Local dynamic perturbation effects on amplitude modulation in turbulent boundary layer flow based on triple decomposition

Tang, Zhanqi; Jiang, Nan; Zheng, Xiaobo; Wu, Yanhua

2019

Tang, Z., Jiang, N., Zheng, X., & Wu, Y. (2019). Local dynamic perturbation effects on amplitude modulation in turbulent boundary layer flow based on triple decomposition. *Physics of Fluids*, 31(2), 025120-. doi:10.1063/1.5083224

<https://hdl.handle.net/10356/105660>

<https://doi.org/10.1063/1.5083224>

© 2019 The Author(s). All rights reserved. This paper was published by AIP Publishing in *Physics of Fluids* and is made available with permission of The Author(s).

Downloaded on 26 Apr 2023 21:45:48 SGT

Local dynamic perturbation effects on amplitude modulation in turbulent boundary layer flow based on triple decomposition

Cite as: Phys. Fluids 31, 025120 (2019); doi: 10.1063/1.5083224

Submitted: 29 November 2018 • Accepted: 4 February 2019 •

Published Online: 25 February 2019

Zhanqi Tang,^{1,2,a)} Nan Jiang,^{1,2,b)} Xiaobo Zheng,¹ and Yanhua Wu^{3,c)}

AFFILIATIONS

¹Department of Mechanics, Tianjin University, Tianjin 300350, China

²Tianjin Key Laboratory of Modern Engineering Mechanics, Tianjin 300350, China

³School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore

^{a)}zhanqitang@tju.edu.cn

^{b)}nanj@tju.edu.cn

^{c)}yanhuawu@ntu.edu.sg

ABSTRACT

This work studies amplitude modulation (AM) of a turbulent boundary layer flow perturbed by a wall-mounted piezoelectric (PZT) actuator. Hot-wire measurements were executed downstream of the PZT actuator working at a certain frequency but several different amplitudes. Turbulent nonlinear fluctuations acquired by triple decomposition were devoted to observing the AM effects. The PZT actuator has a significant impact on the distribution of AM coefficients and joint probability-density functions of large-scale fluctuations and the representatives of small scales in the inner region. Moreover, the energy dependence of small scales on large-scale structures was observed. It proposes that an interlayer region of $y^+ \lesssim 14$ characterized by strong energy dependence of high linear slope occurs between innate near-wall structures in the underlying boundary layer flow and wall surface. It was suggested that this interlayer probably suppresses turbulence generation and self-sustaining process of the near-wall cycle. In addition, the conditional AM coefficients further manifests that the AM in the interlayer is insensitive to the condition of large-scale structures.

Published under license by AIP Publishing. <https://doi.org/10.1063/1.5083224>

I. INTRODUCTION

In turbulent boundary layer (TBL) flows, the early investigations reported that the near-wall structures, such as streamwise vortices¹ and velocity streaks,² constitute near-wall cycle.^{3,4} It was argued that the near-wall structures sustain autonomously without the need of external triggers.³ Recently, large-scale structures in the outer layer have received more attentions, as advances in particle image velocimetry (PIV) and direct numerical simulation (DNS). Hairpin vortex packets⁵ as one of the popular modeling frameworks, combine uniform momentum zones (UMZs),⁵⁻⁸ and high shear interface region.^{5,6,8} The streamwise alignment of these hairpin packets results in low-speed large-scale

structures extending several boundary layer thicknesses in the streamwise direction.⁹⁻¹¹ Statistically, pre-multiplied spectra of streamwise fluctuations have long hinted at the existence of the large-scale structures with increasing Reynolds number.¹¹⁻¹³ Moreover, these large-scale structures possess a significant fraction of turbulent kinetic energy and Reynolds shear stress.^{14,15}

Then, there has been a considerable refocus on the impact of large-scale structures on the near-wall cycle.¹⁶⁻²⁸ Early studies by Rao *et al.*¹⁶ found that the large-scale structures influence the near-wall cycle, by presenting the bursting period and interval scaled with outer variables. Alfredsson and Johansson²⁹ reported that the governing time scale of the bursting events is a mixture of inner and outer scales.

Observing scaling behavior of the bursting events by the use of the mixed time scales, they ascribed the scaling behavior to an interaction process of the outer layer flow and the flow in the near-wall region. By means of correlating the low-frequency components with the envelop of high-frequency parts of velocity signals, Bandyopadhyay and Hussain³⁰ found a significant coupling between the large- and small-scale motions. Recently, Hutchins and Marusic¹⁷ revealed the amplitude modulation of very large-scale structures on near-wall cycle, which has attracted many studies to quantify amplitude modulation (AM) effect.^{19,21,23,24} Mathis *et al.*¹⁹ used the Hilbert transformation on spectrally filtered small-scale components and substantiated that the small-scale structures are subject to a high degree of AM originating from the much larger scales. They also revealed that the AM effect becomes progressively stronger as the Reynolds number increases through three orders of magnitude ($Re_\tau \sim 10^4 - 10^6$). Even though Schlatter and Örlü³¹ demonstrated that AM correlation coefficient may not be an independent tool to quantify the AM effect, they did believe that there exists scale interaction between large and small scales in TBL flows, which has been supported by numerous following studies.^{21,23,32,33} Bernardini and Pirozzoli³³ used a systematic analysis of two-point AM correlation to provide a top-down influence of large-scale outer events on the near-wall signature. Ganapathisubramani *et al.*²¹ examined the AM effect by conditionally averaging the small-scale intensity for various values of the large-scale fluctuations. Hutchins *et al.*³² captured the AM effect in conditional analyses based on wall shear stress. Then, Baars *et al.*²³ used wavelet analysis to examine the AM in small-scale broadband signals and obtained the consistent results by comparing with the approach of Hilbert transformation by Mathis *et al.*¹⁹ Recently, based on a well-resolved large-eddy simulation (LES) dataset in a wide range of $Re_\theta = 800 - 8200$, Dogan *et al.*³⁴ comprehensively revisited the amplitude modulation phenomenon by regarding the method for decomposing the scales (such as, temporal or special spectral filters, empirical mode decomposition), and the modulation quantification of the scale components by the various decomposing approaches. Additionally, considering that the AM coefficients calculated by correlating the large-scale fluctuations and the representatives of the small scales is an integrated measure, Howland and Yang³⁵ reappraise the predictive inner-outer model based on the AM mechanism,^{36,37} by stressing the piecewise-linear dependence of small-scale energy on the large-scale fluctuations.

Apart from the amplitude modulation, the phase relationship between the large- and small-scale structures has been also observed in the recent investigations.^{25,26,28,30} It was summarized that the small scales exhibit a phase lead relative to the large-scale fluctuations in the near wall region^{21,23,28,30} and a “phase reversal” happens in the log layer region.^{21,23,30}

On the basis of the above understanding, Baars *et al.*^{23,24} presented a conceptual mechanism of scale interactions and arrangements in TBL flows, which is described from three regimes. In the near-wall region, a quasi-steady response of the near-wall cycle to large-scale structures in the outer

flow was raised, which was then proved as a “Quasi-Steady, Quasi Homogenous (QSQH)” response.^{38,39} In the intermittent region, owing to the turbulent/non-turbulent zone intermittency, a reversed scale-interaction phenomenon was observed in contrast to that in the near-wall region.^{23,24,40} Moreover, at the centre of the log layer, it was indicated that the most energetic fluctuations of small scales are aligned with the internal shear layers along the inclined back of low-speed large-scale structures.^{23,24}

