profiles ([figure 7a](#)). In the near-wall region, $y^+ < 70$ ($y/\delta < 0.15$), the three contour levels of $k_x\phi_{uu}^+ = 0.5, 0.8$ and 1.1 show a discrepancy between the MVG and local TBL results for a wavelength range of $\lambda_x^+ > 2000$, and the difference sustains until $x^*/h = 100$. The contour discrepancy indicates that there is less large-scale energy for the MVG case than the local TBL case, which is associated with the MVG effect on interrupting the large-scale structures in the near-wall region, and this MVG effect sustains downstream up to $x^*/h = 100$.

The Reynolds number effect is evaluated by comparing the MVG results of MVG_{400}^{18} and MVG_{900}^{18} ([figure 9a,b](#)). Compared with the lower- Re_τ case of MVG_{400}^{18} , the higher- Re_τ case of MVG_{900}^{18} shows an increase in turbulence energy for a larger wavelength range of $\lambda_x^+ < 5000$ at the MVG blade height $y^+ \approx 150$ (dash-dot line) at the near-wake station of $x^*/h = 5$. At $x^*/h = 25$, the outer peak of the higher- Re_τ case moves farther away from the wall, and has a longer wavelength of $\lambda_x^+ \approx 2800$. The outer hump denoted by the contour level of $k_x\phi_{uu}^+ = 0.8$ starts attenuating from $x^*/h = 25$ and nearly disappears at $x^*/h = 100$, with turbulence intensity reduced to the adjacent level in a wall-normal direction, which is farther downstream than the lower- Re_τ case. This hump shifts away from the wall, with dominant structures growing in wavelength from $\lambda_x^+ \approx 2800$ to 4000 (or $\lambda_x/\delta \approx 2.5$ to 3.1). The result implies that increasing Reynolds number leads to amplifying the turbulence energy of larger-scale structures at the near-wake station and causes the outer hump to develop into longer motions and extend farther downstream. Additionally, the contour level of $k_x\phi_{uu}^+ = 0.8$ for the higher- Re_τ MVG case shows a more pronounced separation between the near-wall and outer peaks from $x^*/h = 25$ – 100 , compared with the lower- Re_τ case. This output indicates the higher- Re_τ case experiences stronger turbulence energy attenuation, which will be discussed later.

The spectral maps of MVG_{600}^{09} and MVG_{1600}^{09} for the smaller MVG height ratio, $h/\delta_0 = 0.09$, at two friction Reynolds numbers ($Re_\tau \approx 600$ and 1600) are plotted in [figure 9\(c,d\)](#). The comparison of the outer hump in the two friction Reynolds number cases shows a similar trend to the results of the larger MVG height ratio in [figure 9\(a,b\)](#). The two relatively high- Re_τ cases of MVG_{900}^{18} and MVG_{1600}^{09} at the two MVG height ratios are also compared with reveal the MVG height ratio effects. For the smaller MVG height ratio case of MVG_{1600}^{09} at $x^*/h = 25$ – 50 , the contour level of $k_x\phi_{uu}^+ = 0.8$ shows that the outer peak is not fully separated from the near-wall peak ([figure 9d](#)), in contrast to the full separation observed in the corresponding case of MVG_{1600}^{09} at the larger MVG height ratio $h/\delta_0 = 0.18$ ([figure 9b](#)). The separation phenomenon in the case of MVG_{1600}^{09} disappears earlier at $x^*/h < 100$ than that of MVG_{900}^{18} . Despite the difference in Reynolds numbers, the result implies that decreasing MVG height ratios leads to weaker turbulence energy attenuation and a shorter effective distance of turbulence structure attenuation.

The MVG manipulation of turbulence energy with respect to the smooth-wall TBL is analysed by subtracting the local TBL results from the MVG spectral maps. For the four MVG cases MVG_{400}^{18} , MVG_{900}^{18} , MVG_{600}^{09} and MVG_{1600}^{09} , the spectra difference is plotted in [figure 10](#), where blue indicates attenuation and red indicates amplification of turbulence

