Canadian Journal of Physics

Vortex Identification in Turbulent Flows Past Plates using Lagrangian Method

Journal:	<i>Canadian Journal of Physics</i>
Manuscript ID	cjp-2018-0625.R1
Manuscript Type:	Article
Date Submitted by the Author:	25-Nov-2018
Complete List of Authors:	Attiya, Bashar; Lehigh University Liu, I-Han; Lehigh University, Altimemy, Muhannad; Lehigh University, Mechanical Engineering Daskiran, Cosan; Lehigh University Oztekin, Alparslan; Lehigh University, Dept.of Mechanical Engineering & Mechanics; Lehigh University
Keyword:	Large eddy simulations, vortex detection, visualization and dynamics, Lagrangian coherent structures;, turbulent flows
Is the invited manuscript for consideration in a Special Issue? :	Not applicable (regular submission)

SCHOLARONE™
Manuscripts

Vortex Identification in Turbulent Flows Past Plates using Lagrangian Method

Bashar Attiya^{a,b}, I-Han Liu^a, Muhannad Altimemy^{a,c}, Cosan Daskiran^a and Alparslan Oztekin^{a,*}

^aP.C. Rossin College of Engineering and Applied Science, Lehigh University, Bethlehem, PA 18015

^bHaditha Hydropower Station, Ministry of Electricity, Haditha, Iraq

^cCollege of Engineering, Thi-Qar University, Thi-Qar, Iraq

*Corresponding author (alo2@lehigh.edu)

Abstract

Vortex identifications in turbulent flows past arrays of tandem plates are performed by employing the velocity field obtained by high fidelity large eddy simulations (LES). Lagrangian coherent structures (LCSs) are extracted to examine the evolution and the nonlinear interaction of vortices and to characterize the spatial and temporal characteristics of the flow. LCSs identification method is based on the Finite-Time Lyapunov Exponent (FTLE) which is evaluated using the instantaneous velocity data. The simulations are performed in three-dimensional geometries to understand the physics of fluid motion and the vortex dynamics in the vicinity of plates and surfaces at Reynolds number of 50,000. The instantaneous vorticity fields, Eulerian Q -criterion and LCSs are presented to interpret and understand complex turbulent flow structures. The three-dimensional FTLE fields provide valuable information about the vortex generation, spatial location, evolution, shedding, decaying and dissipation of vortices. It is demonstrated here that FTLE can be used together with Eulerian vortex identifiers to characterize the turbulent flow field effectively.

Keywords

Large eddy simulations; vortex detection, visualization and dynamics; Lagrangian coherent structures; turbulent flows

1. Introduction

Coherent structure is a concept that was introduced to characterize turbulent flow field. It can be defined simply as a mass of turbulent mixing fluid where there is a lower level of movement than the expected level associated with the velocity field; indicating that the mass of fluid exhibit coherent characteristics over a certain time window [1, 2]. Many visualization approaches are developed to detect and visualize coherent structures in turbulent flows. Even though the vortex detection, visualization, and dynamics of flow receive considerable interest in the field of fluid dynamics, a clear and unambiguous definition of a vortex is still an open question [3]. The ambiguity is coming from the lack of a clear definition of the vortex edges. The definition of a vortex is described as a circulating motion resides in the flow, and thus based on this definition, regions can be classified as either low or high regions of vortical activity. However, a universal agreement about how far the vortex edges can extend from the vortex center of rotation is not available [4, 5]. Moreover, an accurate threshold that can be implemented to describe the intensity of the vorticity is also difficult to define [6, 7]. An objective and unambiguous definition for the vortex is crucial in understanding of the vortex dynamic which includes the generation and the evolution of a vortex within the turbulent flows. Generally, there are two methods to identify coherent structures: Eulerian and Lagrangian. The most widely used is the Eulerian method, which directly relies on the instantaneous velocity field and its gradient [8, 9]. Although they have been used extensively in vortex dominated flows, they have several disadvantages [10]. For example, Eulerian methods are variant with respect to the time-dependent rotations of the reference frame, and hence they are not objective [6]. Additionally, Eulerian methods require a user-defined threshold to identify the regions with coherent structures. The Γ_1 -criterion [9], Q -criterion [11], λ_2 criterion [8] are some examples of the widely used Eulerian methods.

In contrast, Lagrangian coherent structures (LCS) methods proposed by Haller [6] and studied by Shadden *et al.* [12] and several other investigators [13, 14, 15] are objective in identifying a vortex compared to Eulerian methods. LCS methods identify coherent structures based on the flow properties

51 along the trajectories of tracer fluid particles. The key advantage of such methods is that they are
52 independent of the rotations of the reference frame. An additional advantage of LCSs lies within the fact
53 that it is relatively insensitive to the anomalies in the velocity data as long as the anomalies remain
54 spatially and temporarily localized [13, 14, 15]. LCS methods have been used successfully for
55 experimental and computational studies. Shadden *et al.* [12] proposed an approach to identify LCS. They
56 stated that LCS could be characterized as the ridges of Finite-Time Lyapunov Exponent (FTLE) fields.
57 FTLE ridges represent the locations that show a maximum degree of separations among trajectories of
58 several fluid particles. They reported that FTLE fields have a high capability to detect unsteady separation
59 profiles in highly chaotic flows over structures. This approach will be implemented in the present study to
60 get a better understanding of the turbulent coherent structures in the wake of flow past arrays of tandem
61 plates.

62 Green *et al.* [16] employed LCS method to investigate the formation and evolution of the
63 unsteady wake behind a pitching panel for Reynolds numbers in the range of 4,200 – 14,000. Their
64 experimental study illustrated that the LCS reveals and identifies patterns as a quantitative event in a way
65 not dependent on the user-defined arbitrary threshold. Kourentis *et al.* [17] identified LCS associated with
66 the results acquired from the turbulent wake of a circular cylinder at Reynolds number of 2,150. To
67 identify the LCSs, they used the most widely used approach, FTLE method [6]. They reported that the
68 LCSs provide a powerful visualization tool that can be used to reveal the vortex street in the cylinder's
69 wake. Recent studies successfully implemented the Lagrangian method to investigate the cavitating
70 turbulent flows around hydrofoil [18, 19, 20, 21]. Cheng *et al.* [18] and Long *et al.* [19] identified two and
71 three-dimensional FTLE fields, respectively, to analyze turbulent flows around the Delft twisted
72 hydrofoil. Their results showed a very good correlation between the FTLE and the Eulerian vortex
73 identification techniques. The three-dimensional LCSs [19] provides a promising visualization alternative
74 to study the vortex dynamics in turbulent flows. Tseng & Liu [20] and Cheng *et al.* [21] implemented the
75 Lagrangian approach to study the dynamics of the cavitating turbulent flows over the ClarkY hydrofoil.

They reported that LCSs provide a better understanding of the cavitation evolution, and the spatial and temporal characteristics of the wake flow. The present authors have applied the Lagrangian approach to study the turbulent wake of flows past arrays of tandem plates in a two-dimensional geometry [22]. It is reported that LCS provides very clear turbulent coherent structures within the flow domain when compared with instantaneous vorticity fields.

