

Alma Mater Studiorum Università di Bologna
Archivio istituzionale della ricerca

Aerodynamic overshoot of rectangular cylinders under accelerating inflow conditions

This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

Published Version:

Li, W., Yao, Y., Zhao, L., Chen, C., Patruno, L. (2025). Aerodynamic overshoot of rectangular cylinders under accelerating inflow conditions. *PHYSICS OF FLUIDS*, 37(6), 1-19 [10.1063/5.0272163].

Availability:

This version is available at: <https://hdl.handle.net/11585/1037256> since: 2026-01-15

Published:

DOI: <http://doi.org/10.1063/5.0272163>

Terms of use:

Some rights reserved. The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website.

This item was downloaded from IRIS Università di Bologna (<https://cris.unibo.it/>).
When citing, please refer to the published version.

(Article begins on next page)

Aerodynamic overshoot of rectangular cylinders under accelerating inflow conditions

Weilin Li^{a,b} (李威霖), Yunkai Yao^{a,b} (姚云开), Lin Zhao^{a,b*} (赵林), Cong Chen^{a,b} (陈聪), Luca Patruno^c

^a State Key Laboratory of Featured Metal Materials and Life-cycle Safety for Composite Structures (Provincially and Ministerially Co-constructed), Nanning Guangxi 530004, China

^b School of Civil Engineering and Architecture, Guangxi University, Nanning Guangxi 530004, China

^c DICAM, University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy

* Correspondence: zhaolin-gxu@gxu.edu.cn

Abstracts: The overshoot phenomenon, where aerodynamic coefficients of bluff sections under accelerating flows exceed those in steady flows, is critical and controversial issue in the study of non-synoptic wind effects. Experimental simulation of accelerating flows requires complex dedicated facilities, which makes the investigation of key acceleration parameters affecting the aerodynamic overshoot still a challenging task. Therefore, numerical methods that allow easy control of acceleration parameters are urgently needed. In this study, aiming at verifying the accuracy of existing force evaluation approaches, we consider four types of accelerating inflows, namely, *Linear*, *Hyperbolic*, *Sinusoidal*, and *Turbulent*. The unsteady aerodynamic forces of rectangular cylinders with aspect ratios ranging from 3 to 16 are investigated using Unsteady Reynolds-averaged Navier-Stokes and Large Eddy Simulations. Sixteen different accelerating cases are considered to examine the effects of dimensionless acceleration parameters (a_p) that defined by flow acceleration relative to velocity and deck height. Results show that accelerating flows cause drag overshoots well described by Morison equation, but reduce vortex-induced lift forces. The a_p is the key parameter governing drag overshoot, as it increases the absolute values of windward positive and leeward negative pressures. Additionally, the added mass coefficients are identified and an empirical formula is proposed to accurately estimate drag overshoot. The study provides guidance for the numerical simulation and drag estimation for bluff sections impinged by non-synoptic winds.

Key words: Accelerating inflows; Rectangular cylinders; Overshoot; Aerodynamic loads; Computational Fluid dynamics (CFD);

29 **1. Introduction**

30 With global climate change, more frequent strong typhoons, thunderstorms, and
31 downbursts, non-synoptic winds become a significant challenge in wind-resistant safety for
32 infrastructure [1-3]. In fact, such non-synoptic winds can show maximum speeds which can
33 exceed 75 m/s [4] and exhibit rapid acceleration, leading to significant wind-induced vibrations
34 [5, 6] and damage [7] on slender structures. Current analysis methods for non-stationary wind-
35 induced vibrations are well-established [8-13], but generally assume that aerodynamic
36 coefficients are independent from the flow acceleration and rely on results obtained under
37 stationary flow conditions [9]. However, if overshoots of the aerodynamic forces occur due to
38 the flow acceleration, existing wind-resistant design approaches may result in unsafe
39 predictions. Therefore, investigating the aerodynamic overshoot of bluff sections in
40 accelerating flows is essential for non-synoptic wind designs.