Many studies have attempted to modify/alter the TBL flow, most of the approaches probably fall into two categories, by aiming on the large-scale structures in the outer layer and the near-wall coherent structures, respectively. The recently proposed approach revolves around the large-scale structures due to their modulation effects on the near-wall cycle. Several different perturbations were introduced to modify the large-scale structures,^{41–43} such as, cylindrical element,^{41,42,44} two-dimensional static, and dynamic roughness element.^{43,45–47} This kind of perturbations not only alters the large-scale structures^{42,44} but also rearranges the scale interactions and arrangements of the TBL.^{43,44} The other kind of method is a more traditional one, by focusing on the near-wall coherent structures.^{3,4} Based on the flow mechanism, numerous passive and active control techniques have been developed, which are not illustrated in this study. Among them, wall deformation is considered as a robust approach by comparing with passive control in the rough environment conditions. A wall-mounted piezoelectric (PZT) actuator provides such a potential way to achieve the local wall deformation in TBL flows.^{48–50} Zheng *et al.*⁴⁹ utilized a single wall-mounted PZT actuator to disturb the streamwise vortices. They found that the most drag reduction is obtained when the oscillator frequency is matched with the wavelength of the near-wall coherent structures containing the most energy. Bai *et al.*⁴⁸ employed a spanwise-aligned array of wall-mounted piezoelectric actuators to generate a transverse traveling wave with a specified phase shift between adjacent actuators and found that the wave perturbation generates a layer of organized structures, which act as a barrier between the near-wall coherent structures and wall surfaces. Furthermore, based on an array of PZT actuators, Qiao *et al.*⁵⁰ carried out the feed-forward and feedback proportional-derivative controls to suppress high-speed events in near-wall cycle. It concludes that the coherent structures in TBL can be manipulated by an appropriate perturbed approach. However, the amplitude modulation of large-scale structures on small scales under the local perturbation is still poorly understood. Especially, the PZT oscillator introduces a local spatial-temporal perturbation on the near-wall cycles. Thus, it arose our interest to observe the AM performance under the PZT actuator perturbation.

In the current study, considering the periodic input perturbation by the PZT actuator, triple decomposition by Hussain and Reynolds⁵¹ is employed to decompose the raw fluctuations to acquire turbulent nonlinear fluctuations around periodic component. Then, the amplitude modulation is discussed, and the dependence of small-scale energy on large scales is also observed.

II. EXPERIMENTS

A. Experimental setup and parameters

Experiments were conducted in a closed-circuit wind tunnel in Tianjin University, as described in previous studies.^{42,44,49} The test section of the tunnel was 2.0 m long, 0.6 m tall, and 0.8 m wide, and a smooth boundary-layer plate was vertically fastened at the test section. Zero-pressure-gradient conditions were achieved by adjusting the inclination angle of the experimental plate. The freestream velocity was $U_\infty = 9.0$ m/s. A trip wire of 2 mm height and a 240-grit sandpaper trip band were utilized to accelerate the development of the fully developed turbulent boundary layer. A turbulent boundary layer was developed with a thickness of 35 mm at the downstream location of 1.1 m. The friction Reynolds number was $Re_\tau = u_\tau \delta / \nu = 1024$ (u_τ is the friction velocity, ν is the kinematic viscosity, and δ is the boundary layer thickness), and the Reynolds number based on momentum thickness θ and free-stream velocity U_∞ was $Re_\theta = U_\infty \theta / \nu = 2552$. The Reynolds number follows the relationship $Re_\tau = 1.13 \times Re_\theta^{0.843}$.⁵² The data in the outer layer region, especially in the range of $0.7 \leq \bar{U}/U_\infty \leq 0.9$, follow a linear relation as suggested by Sanmiguel Vila et al.,⁵³

$$\frac{\langle uu \rangle^{1/2}}{\bar{U}} = \alpha - \beta \frac{\bar{U}}{U_\infty}, \quad (1)$$

where $\alpha = 0.28, \beta = 0.245$, which further indicates that the current turbulent boundary layer flow is in the canonical condition. Although it is known that the scale separation becomes more relevant in higher Reynolds numbers, the previous investigations showed that the spectral signature of scale separation is already discernible in the comparable Reynolds number ($Re_\tau \approx 910 - 1320$).^{26,27,33,41,42,44}

As the benchmark for comparison, unperturbed TBL-flow measurement was performed at the streamwise location of $x = 1.1$ m downstream of the leading edge, where a turbulent boundary layer was fully developed and then a PZT actuator was mounted on the wall. Figure 1 shows the sketch of the experimental setup. The PZT element was flush-mounted on

the plate surface. The PZT element had a dimension of 30 mm $\times$ 0.42 mm $\times$ 3.62 mm (length $\times$ thickness $\times$ width), which is comparable with the size of near-wall streamwise vortices playing a key role in near-wall cycle. The PZT oscillator worked as a cantilever beam,⁵⁴ and its inactive part was glued to a substrate. A power supply of YuanFang-GK10005 that supports a wide range of working frequency and driving voltage was utilized to actuate the free end of the PZT oscillator to move up and down with a certain frequency and amplitude in the x - y plane. The coordinates x , y , and z refer to the streamwise, wall-normal, and spanwise directions, respectively. In the current experiment, the actuating frequency was fixed at $f_p = 160$ Hz, and three different driving voltage of $U_p = 100$ V, 60 V, and 20 V were executed to actuate the PZT actuator. To guarantee the working frequency and amplitude of the actuator, the high-speed CMOS camera with a micro lens was employed to monitor its free-end movement. It provided that the oscillating frequency was $f_p = 160$ Hz, and the amplitudes of the free end were $A_p = 0.6$ mm, 0.4 mm, and 0.1 mm corresponding to the driving voltage of $U_p = 100$ V, 60 V, and 20 V, respectively.

B. Hot-wire measurements

Hot-wire measurements were carried out in the turbulent boundary layer. A miniature single sensor boundary layer probe (TSI-1621A-T1.5) was used with a constant temperature anemometer system of IFA-300 operating at an overheat ratio of 1.5. The tungsten hot wire has the sensitive length of 1.25 mm (the viscous scaled length is $l^+ = lu_\tau / \nu = 36.6$ in the unperturbed case) and the diameter of 4 μ m, corresponding to a length-to-diameter ratio (l/d) more than 200. Calibration was employed by air velocity calibrator over a velocity range of 0–18 m/s. The hot-wire probe was translated to all the measurement locations by using a computer-controlled translation stage. The sampling frequency and low-pass filter settings were $f = 100$ kHz and $f_{lp} = 50$ kHz, respectively. The non-dimensional sample interval was $\Delta t^+ = 0.13$ ($\Delta t^+ = \Delta t u_\tau^2 / \nu$, where $\Delta t = 1/f$). Note that the sampling frequency $f = 100$ kHz is an integral multiple of the PZT oscillating frequency of $f_p = 160$ Hz, which benefits to discuss the periodic information of the flow fields. The sample length of 41.9 s of the velocity samples was recorded at each measurement point, which includes 10 805 boundary-layer turnover time to adequately cover the energy contained in the largest scales⁵⁵ and also acquire the converged statistics. The streamwise measurement position was 2 mm downstream of the free end of the PZT oscillator. The measurements were executed along the logarithmically spaced wall-normal positions to provide a higher spatial resolution in the inner region.

In the near-wall measurement of turbulent boundary layer flow, it has been widely recommended that to obtain the adequately accurate results, the viscous-scaled wire length (l^+) should be less 20–25 and the length-to-diameter ratio (l/d) should be larger than 200.^{55,56} The effects of hot-wire spatial resolution are significantly acute in the inner peak energy.^{55–57} In the viewpoint of statistics, it was also reported that the value of this inner peak becomes higher as the Reynolds

FIG. 1. Sketch of hot-wire measurements in turbulent boundary layer perturbed by a PZT actuator.