Turbulent flows past bluff bodies with different arrangements have received significant attention. Understanding the complex phenomena related to fluid-structure interactions, such as vortex formation, flow separation, reattachment, and hydrodynamic loadings are necessary for the design process of structures. The complex nature of turbulent flows with the non-linear and strongly coupled interactions complicates the hydrodynamic loadings exerted on the structures. Off-shore constructions, submerged bridges piers, and marine-current energy harvesting devices are some examples of such systems. Recently, Liu *et al.* [23] investigated the flows past a single and arrays of plates by conducting three-dimensional LES simulations with Reynolds number of 50,000. They reported that the spacing and the spatial position of the plates influence the flow patterns and the hydrodynamic forces exerted on plates. In the case with a tight gap between the plates, the downstream plate experiences a much lower drag coefficient compared to that of the upstream plate. As the gap between plates increases to 20 heights of the plate, the drag coefficient of the downstream plate is fully recovered. Liu *et al.* [24] conducted an experimental study to characterize the flow around two identical square cylinders in a tandem arrangement. The distance between the two cylinders varies from $1.5D$ to $9D$, where D is the diameter of the cylinder. Reynolds number is ranging from 2,000 to 16,000. They reported that the flow characteristics around the two cylinders are profoundly influenced by the length to diameter ratio and the spacing between the cylinders. The experimental study by Yen *et al.* [25] using two tandem square cylinders placed in a vertical water tank showed that multiple shedding modes occur depending on different spacing and spatial position of the downstream cylinder. Sohankar [26] studied the wake flow interaction between two square cylinders in a tandem arrangement by conducting Large Eddy Simulations

(LES) and reported that highly vortical activities with distinct patterns and discontinuities occur corresponding to different spacing. Liu & Oztekin [27] studied flows past arrays of a finite plate placed near the rigid surfaces using LES. They reported that the drag forces decrease rapidly when the plate is situated very close to the wall. Their results reveal strong interactions between the wall boundary layer and the plate. Huang *et al.* [28] analyzed the flow over tandem cylinders near a moving wall to investigate the effect of wall presence on the wake dynamics. They reported that the wall affected the flow dynamics and shedding structures which in turn promoted higher fluctuations in the hydrodynamic loading exerted on the cylinders.

Flows past arrays of finite plates are studied to characterize turbulent flows using the LCS method in three-dimensional geometries. The motivation of this work is to identify three-dimensional LCS in complex turbulent flows past arrays of plates. LCS approach using FTLE fields is compared against the Eulerian methods of Q -criterion. To the best of the present authors' knowledge, Lagrangian coherent structure method in conjunction with three-dimensional turbulent flows past tandem finite plates at high Reynold number has not been investigated. The equations governing the FTLE to capture the LCSs are described. The validation of the LCS analysis and the FTLE is presented. Results will be presented for turbulent flows past arrays of finite plate confined in a channel to elucidate the effectiveness of LCS and to characterize complex turbulent flows.

NOMENCLATURE

A	projection area	Δt	time step size
C_D	drag coefficient	u_i, u_j	velocity
C_L	lift coefficient	$\bar{u}_i, \bar{u}_j$	resolved scale velocity vector
C_p	pressure coefficient	U_∞	free stream velocity
C_w	WALE constant	V	volume of cell
D	plate height	w	prism width
d	tip to the centerline distance	ω	vorticity magnitude
F_D	drag force	x_i, x_j	position vector
F_L	lift force	y	distance to the nearest wall
$FTLE$	Finite-time Lyapunov exponent		
G	spacing distance		

GREEK SYMBOLS

L	prism length	θ	yaw angle
L_s	SGS mixing length	δ_{ij}	Kronecker delta
N	number of cells	μ	dynamic viscosity
$\bar{p}$	resolved pressure	ν	kinematic viscosity
p_∞	reference pressure	ν_t	SGS eddy viscosity
Re	Reynolds number	ρ	density
SGS	subgrid scale	κ	von Karman constant
$\bar{S}_{ij}$	rate-of-strain tensor		
t	time		

2. Mathematical Model

2.1 Governing Equations - Turbulence Modeling

LES model, which applies spatial filtering to the Navier-Stokes equations, is used in the current study. The large-scale eddies are resolved explicitly, while the eddies smaller than the grid size are modeled with a subgrid scale (SGS) model. Since the present study aims at identifying individual coherent structures, the large-scale turbulent structures should be resolved in the flow domain. Therefore, the LES model is preferred to obtain the flow field.

The filtered form of Navier-Stokes equations with the low pass filtering is given by:

$$\frac{\partial \bar{u}_j}{\partial x_j} = 0 \quad (1)$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_j \bar{u}_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} \quad (2)$$

Here $\bar{u}_j = u_j - \hat{u}_j$ is the filtered velocity vector and the over bar stands for the filtering operator; ρ represents the density of the fluid; $\bar{p}$ is the resolved pressure; t represents the time, and the subgrid shear stress is given by: $\tau_{ij} = \overline{u_i u_j} - \bar{u}_j \bar{u}_i$, which is computed through the subgrid-scale (SGS) models. By applying the Boussinesq hypothesis, the SGS turbulent stress is computed by:

$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = -2\nu_t\bar{S}_{ij} \quad (3)$$

Here δ_{ij} is the Kronecker delta; ν_t is the SGS eddy viscosity; τ_{kk} subgrid-scale stresses, and $\bar{S}_{ij} = \frac{1}{2}\left(\frac{\partial\bar{u}_i}{\partial x_j} + \frac{\partial\bar{u}_j}{\partial x_i}\right)$ is the strain-rate tensor. The wall-adapting local eddy-viscosity (WALE) method [29] is implemented to calculate the SGS eddy-viscosity:

$$\nu_t = L_s^2 \frac{(S_{ij}^d S_{ij}^d)^{3/2}}{(\bar{S}_{ij}\bar{S}_{ij})^{5/2} + (S_{ij}^d S_{ij}^d)^{5/4}} \quad (4)$$

$$S_{ij}^d = \frac{1}{2}\left(\left(\frac{\partial\bar{u}_i}{\partial x_j}\right)^2 + \left(\frac{\partial\bar{u}_j}{\partial x_i}\right)^2\right) - \frac{1}{3}\delta_{ij}\left(\frac{\partial\bar{u}_k}{\partial x_k}\right)^2 \quad (5)$$

$$L_s = \min(\kappa y, C_w V^{1/3}) \quad (6)$$

where L_s represents the mixing length for subgrid scales; κ is the von Karman constant; y is the shortest distance to the wall; the WALE constant C_w is 0.325; and V is the mesh cell volume. In the WALE model, the eddy-viscosity will be approximately zero in regions close to walls without applying any damping function. This is necessary to ensure proper near-wall scaling for the eddy-viscosity. Further details of the WALE model are documented by Nicoud and Ducros [29].

