

Turbulent Kinetic Energy Budget and Dynamics of Composed Wakes in TBL

Majd Armaly, J M Foucaut, Christophe Cuvier, Pierre Braganca, Romain Beauvais, Corine Lacour, Luminita Danaila, Bertrand Lecordier

► To cite this version:

Majd Armaly, J M Foucaut, Christophe Cuvier, Pierre Braganca, Romain Beauvais, et al.. Turbulent Kinetic Energy Budget and Dynamics of Composed Wakes in TBL. 23rd Australasian Fluid Mechanics Conference - 23AFMC, Dec 2022, Sydney (Australia), Australia. hal-04297102

HAL Id: hal-04297102 https://hal.science/hal-04297102

Submitted on 21 Nov 2023 $\,$

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers. L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Turbulent Kinetic Energy Budget and Dynamics of Composed Wakes in TBL

Majd Armaly^{1*}, J.M.Foucaut³, Christophe Cuvier³, Pierre Braganca³, Romain Beauvais³, Emilien Varea¹, Corine Lacour¹, Luminita Danaila², Bertrand Lecordier¹

¹ CORIA UMR 6614, University of Rouen Normandy and INSA Rouen, Saint Étienne du Rouvray, 76800, France, ² M2C UMR 6143, University of Rouen Normandy, Mont Saint Aignon, 76130, France ³ LMFL UMR 9014, University of Lille, ONERA, Arts and Metiers Institute of Technology, Centrale Lille, Lille, 59000, France. *mail to: majd.armaly@coria.fr

Abstract

The far aim of the study is to reveal the role exerted by a cylinder wake placed in a Turbulent Boundary Layer (TBL), on the downstream flow. Applications are wide and a simple example deals with understanding the flow around a wind turbine blade as a function of upstream turbulent fluctuations. The methodology is based upon assessing transport equations for the total kinetic energy (TKE), with the inclusion of both Coherent (CM) and Random (RM) Motions. Transport equations of TKE provide insight into the exchange of kinetic energy between the mean flow, CM and RM, through mechanisms of production, advection, diffusion and dissipation. Of particular interest is the way those mechanisms evolve at each phase of the CM (upstream flow). 2C-2D in-plane velocity fields (couples of 30000 images) are measured behind the obstacles (Cylinder -Blade) by Particle Image Velocimetry (PIV). The measurements planes are at three different heights from the wall: $y^+ = 500$, $y^+ = 1500$ and $y^+ = 3125$. Different heights lead to different local Reynolds numbers based on the cylinder diameter, i.e. Re = 4666, 5333 and 6000.

1 Introduction

Engineers are vigilant to understand more about the disasters of turbulence on their structures, as in aircraft, wind turbine parks, or buildings. In the turbulence framework, wakes behind obstacles have been studied for over a century. Roshko (1954) used his measurements based on velocity fluctuation to define flow regimes and vortex shedding behind a cylinder. After that, scientists gain much attention for two obstacle studies, where Igarashi (1981) start to investigate the flow characteristics around two cylinders. The wake behind obstacles comprises coherent motions (CM) and random motion (RM). The classical postulates of turbulence are based upon the concept of the cascade, i.e., kinetic energy is injected at the largest scales of the flow and is transferred to smaller scales through the cascade process. Furthermore, the turbulent kinetic energy budget is illustrated by Townsend (1976) to highlight the exchange between the mean and the fluctuations (CM & RM). The assessment of the energy budget allows for detecting the basic mechanisms of production, transport, and kinetic energy dissipation. Coherent motion (CM), reminiscent of the Von Kármán street, is created by the first obstacle and interacts with RM, thus inducing a locally enhanced turbulent cascade and impacting any possible obstacle placed in the wake. The interest of the study is to reveal the role of the shedding vortices created by the first obstacle (a cylinder) on any other object placed downstream (a blade). The study of Medici & Alfredson (2005) highlighted low-frequency vortices shed from turbines, with a specific frequency due to the turbine wake meandering.

Within the statistical framework, it often appears that the operation of averaging applied to equations of motion hides from view many important features of turbulent flow. For instance, the experimental



study of Thiesset (2011) assessed the turbulent kinetic energy budget in the cylinder wake at all phases of vortex shedding mixed together. The present contribution resolves this shortcoming by a careful selection of each phase that is required in order to discern processes at each specific phase, as done by Armaly (2022) for a cylinder wake. Section 2 is devoted to the description of the experimental set-up, and section 3 to low–order statistics. In sections 4 and 5, triple decomposition and turbulent kinetic energy budget are shown respectively. We conclude in section 6.