FIG. 2. Distribution of mean streamwise velocity profiles in inner scaling, $\bar{U}^+ = \bar{U}/u_\tau$.

number (Re_τ) increases.⁵⁵ Referring to the empirical expression given by Hutchins *et al.*,⁵⁵ the current measurement provides an energy attenuation of 17%, against a fully resolved case ($l^+ = 0$) at the same Reynolds number ($Re_\tau = 1024$). By comparing with the previous hot-wire results with $l/d > 200$ in comparable Reynolds number ($Re_t \sim 1000$), the near-wall peak in the present study is in the scatter range of the data measured with a smaller wire length of $3 < l^+ < 20$.^{56,57} The ratio of u_τ^2/ν was used to judge the frequency content of turbulent energy in turbulent boundary layer flows.⁵⁸ The current ratio is $u_\tau^2/\nu < 0.12 \times 10^5 \text{ s}^{-1}$, which is in the condition of $u_\tau^2/\nu \lesssim 0.3 \times 10^5 \text{ s}^{-1}$. This means that the error due to frequency response is minimal in this study.⁵⁸ Meanwhile, the sampling frequency in the present experiment is far greater than the frequency of the substantial turbulent energy. It indicates that the hot-wire measurements are sufficient for the purpose of this study.

III. RESULTS AND DISCUSSION

A. Basic statistics

Figure 2 shows the distribution of mean velocity in inner scaling, $\bar{U}^+ = \bar{U}/u_\tau$, where u_τ is the friction velocity. The mean velocity, $\bar{U}^+$, is a function of wall-normal positions, $y^+ = yu_\tau/\nu$. As the non-equilibrium status of the flow fields downstream of the PZT oscillator, the Clauser method is not applied to estimate the friction velocity in this study. Instead, following the law of the wall, this study intends to use the linear fit based on a no-slip condition to estimate the friction velocity, u_τ . Considering the hot-wire near-wall measurement accuracy and

linear velocity profile fidelity in the sublayer, it was recommended that the region around $3.5 \leq y^+ < 5$ is a usable linear region for hot-wire measurements.⁵⁹ In such a narrow region, a high number of measurement points are required for a reliable linear fitting, which indeed challenges the accuracy of the hot-wire probe traversing system. Referring to the high order terms of Taylor series expansion, the linear law of the wall can be defined as⁶⁰

$$\bar{U}^+(y^+) = y^+ - \frac{y^{+2}}{2Re_\tau} - \frac{\sigma_1}{4}y^{+4} + \frac{\sigma_2}{4}y^{+5} + \dots \quad (2)$$

Based on direct numerical simulation data of canonical turbulent boundary layer flows, Örlü *et al.*⁵⁹ found that the fourth and fifth order terms can be used to extend the valid fitting range up to around 9 and 15 wall units, respectively.

Thus, in this study, the mean velocity data in the near-wall region around $y^+ \approx 3.5 - 9$ are adopted for friction velocity estimation by fitting the expended linear velocity profile expanded with the fourth order term ($\sigma_1 = 7.69 \times 10^{-4}$, $\sigma_2 = 0$, $Re_\theta = 2573$; DNS data by Schlatter *et al.*⁶¹). Then, the local skin drag reduction is defined by

$$R_f = \frac{\tau_N - \tau_P}{\tau_N} \times 100\%, \quad (3)$$

where $\tau_P = \rho u_\tau^2$ is the skin-friction stress in perturbed cases and, similarly, τ_N is the skin-friction stress in canonical TBL. In the current study, under the PZT actuator perturbation, the TBL flow fields present different degrees of drag reduction. At the same actuating frequency of $f_p = 160 \text{ Hz}$, the drag reduction effect is promoted by increasing the PZT oscillating amplitude. As shown in Table I, Case I acquires the highest reduction rate of $R_f = 24.0\%$, and Case III presents the lowest reduction rate of $R_f = 2.4\%$. In Fig. 2, it is expected that the profiles present a good agreement in the near-wall region around $y^+ \lesssim 9$. In the outer layer region around $y^+ \gtrsim 30$, the mean velocity profiles are lifted up with different levels. The profiles are gradually lifted up by increasing the PZT oscillator amplitude, which is in accordance with the improvement of the local drag reduction rate.

To investigate the PZT perturbation impact on the structural composition of the flow fields, Fig. 3 shows the pre-multiplied energy spectra $[k_x \phi(uu)/u_\tau^2]$, k_x is the streamwise wavenumber in streamwise wavelength (λ_x) for both unperturbed and perturbed cases. Note that based on the Taylor frozen hypothesis, the frequency is transformed into streamwise wavelength by using the local mean velocity. Here, the fluctuations, u , are traditionally decomposed by the Reynolds decomposition from raw velocity signals as $u(y, t) = \bar{U}(y, t) - \bar{U}(y, t)$.

TABLE I. Summary of the experimental parameters.

Case	Re_τ	U_∞ (m/s)	δ (m)	u_τ (m/s)	l^+	l/d	f (kHz)	T (s)	Δt^+	TU_∞/δ	f_p (Hz)	A_p (mm)	R_f
None	1024	9.0	0.035	0.44	36.6	312	100	41.9	0.13	10 805	0	0	...
I	892	9.0	0.035	0.39	31.9	312	100	41.9	0.10	10 760	160	0.6	24.0
II	942	9.0	0.035	0.41	33.7	312	100	41.9	0.11	10 839	160	0.4	15.3
III	1012	9.0	0.035	0.44	36.1	312	100	41.9	0.13	10 772	160	0.1	2.4

FIG. 3. Pre-multiplied energy spectra of velocity fluctuations, $k_x \phi \langle u'u' \rangle / u_\tau^2$, as a function of wall normal position and wavelength. The dashed vertical line represents the cutoff length to decompose the fluctuations into large and small scales.

It can be noted that the pre-multiplied spectra are a function of wall-normal positions and streamwise wavelength (λ_x). For the unperturbed case, as reported in the previous investigations, the inner peak can be obviously observed, as in Fig. 3(a). Under the PZT actuator perturbation, a clearly dominant energy peak band in red spectra contour displays at the streamwise wavelength corresponding to the perturbation frequency (f_p) in each perturbed case [in Figs. 3(b)–3(d)]. It means that the PZT actuator expectedly performs a periodic impact on the downstream flow fields where the hot-wire is measured. That is, the flow fields show a coherent signature of the forcing frequency. In addition, several associated harmonics with shorter wavelength (higher frequency) are noted, which decay by reducing the PZT actuator amplitude.

From the energy spectra shown in Fig. 3, it can be observed that the perturbed region is predominantly located in the inner region around $y^+ \lesssim 100$, where the fundamental forcing frequency is coupled with the innate inner peak in the underlying TBL flow. Furthermore, for Cases I and II, the inner perturbed region could be divided into two sublayers: one is closer to the wall surface ($y^+ \lesssim 20$) and the other is in the upper region around $20 \lesssim y^+ \lesssim 100$. The potential reason for this spectra configuration could be that the inner region is instead occupied by two kinds of dominant coherent structures at different wall-normal regions under the

PZT perturbation. Moreover, the near-wall energy containing frequency in each sublayer is still coupled with the forcing frequency, which means that the PZT actuator has a coherent periodic impact on the turbulent structures in both two sublayers.

B. Triple decomposition

As discussed in Fig. 3, the PZT oscillator provides a coherent periodic input perturbation on the downstream flow fields. In the inner region ($y^+ \lesssim 100$), there is a coupling between the fundamental forcing and the turbulent structures of the innate inner peak in the underlying TBL flows. To separate the linear forcing frequency mode and the associated nonlinear turbulent aspects, triple decomposition by Hussain and Reynolds⁵¹ provides a natural approach to achieve it. The instantaneous raw velocity signals ($U(y, t)$) under the PZT periodic perturbation can be decomposed into a periodic component associated with the input forcing, $\tilde{u}(y, t)$, the turbulent nonlinear components around the periodic forcing, $u'(y, t)$, and the time-averaged mean velocity, $\bar{U}(y)$, as below,

$$U(y, t) = \bar{U}(y) + \tilde{u}(y, t) + u'(y, t). \quad (4)$$

The periodic averaging result in a phase period is obtained as

$$\tilde{u}(y, t_p) = \frac{1}{N_c} \sum_{n=0}^{N_c} u(y, t_p + nT_c), \quad (5)$$

where N_c is the number of cycles by dividing the turbulent fluctuations signals, $u(y, t)$, based on the phase period T_c ($T_c = 1/f_p$, $f_p = 160$ Hz), and t_p is the phase time variable in the phase period range of $0 < t_p \leq T_c$. Then, $\tilde{u}(y, t_p)$ is repeated along the temporal domain to generate the periodic contribution series ($\tilde{u}(y, t)$). Figure 4 shows a segment comparison between the periodic components $\tilde{u}(y, t)$ and (a) turbulent fluctuations by Reynolds decomposition ($u(y, t)$) and (b) turbulent nonlinear components based on triple decomposition ($u'(y, t)$). The signals are based on the data at the wall-normal position of $y^+ = 11$ in Case I. In Fig. 4, the periodic contributions clearly present periodic distribution at the frequency of $f = 160$ Hz, which corresponds to the PZT forcing frequency. Note that for the unperturbed case in the present experiment, periodic components ($\tilde{u}(y, t)$) are equal to 0. In the following parts, the turbulent nonlinear fluctuations around the periodic components, $u'(y, t)$, are devoted to further observe the amplitude modulation effects of the TBL flows under the PZT perturbation.