2.2 Lagrangian Coherent Structures Analysis

The approach that is used to identify LCS was introduced by Shadden *et al.* [12]. This approach relies on detecting ridges with a high degree of separation in the FTLE fields to define LCS. In order to evaluate FTLE fields, fluid particle tracers need to be tracked inside the flow domain for a finite interval of time. The velocity data generated by LES simulations are prerequisite to computing the FTLE fields. Here, we will briefly describe the theory and notation related to the evaluation of the FTLE. Further descriptions and details are available in Ref. [12, 30].

First, the FTLE evaluation requires the time-dependent velocity field, $u(x,t)$, which is defined on the three-dimensional domain $x \in \mathbb{R}^3$, over a finite time interval $t \in (t_0, t_1)$. The velocity field $u(x,t)$ may be provided by means of analytical solutions, experimental or numerical simulation results [31]. Taking into account the time interval, $t \in (t_0, t_1)$, the flow map $\Phi_{t_0}^{t_1}(x_0, t_0)$ can then be defined as the function that execute the integration of the passive tracers starting from the initial position, x_0 , at time t_0 along the tracers trajectories to their advected location, x , at time t_1 . The flow map is defined as:

$$\Phi_{t_0}^{t_1}(x_0, t_0) = x_0 + \int_{t_0}^{t_1} u(x(\tau), \tau) d\tau \quad (7)$$

The objective is to detect the ridges where the degree of stretching of particle trajectories is the greatest. The stretching, distance between the two particles, is initially set by the infinitesimal perturbation, δx_0 . After time t_1 , the two particles will be separated by distance, δx . This separation can be written in terms of the flow map in Eq. (7) [30]:

$$\begin{aligned} \delta x(t_1) &= \Phi_{t_0}^{t_1}(x_0 + \delta(x_0), t_0) - \Phi_{t_0}^{t_1}(x_0, t_0) \\ &= J\Phi_{t_0}^{t_1}(x_0, t_0)\delta(x_0) + H.O.T \end{aligned} \quad (8)$$

Here, $J\Phi_{t_0}^{t_1}(x_0, t_0)$ represents the Jacobian of the flow map which is evaluated at the initial particle coordinate x_0 . The magnitude of separation, $\|\delta x(t_1)\|$, is found by:

$$\begin{aligned} \|\delta x(t_1)\| &= \sqrt{\langle [J\Phi_{t_0}^{t_1}(x_0, t_0)]\delta x_0, [J\Phi_{t_0}^{t_1}(x_0, t_0)]\delta x_0 \rangle} \\ &= \sqrt{\langle \delta x_0, [J\Phi_{t_0}^{t_1}(x_0, t_0)]^T [J\Phi_{t_0}^{t_1}(x_0, t_0)]\delta x_0 \rangle} \end{aligned} \quad (9)$$

where, $[]^T$, denotes the transpose, and $\langle ., . \rangle$ indicates the Euclidean inner product. The Cauchy-Green deformation tensor can be defined from the above equation as follows:

$$C_{t_0}^{t_1}(x_0, t_0) = [J\Phi_{t_0}^{t_1}(x_0, t_0)]^T [J\Phi_{t_0}^{t_1}(x_0, t_0)] \quad (10)$$

The principal eigenvalue of the Cauchy-Green deformation tensor, $C_{t_0}^{t_1}(x_0, t_0)$, defines the extent of stretching for the specified time interval, (t_0, t_1) , of the initially adjacent path lines at a time t_0 . Finally, the FTLE field representing the maximum stretching rate over the finite time interval (t_0, t_1) is given in Eq. (11):

$$\sigma_{t_0}^{t_1}(x_0, t_0) = \frac{1}{|t_1 - t_0|} \log \sqrt{\lambda_{\max}(C_{t_0}^{t_1}(x_0, t_0))} \quad (11)$$

The FTLE evaluation can be done either in forward time ($t_1 > t_0$) or in backward time ($t_1 < t_0$). Forward and backward integration produce two different types of LCS; forward time integration produces a repelling LCS while backward integration produces an attracting LCS [12]. In the present study, the FTLE fields for all cases are computed using the backward time integration for a better visualization of the vortex shedding. The LCS visualization is presented in comparison with the Q -criterion in order to be consistent with previously published studies [3, 13, 22].

3. Numerical method and computational overview

LES turbulent model is employed to simulate flows past array of plates in three-dimensional geometries at Reynolds number of 50,000. Reynolds number is defined as $Re = \rho U_\infty D / \mu$, where U_∞ is the free stream velocity, D is the plate height, and μ is the dynamic viscosity. The implementation of high fidelity LES model aids in identifying coherent structures accurately. The numerical code used to extract LCS is generated in-house, and the authors are pleased to share with other researchers upon request.

The simulations are performed by utilizing the open source Computational Fluid Dynamics (CFD) software package OpenFOAM. Transient flow solver, pimpleFoam combining two algorithms: Pressure-Implicit with Splitting of Operators (PISO) and Semi-Implicit Method for Pressure-Linked Equations (SIMPLE), is used. The adjustable time step based on the dimensionless Courant–Friedrichs–Lewy

condition (CFL) number of less than one is used for all simulations. The second order discretization schemes are utilized for the time discretization and also for convection and diffusion terms. Further descriptions of these discretization methods can be found in Ref. [32].

The schematic of the three-dimensional computational domain for flows past arrays of plates is depicted in Fig. 1 (a). The two plates positioned perpendicular to the incoming flow direction are arranged in a tandem array. The plate tip angle is illustrated in the side view ($z = 0$ plane) of the tandem plates in Fig. 1 (b). The geometry of a single plate is illustrated in Fig. 1(c), where, L , D , and w are the plate's length, height, and width, respectively. The gap between the two tandem plates is indicated by G , the distance from the top of the plate to the top wall is indicated by H_T , and the distance from the bottom of the plate to the bottom wall is indicated by H_B . Plates are labeled as P1 and P2, numbered in order from upstream to downstream. In all cases, the spatial distance from the inlet boundary to the upstream plate is chosen to be $12.5D$, and the distance from the downstream plate to the outlet boundary is selected to be $25D$. The size of the computational domain is selected in a manner to minimize the influence of the inlet and the outlet boundary conditions on the flow field near the plates. The top and bottom surfaces are rigid walls. Two cases are considered: 1) $H_B = 8D$, $H_T = 8D$ – plates are placed away from rigid walls so that the effects of the walls on the flow near the plates are negligible and 2) $H_B = 8D$, $H_T = 0.1D$ – the plates are close enough to the top wall so that a strong influence of the wall on the flow near plates is expected. For the case 1, the plates have a 45° corner angle (see Fig. 1) and for the case 2, the plates have a 90° angle.

Fig. 1. Schematic diagram of the arrays of plate: (a) three-dimensional illustration of the computational domain, (b) side view illustrated at $z = 0$ plane and (c) plate geometry.

No-slip and no-penetration boundary conditions are applied at the plate surface and the top and bottom boundaries of the computational domain. The side boundaries of the computational domain are set with periodic boundary conditions. Uniform velocity is applied at the inlet with the velocity magnitude of 0.5 m/s in the streamwise direction. The outlet boundary is set to be zero-gage pressure. Geometric parameters with physical properties and flow parameters are tabulated in Table 1 for the case 1.