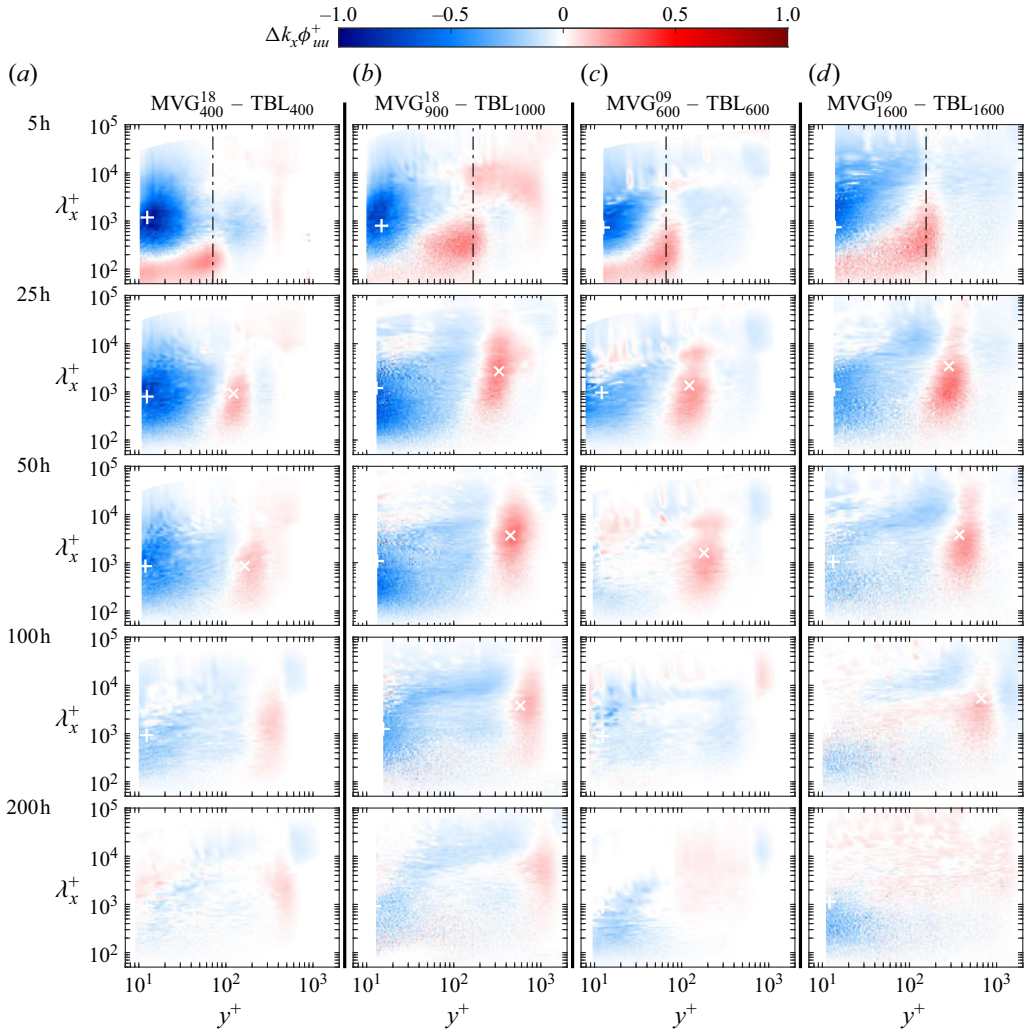


Figure 10. Contours of the premultiplied spectra difference between the four MVG and local TBL results (referring to figure 9). The white symbols + and × denote the near-wall and outer peaks for the MVG results, respectively. Vertical dash-dot lines are the locations of h^+ .

energy. The $5h$ row confirms that the large-scale structures in the near-wall region are attenuated for various Reynolds numbers and MVG height ratios at the near-wake station of $x^*/h = 5$. Comparing the energised structures shows that the MVGs can amplify a boarder range of small-scale structures below the MVG height at higher Reynolds numbers. Additionally, the case of MVG_{900}^{18} at $x^*/h = 5$ shows that large-scale structures are also amplified in the outer region at $y^+ > h^+$, indicating that the combination of a large MVG height ratio $h/\delta_0 = 0.18$ and a friction Reynolds number $Re_\tau \geq 900$ can energise large-scale structures above the MVG blade in the near-wake station.

For downstream stations, $x^*/h \geq 25$, the MVGs attenuate turbulence energy for a broad range of turbulence structures at wall-normal distances below the outer-peak wall-normal locations. This attenuation is associated with the spanwise motion below the MVG vortex core in the log region, as shown in figure 4. The turbulence energy reduction magnitude is higher for the larger MVG height ratio cases of MVG_{400}^{18} and MVG_{900}^{18} . Compared

with the lower- Re_τ case of MVG_{400}^{18} , the turbulence energy attenuation sustains farther downstream, up to $x^*/h = 100$, and extends to higher wall-normal positions at higher Reynolds numbers. This result indicates that the MVG effects on the turbulence structure attenuation can be enhanced by increasing the MVG height ratio and the Reynolds number. Notably, the MVG-induced streamwise vortices exhibit some similarity to the turbulence energy manipulation achieved by an active control technique of real-time actuator jets, which generate upward jets to introduce vortical structures into TBLs (Abbassi *et al.* 2017). Abbassi *et al.* (2017) report an increase in turbulence energy in the log region at a downstream distance of $\sim 2\delta$ behind the actuator device, comparable to the streamwise location of $x^*/h = 25$ in the present study. Below this region of energy amplification, the upward jets primarily reduced the large-scale energy to the wall (see figure 7 of Abbassi *et al.* (2017)). This differs from the MVG manipulation effect, which broadly attenuates turbulence energy across multiple scales. In addition, the MVG attenuation differs from the existing passive control device of LEBUs that only attenuate large-scale structures in the outer region and are effective relatively far downstream of the LEBUs (Chin *et al.* 2017).

In figure 11, the spectral maps of $h/\delta_0 = 0.18$ and 0.09 at a similar friction Reynolds number $Re_\tau \approx 900$ are compared, corresponding to the cases of MVG_{900}^{18} and MVG_{900}^{09} , respectively. This comparison isolates the effects of MVG height ratio from the Reynolds number influences. Both show a similar streamwise development of the outer peak at $x^*/h = 5\text{--}200$, as discussed in figure 9. The case with a larger MVG height ratio, MVG_{900}^{18} , has an outer peak dominated by longer motions, $\lambda_x^+ = 2800\text{--}4000$ (or $\lambda_x/\delta = 2.5\text{--}3.1$), compared with the dominant motions $\lambda_x^+ = 1000\text{--}2500$ (or $\lambda_x/\delta = 1.3\text{--}2.6$) in the case MVG_{900}^{09} . This result implies that the streamwise length of the outer-peak structures is dependent on the MVG height ratio and the Reynolds number. Additionally, the larger MVG height ratio case shows a smaller high-energy area ($k_x\phi_{uu}^+ = 1.1$) in the near-wall region at $x^*/h = 25\text{--}100$ than those of the lower MVG height ratio. Compared with the local TBL result, the case MVG_{900}^{18} shows a reduced amount of turbulence energy in the near-wall region until $x^*/h = 200$, which is farther downstream than in the case of MVG_{900}^{09} . This outcome confirms that the MVG height ratio of $h/\delta_0 \approx 0.18$ imposes a stronger turbulence energy attenuation in the near-wall region and sustains to a farther downstream location than the smaller MVG height ratio of $h/\delta_0 = 0.09$.