C. Scale decomposition of nonlinear fluctuations

To observe the amplitude modulation effects in the turbulent boundary layer under the PZT perturbation, it is necessary to decompose the nonlinear fluctuations, $u'(y, t)$, into different scales by a certain filter length. The decomposition used in the current study is based on a cutoff wavelength which is carefully selected from the pre-multiplied energy spectra, as shown in Fig. 3. As explained in our previous work, the present Re_τ number is relatively low, and there is no obviously high-energy lobe representing very large-scale motions (VLSMs) in the outer layer region.^{42,44} Nevertheless, it is not

FIG. 4. Representative signal segment comparison of periodic components, $\tilde{u}(y, t)$, and (a) turbulent fluctuations by Reynolds decomposition, $u(y, t)$, and (b) nonlinear fluctuations obtained from triple decomposition fluctuations, $u'(y, t)$, at $y^+ = 11$ in Case I.

hard to note that in Fig. 3, the large-scale region with high energy exists in the wavelength more than $\lambda_x/\delta \geq 2$, which has been similarly reported in the comparable Reynolds number.^{26,41,44} As executed in our previous investigations,^{42,44} the filter cutoff of $\lambda_x/\delta = 2$ (as shown by the vertical dashed lines in Fig. 3) is employed to separate the nonlinear fluctuations, $u'(y, t)$, into the large- and small-scale fluctuations ($\lambda_x/\delta > 2$ and $\lambda_x/\delta < 2$). The nonlinear fluctuations of the large and small scales are marked as u'_L and u'_S in this study. The robustness of modulation results on the filter length is confirmed by using the cut-off filter in a wider length-range selection of $\lambda_x/\delta = 1.5 \sim 4$.

Figure 5 plots the turbulent intensity distribution of large- and small-scale nonlinear fluctuations. For the unperturbed case, it shows that the large-scale fluctuations provide higher

turbulent intensity in the outer layer region [Fig. 5(a)], and small-scale fluctuations contribute more energy in the inner region [Fig. 5(b)]. It signifies that large-scale structures are popular in the outer layer and the near-wall region is dominated by small-scale structures, which was also reported in pervious investigations.^{42,55} As shown in Fig. 5, the PZT actuator does not perform an obvious impact on neither the large- or small-scale turbulent intensity in the outer layer region. The perturbed region is mainly located in the inner layer region of $y^+ \lesssim 100$, which is consistent with the spectra results in Fig. 3. In Fig. 5(a), the turbulent intensity of u'_L is dramatically reduced in the perturbed Case I and II. On the contrary, Fig. 5(b) shows that the perturbation promotes the small-scale intensity. Clearly, the perturbation redistributes the near-wall turbulent energy of u'_L and u'_S . However, for the perturbed Case III, both the large- and small-scale turbulent intensities has a good agreement with the results of the unperturbed case, which implies that the oscillating amplitude of Case III is too weak to modify the turbulent energy distribution of u'_L and u'_S .

D. Amplitude modulation

To explore the amplitude modulation (AM) effects of the large-scale fluctuations on the small scales in TBL flows, various methods have been used in the previous studies.^{19,21,23,25,30} The major difference among these procedures is how to identify a characteristic representative to quantify the amplitude of the small scales. Following the procedure by Mathis et al.,¹⁹ the envelop of the small-scale fluctuations (u'_S) is returned by Hilbert transformation, and then the large-scale variation of the small-scale envelop, $E_L(u'_S)$, is obtained with the cutoff wavelength pass filter of $\lambda_x/\delta > 2$. This procedure has been widely used to characterize the amplitude of the small scales; a consistent result can be observed by comparing it with the approach of continuous wavelet analysis,^{23,24} even though Dogan et al.³⁴ reported that there are certain amplitude modulation differences dependent on how the cutoff and quantification are performed, by exhibiting a more comprehensive comparison about the method for decomposing the scales and the quantification of the modulation.

Following the above procedure, it produces the representatives of the instantaneous small-scale amplitude variations, $E_L(u'_S)^+$. Then, the amplitude modulation of the large-scale fluctuations on small scales can be achieved, by computing

FIG. 5. Distributions of turbulent intensity of (a) large- and (b) small-scale fluctuations, $\langle u'_L u'_L \rangle^+$ and $\langle u'_S u'_S \rangle^+$, as function of wall normal positions, y^+ .

FIG. 6. Distribution of the amplitude modulation coefficients (R_{AM}) of the large-scale fluctuations on the small scales.

the cross-correlation coefficients between $u_L'^+$ and $E_L(u_S')^+$, as follows:

$$R_{AM} = \frac{\langle u_L'^+ E_L(u_S')^+ \rangle}{\sqrt{\langle u_L'^+{}^2 \rangle \langle E_L(u_S')^+{}^2 \rangle}}. \quad (6)$$

Figure 6 shows the AM coefficient distribution in both perturbed and unperturbed cases. The AM coefficients of the

unperturbed case can be categorized as three different trends, which were also described in the previous investigations.^{24,40,44,62} In the near-wall region, the AM coefficients present the positive value, which means that the high-speed large-scale motions occur with relatively more energetic small scales and vice versa. The AM effect has been explained as the footprint of the large-scale motions on near-wall cycle.^{40,63} In the intermittent region (almost $y/\delta > 0.4$), it presents a reverse observation ($R_{AM} < 0$), which is attributed to the intermittency of turbulent/non-turbulent fluids in the wake region. Between the near-wall region and intermittent region, the AM coefficient has been named a ‘phase reversal’ in the log layer region,^{28,30} where R_{AM} is around zero.

For the perturbed cases, R_{AM} of Case III has a good agreement with that shown in canonical TBL. For Cases I and II, the AM coefficients collapse in the outer region, but an obvious modification of R_{AM} can be noted in inner region around $y^+ < 100$. As shown, this region probably can be further divided into three sub-regions: (a) In the near-wall region of $y^+ \lesssim 10$, the AM coefficients are reduced, which indicates that the AM effect is attenuated under the perturbation; (b) in the region of $10 \lesssim y^+ \lesssim 30$ corresponding to the buffer region of canonical TBL, R_{AM} shows the increased positive coefficients indicating stronger AM effect. (c) In the region between $y^+ \gtrsim 30$ and

FIG. 7. Joint PDFs ($u_L'^+ - E_L(u_S')^+$) at the wall normal position of $y^+ = 5$. (a) Unperturbed case; (b) Case I; (c) Case II; and (d) Case III.

$y/\delta \leq 0.15$, R_{AM} of Case I becomes negative. The probable reason should be attributed to the new-generated structures induced by the PZT at the highest oscillating amplitude, which enhance the exchange of fluid energy below and above this sub-region.