Table 1. Parameters used in the case 1.

<i>Parameter Values</i>					
D	0.1	[m]	U_{∞}	0.5	[m s ⁻¹]
L	1	[m]	w	0.01	[m]
G/D	5,7,10	[-]	ρ	1000	[kg m ⁻³]
Re	50,000	[-]	μ	0.001	[kg m ⁻¹ s ⁻¹]
H_T	$8D$	[m]			
H_B	$8D$	[m]			

The mesh structure for a single plate in the side view ($z = 0$ plane) and for the array of plates in the top view ($y = 0$ plane) are depicted in Fig. 2, respectively. Mesh refinement is applied in regions near surfaces to ensure that boundary layer separation and small eddies can be captured. The mesh element size is gradually increased away from surfaces.

Fig. 2. The mesh structure around (a) the plate in the x - y plane and (b) the array of plates in the x - z plane.

4. Validation and Convergence

4.1 Validation Study of the Mathematical Model and the Numerical Method

The mathematical model and numerical methods used in the current study are validated by conducting a three-dimensional LES simulation for flow past a cylinder with a diameter of 0.06 m confined in a channel. The dimensions of the channel are $0.6 \times 0.6 \times 2.4$ m in width, height, and length, respectively. Reynolds number of the flow based on the cylinder diameter and a free stream velocity, 0.15

m/s, is calculated to be 9,000. The geometry of the computational domain depicted in Fig. 3 and the parameters of the validation study listed in Table 2 match the recent experiments of Rockwood *et al.* [35]. The frequency of the vortex shedding and the evaluated FTLE fields are compared with the experimental results of Rockwood *et al.* [35].

Fig. 3. Computational domain of the validation simulation. (a) Three-dimensional view, (b) side view, and (c) the cylinder geometry.

Table 2. Parameters used in the validation study.

Parameter Values					
D	0.06	[m]	U_∞	0.15	[m s ⁻¹]
L	0.6	[m]	ρ	1000	[kg m ⁻³]
Re	9,000	[-]	μ	0.001	[kg m ⁻¹ s ⁻¹]

For the validation study, the computational domain was divided using structured mesh of 12 million elements, with high refinement near the cylinder with first layer thickness of 1×10^{-4} m. The mesh

yields the maximum value of $y^+ \approx 3$, the minimum value of $y^+ \approx 0.05$, and the mean value of $y^+ \approx 1$ along the surface of the cylinder. The maximum value of the Courant–Friedrichs–Lewy condition (CFL) number is less than unity and the mean value of CFL is about 0.06. In order to describe how the turbulent kinetic energy is distributed between the different sizes of vortices, the “Kolmogorov -5/3 spectrum” is evaluated [33, 34]. The time evolution of the pressure coefficient, $C_p = (p - p_{atm})/(\frac{1}{2}\rho U_\infty^2)$, at the location $(x/D = 1, y/D = 0, z/D = 0)$ upstream of the cylinder is shown in Fig 4(a). The power spectrum density (PSD) of the pressure coefficient signal is shown in Fig 4(b). The pressure power spectrum decays with a slope of about -5/3; indicating that the LES model with the spatial and temporal resolution employed can capture the characteristics of turbulent flow structures.

Fig. 4. (a) The pressure coefficient versus time and (b) the power spectral density (PSD) of the pressure coefficient signature at the location $(x/D, y/D, z/D) = (1, 0, 0)$ upstream of the cylinder.

The lift and drag coefficient are defined as:

$$C_L = \frac{F_L}{\frac{1}{2}\rho U_\infty^2 A}, \quad C_D = \frac{F_D}{\frac{1}{2}\rho U_\infty^2 A} \quad (12)$$

where F_L and F_D are the lift and the drag force exerted on the cylinder, and A is the reference area of the cylinder. The lift and drag forces are computed from the pressure and viscous forces exerted at all mesh elements on the surface of the plates. The time signature of drag and lift coefficients shown in in Fig. 5 have fluctuations induced by the alternating vortex from the cylinder. The frequency of fluctuations, f , is

evaluated by conducting fast Fourier transform to the time signature of C_L . The dimensionless frequency, Strouhal number, is defined by $St = fD/U_\infty$. The predicted value of the Strouhal number of the vortex shedding agrees well with the measured value, as listed in Table 3.

Fig. 5. The time signature of (a) the drag and (b) lift coefficient as a function of the non-dimensional time ($\lambda = tU_\infty/D$) obtained from the validation simulation.

Table 3. Comparison with experimental data

	Rockwood <i>et al.</i> [35]	Present Study
$St [-]$	0.21	0.21
$f [Hz]$	0.53	0.54

Contours of the LCS evaluated based on the FTLE fields and the normalized Q -criterion, ($Q \times (D/U_\infty)^2$), are depicted in Fig. 6. The LCS is acquired through the integration over two vortex shedding cycles (3.68s). The time interval for the integration coincides with the integration time that was used to detect the FTLE fields in the experiment. The Q -criterion, an Eulerian scalar, is the second invariant of the velocity gradient tensor, which is used to visualize the three-dimensional vortical structures [36]. The Q -criterion is evaluated by $Q = -0.5(\|S\|^2 - \|\Omega\|^2)$, where $S = 0.5[\nabla u + (\nabla u)^T]$ and $\Omega = 0.5[\nabla u -$

($\nabla u)^T$] are the symmetric rate of strain and the antisymmetric rate of rotation tensors, respectively. ∇u identifies and describes the flow regions that possess local rotational movements as vortex core regions [3, 11]. Fig. 6 (a) shows instantaneous contours of the normalized Q -criterion rendered at the $z=0$ plane, which illustrates the spatial distribution and the intensity of the vortices in the near wake region. The LCS depicted in Fig 5(b) detects the boundaries of the vortex and reveals the evolution of vortices. Both Q -criterion and FTLE fields predicted by our simulations agrees reasonably well with the results reported in [35]. The agreement between predicted and measured flow images and hydrodynamic loadings proves that the mathematical model and the numerical methods employed can accurately characterize the spatial and temporal nature of the turbulent flow fields near the finite plate placed in the close proximity of a free surface .

Fig. 6. Vortex formation in the near wake region illustrated by (a) the normalized Q -criterion ($Q \times (D/U_\infty)^2$) contours evaluated at the time $tU_\infty/D = 200$ and by (b) contours of the FTLE fields .

4.2 Spatial Convergence of LES

Mesh optimization study for LES simulations is conducted using three mesh densities: $N_1=1.4 \times 10^6$ cells, $N_2=2.8 \times 10^6$ cells and $N_3=5.6 \times 10^6$ cells. Flows past a tandem array of finite plates separated by $5D$

is considered for the mesh independence study. The averaged values of the drag coefficients are computed for each plate using N_1 , N_2 and N_3 mesh. The drag coefficients predicted for the upstream plate (P1) and the downstream plate (P2) using N_2 and N_3 mesh are nearly the same, as listed in Table 4. This result implies that N_2 is sufficient to ensure the spatial convergence. Table 4 also list the averaged value of y^+ with the mean and maximum values of CFL number obtained for N_1 , N_2 and N_3 mesh. The value of y^+ decreases from 12.78 for N_1 to 6.82 for N_3 along the wall of the upstream plate and from 21.87 for N_1 to 8.64 for N_3 along the downstream plate.