The premultiplied spectra difference between the case MVG_{900}^{18} and two cases of MVG_{400}^{18} and MVG_{900}^{09} are analysed to compare the effects of the Reynolds number and the MVG height ratio in figure 12. For the Reynolds number effect (figure 12a), the outer peak transition (black and white $\times$) indicates the turbulence energy in the outer region is transferred to a larger wavelength and to a higher wall-normal position at $x^*/h = 25\text{--}100$ for higher friction Reynolds numbers, which confirms the Reynolds number effect in figure 9. In figure 12(b), the comparison of two MVG height ratios shows a similar outer peak shifting as the Reynolds number effect, confirming that the MVG effects on the outer peak also depend on the MVG height ratio. In the near-wall region, turbulence energy attenuation is observed for small-scale structures figure 12(a) and figure 12(b) indicating increasing either the Reynolds number or the MVG height ratio has a similar influence on attenuating small-scale energy. The energy attenuation of small-scale structures is associated with the increasing vortex strength of the MVG-induced vortices by increasing the Reynolds number and the MVG height ratio, which increase the vorticity amplitude and enlarge the circulation area, respectively (Lin 2002; Löfgberg *et al.* 2009). Notably, in figure 12(a), the lower turbulence energy observed maybe partially attributed to the lower hot-wire spatial resolution of the higher Reynolds number case ($l^+ \approx 24$), compared with

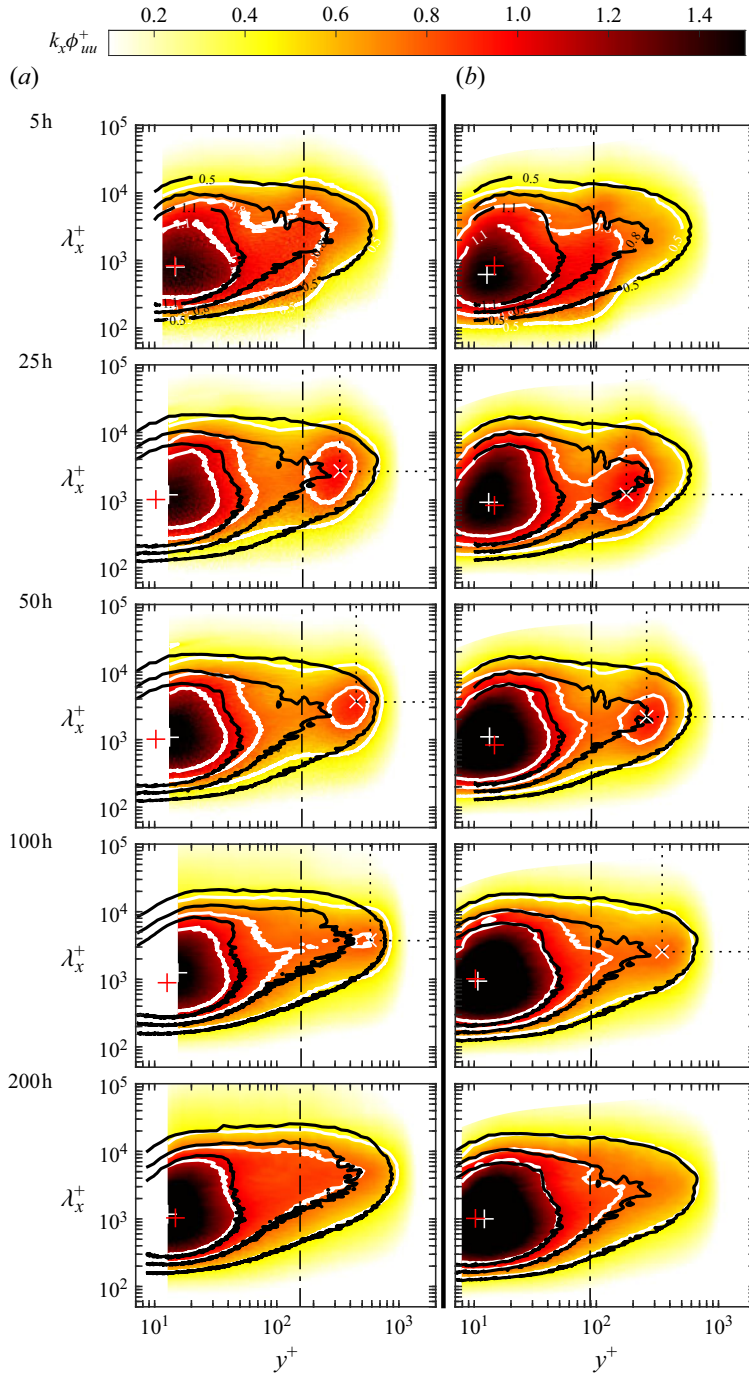


Figure 11. Premultiplied spectra contours for the two cases of MVG_{900}^{18} (a) and MVG_{900}^{09} (b) at $x^*/h = 5-200$. The local TBL results of table 2 are plotted with the MVG results at corresponding Re_τ . The white contour levels are $k_x \phi_{uu}^+ = [0.5, 0.8, 1.1]$ and the white symbol + denotes the near-wall peaks for the MVG results, while the corresponding local TBL results are denoted the black contour and red +. The white symbol × denotes the identifiable outer peak for the MVG results, and the dashed line indicates the wall-normal location and the scaled wavelength of the outer peak. Vertical dash-dot lines are the locations of h^+ .