E. Scale dependence

Admittedly, the cross-correlation calculation of $u_L'^+$ and $E_L(u_S')^+$ signifies that R_{AM} is an integrated metric. The physical interpretation of R_{AM} is based on an assumption that the small-scale energy has a universal response to the large-scale fluctuations.³⁷ Joint probability-density functions (PDFs) of $u_L'^+$ and $E_L(u_S')^+$ provide a potential approach to examine the energy dependence of the small scales on the large scales.⁶⁴

Figures 7–9 show the joint PDFs of $u_L'^+$ and $E_L(u_S')^+$ for all the experimental cases at $y^+ = 5, 18.5$ and 51.7 , respectively. The wall normal positions are chosen from the three typical sub-regions of the perturbed cases, as discussed in Fig. 6. The bin size of both $u_L'^+$ and $E_L(u_S')^+$ is chosen as 0.3 , by compromising joint PDFs bins resolution and statistic convergence.

Figure 7 shows $u_L'^+ - E_L(u_S')^+$ joint PDFs at $y^+ = 5$. In Fig. 7(a), the PDFs contours display an inclined ellipse with larger $u_L'^+$

range relative to $E_L(u_S')^+$. It shows higher probability at the two quadrants of $u_L'^+ < 0, E_L(u_S')^+ < 0$ and $u_L'^+ > 0, E_L(u_S')^+ > 0$. That is to say, the two kinds of events low-speed large-scale fluctuations carrying relatively lower small-scale energy and high-speed large scales accompanying with energetic small scales occur more frequently than the other events. Owing to this joint PDF distribution, it is reasonable to return a positive R_{AM} at $y^+ = 5$. In Fig. 7(d), Case III shows a similar PDF distribution. In Figs. 7(b) and 7(c), the joint PDFs in both Cases I and II present compact contours. The probable reason is that the PZT perturbation attenuates large-scale fluctuations, meanwhile, enhances the small-scale intensity, which is consistent with the distribution of large- and small-scale turbulent intensity shown in Fig. 5. Even though the amplitude range of $u_L'^+$ and $E_L(u_S')^+$ is comparable, it still can be observed that the two quadrants of $u_L'^+ < 0, E_L(u_S')^+ < 0$ and $u_L'^+ > 0, E_L(u_S')^+ > 0$ have higher probability. It reasonably provides that R_{AM} holds lower positive coefficients, as plotted in Fig. 6.

Figure 8 shows the $u_L'^+ - E_L(u_S')^+$ joint PDF distribution at $y^+ = 18.7$. The unperturbed result shows a symmetric PDF distribution for $u_L'^+ > 0$ and $u_L'^+ < 0$, and Case III displays a similar PDF distribution. It is not easy to differentiate which quadrant occupies higher probability [Figs. 8(a) and 8(d)]; thus, R_{AM} is around 0 at this wall normal position, as shown in Fig. 6. For

FIG. 8. Joint PDFs ($u_L'^+ - E_L(u_S')^+$) at the wall normal position of $y^+ = 18.5$. (a) Unperturbed case; (b) Case I; (c) Case II; and (d) Case III.

FIG. 9. Joint PDFs $(u_L'^+ - E_L(u_S')^+)$ at the wall normal position of $y^+ = 51.7$. (a) Unperturbed case; (b) Case I; (c) Case II; and (d) Case III.

Cases I and II, the PDF contours have a clearly inclined ellipse shape, which is very similar as the results at $y^+ = 5$ in canonical TBL. Correspondingly, R_{AM} holds a positive value at $y^+ = 18.7$ in these two perturbed cases.

Furthermore, Fig. 9 shows the joint PDF results at $y^+ = 51.7$. Except Case I [Fig. 9(b)], all the other cases exhibit the symmetric PDF distribution for $u_L'^+ > 0$ and $u_L'^+ < 0$, which returns that R_{AM} is around 0. For Case I, the PDF contours present an antisymmetric PDF distribution, where the two quadrants of $u_L'^+ < 0, E_L(u_S')^+ > 0$ and $u_L'^+ > 0, E_L(u_S')^+ < 0$ perform higher probability. It suggests that at $y^+ = 51.7$, the events that the low-speed large-scale fluctuations occur with the higher-energy small scales and lower small-scale energy accompanies high-speed large scales occur more frequently. Thus, R_{AM} is negative at $y^+ = 18.7$ in Fig. 6.

It concludes that the $u_L'^+ - E_L(u_S')^+$ joint PDF are not “symmetric” distribution through the boundary layer, which is dependent on the wall-normal positions and the PZT perturbation impacts. Based on the direct numerical simulation (DNS) of a canonical turbulent channel at $Re_\tau = 1025$, Agostini and Leschziner⁶⁴ attributed the lack of symmetry of joint PDFs to the major differences in the effects of sweep and ejection on small scales. Thus, it probably infers that the current PZT perturbation modifies the sweep and ejection process in

the near-wall region; even the current hot-wire data are based on the single wire probe.

The further discussion about the dependence of small-scale energy on large-scale fluctuations is presented by the conditionally averaged large-scale envelop of small scales, $\langle E_L(u_S')^+ | u_L'^+ \rangle$. By examining the probability distribution of $u_L'^+$ over all wall-normal positions and also considering the balance between the bin size and the sample number within each bin,^{21,42} the large-scale fluctuations are equally spaced within a spacing of 0.3, ranging from $u_L'^+ = -3.15$ to $u_L'^+ = 3.15$. Figure 10 presents $\langle E_L(u_S')^+ | u_L'^+ \rangle$ as a fluctuation of large scales and wall-normal positions for all the cases. For the unperturbed case, it is as expected that in the near-wall region, $\langle E_L(u_S')^+ | u_L'^+ \rangle > 0$ and $\langle E_L(u_S')^+ | u_L'^+ \rangle < 0$ in the condition of $u_L'^+ > 0$ and $u_L'^+ < 0$, respectively, which could be explained by the footprint of the large scales on the near-wall cycle.^{40,63} Above the buffer region around ($y^+ \gtrsim 14$), the energy dependence of the small scales on the large-scale fluctuations is reversed. The results are consistent with the previous investigations.^{21,42} For the perturbed cases, Case III in Fig. 10(d) shows the similar distribution, which suggests that the energy dependence of the small scales on large scales is not sensitive to the perturbation of Case III. For Cases I and II [Figs. 10(b)

FIG. 10. Conditionally averaged small-scale energy $\langle E_L(u_S^+) | u_L^+ \rangle$ as a function of large-scale fluctuations and wall-normal positions. (a) Unperturbed case, (b) Case I, (c) Case II, and (d) Case III.

FIG. 11. The response function $\langle E_L(u_S^+) | u_L^+ \rangle$ as function of the large-scale fluctuations, u_L^+ , at the different near-wall positions, y^+ . (a) Unperturbed case, (b) Case I, (c) Case II, and (d) Case III. The results come from Fig. 10. The black dashed lines are linear fits at $y^+ = 3$ and 14.

and 10(c)], an obvious modification can be observed in the near wall region ($y^+ \lesssim 30$), where $\langle E_L(u'_S)^+ | u'_L{}^+ \rangle$ displays a higher absolute value. It implies that the perturbation increases the dependence of small-scale energy on the large-scale fluctuations. In fact, the configuration of $\langle E_L(u'_S)^+ | u'_L{}^+ \rangle$ is very similar through the whole boundary layer in all the cases, but for Cases I and II, a region of obviously higher dependence displays around $y^+ \lesssim 14$, which should be attributed to the new-generated structures induced by the PZT actuator. Then, this high energy-dependent region could lift up the innate near-wall energy-dependent region of underlying TBL. As shown, the region around $14 \lesssim y^+ \lesssim 100$ is kind of compressed in the wall normal direction but still remains the contours configuration as shown in the region of $y^+ \lesssim 100$ in the canonical TBL.