2 Experimental Setup

The experiments were carried out in the boundary layer wind tunnel of the Lille Fluid Mechanics Laboratory (LMFL). The test section of the wind tunnel is 2m wide by 1m high and 20m long. The advantage of the wind tunnel length and its relatively low velocity (maximal free-stream velocity $U_{\infty} = 10$ m/s) is to generate thick boundary layer (about 24cm at the end of the test section). The characteristics of the turbulent boundary layer (TBL) is shown in table (1). This shows the following parameters: TBL thickness (δ), displacement thickness (δ_*), momentum thickness (θ), shape factor $(H = \delta_*/\theta)$, wall friction velocity (U_{τ}) , Reynolds number based on momentum thickness $(Re_{\theta} =$ $U_e \theta/\gamma$, Reynolds number based on friction velocity ($Re_\tau = \delta U_\tau/\gamma$), normalized pressure gradient $(\partial p/\partial x^+)$ and the normalisation factor (γ/U_{τ}) . The wind tunnel operates in a closed loop and the test section is transparent on all four sides to allow extensive use of optical techniques. More details about the wind tunnel are available in Carlier & Stanislas (2005). In the present study, a cylinder of 1 cm diameter (40cm long) and 5cm chord NACA 0015 airfoil (40cm long) are installed at 17m downstream, as shown in figure 1(a). The distance between the axis of the cylinder and the airfoil center of rotation (20mm from the leading edge) is 150mm in longitudinal direction and 10mm in transversal direction. The airfoil is inclined with an angle of attack 10° facing shedded vortices by the upstream cylinder. The shedding vortices are at 140, 160 and 180 Hz corresponding to three Reynolds numbers based on the cylinder diameter (Re = 4666, 5333 and 6000). The shedding frequencies are obtained by Strouhal number equation ($St = \frac{fD}{U} = 0.2$), where D is the diameter of the cylinder, U is the free stream velocity and f is the shedding frequency. 2C-2D PIV measurements were carried out in longitudinal direction (along Von Kármán street generation), as shown in figure 1(b).



Figure 1. (a) Cylinder and airfoil in the wind tunnel section. (b) Laser sheet. (c) Laser path.

X (m)	U_e (m/s)	δ (cm)	δ _* (cm)	θ (cm)	Н	U_{τ} (m/s)	Re _θ	Re_{τ}	$\frac{\partial p}{\partial x}^+$	$\frac{\gamma}{U_{\tau}}$ (mm)
17	10	22	3.20	2.5	1.3	0.34	16800	5095	$-1.4 imes 10^-4$	0.04

 Table 1. Characteristics of the turbulent boundary layer (TBL).

Four sCMOS cameras with spatial resolution $2560 \times 2160 pixels^2$ are installed in row at the top of the wind tunnel to enlarge the field of view. The cameras are equipped with a 105mm lens to obtain a

magnification of 15pixel/mm. The cameras are working at 4 frames per second (fps) and f# number is set to 8. A Nd-YAG (BMI) laser (532nm) was used to illuminate $59 \times 15cm^2$ field of view. The laser beam passed through a spherical lens (f = 5000mm), cylindrical lens (f = 80mm) and reflection mirrors, see figure 1(c). The laser sheet at the focus line is 0.7mm thick. The measurements planes are at three different heights from the wall: $y^+ = 500$, $y^+ = 1500$ and $y^+ = 3125$ ($y^+ = U_{\tau}y/\gamma$). These heights correspond to three different Reynolds numbers ($Re = UD/\gamma$) based on the cylinder diameter, Re = 4666, 5333 and 6000, respectively. Time between pulses is $120\mu s$. The PIV post processing was performed using the in-house code developed in LMFL laboratory. The analysis was done with a multipass approach ending with $24 \times 24pixels^2$ (corresponding to $1.6mm \times 1.6mm$). Overlap was set to 50%, yielding a 937 × 211 vector field.

3 Mean and Root Mean Square of Velocities

The first step of the analysis consists in determining the phase of the coherent structures downstream of the cylinder for each instantaneous velocity field. This is performed by using in-house code and it based on comparison with phase lock measurements made in a laminar wind tunnel behind a cylinder of the same diameter in Armaly (2022) study. In the present work, the full period of the CM oscillation is divided into 9 distinct phases. The quality of the phase decomposition must be first checked on lower-order statistics, such as the velocity field's mean and Root Mean Square (RMS). Figures 2(a) and 2(b) show the mean values of the streamwise (x) and spanwise (y) velocities for one particular phase. Noticeable are positive and negative spots in figure 2(b) downstream of the cylinder, indicating the locations of the vortices. Each couple of spots (negative-positive) consists in two vortices on each side of the cylinder, thus corresponding to one period. Figures 2(c), 2(d) and 2(e) show the RMS of velocity on streamwise (x) direction, spanwise directions perpendicular (y) and parallel (z) to the cylinder, respectively.