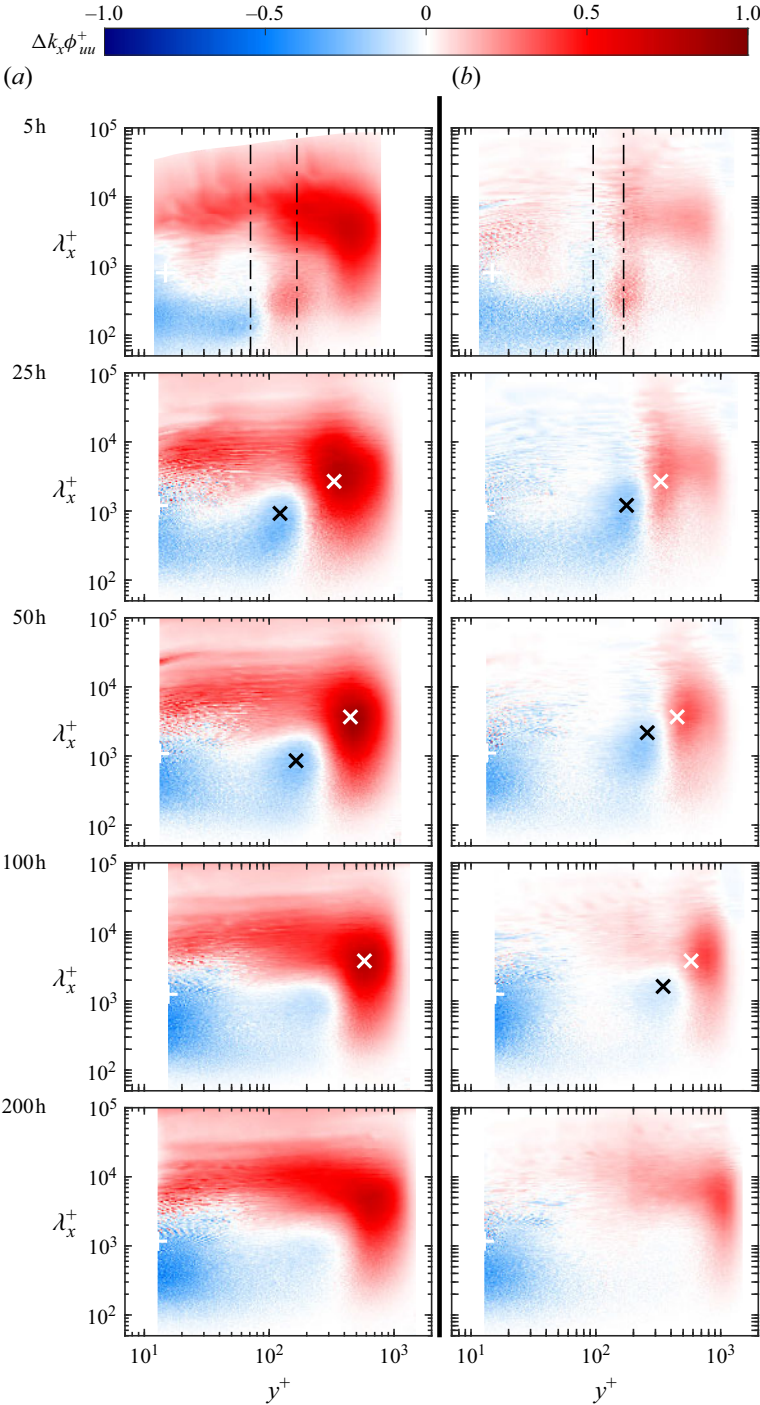


Figure 12. Contours of the premultiplied spectral difference between MVG_{900}^{18} and two other MVG cases, MVG_{400}^{18} (a) and MVG_{900}^{09} (b) at $x^*/h = 5-200$. The white symbols + and × denote the identifiable near-wall and outer peaks of the reference case of MVG_{900}^{18} . The black × denotes the outer peak for the comparative MVG cases. The vertical dashed lines at $x^*/h = 5$ denotes the location of h^+ for the MVG results.

the lower Reynolds number case with $l^+ \approx 10$. Moreover, the downstream result shows that large-scale structures are amplified in turbulence energy as the Reynolds number increases, which is linked to the TBL development by increasing Reynolds numbers, akin to what occurs in the smooth-wall TBL (Hutchins & Marusic 2007b). In contrast to the Reynolds number effect, increasing the MVG height ratio reduces the turbulence energy of near-wall large-scale structures within a streamwise distance $x^*/h \leq 100$.

3.4. Autocorrelation analysis

The normalised energy reduction caused by the MVGs may be related to the large-scale structure breakup effects of MVG-induced vortices (Chan & Chin 2022), which can shorten the average length scale of turbulence structures. It is necessary to investigate the MVG effects on the average streamwise length scale of turbulence structures by analysing the streamwise velocity autocorrelation, $R_{uu}(\Delta x, z, y_{ref})$. The spatial streamwise separation, Δx , is computed by converting temporal measurements using Taylor's hypothesis. Although this hypothesis has its limitations (as discussed in § 3.3), it still provides a reasonable estimate of the average streamwise scale variations induced by the MVGs, given its widespread application in studies of TBLs with secondary flows (Ye, Schrijer & Scarano 2016; Abbassi *et al.* 2017). In figure 13, the autocorrelation maps, $R_{uu}(\Delta x, z, y_{ref})$, and global profiles, $\langle R_{uu}(\Delta x, y_{ref}) \rangle$, for the case MVG₉₀₀¹⁸ that experiences the strongest normalised energy reduction are plotted at three reference wall-normal positions, $y/\delta = 0.06, 0.2$ and 0.6 , corresponding to the near-wall, log and outer regions, respectively. The streamwise distance $\Delta x/\delta$ at which R_{uu} approaches zero (approximated by $R_{uu} = 0.05$ and indicated by the vertical dashed line in figure 13d–f), represents an estimate of the mean of the maximum streamwise length scale of turbulence structures referred to as the average streamwise length scale (Hutchins & Marusic 2007a). Figure 13(a–b) show how the average length scale of large eddies is influenced by the MVGs in the near-wall and log regions ($y/\delta = 0.06$ and 0.2) at $x^*/h \leq 50$. The MVG influence on the average streamwise length scale of turbulence structures becomes negligible at $x^*/h \geq 200$ in the inner region ($y/\delta = 0.06$ and 0.2), consistent with figures 2, 3 and 9. The outer region of $y/\delta = 0.6$ is unaffected by the MVGs from $x^*/h = 5$, as shown in figure 13(c).