Table 4. Results of the mesh independence study.

Mesh Size	CFL_{mean}	CFL_{max}	P1		P2	
			y^+	$\bar{C}_D$	y^+	$\bar{C}_D$
N_1	0.031	1.0	12.78	1.40	21.87	0.052
N_2	0.019	1.0	9.50	1.44	12.73	0.072
N_3	0.011	1.0	6.82	1.46	8.64	0.078

4.3 Temporal and Spatial Convergence of LCS

The evaluation of FTLE fields is dependent on both the integration time, $\Delta t = |t_1 - t_0|$, and the size of the structured grid of particles to be tracked [14]. In order to assess the temporal and spatial convergence of LCS, the FTLE was evaluated for different values of the integration time span and two different meshes. Fig. 7 shows the FTLE fields evaluated at an integration time of $\Delta t = 0.5$ s, 1 s, and 1.5 s. A first look at the images reveals that longer integration time will enhance the evaluation of the FTLE. The increased integration time can aid in evaluating the LCS with a higher extraction accuracy of the FTLE ridges. More coherent structures are revealed, and the topology of structures becomes clearer. This relation between the integration time and the level of the FTLE field's details is consistent with that reported by Green *et al.* [14]. However, a further increase in the integration time increases the population of LCS, which causes a loss of clarity in the flow images. Fig. 7 (b) and (c) show that the prevailing structures of the LCS for the integration times of 1 s to 1.5 s are nearly the same. Yet, a high distortion in the LCS images is noticed in the case of 1.5s integration time. This can be related to the generation of

multiple vortices during a longer period of the integration time. Several large scales dominant vortices will be overlapped, and flow images become slightly hazy for the longer integration time. It is shown that there is an optimal integration interval to extract LCS. The integration time of 1s is suggested for flows in an unbounded domain and 0.5 s for flows near the rigid wall. Determining the optimum integration interval will also help in minimizing the computational resources required for the LCS extraction.

The effect of the number of tracer particles on the FTLE fields is shown in Fig. 8. The FTLE fields predicted by two structured grids: one with 0.25 million grid points and one with 1 million grid points. The integration time was fixed at $t = 0.5$ s to reduce the need for computational resources. The two images show that the topology of the FTLE fields is similar for the main boundaries, but the flow image obtained with the denser grid is sharper. The FTLE ridges obtained with the denser grid are thinner with a greater value. As a result, more details of particle trajectories are revealed. However, simulations using a denser mesh require more computational resources to extract the FTLE fields. For a consideration of the spatial accuracy and the computational cost; the FTLE fields in this study were extracted and evaluated using 1 million structured grid points.

Fig. 7. FTLE contours depicted at $y = 0$ plane obtained using a integration time of (a) $t = 0.5$ s, (b) $t = 1$ s, and (c) $t = 1.5$ s.

Fig. 8. FTLE contours at the $y = 0$ plane obtained using (a) 0.25 million grids and (b) 1 million grids. The integration time is $t = 0.5$ s.

5. Results

5.1 Flows Past Arrays of Plates in an Infinite Domain

Simulations of flows past two plates of 45° corner in a tandem arrangement are conducted in three-dimensional geometries at $Re = 50,000$. Spacing, G , between the plates is $5D$, $7D$, and $10D$ and the distance from the bottom and the top wall is $H_B = 8D$, $H_T = 8D$, respectively. Since the plates are far away from the rigid walls, the effects of the wall on the flow field near the plate are negligible, and these flows are referred as flows past plates in an unbounded domain. Additionally, the hydrodynamic loadings on the plates are investigated and presented.

Fig. 9 and Fig. 10 depict the contours of the instantaneous normalized vorticity ($\omega D/U_\infty$), Q -criterion ($Q \times (D/U_\infty)^2$), and LCSs based on the FTLE field. Images are rendered at $y = 0$ plane (see Fig. 9) and $z = 0$ plane (see Fig. 10) at $\lambda=150$. The predefined arbitrary user threshold which needs to be applied for the Eulerian Q -criterion and vorticity is selected to be the same scale with FTLE fields for a proper comparison. The generated vortex shedding from the upstream plate interacts with the downstream plate, the level of interaction is highly dependent on the spacing between the plates, as also reported by Liu *et al.* [23]. The upstream plate generates a shear layer that rolls up downstream and generates multiple vortices. These vortices deform and spread in all directions in the wake region behind the upstream plate. They interact vigorously and blend together with the vortices generated from the downstream plate. As a result, highly turbulent vortical activities are seen at the front and back face of the downstream plate for each geometry, as shown in Fig. 9 (a, d, g). For the tighter spacing, $5D$, the downstream plate is engulfed by the shear layers induced by the upstream plate, as shown in Fig. 10 (a). For all cases the vortex shedding pattern of the downstream plate is strongly influenced by the wake flow induced by the upstream plate, as shown in Fig. 9 (d, e, g, h) and Fig. 10 (d, e, g, h). Contours of the instantaneous vorticity shown in Fig 8 and Fig 9 reveal very little or no information about the origination and the evolution of the vortices. In principle, the vorticity contours show the regions with the highest vorticity magnitude (vortex core) with its spatial position inside the flow. Vortex core can provide a premise about a coherent vortex, which could be a good candidate for an identification of coherent vortex structures. However, identifying coherent vortical structures in complex flows such as the one studied here using the vortex core intensity alone is not adequate. This is due to the fact that the higher vortex core intensity is influenced by the user predefined threshold, the user judgements, and the selected reference frame [5]. Moreover, it does not provide any information about the vortex boundaries, regions with strong dynamics controlling the vortical structures' creation, decay, and interaction. Such a deeper understanding of the vortex dynamics can be available with the identification of the LCS in complex turbulent flows.