41 Whether aerodynamic coefficients in accelerating flows exhibit overshoot phenomena
42 remains controversial in current studies. Early water tunnel research by Sarpkaya et al. [14-17]
43 defined the overshoot coefficient as the ratio between the aerodynamic coefficients in
44 accelerating flow and that in steady conditions, and found that the overshoot coefficients for
45 circular and rectangular cylinders were 1.35 and 1.62, respectively. Takeuchi et al. [18]
46 conducted active wind tunnel tests (WTTs) and found that overshoot coefficients of elliptical
47 cylinder reach a maximum value of 5. Dong et al. [19] found that the drag, lift, and moment
48 coefficients of a bluff girder increased by approximately 1.1, 1.5, and 1.35 times, respectively,
49 compared to steady flows. They emphasized the importance of considering such amplification
50 in the wind-resistant design of large-span bridges. Yan et al. [20] investigated the pressure
51 coefficients of a wind turbine nacelle using multi-bladed actively controlled WTTs, and found
52 that wind pressure overshooting occurs on the top surface and increases with flow acceleration.
53 However, many scholars have reported opposite conclusions, where aerodynamic coefficients
54 under accelerating flows are lower than those under steady flows. For instance, Li et al. [21]
55 investigated the aerodynamic effects of a 5:1 rectangular cylinder under downburst-strike flows
56 using multi-fan actively controlled WTTs, and found that static lift coefficient is lower than in

57 stationary flows. Yang et al. [22] conducted WTTs on rectangular cylinders with aspect ratios
58 of 1/3, 1, and 3 at angle of attack of 0° and found that acceleration flows did not lead to larger
59 wind loads compared to steady cases. Le et al. [23] conducted active WTTs of the scaled
60 Commonwealth Aeronautical Advisory Research Council (CAARC) building model and found
61 that aerodynamic coefficients under non-stationary inflows decrease to approximately 70% of
62 those under steady inflows. Brusco et al. [24] conducted multiple-fan WTTs and found that
63 drag coefficients of a square cylinder at 0° angle of attack are lower than that in accelerating
64 flows, except for a small overshoot of 1.8% at the start and the end of the ramp-down case.
65 Moreover, the root mean square (RMS) of lift coefficients decreases as the acceleration
66 increases, and the vortex-shedding frequency show constant-frequency time cells phenomenon.
67 Chen et.al [25] conducted multi-fan WTTs of a 3:2 rectangular section and found that drag
68 coefficients under accelerating flows are consistent with the quasi-steady value. In a summary,
69 existing literature shows contradictory findings regarding the intensity of the overshoots in the
70 aerodynamic coefficients when accelerating flows are considered.

71 Another unresolved issue is the lack of clarity regarding the key parameters affecting the
72 overshoots with respect to the quasi-static values. The dimensionless acceleration parameters
73 $a_p (D(dU/dt)/U^2)$ is known to be an important factor affecting the aerodynamic forces of bluff
74 sections during accelerating flows [14, 22, 26]. However, the heterogeneous definition of
75 acceleration parameters a_p within the available sources adds to the uncertainty of overshoot,
76 with sometimes using the time-varying velocity [24] and others relying on the start speeds a_{ps}
77 $(D(dU/dt)/U_s^2)$ [14] or end speeds $a_{pe} (D(dU/dt)/U_e^2)$ [22]. For instance, Takeuchi et al. [18]
78 observed the overshoot coefficient is increasing linear as a_p within the range of 0.43 to 5.11. In
79 contrast, Brusco et al. [24] found no apparent trend between the drag forces of a square cylinder
80 and a_p within the range of 0.001 to 0.008. Sarpkaya et al. [14] introduced a_{ps} to account for the
81 initial history of flow acceleration and found that it strongly affects the overshoot when a_p
82 below 1, but has limited effects on drag and lift forces for $1 < a_{ps} < 2.5$. They further pointed out
83 that a systematic variation of a_p using WTTs is extremely difficult and the best one can hope
84 for is to maintain it as constant and as large as possible. Therefore, the relationship between