Figure 2. Mean and Root Mean Square of velocity fields at $y^+ = 1500$, at one particular phase. (a) Mean of the streamwise velocity. (b) Mean of velocity fields along *y* direction. (c) RMS of the velocity along *x* direction. (d) RMS of the velocity along *y* direction. (e) Estimation of RMS of the velocity along *z* direction.

RMS is maximum in regions where shear is the most important and gradually decreases downstream

behind the cylinder. The knocking down of the vortices takes place at 10 cm from the cylinder (X/D = 5cm), as shown in figure 2(c). Despite the vortex street burial in TBL, the fluctuations at a particular phase persist, as highlighted by figure 2(d). Figure 2(e) shows the RMS of the velocity along (z) direction. Statistics along the (z) direction are not measured and are then estimated by combining the axisymmetric hypothesis in the near wake of a cylinder as in Thiesset (2011) study, and the profiles of turbulence intensity in Carlier & Stanislas (2005) study. For further simplification, computation is carried out by superposing two flows through the continuity between the dominance of the cylinder near-wake (axisymmetric hypothesis) and the dominance of TBL (turbulence intensity profiles). The presented statistics are required to assess the turbulent kinetic energy budget.

4 Triple Decomposition

Triple decomposition is a mathematical decomposition of turbulent fields which accounts for the quasi-periodicity of the CM, for each phase. Tracking the CM and its dynamics provides a significant insight into the nature of the flow. The first term in Eq. (1) represents the temporal average $\overline{f(x,t,\phi_i)}$ (TA) of the whole instantaneous field. The second term in Eq. (1) accounts for the coherent motion $f_c(x,t,\phi_i)$ (CM) and is quasi-periodicity. The third term in Eq. (1) delineates the random motion $f_r(x,t,\phi_i)$ (RM). The three terms in Eq. (1) construct the whole field at an instant t, $f(x,t,\phi_i)$. This equation reflects the decomposition first proposed by Hussain & Reynolds (1970) for an organized wave, further used as a clock for selecting samples. Coherent motion (CM) is obtained by difference between the phase average < f(x,t) > and the time average $\overline{f(x,t,\phi_i)}$, Eq. (2). Figure (3) shows the instantaneous triple decomposition of the wake, at $y^+ = 1500$ and at phase = 0°. The ability of decomposing both of the motions (CM & RM) from the mean will provide a complete understanding of the energy exchange. Access to coherent motion (CM) allows to visualize the behaviour of the blade at each phase of the motion.

$$\underbrace{f(x,t,\phi_i)}_{f(x,t,\phi_i)} = \underbrace{\overline{f(x,t,\phi_i)}}_{f_c(x,t,\phi_i)} + \underbrace{f_c(x,t,\phi_i)}_{f_c(x,t,\phi_i)} + \underbrace{f_r(x,t,\phi_i)}_{f_r(x,t,\phi_i)}$$
(1)

Instantaneous Time average Coherent motion Random motion

$$\underbrace{f_c(x,t,\phi_i)}_{\text{becaution}} = \underbrace{\langle f(x,t) \rangle}_{\text{Becautorage}} - \underbrace{\overline{f(x,t,\phi_i)}}_{\text{Time evenes}}$$
(2)

Coherent motion Phase average Time average



Figure 3. Triple decomposition at $y^+ = 1500$ and $\phi = 0$

Figure (4) shows the evolution of the coherent motion (CM) at $\phi = 0^{\circ}, 90^{\circ}, 180^{\circ}$ and 270° . The spatial distribution of the vortices at $\phi = 0^{\circ}$ and $\phi = 90^{\circ}$, are typically opposed to those $\phi = 180^{\circ}$ and $\phi = 270^{\circ}$, respectively. The CM evolution ideally validates the phase decomposition of the

wake, which further unlocks our study's gateway. Coherent motion is dominant near the cylinder but gradually weakens before completely disappearing further downstream, as shown in figure (4). Within the TBL, low energetic coherent vortices can still climb the downstream blade, as shown in figure (4). Coherent motion (CM) renders the flow more complex as it induces additional shear and interactions with other scales of the motion. Coherent Motion enhances the exchange of energy between different flow components. One way to detect and assess energy production and exchange mechanisms is to investigate the turbulent kinetic energy (TKE) budget. TKE budget evidences how Coherent Motion contributes to different phenomena.