The Q -criterion depicted in Fig. 9 (b, e, h) and Fig. 10 (b, e, h) reveals instantaneous structures inside the flow with $Q > 0$ as coherent structures, in which the rotation dominates over the strain [37]. In contrast; the FTLE fields depicted in Fig. 9 (c, f, i) and Fig. 10 (c, f, i) shows the evolution of highly coherent vortex structures generated from the upstream plate tips which then spread in the streamwise direction and interact with the vortex structures originating from the downstream plate. Again, as in the Eulerian Q -criterion, for the case with tighter spacing, $5D$, the LCSs are equally concentrated in the front and back faces of the downstream plate. While for the larger spacing cases, the main concentration of LCSs are at the back of the downstream plate. In those cases, few coherent structures can be seen to extend all the way from the tips of the upstream plate until it resides at the front face of the downstream plate. LCSs show that the level of vortical activities between the two plates in the case of $G=5D$ is lower than the cases with $G=7D$ and $10D$, this is because the two plates in the case of $G=5D$ are acting like a single plate with no significant shedding from the downstream plate. The LCS also detected very clearly the shear layer and its separation from the upstream plate for all three spacing. It is evident that FTLE provides an effective tool to detect and reveal the coherent vortex structures and present an intriguing process for the mutual vortex interactions. While the flow field plots generated by Lagrangian and Eulerian methods are similar, the FTLE fields provide higher resolution images with highly detailed flow structures. Comparing the output of the two approaches, FTLE fields detect coherent structures in the flow domain where the Q -criterion could not. Figure 9 and Figure 10 show the contrast difference between the two methods for the evolution and interaction of the detected vortices. The reason for lack of correlation between the two approaches and the presence of discrepancy is the arbitrary threshold used in Q -criterion. Smaller threshold values will give a higher vortex intensity and will change the spatial position distribution due to the generation of new rotational core regions. In contrast, FTLE spatial distribution is independent of any arbitrary threshold. Additionally, some of the discrepancy seen in the results might be because Q -criterion relies on the second invariant of the velocity gradient; making it highly sensitive to any abnormality in the input data. Lagrangian approach tracks the velocity changes of the fluid particles along the particle paths, which make it insensitive to the short-term abnormality in the

velocity input. Thus, the Lagrangian approach of detecting coherent structures is better when compared to the instantaneous Q -criterion contours. Identification of such coherent structures is beneficial in the process of understanding the fluid-structure interactions, which is attempted in this study for the three-dimensional turbulent flows past finite plates.

Fig. 9. Instantaneous contours of normalized vorticity (a, d, g), contours of normalized Eulerian Q -criterion (b, e, h) at constant value of $Q = 0.025$, and FTLE contours (c, f, i). Eulerian flow images are rendered at time $\lambda = 150$ for flow past two tandem plates. Plates are separated by $5D$ (a, b, c), $7D$ (d, e, f), and $10D$ (g, h, i).

Fig. 10. Instantaneous contours of normalized vorticity (a, d, g), contours of normalized Eulerian Q -criterion (b, e, h) at constant value of $Q = 0.025$, and FTLE contours (c, f, i). Eulerian flow images are rendered at time $\lambda=150$ for flow past two tandem plates. Plates are separated by $5D$ (a, b, c), $7D$ (d, e, f), and $10D$ (g, h, i).

Instantaneous isosurfaces of the Eulerian Q -criterion colored by normalized vorticity at the user-defined threshold of $Q = 0.025$ and the isosurfaces of the FTLE are illustrated in Fig. 11. Since the two tandem plates studied here have finite length, the vortices generated from the plate tips wrap around the end of plates, as shown in Fig. 11 (a, c, e). However, because the length to height ratio is large, these tip vortices have a slight influence on the wake flow structures, as illustrated by the iso-surfaces of FTLE and the Q -criterion. Although the isosurfaces of the Q -criterion provide an idea about coherent vortex structures, they are highly sensitive to the arbitrary thresholds defined by the user. In this study, the authors experimented with various threshold values and selected $Q = 0.025$. The choice was merely based on the authors own judgments of what is clearer and more appropriate to present. The isosurfaces of the

FTLE ridges reveal the same general patterns of Q -criterion. LCS images clearly illustrate that the flows in the vicinity of the plates are dictated by Karman vortex shedding from the top and bottom sides of the plate, as seen in Fig. 11 (d and f).

Fig. 11. (a, c, e) Instantaneous normalized isosurfaces of Q -criterion at a constant value of 0.025 colored with normalized vorticity, and FTLE isosurfaces (b, d, f). Eulerian Q -criterion images are rendered at time $\lambda=150$ for flow past two tandem plates. Plates are separated by $5D$ (a, b), $7D$ (c, d), and $10D$ (e, f).

Fig. 12 shows the time signature of the drag coefficient for the upstream and downstream plate. The spacing between plates has a profound influence on the drag exerted on the downstream plate. For $5D$ spacing, the drag coefficient fluctuates about nearly zero nominal value. The drag coefficient of the downstream plate recovers by roughly 80% for $7D$ spacing and even exceed the drag of the upstream plate for $10D$, as seen in Fig. 12. The recovery of drag coefficient with increased spacing occurs with a shorter distance for plates with 45° corner angle compared to those with 90° reported in Refs [23, 38]. The dependence of the drag coefficient of the downstream plate on the spacing can be explained by examining the LCS depicted in Figs. 8 and 9. The population density of LCS in regions near the front and back face of the downstream plate is nearly the same for $5D$ while the population density is significantly reduced in the region near the front face of the downstream plate for $7D$. For $10D$ spacing, only a few LCS in the region near upstream of the downstream plate is identified. The population density of LCS is directly correlated with the pressure distribution: the lower pressure is observed in regions with a higher population of LCS. Contours of pressure coefficient along the front and back face of both plates are depicted in Fig. 13 for $5D$, $7D$ and $10D$ spacing. The pressure coefficient is defined by $C_p = (p - p_\infty) / (\frac{1}{2}\rho U_\infty^2)$. The low pressure is observed along the front and rear face of the downstream plate with a similar level for $5D$; explaining the reason for attaining a low drag coefficient for this plate. The drag force exerted on the plate in these flows is governed by the pressure difference between the front and back face of the plate. The pressure difference between the front and rear face is increased greatly for $7D$, as depicted in Fig. 13. For $10D$ spacing, the pressure difference between the two faces of the plate is further increased. As a result, the drag coefficient of the downstream plate is further decreased.

Fig. 12. Time evolution signature of the drag coefficient for the upstream (P1) and downstream (P2) plates. Plates are separated by: (a) $5D$, (b) $7D$ and (c) $10D$.

Fig. 13. Time-mean pressure coefficient contours distributed along the front and back surfaces of the upstream (P1) and downstream (P2) plates. Plates are separated by: (a) $5D$, (b) $7D$ and (c) $10D$.

5.2 Flows Past Arrays of Plates in the Vicinity of Surfaces

We next consider flows past a single plate and an array of tandem plates of 90° corner angle operating beneath a rigid wall, $H_B = 8D$ and $H_T = 0.1D$, to elucidate the capability of the FTLE fields in detecting LCSs at another fluid-structure interaction scenario. This type of flow involves highly complex vortex dynamics due to the interaction between the boundary layer and the plate(s) [27]. The FTLE fields are calculated using the structured mesh with 0.25 million grid points and the integration time of $t=0.35$ s for the single plate geometry and $t=0.5$ s for the arrays of two tandem plates geometry. Those parameters are selected to reduce the computational cost needed to compute the LCSs. The FTLE and the instantaneous Q -criterion contours of a single plate near a wall are illustrated in Fig. 14. The images are rendered at the $y = 0$ plane (a,b) and the $z = 0$ plane (c,d). The vortices shed from the bottom side of the plate advect

downstream. The FTLE field captures the evolution of these vortices and the instantaneous images of the Q -criterion display cores of these vortices, as seen in the side view of flow images in Fig. 14. It is noted that the intense FTLE ridges concentrated in the region behind the top side of the plate. These ridges are not extended away from the plate; implying the presence of a stationary vortex. The strong vortex core in the region where the FTLE ridges are sharper and brighter as seen in the Eulerian Q -criterion images. The lack of LCS and the vortex core in the region further downstream of the plate near the wall indicates subdued turbulent activities in this region. The top view of flow images indicates that there are strong vortical activities in the region near upstream of the plate. Vortices generated by the boundary layer of the wall impinge on the plate, as seen in the Lagrangian and Eulerian flow images. It is demonstrated here that the Lagrangian and the Eulerian flow images together can be used effectively to characterize the flow field. Even though the Q -criterion contours may lose some details because of its' instantaneous information, the contours of the Eulerian vortex field match well with the flow pattern revealed by LCS.