85 acceleration parameters a_p and aerodynamic overshoot remains debated. Regarding the effects
86 of incoming turbulence, non-synoptic winds are inherently turbulent and can be regarded as a
87 superposition of a time-varying mean velocity with zero-mean fluctuating turbulent
88 fluctuations [27-29]. Full-scale measurements [27, 30] of non-synoptic wind events found that
89 the ensemble mean value of turbulence intensity is in the order of 11% to 34%. It is well-known
90 that free-stream turbulence significantly affects the flow separation of bluff sections, so
91 potentially affecting the intensity of the overshoots. However, research on the effect of
92 turbulence in accelerating flows is limited, due to the challenges of controlling turbulence
93 properties in WTTs while dealing with accelerating inflows. Briefly, available facilities for such
94 studies can be subdivided into impinging jet simulators [31], such as the WindEEE [32-34],
95 multi-fan wind tunnel [19, 35, 36], and active-controlled multi-blade device [20, 23, 37].
96 Despite the remarkable advancements made by using such dedicated infrastructures [38-41],
97 challenges remain in investigating accelerating inflows using WTTs, especially as achieving
98 high a_p requires rapid wind speed increase that may exceeds the capabilities.

99 A possible alternative to WTTs is represented by Computational Fluid Dynamics (CFD)
100 simulations [42-49], which has become an important tool for studying aerodynamic forces of
101 bluff sections [50, 51]. Guo et al. [52] performed Large Eddy Simulations (LES) to investigate
102 the flow field evolution and its aerodynamic characteristics of a square cylinder in accelerating
103 inflows. Lunghi et al. [53] investigated a square cylinder under Gaussian-type accelerating
104 inflows with a_p range of 0.0076~0.0151 and found no overshoot in aerodynamic coefficients.
105 Takeuchi et al. [54] conducted LES of a square building under short-duration gusts and found
106 significant overshoot in pressures and displacements compared to steady cases. Xing et al. [55]
107 conducted LES of a large sports stadium and found that non-stationary inflows could amplify
108 wind loads when the rump-up time is in the order of 30 s. Xue et. al utilized an improved
109 Delayed Detached Eddy Simulation (DDES) and observed a significant overshoot in
110 aerodynamic loads acting on the train during short-rise gusts. However, CFD studies focus on
111 the aerodynamic overshoot of bluff sections under accelerating flows remain very limited.

112 In this paper, Unsteady Reynolds-averaged Navier-Stokes (URANS) and LES simulations
113 are adopted to investigate the aerodynamic coefficient overshoot with respect to quasi-static
114 theory for rectangular cylinders with different aspect ratios. The accuracy of present
115 simulations is verified by comparison with accelerating inflows WTTs [22, 56]. First, we focus
116 on a rectangular cylinder with aspect ratio 4 and use three types of accelerating inflows *Linear*,
117 *Hyperbolic*, *Sinusoidal* characterized by different acceleration speeds, durations and non-
118 dimensional parameters a_p . This approach allows us to maintain a constant a_p or a_{ps} to examine
119 their effect on the aerodynamic overshoot. Given the large number of considered acceleration
120 cases, URANS-based simulations are adopted aiming to identify the key parameters
121 determining the overshoot. Next, *Sinusoidal*-type accelerating inflows with three-dimensional
122 turbulence synthesized using Prescribed-wavevector Random Flow Generator (PRFG³) [45]
123 and LES are adopted to clarify the effects of turbulence. Finally, rectangular cylinders with
124 aspect ratios ranging from 3 to 16 under the same *Sinusoidal*-type accelerating inflow are
125 adopted to investigate the effect of aspect ratio. The added mass coefficients due to flow
126 acceleration are identified and an empirical equation is proposed to accurately account for drag
127 overshoot, aiming to establish a relationship between accelerating inflows and steady cases.

128 This paper is organized as follows: Section 2 introduces the Morison theory and the
129 synthetic generation of four types of accelerating inflows. Section 3 briefly presents active
130 WTTs setup to validate the subsequent CFD simulations. Section 4 describes the URANS and
131 LES settings. Section 5 discusses the results, and finally conclusions are drawn in Section 6.