Figure 4. Evolution of the Coherent Motion (CM) at $y^+ = 1500$ for 4 different phases.

5 Turbulent Kinetic Energy

We made sure that all phases of the CM are correctly extracted. Transport equation for the turbulent kinetic energy is further reported. This equation underlines the nature and the mechanics of the turbulence in the flow at one point, (Eq. 3).



In equation Eq. (3), U and V are the mean velocities along (x) and (y) directions respectively. Terms u, v and w represent the fluctuations of the instantaneous velocity field along (x), (y) and (z) directions respectively. q^2 represents the kinetic energy ($u^2 + v^2 + w^2$). Finally, ε is the mean kinetic energy dissipation rate. The TKE transport equation contains four main terms (Advection,

Generation, Diffusion and Dissipation). The first term in the equation is the advection, or the transport of the fluctuations due to mean velocity. Advection terms along (x) and (y) directions are reported. Generation of turbulent energy is the second term, and will be greatest near the position of maximum shear and deformation. It represents the exchange of kinetic energy between the mean flow and turbulent fluctuations. In general, the energy exchange involves a loss of the mean flow and gain to the turbulence. The third term is the diffusion, which is divided into diffusion due to pressure and diffusion due to turbulence. Turbulent diffusion term explains how the turbulent kinetic energy is diffused from locations where it is produced, to other places where production is smaller, or absent. On the other hand, diffusion by pressure diffused from higher pressure places. The last term is the dissipation (occurring at smallest scales, comparable to Kolmogorov scales), and reflects the work done by smallest eddies against viscous stresses. As our analysis is based upon 2D-2C PIV, terms involving derivatives are not available for w and along (z) direction. For instance, it is well known that the energy dissipation rate is underestimated. Other methods are to be used to assess a good estimated values of this quantity. The dissipation rate ε_{PIV} is first computed by Eq. (4), and then corrected using Stanislas (2008) data to get access to the non-resolved data. The dissipation rate ε_{PIV} (computed from PIV data) is much smaller than the values of ε estimated with hot-wire anemometry in Stanislas (2008). Therefore, a correction is applied to ε_{PIV} to reach the values reported by Stanislas (2008) in TBL, but in the outer region of the wake.

$$\varepsilon_{PIV} = \gamma \left[\frac{5}{3} \overline{\left(\frac{\partial u}{\partial x}\right)^2} + 2 \overline{\left(\frac{\partial u}{\partial y}\right)^2} + \overline{\left(\frac{\partial v}{\partial x}\right)^2} + \frac{8}{3} \overline{\left(\frac{\partial v}{\partial y}\right)^2} \right].$$
(4)



Figure 5. One-point turbulent kinetic energy balance. Advection on x direction term $U \frac{\partial(0.5\overline{q^2})}{\partial x}$ normalised by D/U_0^3 . Phases decomposed at 0°,90°,180° and 270° phase shifts. (a) At $y^+ = 1500$. (b) Profiles at the center chord of the blade on y direction at $y^+ = 500$ and $y^+ = 3125$.

The interference between negative and positive advection is responsible for the existence of the coherent vortices in the cylinder wake, as shown in Armaly (2022), Abernathy & Kronauer (1983). Figure 5(a) shows the advection along x direction at $y^+ = 1500$ for four different phases. Negative and positive advection is not intervened within the existence of TBL. Consequently, the energy of the vortices in Von Kármán street will be minimized. As far as the blade is concerned, the positive advection over the blade starts the rolling up process of the blade boundary layer (BL), as illustrated in figure 5(a). Moreover, TBL influences the rolling process of the BL over the blade, as shown in figure 5(b). Figure 5(b) shows the profiles at chord-center of the blade in y direction at two extremes heights ($y^+ = 500$ and $y^+ = 3125$) for four different phases.



Figure 6. One-point turbulent kinetic energy balance at $y^+ = 1500$, phases decomposed at $0^{\circ},90^{\circ},180^{\circ}$ and 270° phase shifts. All terms are normalised by D/U_0^3 . (a) Advection on y direction term $V \frac{\partial(0.5q^2)}{\partial y}$. (b) Diffusion term $(\frac{\partial\overline{0.5q^2v}}{\partial y} + \frac{\partial\overline{pv}}{\partial y})$.



Figure 7. One-point turbulent kinetic energy balance at $y^+ = 1500$, phases decomposed at $0^{\circ},90^{\circ},180^{\circ}$ and 270° phase shifts. All terms are normalised by D/U_0^3 . (a) Generation term $\overline{uv}\frac{\partial U}{\partial y}$. (b) Energy dissipation rate term ε .