The FTLE and the instantaneous Q -criterion contours for the two tandem plates near a wall are presented in Fig. 15 for $G = 5D$. The vortices generated inside the boundary layer impinge on the upstream plate and strongly interact with the plate, see Fig. 15 (a and c). The vortex shedding from the top side of the upstream plate is suppressed by the wall boundary layer and the vortices generated from the bottom of the upstream plate expand downstream in the wake region and interact with the downstream plate. The shedding from the bottom side of the downstream plate becomes very irregular. Comparison of the spatial distribution and the intensity of the Eulerian Q -criterion depicted in Fig. 15 (b, d) with the Lagrangian FTLE fields depicted in Fig. 15 (a, c) illustrates that the Eulerian and Lagrangian flow images are very complimentary in characterizing the flow field in complex turbulent flows. It is shown that the Eulerian Q -criterion can capture the center of the vortex at any instant while the FTLE fields reveal the vortex boundaries with no user defined threshold.

Fig. 14 Instantaneous contours of normalized Eulerian Q -criterion (b, d) at a constant value of $Q = 0.025$, and FTLE contours (a, c). Eulerian flow images are rendered at time $\lambda = 150$ for flow past single plates.

Fig. 15 Instantaneous contours of normalized Eulerian Q -criterion (b, d) at a constant value of $Q = 0.025$, and FTLE contours (a, c). Eulerian flow images are rendered at time $\lambda = 150$ for flow past single plates.

6. Conclusion

High fidelity large eddy simulations are conducted for flows past arrays of finite plates confined in a channel. Three-dimensional and transient flow fields are characterized for various array configurations of plates. The Finite-Time Lyapunov Exponent (FTLE) fields are used to detect the three-dimensional Lagrangian coherent structures (LCSs) using the velocity fields obtained by LES. A parametric study is performed to determine the optimum time interval for the integration to obtain the FTLE field and the grid size to achieve the spatial resolution. Our results showed that a longer integration time could enhance the accuracy of the FTLE and the resulting LCS. However, no

additional structures were revealed with much longer integration time. A proper choice of the integration time varies with the turbulent characteristics of the flow, i.e., the integration time 1 s is appropriate for flows in an unbounded domain while less than 0.5 s is more appropriate for flows near the rigid surface. Increasing the number of the structured grid of tracer particles results in enhancing FTLE field accuracy, however, this will come with a higher computational cost.

The contours and isosurfaces of the FTLE fields and the Eulerian flow fields are presented to better understand the vortex dynamics and the nonlinear vortex interactions in these complex turbulent flows. The instantaneous flow structures reveal a high level of vortical activities in the flow domain. However, Lagrangian methods show coherent structures that are not visible in the instantaneous Eulerian fields. FTLE fields reveal coherent structures including the information about the vortex generation, spatial location, evolution, shedding, decaying, stretching and dissipation of vortices. The Eulerian Q -criterion does provide a spatial distribution of the vortices with intensity information only. Even with a lower integration time and a coarser grid of tracer particle, the LCS method still produces a framework for the vortex dynamics in complex turbulent flows. It is demonstrated that the application of the LCS approach with the well-known Eulerian methods for the vortex identification can enhance the understanding of the spatial and temporal structures of complex flows. Although the LCS approach is computationally expensive, it identifies coherent structures with a minimal user influence and can be complementary to the Eulerian method.

Acknowledgments

This work used the Extreme Science and Engineering Discovery Environment (XSEDE) supported by National Science Foundation grant number TG-CTS170051. The authors would like to thank Guanyang Xue for his help with optimizing the MATLAB code to determine LCS structures.

527 **References**
528

- [1] A. F. Hussain, "Coherent structures and turbulence," *Journal of Fluid Mechanics*, vol. 173, pp. 303-356, 1986.
- [2] A. K. M. F. Hussain, "Coherent structures and studies of perturbed and unperturbed jets," in *In The Role of Coherent Structures in Modelling Turbulence and Mixing*, Berlin, Heidelberg, 1981.
- [3] M. Rockwood, Y. Huang and M. Green, "Tracking coherent structures in massively-separated and turbulent flows," *Physical Review Fluids*, vol. 3, no. 1, p. 014702, 2018.
- [4] H. J. Lugt, "The dilemma of defining a vortex," in *In Recent developments in theoretical and experimental fluid mechanics*, Berlin, Heidelberg, Springer, 1979, pp. 309-321.
- [5] G. Haller, A. Hadjighasem, M. Farazmand and F. Huhn, "Defining coherent vortices objectively from the vorticity," *Journal of Fluid Mechanics*, vol. 795, pp. 136-173, 2016.
- [6] G. Haller, "An objective definition of a vortex," *Journal of fluid mechanics*, vol. 525, pp. 1-26, 2005.
- [7] G. Haller, "Lagrangian coherent structures," *Annual Review of Fluid Mechanics*, vol. 47, pp. 137-162, 2015.
- [8] J. Jeong and F. Hussain, "On the identification of a vortex," *Journal of fluid mechanics*, vol. 285, pp. 69-94, 1995.
- [9] L. Graftieaux, M. Michard and N. Grosjean, "Combining PIV, POD and vortex identification algorithms for the study of unsteady turbulent swirling flows," *Measurement Science and technology*, vol. 12, no. 9, p. 1422, 2001.
- [10] M. Green, C. Rowley and A. Smits, "Using hyperbolic Lagrangian coherent structures to investigate vortices in bioinspired fluid flows," *Chaos: An Interdisciplinary Journal of Nonlinear Science*, vol. 20, no. 1, p. 017510, 2010.
- [11] J. Hunt, A. Wray and P. Moin, "Eddies, streams, and convergence zones in turbulent flows," in *Center for Turbulence Research*, Moffett Field, CA, 1988.
- [12] S. Shadden, F. Lekien and J. Marsden, "Definition and properties of Lagrangian coherent structures from finite-time Lyapunov exponents in two-dimensional aperiodic flows," *Physica D: Nonlinear Phenomena*, vol. 212, no. 3-4, pp. 271-304, 2005.
- [13] R. Kumar, J. King and M. Green, "Three-Dimensional Pitching Panel Wake: Lagrangian Analysis and Momentum Distribution from Experiments," *AIAA Journal*, pp. 1-15, 2018.
- [14] M. Green, C. Rowley and G. Haller, "Detection of Lagrangian coherent structures in three-dimensional turbulence," *Journal of Fluid Mechanics*, vol. 572, pp. 111-120, 2007.