For the near-wall region at $y/\delta = 0.06$ (figure 13a), the autocorrelation map of $x^*/h = 5$ shows a decrease in the streamwise length scale at $z/\Lambda_z = 0.2$, which indicates that the MVGs impose a strong reduction on the average length scale of turbulence structures near the outside tip of the MVG blades. The downstream results of $x^*/h = 25$ and 50 in figure 13(a) illustrate that the average length scale becomes longer and shorter downstream at the upwash ($z/\Lambda_z = 0.1$ – 0.2) and downwash regions ($z/\Lambda_z = 0.3$ – 0.5), respectively, which is related to the low- and high-speed streaks induced by the MVGs, respectively (Chan & Chin 2022). The average streamwise length scale alteration in the spanwise range of $z/\Lambda_z = 0$ – 0.5 disappears at $x^*/h \geq 200$, and the length scale becomes similar to the local TBL result. In the context of the spanwise-averaged autocorrelation (figure 13d), the MVG-induced streak has a minor influence on the average streamwise length scale of streamwise structures in the near-wall region due to the combination of averaged length scale increase and decrease.

In the log region, as shown in figure 13(b), the comparison between the contour lines $R_{uu} = 0.05$ of the MVG and local TBLs shows that the MVGs reduce the average streamwise length scale of the upwash region ($z/\Lambda_z = 0$ – 0.2) at the near-wake station, $x^*/h = 5$. The alteration of the average streamwise length scale persists at downstream stations, $x^*/h = 25$ – 50 , similar to the result at the near-wall region. Compared with the