Closer to the wall, negative advection is observed over large regions, constant at all phases. Far away from the wall, the negative advection (BL) changes its magnitude from one phase to another, thus emphasizing the BL rolling over the blade. Figures 6(a) and 6(b) show the advection along (y) direction and the total diffusion at $y^+ = 1500$, for four different phases. In figure 6 (a), each couple of counter-advection is responsible for two counter-rotation coherent structures at each side of the wake. Coherent structures progressively disappear when moving downstream within the TBL. The pressure field and the fluctuations (w') are not available experimentally. Therefore, diffusion terms cannot be directly assessed, but they can be estimated through the TKE equation by difference. The diffusion term is thus determined from the budget equation by considering that all the other terms are correctly evaluated. The two main terms, advection and diffusion, appear to be complementary. Regions where advection terms are positive, diffusion terms are negative, and vice versa (also shown by Townsend (1976)). Figures 7(a) and 7(b) show the generation term map and the dissipation term at $y^+ = 1500$ for four different phases. Generation takes place where the maximum gradient of the mean velocity and the maximum level of anisotropy $(\overline{u^2}/\overline{v^2} > 1 \text{ or } \overline{u^2}/\overline{v^2} < 1)$ occur. Vortices generation by the blade is not affected by the cylinder CM, as they weaken through the TBL, see figure 7(a). The generation of blade vortices is affected by the TBL. Vortices start shedding before arriving at the trailing edge, contrasting with a laminar flow. By approaching the wall (for instance, $y^+ = 20mm$), the maximum generation amount upstream over the blade and rolling process time are reduced. In the dissipation map, the maximum takes place where higher strain and shear occur, which enhances the energy of the small scales. The dissipation rate is distributed over the whole flow and is not necessarily large in regions of strong generation, as shown in figure 7(b). The dissipation increases by approaching the blade, particularly at phases ($\phi = 180^\circ, 270^\circ$) and near the leading edge.

6 Conclusions

The role played by a cylinder wake placed in a turbulent boundary layer downstream of a wind turbine blade is revealed by assessing the turbulent kinetic energy (TKE) budget. TKE computations were performed for different phases to get an insight into the energy exchanges between the mean flow and (CM and RM) fluctuations and their evolution at different phases of the flow. Validation of the phase decomposition is done through the computation of turbulence statistics (Mean and RMS) and the triple decomposition method. Results show that TBL affects the interference of negative and positive streamwise advection. TBL also involves the shedding of the vortices from the blade by advancing the maximum generation upstream over the blade. Low energetic CM (due to the cylinder) creates a high dissipation by arrival at the blade's leading edge.

Acknowledgements

The project (DYNEOL) was funded by the French National Research Agency (ANR) under contract no. ANR-17-CE06-0020.

References

Abernathy, F.H., and Kronauer, R.E., 1961, The formation of vortex streets, J.Fluid Mech., 13, 1-20.

- Armaly, M., Varea, E., Lacour, C., Danaila, L. and Lecordier, B., 2022, Dynamics and phase decomposition in a cylinder wake, *Congrès Français de Mécanique*, France.
- Carlier, J. and Stanislas, M., 2005, Experimental study of eddy structures in a turbulent boundary layer using particle image velocimetry, *J. Fluid Mech.*, **535**, 143-188.
- Hussain, A.K.M.F. and Reynolds, W.C., 1970, The mechanics of an organized wave in turbulent shear flow, *J. Fluid Mech.*, **41-part 2**
- Igarashi, T., 1981, Characteristics of the flow around two circular cylinders arranged in tandem, *Bulletin of the JSME*, **24**, 532-582.
- Medici, D. and Alfredsson, P.H., 2005, Measurements on a Wind Turbine Wake: 3D Effects and Bluff Body Vortex Shedding, *J. Wind Energy*, **9-part 3**, 219-236.
- Roshko, A., 1954, On the development of turbulent wakes from vortex streets, *California Institute of Technology*, Report 1191.
- Stanislas, M., Perret, L. and Foucaut, J.M., 2008, Vortical structures in the turbulent boundary layer: a possible route to a universal representation, J. Fluid Mech., 602, 327-382.
- Townsend, A.A., Batchelor (editor) and Miles (editor), 1976, The structure of turbulent shear flow, Cambridge, Cambridge university press, 205-209.
- Thiesset, F., 2011, Exploration analytique et experimentale des interactions cohérence-turbulence au sein d'un écoulement de sillage, *Université de Rouen.*, HAL Id :tel-00880987.