- [15] T. Peacock and J. Dabiri, "Introduction to focus issue: Lagrangian coherent structures," *Chaos*, vol. 20, no. 1, p. 017501, 2010.
- [16] M. Green, C. Rowley and A. Smits, "The unsteady three-dimensional wake produced by a trapezoidal pitching panel," *Journal of Fluid Mechanics*, vol. 685, pp. 117-145, 2011.
- [17] L. Kourentis and E. Konstantinidis, "Uncovering large-scale coherent structures in natural and forced turbulent wakes by combining PIV, POD, and FTLE," *Experiments in fluids*, vol. 52, no. 3, pp. 749-763, 2012.
- [18] H. Y. Cheng, X. P. Long, J. I. Bin, Z. H. U. Ye and J. J. Zhou, "Numerical investigation of unsteady cavitating turbulent flows around twisted hydrofoil from the Lagrangian viewpoint," *Hydrodynamics*, vol. 28, no. 4, pp. 709-712, 2016.
- [19] X. Long, H. Cheng, B. Ji, R. E. Arndt and X. Peng, "Large eddy simulation and Euler–Lagrangian coupling investigation of the transient cavitating turbulent flow around a twisted hydrofoil," *International Journal of Multiphase Flow*, vol. 100, pp. 41-56, 2018.
- [20] C. Tseng and P. Liu, "Dynamic behaviors of the turbulent cavitating flows based on the Eulerian and Lagrangian viewpoints," *International Journal of Heat and Mass Transfer*, vol. 102, pp. 479-500, 2016.
- [21] H. Cheng, X. Long, B. Ji, Q. Liu and X. Bai, "3-D Lagrangian-based investigations of the time-dependent cloud cavitating flows around a Clark-Y hydrofoil with special emphasis on shedding process analysis," *Hydrodynamics*, vol. 30, no. 1, pp. 122-130, 2018.
- [22] B. Attiya, I. H. Liu, C. Daskiran, J. Riglin and A. Oztekin, "Computational Fluid Dynamics Simulations in Flow Past Arrays of Finite Plate: Marine Current Energy Harvesting Applications," In *ASME 2017 International Mechanical Engineering Congress and Exposition*, pp. V007T09A064-V007T09A064, 2017.
- [23] I. -H. Liu, B. Attiya and A. Oztekin, "Transient flows past arrays of yawed finite prisms," *Canadian Journal of Physics*, vol. 95, no. 12, pp. 1285-1298, 2017.
- [24] C.-H. Liu and J. M. Chen., "Observations of hysteresis in flow around two square cylinders in a tandem arrangement," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 90, no. 9, pp. 1019-1050, 2002.
- [25] S. C. Yen, K. C. San and T. H. Chuang, "Interactions of tandem square cylinders at low Reynolds numbers," *Experimental Thermal and Fluid Science*, vol. 32, no. 4, pp. 927-938, 2008.
- [26] A. Sohankar, "A LES study of the flow interference between tandem square cylinder pairs," *Theoretical and Computational Fluid Dynamics*, vol. 28, no. 5, pp. 531-548, 2014.
- [27] I. H. Liu and A. Oztekin, "Three-dimensional transient flows past plates translating near a wall," *Ocean Engineering*, vol. 159, pp. 9-21, 2018.

- [28] J. D'Souza, R. Jaiman and C. Mak, "Dynamics of tandem cylinders in the vicinity of a plane moving wall," *Computers & Fluids*, vol. 124, no. 2, pp. 117-135, 2016.
- [29] F. Nicoud and F. Ducros, "Subgrid-scale stress modelling based on the square of the velocity gradient tensor," *Flow, turbulence and Combustion*, vol. 62(3), pp. 183-200, 1999.
- [30] J. Finn and S. Apte, "Integrated computation of finite-time Lyapunov exponent fields during direct numerical simulation of unsteady flows," *Chaos: An Interdisciplinary Journal of Nonlinear Science*, vol. 23, no. 1, p. 013145, 2013.
- [31] S. Brunton and C. Rowley, "Fast computation of finite-time Lyapunov exponent fields for unsteady flows," *Chaos: An Interdisciplinary Journal of Nonlinear Science*, vol. 20, no. 1, p. 017503, 2010.
- [32] C. Greenshields, "Openfoam user guide," *OpenFOAM Foundation Ltd*, Vols. version, 3(1), 2015.
- [33] Y. Chen, X. Chen, J. Li, Z. Gong and C. Lu, "Eddy Simulation and investigation on the flow structure of the cascading cavitation shedding regime around 3D twisted hydrofoil," *Ocean Engineering*, vol. 129, pp. 1-19, 2017.
- [34] B. Ji, X. Luo, R. Arndt, X. Peng and Y. Wu, "Large eddy simulation and theoretical investigations of the transient cavitating vortical flow structure around a NACA66 hydrofoil," *International Journal of Multiphase Flow*, vol. 68, pp. 121-134, 2015.
- [35] M. Rockwood, K. Taira and M. Green, "Detecting vortex formation and shedding in cylinder wakes using lagrangian coherent structures," *AIAA Journal*, vol. 55, no. 1, pp. 15-23, 2016.
- [36] Z. Liu, A. Vakhrushev, M. Wu, E. Karimi-Sibaki, A. Kharicha, A. Ludwig and B. Li, "Effect of an Electrically-Conducting Wall on Transient Magnetohydrodynamic Flow in a Continuous-Casting Mold with an Electromagnetic Brake," *Metals*, vol. 8, no. 8, p. 609, 2018.
- [37] P. Chakraborty, S. Balachandar and R. Adrian, "On the relationships between local vortex identification schemes," *Journal of fluid mechanics*, vol. 535, pp. 189-214, 2005.
- [38] B. Attiya, I. -H. Liu, C. Daskiran, J. Riglin and A. Oztekin, "Computational Fluid Dynamics Simulations in Flow Past Arrays of Finite Plate: Marine Current Energy Harvesting Applications," In *ASME 2017 International Mechanical Engineering Congress and Exposition*, pp. V007T09A064-V007T09A064, 2017.
- [39] C. Daskiran, J. Riglin, W. Schleicher and A. Oztekin, "Transient analysis of micro-hydrokinetic turbines for river applications," *Ocean Engineering*, vol. 129, pp. 291-300, 2017.
- [40] C. Daskiran, B. Attiya, I. Liu, J. Riglin and A. Oztekin, "Large Eddy Simulations of Ventilated Micro Hydrokinetic Turbine," in *ASME 2017 International Mechanical Engineering Congress and Exposition*, 2017.

- [41] T. Peacock and J. Dabiri, "Introduction to focus issue: Lagrangian coherent structures," vol. *Chaos*, no. 1, p. 017501, 2010.
- [42] I. Liu and A. Oztekin, "Three-dimensional transient flows past plates translating near a wall," *Ocean Engineering*, vol. 159, pp. 9-21, 2018.

529

530

531

For Review Only