132 **2. Aerodynamic forces and synthetic generation of accelerating inflows**

133 **2.1 Morison equation and non-dimensional acceleration parameters**

134 The aerodynamic forces acting on a fixed body in an accelerating flow can be described
135 by the Morison equation [57-59]. Such equation represents the force as the sum of two
136 components: a drag force proportional to the square of the instantaneous velocity $U(t)$, and an
137 inertia force in phase with the local flow acceleration $\dot{U}(t)$, as below:

138
$$F_D(t) = \frac{1}{2} \rho U(t)^2 D \bar{C}_D + \rho A C_a \dot{U}(t) = \frac{1}{2} \rho U(t)^2 D \left(\bar{C}_D + 2C_a R D \frac{\dot{U}(t)}{U(t)^2} \right), \quad (1)$$

139 where ρ is the flow density, B and D is the immersed body characteristic width and depth,
 140 respectively. $A=B \times D$ is the reference area, $R=B/D$ is the aspect ratio, C_a is the added mass
 141 coefficient, and \bar{C}_D is the drag coefficient obtained in stationary flows. The non-dimensional
 142 acceleration parameter a_p is defined as [14, 24]:

143
$$a_p = D \frac{\dot{U}(t)}{U(t)^2}. \quad (2)$$

144 Substituting Equation (2) into Equation (1), the time-varying drag coefficient under
 145 accelerating flows can be obtained as:

146
$$C_D(t) = \frac{2F_D(t)}{\rho U(t)^2 D} = \bar{C}_D + 2C_a R a_p. \quad (3)$$

147 Equation (3) establishes a relationship between the aerodynamic coefficients under
 148 stationary and non-stationary conditions, with the added mass coefficient C_a as parameter to be
 149 identified. In order to simplify the formulation above for practical purposes, an acceleration
 150 parameter a_{ps} , made non-dimensional using the speed at the start of the accelerating phase, U_s ,
 151 has been adopted by many scholars [22, 52]:

152
$$a_{ps} = D \frac{\dot{U}(t)}{U_s^2}. \quad (4)$$

153 It worth noting that although Morison theory has been widely adopted to calculate the
 154 hydrodynamic forces on slender cylinders under accelerating wave [60, 61], its applicability to
 155 the aerodynamic characteristics of bluff sections under accelerating winds is worth being
 156 revisited, especially for immersed bodies presenting flow separations and reattachments.

157 **2.2 Accelerating inflows**

158 To clarify the effects of the different definition of the acceleration parameters on
 159 aerodynamic forces (i.e. a_p and a_{ps}), the following four types of synthetic accelerating inflows
 160 are adopted. The first is the *Linear*-type accelerating inflow [52], characterized by a constant

161 non-dimensional parameter a_{ps} , while the parameter a_p changes continuously with the
 162 acceleration time. The theoretical expression for the *Linear*-type accelerating inflow is:

$$163 \quad U(t) = \frac{U_s^2 a_{ps}}{D} (t - t_s) + U_s \quad (t_s \leq t \leq t_e), \quad (5)$$

164 where t_s and t_e represents the acceleration start and end time, respectively, and $\Delta T = t_e - t_s$ denotes
 165 the acceleration duration time. The second is the *Hyperbolic*-type accelerating inflow,
 166 characterized by a constant non-dimensional acceleration parameter a_p while a_{ps} changes over
 167 time. The expression for the *Hyperbolic*-type acceleration inflows is defined as:

$$168 \quad U(t) = \frac{-DU_s}{a_p U_s t - a_p U_s t_s - D} \quad (t_s \leq t \leq t_e). \quad (6)$$