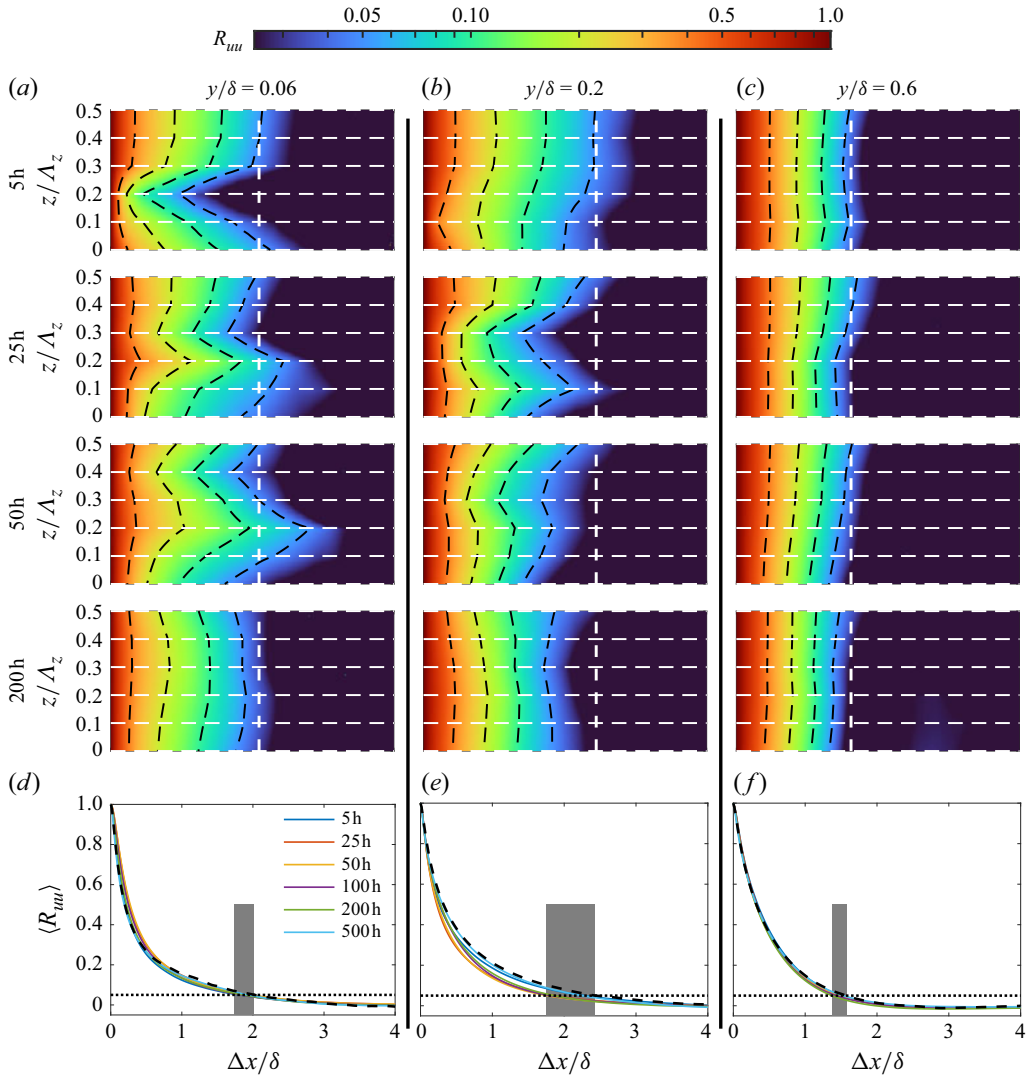


Figure 13. Autocorrelation maps (a–c) and profiles (d–f) of the streamwise velocity fluctuation R_{uu} for the experiment MVG₉₀₀¹⁸ at $y/\delta = 0.06, 0.2$ and 0.6 . The autocorrelation maps (a–c) are plotted with spanwise profiles of R_{uu} at $x^*/h = 5, 25, 50$ and 200 . The horizontal dashed lines indicate the spanwise profiles' locations of $z/\Lambda_z = 0, 0.1, 0.2, 0.3, 0.4$ and 0.5 . Four black contour levels of the MVG results are $R_{uu} = 0.05, 0.1, 0.2$ and 0.5 . The value of $R_{uu} = 0.05$ for the local TBL is denoted by the white vertical dashed line. The autocorrelation profiles (d–f) are spanwise-averaged profiles at $x^*/h = 5–500$. The dashed profile is the corresponding local TBL result of TBL₁₀₀₀. The dashed horizontal line is $R_{uu} = 0.05$, which indicates the average streamwise length scale of turbulence structures for each profile. The shaded band indicates the average streamwise length scale variation for the six streamwise stations of $x^*/h = 5–500$.

local TBL result, the average streamwise length scale of structures reduces for the spanwise range of $z/\lambda_z = 0–0.5$ at downstream stations $x^*/h = 25–50$. In figure 13(e), the spanwise-averaged autocorrelation map shows that the global average length scale of turbulence structures is the lowest at $x^*/h = 50$. The structures with a reduced length scale in the log region at $x^*/h = 25–50$ are associated with the normalised energy reduction at $y^+ \approx 180$

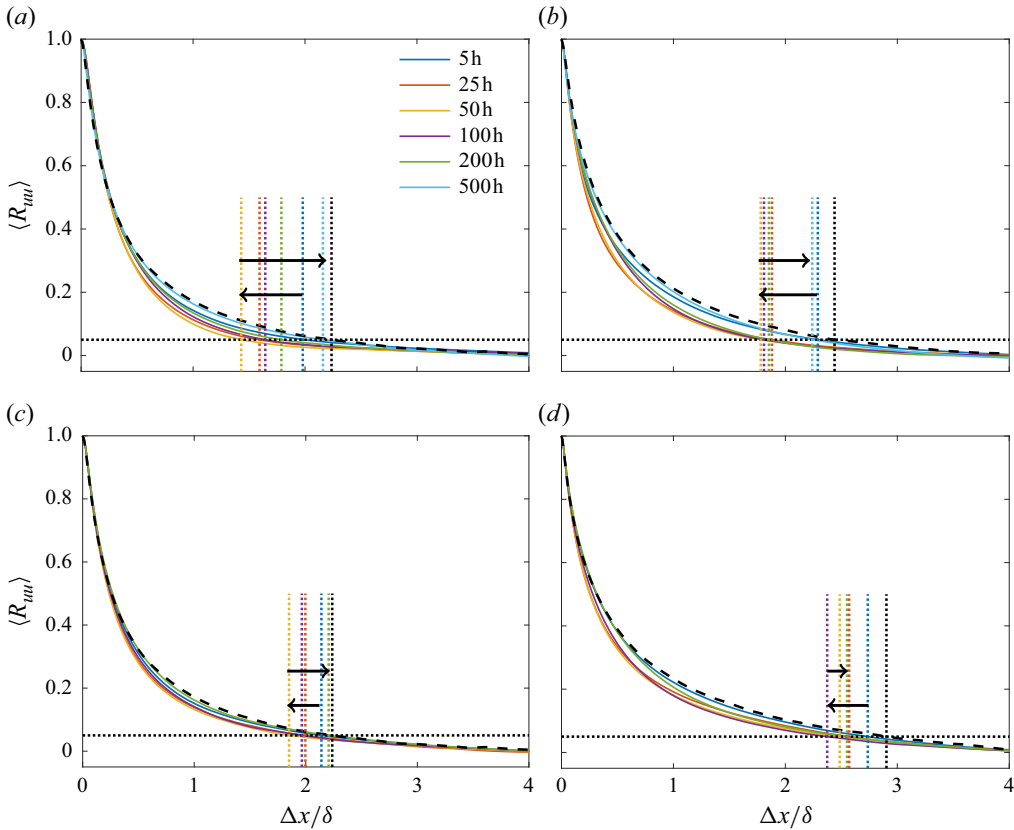


Figure 14. Autocorrelation profiles of the streamwise velocity fluctuation R_{uu} for the MVG cases MVG_{400}^{18} (a), MVG_{900}^{18} (b), MVG_{600}^{09} (c) and MVG_{1600}^{09} (d) at $y/\delta = 0.2$. The black dashed line refers to the local TBL in table 2. The vertical dashed line indicates the average sizes of turbulent structures for each case by marking the crossings of the MVG and local TBL profiles with the horizontal dashed line at $R_{uu} = 0.05$.

(figure 10b). This outcome implies that the MVGs reduce the normalised energy of the log-region structures by breaking up structures, resulting in reducing the average length scale of turbulence structures at high Reynolds numbers.

The effects of the Reynolds number and MVG height ratio on modulating the average length scale of turbulence structures can be observed in figure 14, which shows the global autocorrelation profiles at $y/\delta = 0.2$ for the four cases of MVG_{400}^{18} , MVG_{900}^{18} , MVG_{600}^{09} and MVG_{1600}^{09} . The left and right shifting of the vertical dashed lines indicates the decrease and increase in the average length scale of turbulence structures. The arrow indicates that all experiments follow a trend, such that the turbulence structure's average length scale reduces downstream of the MVGs and reaches the lowest length scale at $x^*/h = 50$ – 100 . After this streamwise distance, the average length scale increases and approaches that of the local TBL result. The cases with the largest MVG height ratio, MVG_{400}^{18} and MVG_{900}^{18} , show a more pronounced shift of the vertical dashed lines than those of MVG_{600}^{09} and MVG_{1600}^{09} with the smallest MVG height ratio. The difference in the shift of the vertical dashed lines indicates that a larger MVG height ratio imposes a stronger breaking-up effect on turbulence structures in the log region for the considered range of $h/\delta_0 = 0.09$ – 0.18 .