Figure 10 indicates that the main difference of conditionally averaged small-scale energy is located in the near-wall region around $y^+ \lesssim 28$. Furthermore, Fig. 11 plots $\langle E_L(u'_S)^+ | u'_L{}^+ \rangle$ as a function of $u'_L{}^+$ at the different wall-normal positions no more than $y^+ \leq 28$. For the unperturbed case in Fig. 11(a), it shows the response function distributions in $3 \leq y^+ \leq 14$. As reported by Howland and Yang,³⁵ the response function is linear at $y^+ = 3$. Then, the response function gradually deviates from the linear distribution by increasing y^+ . Clearly, at $y^+ = 14$, the small scales respond differently to the large-scale structures, relying on the sign of $u'_L{}^+$. As expected, Case III in Fig. 11(d) shows the similar trend in the wall normal region of $3 \leq y^+ \leq 14$ as the canonical TBL.

More interestingly, for the perturbed Cases I and II, both of them show that in the wall normal region of $14 \lesssim y^+ \lesssim 28$, the response function is consistent with that shown in the canonical TBL. However, in the region very close to the wall ($3 \lesssim y^+ \lesssim 14$), the response function exhibits linear distribution with a higher slope. By recalling the compact $u'_L{}^+ - E_L(u'_S)^+$ joint PDF distribution at $y^+ = 5$, the result indicates the small scales perform a stronger energy dependence on the large-scale fluctuations, while the amplitude of the large scales is attenuated. The probable reason of the response function in $y^+ \lesssim 28$ should be that the PZT perturbation induces new-generated structures in the region very close to the wall with the high energy-dependence; meanwhile, these new structures push the innate near-wall structures in the underlying boundary layer away from the wall and exist between them.

Furthermore, as the small-scale energy responds differently to the large scales depending on whether $u'_L{}^+ > 0$ or $u'_L{}^+ < 0$, it was suggested to consider a conditional amplitude modulation metric by the sign of the large scales.^{35,65} Following this suggestion, the current study defines conditional AM coefficients as

$$R_{>\text{rms}} = \frac{\langle (E_L(u'_S)^+ | u'_L{}^+ > u'_{L^+ \text{rms}}) (u'_L{}^+ | u'_L{}^+ > u'_{L^+ \text{rms}}) \rangle}{\sqrt{\langle (E_L(u'_S)^+ | u'_L{}^+ > u'_{L^+ \text{rms}})^2 \rangle \langle (u'_L{}^+ | u'_L{}^+ > u'_{L^+ \text{rms}})^2 \rangle}} \quad (7)$$

based on the conditional event that the large-scale fluctuations are higher than their root mean square ($u'_L{}^+ > u'_{L^+ \text{rms}}$) and $R_{<-\text{rms}}$ is defined similarly.

FIG. 12. Conditional amplitude coefficients (a) $R_{>\text{rms}}$ and (b) $R_{<-\text{rms}}$ as a function of y^+ for all the cases. For comparison, $R_{>\text{rms}}$ and $R_{<-\text{rms}}$ in the unperturbed case are shown in both (a) and (b).

Figure 12 shows the conditional amplitude modulation coefficients distribution, which is as a function of wall-normal positions. In the unperturbed case, $R_{>\text{rms}}$ and $R_{<-\text{rms}}$ display a similar distribution along the wall normal direction. The boundary layer can be also divided into three main regimes as indicated by the AM coefficients (R_{AM}) without conditional events. In the near wall region, the positive coefficients are attributed to the footprint of large-scale structures on near-wall cycle.^{40,63} In the wake region, both $R_{>\text{rms}}$ and $R_{<-\text{rms}}$ show clear negative coefficients due to the turbulent/non-turbulent intermittency. Between these two regions, both $R_{>\text{rms}}$ and $R_{<-\text{rms}}$ are around zero as a “phase reversal.” As shown, the distributions of $R_{>\text{rms}}$ and $R_{<-\text{rms}}$ are only quantitatively different. $R_{<-\text{rms}}$ is greater than $R_{>\text{rms}}$ through the whole boundary layer except the region around the boundary layer edges, which is attributed to the dependence difference of the small-scale energy on the conditional large-scale fluctuations. Moreover, in the region of $y^+ < 5$, $R_{>\text{rms}}$ and $R_{<-\text{rms}}$ are almost equal, which indicates that $u'_L{}^+ > u'_{L^+ \text{rms}}$ and $u'_L{}^+ < -u'_{L^+ \text{rms}}$ have the same amplitude modulation extent on the small scales, which is consistent with that reported by Howland and Yang.³⁵ Under the perturbed Cases I and II, the clear impact on both $R_{>\text{rms}}$ and $R_{<-\text{rms}}$ can be noted in the near wall region of $y^+ < 100$. Similarly, three sub-regions in $y^+ < 100$, as the R_{AM} results shown in Fig. 6, are also observed in both $R_{>\text{rms}}$ and $R_{<-\text{rms}}$ distributions. Looking carefully, comparing $R_{>\text{rms}}$ and $R_{<-\text{rms}}$ [Figs. 12(a) and 12(b)] shows that in the region of $y^+ \lesssim 14$, the conditional AM coefficients are comparable. This result reveals that the AM effects in this near-wall region ($y^+ \lesssim 14$) are insensitive to

the conditions of the large-scale structures under the PZT perturbation.

As reported by Bai *et al.*⁴⁸ it was proposed that under the PZT perturbation, an interlayer occurring between the near wall structures and the wall surface suppresses the turbulence generation and self-sustained process of the near-wall cycle. By combining the results of joint PDFs and energy dependence, it infers that this interlayer is characterized by high linear energy dependence of small scales on large scales and compact scale probability distribution. Accordingly, the conditional AM coefficients hold comparable values no matter the condition of the large scales in the near wall region of $y^+ \leq 14$, which is much thicker than the region ($y^+ \leq 5$) in the canonical TBL.

IV. CONCLUSIONS

Amplitude modulation effects of a TBL flow manipulated by a wall-mounted PZT actuator was studied by hot wire measurements. The PZT actuator provided the local dynamic perturbation at a frequency of $f_p = 160$ Hz but different oscillating amplitudes ($A = 0.6$ mm, 0.4 mm, and 0.1 mm). Energy spectra maps indicated that the PZT actuator imposes a clear periodic input perturbation on the near wall flow fields. Then, turbulent nonlinear fluctuations around the periodic component ($u'(y, t)$) acquired by triple decomposition were further used to observe the AM effects under the PZT perturbation.

By decomposing turbulent nonlinear fluctuations $u'(y, t)$ into large- and small-scale fluctuations (u'_L and u'_S) based on a cutoff filter of $\lambda_c/\delta = 2$, the PZT impact on turbulent intensity was significantly observed in the near-wall region by enhancing the small-scale intensity and attenuating the turbulent energy of large scales. The PZT actuator modified the distribution of AM coefficients and the joint PDFs of the large-scale structures and the representatives of small scales in the inner region of $y/\delta \leq 0.15$. The modified region could be divided into three sub-regions. In the near-wall region of $y^+ \leq 10$, large-scale fluctuations and the signature of small scales display a compact joint PDF, which returns a lower positive AM coefficient value. In the region of $10 \leq y^+ \leq 30$, R_{AM} shows enhanced positive coefficients, as the joint PDF distribution is very similar as that shown in the near-wall region of canonical TBL. In the region between $y^+ \geq 30$ and $y/\delta \leq 0.15$, R_{AM} of Case I becomes negative, which indicates that the new-generated structures by the PZT actuator increase the occurrence probability of $u'_L{}^+ < 0$, $E_L(u'_S)^+ > 0$ and $u'_L{}^+ > 0$, $E_L(u'_S)^+ < 0$.

Then, the energy dependence of the small scales on large-scale fluctuations was observed. Under the PZT perturbation, the distributions of conditionally averaged small-scale energy $\langle E_L(u'_S)^+ | u'_L{}^+ \rangle$ were modified by presenting a stronger linear dependence in the near-wall region of $y^+ \leq 14$. Meanwhile, the region around $14 \leq y^+ \leq 28$ indicated that the energy dependence is very similar as that shown in the near wall region ($y^+ \leq 14$) of canonical TBL. It inferred that an interlayer region characterized by a linear energy dependence of a higher slope occurs between the innate near wall structures and the wall surface. The conditional AM coefficients $R_{>rms}$

and $R_{<-rms}$ further confirmed this result by displaying insensitive response on the PZT actuator perturbation in the region of $y^+ \leq 14$.

Moreover, it was found that the amplitude modulation performance is dependent on the PZT oscillating amplitude. More intense oscillating amplitude exhibited stronger perturbation effects on the AM. Cases I and II introduced an obvious change on AM in the near-region. On the contrary, Case III exhibited a negligible effect due to its low oscillating amplitude, in which the result was very similar to that shown in canonical TBL flow. In Cases I and II, due to the higher PZT oscillating amplitude, the interlayer as reported by Bai *et al.*⁴⁸ occurred in the region between the wall surface and the innate near-wall cycles of the underlying turbulent boundary layer flow. This sublayer is characterized by a lower AM degree of the large scale on the near-wall small scales as the large and small scales have a more compact distribution, which results in highly related linear response function.

Based on the flow mechanism that a high wall shear stress is closely associated with the presence of streamwise vortices,^{66,67} previous investigation employed wall-mounted PZT actuators to achieve TBL flow control.⁴⁸ It reported that the connection between the wall and streamwise vortices has been weakened by the interlayer of highly regularized streamwise vortices, which were generated by the PZT actuator. The local drag reduction mechanism of the PZT control was proposed as the interlayer was introduced to be a barrier that prevents the large-scale sweep motion from reaching the wall, which impairs the sustaining process of the near-wall cycle. The interlayer was also found in this study by characterizing the AM phenomenon, even though that the current data were only collected from the local location downstream of the PZT, which may be not advisable for a comprehensive discussion of drag reduction. According to the AM observation in this interlayer, it probably implied a potential explanation of drag reduction in the viewpoint of the amplitude modulation. It will be necessary to employ more PZT actuators to fabricate a global control area for more comprehensive measurements to further discuss the skin drag reduction.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China with Grant Nos. 11872272, 11502066, 11732010, 11572221, U1633109, and 11332006 and the China Postdoctoral Science Foundation with Grant No. 2018M630270.

REFERENCES

- ¹R. F. Blackwelder and H. Eckelmann, "Streamwise vortices associated with the bursting phenomenon," *J. Fluid Mech.* **94**, 577 (1979).
- ²S. J. Kline, W. C. Reynolds, F. A. Schraub, and P. W. Runstadler, "The structure of turbulent boundary layers," *J. Fluid Mech.* **30**, 741 (1967).
- ³J. Jimenez and A. Pinelli, "The autonomous cycle of near-wall turbulence," *J. Fluid Mech.* **389**, 335 (1999).
- ⁴W. Schoppa and F. Hussain, "Coherent structure generation in near-wall turbulence," *J. Fluid Mech.* **453**, 57 (2002).
- ⁵R. J. Adrian, C. D. Meinhardt, and C. D. Tomkins, "Vortex organization in the outer region of the turbulent boundary layer," *J. Fluid Mech.* **422**, 1 (2000).