4. Conclusions

Hot-wire anemometry measurements of a spanwise array of MVGs in TBL flows were conducted to investigate the influence of the MVGs on the turbulence structures across the TBL and at a series of downstream locations. Experiments were conducted for two MVG height ratios ($h/\delta_0 = 0.09$ and 0.18) and a range of friction Reynolds numbers ($400 \lesssim Re_\tau \lesssim 2000$), thereby extending the LES MVG study of Chan & Chin (2022) that was restricted to a single test (one height ratio and one Reynolds number). The experiments showed that the MVG effects on the turbulence structures are connected to the MVG-induced vortices that extend far downstream, consistent with the finding of Chan & Chin (2022). Here, the MVG-induced vortices were found to originate from the inside tip of the MVG blades and produce alternating high- and low-momentum regions with respect to the spanwise direction downstream of the flow. In the high-momentum regions, the turbulence intensity in the log region is reduced in comparison with the corresponding TBL flow without MVGs, whereas in the low-momentum region the turbulence intensity is amplified. This observation suggests that near-wall turbulence is lifted into the outer flow at the upwash region, supporting the drag reduction mechanism enabled by the upward transport of turbulence.

Close behind the MVGs ($x^*/h = 5$) in the streamwise direction, the MVG-induced vortices were found to amplify the smaller-scale turbulence structures ($\lambda_x^+ < 200$) and attenuate the larger-scale structures ($\lambda_x^+ > 200$). This finding is consistent with the previous LES MVG study by Chan & Chin (2022). However, we also show the energised structures shift to the outer region downstream and aggregate into an outer peak with a wavelength range of $1000 \lesssim \lambda_x^+ \lesssim 6000$. The outer peak in turbulence energy sustains up to 100 times the MVG height downstream (up to $18\delta_0$). Turbulence structures below the outer peak are attenuated due to spanwise motions induced by the MVGs. These spanwise motions arise from the lateral transfer of fluid from downwash to adjacent upwash regions beneath the vortices, consistent with those observed in the spanwise plasma actuator control studies by Yao *et al.* (2018) and Cheng *et al.* (2021). In those studies, the spanwise motion was found to promote the formation of low-momentum streaks in the upwash region and suppresses the formation of new quasistreamwise vortices, thereby reducing skin friction. In the present study, the reduction of turbulence energy beneath the outer peak is consistent with the mechanisms reported in those previous works, highlighting the importance of MVG-induced spanwise motion in turbulence modulation. The turbulence modulation due to the spanwise motion induced by the MVGs originates from the lower log region and below, covering but extending above the buffer region where Cheng *et al.* (2021) and Duong *et al.* (2021) used plasma actuators to impose spanwise motions and achieved substantial drag reduction. This suggests that the MVG-induced spanwise motion does not reach the buffer layer and, therefore, is unable to produce global viscous drag reduction. While the lift up of low-speed flows contributes to local drag reduction in the upwash region, achieving global drag reduction is likely to require optimising the induced spanwise flows within the buffer layer. Moreover, by extending to higher Reynolds numbers, $Re_{\tau 0} \gtrsim 900$, compared with the LES MVG study where $Re_{\tau 0} \approx 400$, our experiments reveal that higher Reynolds numbers cause the dominant structures of the outer peak to develop into longer motions and move farther away from the wall. The energy attenuation below the outer peak also extends into the log region with increasing Reynolds numbers. The outward shift of the outer-peak structures enlarges the wall-normal attenuation layer beneath them. This behaviour aligns with the spanwise-jet study of Yao *et al.* (2018), where a thicker attenuation zone was correlated with reduced near-wall turbulence and lower skin friction. Increasing the MVG height ratio was shown to

have similar influences on shifting the outer peak and attenuating the near-wall small-scale structures as increasing the Reynolds number, which are associated with the higher vorticity amplitude and larger circulation area by increasing the Reynolds number and the MVG height ratio, respectively. In the near-wall region, the larger MVG height ratio exhibits a contrasting effect compared with increasing the Reynolds number, as it attenuates the turbulence energy of the large-scale structures.

In conclusion, our study has shown that MVGs suppress both log-region large eddies and near-wall small scales. This multiscale effect differs from those existing active and passive control techniques (i.e. LEBUs and upward jets), which predominately attenuates large-scale structures. Previous investigations have shown local viscous drag reductions from MVG-induced streamwise vortices, highlighting their potential for drag control (Yao *et al.* 2018; Cheng *et al.* 2021; Chan & Chin 2022). However, our non-optimised MVG configuration observed a slight global drag increase relative to a smooth-wall TBL, implying an opportunity to refine the MVG design to target the most relevant turbulence scales. Nonetheless, our results confirm that MVG-driven turbulence modulation can be sustained over long streamwise distances. The results from Cheng *et al.* (2021) and Chan & Chin (2022) suggest that maximising the spanwise extent of the induced streamwise vortices promotes drag reduction. Notably, the spanwise motions imposed by LSSVs have been shown to intervene in the buffer layer, effectively suppressing the near-wall turbulence and reducing viscous drag (Cheng *et al.* 2021). This provides a useful reference for refining MVG designs to aim for buffer-layer interventions towards spanwise-averaged viscous drag reduction configurations. By optimising MVG design to modulate these turbulence structures effectively, MVGs hold promise as a passive flow control device for achieving global viscous drag reduction (Marusic *et al.* 2021). To further substantiate these findings, direct skin friction measurements (e.g. oil film interferometry) are needed to quantify the drag modification by MVGs in the spanwise direction. Future studies should optimise MVG designs to enhance shear stress modulation and expand the upwash region for more effective global drag reduction. Hot-wire probe rakes or cross-correlated probe configurations could be useful for capturing the spanwise motion effects associated with MVG-induced streamwise vortices. Additionally, the use of Taylor's hypothesis, while common in TBLs, may be limited in accuracy due to the presence of MVG-induced vortices. A future work, e.g. using high-spatial-range PIV or direct numerical simulation dataset, could potentially assess the Taylor's hypothesis for TBLs embedded with LSSVs.