- ⁶Z. Tang, N. Jiang, A. Schröder, and R. Geisler, "Tomographic PIV investigation of coherent structures in a turbulent boundary layer flow," *Acta Mech. Sin.* **28**, 572 (2012).
- ⁷C. D. Meinhardt and R. J. Adrian, "On the existence of uniform momentum zones in a turbulent boundary layer," *Phys. Fluids* **7**, 694 (1995).
- ⁸S. C. Deng, C. Pan, J. J. Wang, and G. S. He, "On the spatial organization of hairpin packets in a turbulent boundary layer at low-to-moderate Reynolds number," *J. Fluid Mech.* **844**, 635 (2018).
- ⁹C. D. Tomkins and R. J. Adrian, "Spanwise structure and scale growth in turbulent boundary layers," *J. Fluid Mech.* **490**, 37 (2003).
- ¹⁰J. Zhou, R. J. Adrian, S. Balachandar, and T. M. Kendall, "Mechanisms for generating coherent packets of hairpin vortices in channel flow," *J. Fluid Mech.* **387**, 353 (1999).
- ¹¹N. Hutchins and I. Marusic, "Evidence of very long meandering features in the logarithmic region of turbulent boundary layers," *J. Fluid Mech.* **579**, 1 (2007).
- ¹²B. J. Balakumar and R. J. Adrian, "Large- and very-large-scale motions in channel and boundary-layer flows," *Philos. Trans. R. Soc., A* **365**, 665 (2007).
- ¹³K. C. Kim and R. J. Adrian, "Very large-scale motion in the outer layer," *Phys. Fluids* **11**, 417 (1999).
- ¹⁴V. K. Natrajan and K. T. Christensen, "The role of coherent structures in subgrid-scale energy transfer within the log layer of wall turbulence," *Phys. Fluids* **18**, 065104 (2006).
- ¹⁵B. Ganapathisubramani, E. K. Longmire, and I. Marusic, "Characteristics of vortex packets in turbulent boundary layers," *J. Fluid Mech.* **478**, 35 (2003).
- ¹⁶K. N. Rao, R. Narasimha, and M. A. B. Narayanan, "The 'bursting' phenomenon in a turbulent boundary layer," *J. Fluid Mech.* **48**, 339 (1971).
- ¹⁷N. Hutchins and I. Marusic, "Large-scale influences in near-wall turbulence," *Philos. Trans. R. Soc., A* **365**, 647 (2007).
- ¹⁸R. Mathis, J. P. Monty, N. Hutchins, and I. Marusic, "Comparison of large-scale amplitude modulation in turbulent boundary layers, pipes, and channel flows," *Phys. Fluids* **21**, 111703 (2009).
- ¹⁹R. Mathis, N. Hutchins, and I. Marusic, "Large-scale amplitude modulation of the small-scale structures in turbulent boundary layers," *J. Fluid Mech.* **628**, 311 (2009).
- ²⁰R. Mathis, I. Marusic, N. Hutchins, and K. R. Sreenivasan, "The relationship between the velocity skewness and the amplitude modulation of the small scale by the large scale in turbulent boundary layers," *Phys. Fluids* **23**, 121702 (2011).
- ²¹B. Ganapathisubramani, N. Hutchins, J. P. Monty, D. Chung, and I. Marusic, "Amplitude and frequency modulation in wall turbulence," *J. Fluid Mech.* **712**, 61 (2012).
- ²²K. M. Talluru, R. Baidya, N. Hutchins, and I. Marusic, "Amplitude modulation of all three velocity components in turbulent boundary layers," *J. Fluid Mech.* **746**, R1 (2014).
- ²³W. J. Baars, K. M. Talluru, N. Hutchins, and I. Marusic, "Wavelet analysis of wall turbulence to study large-scale modulation of small scales," *Exp. Fluids* **56**, 188 (2015).
- ²⁴W. J. Baars, N. Hutchins, and I. Marusic, "Reynolds number trend of hierarchies and scale interactions in turbulent boundary layers," *Philos. Trans. R. Soc., A* **375**, 20160077 (2017).
- ²⁵M. Guala, M. Metzger, and B. J. McKeon, "Interactions within the turbulent boundary layer at high Reynolds number," *J. Fluid Mech.* **666**, 573 (2011).
- ²⁶I. Jacobi and B. J. McKeon, "Phase relationships between large and small scales in the turbulent boundary layer," *Exp. Fluids* **54**, 1481 (2013).
- ²⁷S. Duvvuri and B. J. McKeon, "Triadic scale interactions in a turbulent boundary layer," *J. Fluid Mech.* **767**, R4 (2015).
- ²⁸D. Chung and B. J. McKeon, "Large-eddy simulation of large-scale structures in long channel flow," *J. Fluid Mech.* **661**, 341 (2010).
- ²⁹P. H. Alfredsson and A. V. Johansson, "Time scales in turbulent channel flow," *Phys. Fluids* **27**, 1974 (1984).
- ³⁰P. R. Bandyopadhyay and A. K. M. F. Hussain, "The coupling between scales in shear flows," *Phys. Fluids* **27**, 2221 (1984).
- ³¹P. Schlatter and R. Örlü, "Quantifying the interaction between large and small scales in wall-bounded turbulent flows: A note of caution," *Phys. Fluids* **22**, 051704 (2010).
- ³²N. Hutchins, J. P. Monty, B. Ganapathisubramani, H. C. H. Ng, and I. Marusic, "Three-dimensional conditional structure of a high-Reynolds-number turbulent boundary layer," *J. Fluid Mech.* **673**, 255 (2011).
- ³³M. Bernardini and S. Pirozzoli, "Inner/outer layer interactions in turbulent boundary layers: A refined measure for the large-scale amplitude modulation mechanism," *Phys. Fluids* **23**, 061701 (2011).
- ³⁴E. Dogan, R. Örlü, D. Gatti, R. Vinuesa, and P. Schlatter, "Quantification of amplitude modulation in wall-bounded turbulence," *Fluid Dyn. Res.* **51**, 011408 (2018).
- ³⁵M. F. Howland and X. I. A. Yang, "Dependence of small-scale energetics on large scales in turbulent flows," *J. Fluid Mech.* **852**, 641 (2018).
- ³⁶I. Marusic, R. Mathis, and N. Hutchins, "Predictive model for wall-bounded turbulent flow," *Science* **329**, 193 (2010).
- ³⁷R. Mathis, N. Hutchins, and I. Marusic, "A predictive inner-outer model for streamwise turbulence statistics in wall-bounded flows," *J. Fluid Mech.* **681**, 537 (2011).
- ³⁸L. Agostini and M. Leschziner, "On the validity of the quasi-steady-turbulence hypothesis in representing the effects of large scales on small scales in boundary layers," *Phys. Fluids* **28**, 045102 (2016).
- ³⁹C. Zhang and S. I. Chernyshenko, "Quasisteady quasihomogeneous description of the scale interactions in near-wall turbulence," *Phys. Rev. Fluids* **1**, 014401 (2016).
- ⁴⁰N. Hutchins, *Large-Scale Structures in High Reynolds Number Wall-Bounded Turbulence* (Springer International Publishing, Cham, 2014).
- ⁴¹G. Pathikonda and K. T. Christensen, "Structure of turbulent channel flow perturbed by a wall-mounted cylindrical element," *AIAA J.* **53**, 1277 (2014).
- ⁴²Z. Tang, N. Jiang, X. Zheng, and Y. Wu, "Bursting process of large- and small-scale structures in turbulent boundary layer perturbed by a cylinder roughness element," *Exp. Fluids* **57**, 79 (2016).
- ⁴³I. Jacobi and B. J. McKeon, "Phase-relationships between scales in the perturbed turbulent boundary layer," *J. Turbul.* **18**, 1120 (2017).
- ⁴⁴Z. Tang and N. Jiang, "Scale interaction and arrangement in a turbulent boundary layer perturbed by a wall-mounted cylindrical element," *Phys. Fluids* **30**, 055103 (2018).
- ⁴⁵I. Jacobi and B. J. McKeon, "Dynamic roughness perturbation of a turbulent boundary layer," *J. Fluid Mech.* **688**, 258 (2011).
- ⁴⁶I. Jacobi and B. J. McKeon, "New perspectives on the impulsive roughness-perturbation of a turbulent boundary layer," *J. Fluid Mech.* **677**, 179 (2011).
- ⁴⁷Z. Tang, Y. Wu, Y. Jia, and N. Jiang, "PIV measurements of a turbulent boundary layer perturbed by a wall-mounted transverse circular cylinder element," *Flow, Turbul. Combust.* **100**, 365 (2017).
- ⁴⁸H. L. Bai, Y. Zhou, W. G. Zhang, S. J. Xu, Y. Wang, and R. A. Antonia, "Active control of a turbulent boundary layer based on local surface perturbation," *J. Fluid Mech.* **750**, 316 (2014).
- ⁴⁹X.-B. Zheng, N. Jiang, and H. Zhang, "Predetermined control of turbulent boundary layer with a piezoelectric oscillator," *Chin. Phys. B* **25**, 014703 (2016).
- ⁵⁰Z. X. Qiao, Z. Wu, and Y. Zhou, "Turbulent boundary layer manipulation under a proportional-derivative closed-loop scheme," *Phys. Fluids* **30**, 115101 (2018).
- ⁵¹A. K. M. F. Hussain and W. C. Reynolds, "The mechanics of an organized wave in turbulent shear flow," *J. Fluid Mech.* **41**, 241 (1970).
- ⁵²P. Schlatter and R. Örlü, "Assessment of direct numerical simulation data of turbulent boundary layers," *J. Fluid Mech.* **659**, 116 (2010).
- ⁵³C. Sanmiguel Vila, R. Vinuesa, S. Discetti, A. Ianiro, P. Schlatter, and R. Örlü, "On the identification of well-behaved turbulent boundary layers," *J. Fluid Mech.* **822**, 109 (2017).
- ⁵⁴J. Söderkvist, "Dynamic behavior of a piezoelectric beam," *J. Acoust. Soc. Am.* **90**, 686 (1991).
- ⁵⁵N. Hutchins, T. B. Nickels, I. Marusic, and M. S. Chong, "Hot-wire spatial resolution issues in wall-bounded turbulence," *J. Fluid Mech.* **635**, 103 (2009).

- ⁵⁶P. M. Ligrani and P. Bradshaw, "Spatial resolution and measurement of turbulence in the viscous sublayer using subminiature hot-wire probes," *Exp. Fluids* **5**, 407 (1987).
- ⁵⁷S. Mochizuki and F. T. M. Nieuwstadt, "Reynolds-number-dependence of the maximum in the streamwise velocity fluctuations in wall turbulence," *Exp. Fluids* **21**, 218 (1996).
- ⁵⁸N. Hutchins, J. P. Monty, M. Hultmark, and A. J. Smits, "A direct measure of the frequency response of hot-wire anemometers: Temporal resolution issues in wall-bounded turbulence," *Exp. Fluids* **56**, 18 (2015).
- ⁵⁹R. Örlü, J. H. M. Fransson, and P. Henrik Alfredsson, "On near wall measurements of wall bounded flows—The necessity of an accurate determination of the wall position," *Prog. Aerosp. Sci.* **46**, 353 (2010).
- ⁶⁰A. A. Townsend, *The Structure of Turbulent Shear Flow* (Cambridge University Press, Cambridge, United Kingdom, 1976).
- ⁶¹P. Schlatter, Q. Li, G. Brethouwer, A. V. Johansson, and D. S. Henningson, "Simulations of spatially evolving turbulent boundary layers up to," *Int. J. Heat Fluid Flow* **31**, 251 (2010).
- ⁶²G. Pathikonda and K. T. Christensen, "Inner-outer interactions in a turbulent boundary layer overlying complex roughness," *Phys. Rev. Fluids* **2**, 044603 (2017).
- ⁶³R. Mathis, I. Marusic, S. I. Chernyshenko, and N. Hutchins, "Estimating wall-shear-stress fluctuations given an outer region input," *J. Fluid Mech.* **715**, 163 (2013).
- ⁶⁴L. Agostini and M. A. Leschziner, "On the influence of outer large-scale structures on near-wall turbulence in channel flow," *Phys. Fluids* **26**, 075107 (2014).
- ⁶⁵J. Hwang, J. Lee, H. J. Sung, and T. A. Zaki, "Inner-outer interactions of large-scale structures in turbulent channel flow," *J. Fluid Mech.* **790**, 128 (2016).
- ⁶⁶A. G. Kravchenko, H. Choi, and P. Moin, "On the relation of near-wall streamwise vortices to wall skin friction in turbulent boundary layers," *Phys. Fluids A* **5**, 3307 (1993).
- ⁶⁷P. Orlandi and J. Jiménez, "On the generation of turbulent wall friction," *Phys. Fluids* **6**, 634 (1994).