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Appendix A. The inner2 method

The inner2 method employs the modified Musker function as the mathematical description of the inner layer profile, including the viscous, buffer and log layers (Musker 1979),

$$U_{inner}^+(\text{Musker}) = \frac{1}{\kappa} \ln \left(\frac{y_*^+ - a}{-a} \right) + \frac{P^2}{a(4\alpha - a)} \left[(4\alpha + a) \ln \left(-\frac{a}{P} \frac{\sqrt{(y_*^+ - \alpha)^2 + \beta^2}}{y_*^+ - a} \right) + \frac{\alpha}{\beta} (4\alpha + 5a) \left(\arctan \left(\frac{y_*^+ - \alpha}{\beta} \right) + \arctan \left(\frac{\alpha}{\beta} \right) \right) \right], \quad (\text{A1})$$

where $\alpha = (-1/\kappa - a)/2$, $\beta = \sqrt{-2a\alpha + \alpha^2}$ and $P = \sqrt{\alpha^2 + \beta^2}$. Here $y_* = y + \epsilon$, where ϵ is the wall-normal distance offset. The Musker function is modified by adding a hump function (Monkewitz, Chauhan & Nagib 2007), as follows:

$$U_{inner}^+(\text{modified}) = U_{inner}^+(\text{Musker}) + \frac{\exp[-\ln^2(y_*/30)]}{2.85}. \quad (\text{A2})$$

The procedure of the inner2 method is illustrated in the following optimisation technique. The modified Musker function depends on four variables, U_τ , a , ϵ and κ . The variable of a is designed to be floating to fit with the shifting log layers of MVG-modified TBLs (Kong *et al.* 2024). According to the analysis of the inner2 method by Kong *et al.* (2024), two variables are suggested to be fixed at $\epsilon = 0$ and $\kappa = 0.41$ for simplicity. The optimisation function can be defined as follows:

$$E(U_\tau, a) = \frac{|U_{inner}^+(U_\tau, a) - U_{measured}^+(U_\tau)|}{U_{inner}^+(U_\tau, a)}. \quad (\text{A3})$$

The optimisation problem is

$$\text{find min}[E(U_\tau, a)], \quad \text{subject to} \begin{cases} U_\tau \in [U_{\tau, \min}, U_{\tau, \max}], \\ a \in [a_{\min}, a_{\max}], \end{cases} \quad (\text{A4})$$

which can be defined in the form of the Lagrangian problem $\mathcal{L}(\mathbf{x}_k, \lambda) = E(\mathbf{x}_k) - \lambda^T \mathbf{b}(\mathbf{x}_k)$, where $\mathbf{x}_k$ are the optimised variables, $\mathbf{b}$ are the constraining bounds of two variables and λ are the Lagrange multipliers. The Lagrangian problem $\mathcal{L}$ is approached by a quadratic subproblem (Nocedal & Wright 2006). For an iterate $\mathbf{x}_k$, an appropriate search direction $\mathbf{d}_k$ can be found as a solution to the quadratic subproblem

$$\begin{aligned} \text{find min}_d \left[E(\mathbf{x}_k) + \nabla E(\mathbf{x}_k)^T \mathbf{d} + \frac{1}{2} \mathbf{d}^T \nabla^2 E(\mathbf{x}_k) \mathbf{d} \right], \\ \text{subject to } \mathbf{b}(\mathbf{x}_k) + \nabla \mathbf{b}(\mathbf{x}_k)^T \mathbf{d} \geq 0. \end{aligned} \quad (\text{A5})$$

Once the solution of the quadratic subproblem is determined, the next iterate step is $\mathbf{x}_{k+1} = \mathbf{x}_k + \mathbf{a}_k \mathbf{d}_k$, where $\mathbf{a}_k$ is the step length parameter. The sequential quadratic programming is implemented with a MATLAB function `fmincon`. As suggested by Kong *et al.* (2024), the fitting range can be selected from the wall to $y^+ = 2\sqrt{Re_\tau}$.

Appendix B. Spanwise averaging procedure for spectra analysis

To obtain the global premultiplied spectra, the six local spectra obtained at different spanwise positions are averaged. However, since both the wall-normal measurement locations and streamwise wavenumber resolution vary slightly across the span, two interpolation steps are necessary before averaging.

The six spectral maps are initially recorded at slightly different wall-normal positions due to alignment limitations of the hot-wire probe at different spanwise locations. To enable consistent averaging, each spectrum is interpolated onto a common set of wall-normal coordinates. This ensures that the spectral energy at a given wall-normal height is consistently represented across all spanwise locations.

The streamwise axis, denoted as λ_x , depends on the local convection velocity at each spanwise position via the relation $\lambda_x(z) = U_c(z)/f$, where $U_c(z)$ is the local convection velocity and f is the sampling frequency. Since U_c varies in z due to the influence of the MVG-induced vortices, the effective streamwise spacing and hence wavenumber

resolution differ slightly between spanwise locations. To perform consistent averaging, all local spectra are interpolated onto a common λ_x axis. This reference axis is constructed based on the wavenumber discretisation at $z/\Lambda_z = 0$. All six spectra are then interpolated onto this fixed axis. After these two interpolation steps, the spectra are averaged across the spanwise positions to yield the global premultiplied spectrum.

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