169 It is noteworthy that the above accelerating inflows do not satisfy the conditions for
 170 continuous differentiability at the acceleration start and end positions, which is inconsistent
 171 with the accelerating flows simulated in WTTs [18, 35]. To better match WTTs, the third
 172 *Sinusoidal*-type accelerating inflows, characterized by time-varying non-dimensional
 173 acceleration parameter a_p and a_{ps} . The theoretical expression is given as follows:

$$174 \quad U(t) = \frac{U_e + U_s}{2} + \frac{U_e - U_s}{2} \cos\left(\frac{t - t_s}{t_e - t_s} \pi\right) \quad (t_s \leq t \leq t_e), \quad (7)$$

175 where U_e represents the acceleration end speed. Aiming at investigating the effects of incoming
 176 turbulence superimposed to the accelerating flow, the fourth *Turbulent*-type accelerating
 177 inflows is considered. Three-dimensional turbulence is generated using the synthetic spectra
 178 method PRFG³ [45] and can be described as follows [62]:

$$179 \quad \mathbf{u}(\mathbf{x}, t) = \sum_{n=1}^N \left[\mathbf{p}^n \cos(\mathbf{k}^{nT} \mathbf{x} + \omega^n t) + \mathbf{q}^n \sin(\mathbf{k}^{nT} \mathbf{x} + \omega^n t) \right], \quad (8)$$

180 where $\mathbf{u} = [u, v, w]^T$ is the fluctuating wind components vector, $x = [x, y, z]$ denotes the three-
 181 dimensional coordinate vector, t is time, N is the number of sampled wavevectors, \mathbf{p}^n and \mathbf{q}^n
 182 are random amplitude vectors, \mathbf{k}^n is a vectorial wavenumber, ω^n is a circular frequency and $(\cdot)^T$
 183 denotes the transposition operator. Then, the time-varying mean wind speed using Eq. (7) is

184 superimposed to generate accelerating inflows with three-dimensional turbulent components,
 185 as detailed below:

$$\begin{aligned}
 \mathbf{U}(\mathbf{x}, t) = (U(t), 0, 0) + \mathbf{u}(\mathbf{x}, t) = & \left(\frac{U_e + U_s}{2} + \frac{U_e - U_s}{2} \cos\left(\frac{t - t_s}{t_e - t_s} \pi\right), 0, 0 \right) \\
 & + \sum_{n=1}^N \left[\mathbf{p}^n \cos(\mathbf{k}^{nT} \mathbf{x} + \omega^n t) + \mathbf{q}^n \sin(\mathbf{k}^{nT} \mathbf{x} + \omega^n t) \right]
 \end{aligned} \tag{9}$$

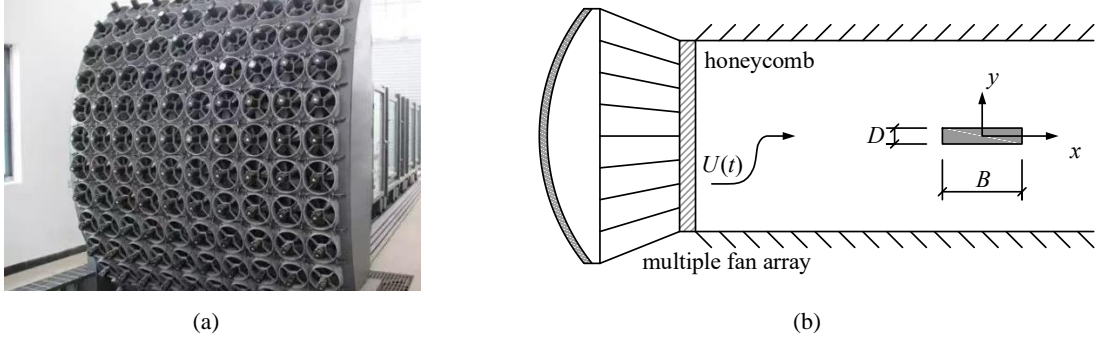
187 Based on the above mentioned four types of accelerating inflows, the acceleration parameters
 188 including acceleration types, start and end speeds, duration time, as well as non-dimensional
 189 parameters a_p and a_{ps} , can be easily controlled.

190 3. Active wind tunnel tests

191 This section provides a brief overview of the active WTTs setup [56], which serve as
 192 validation data for numerical simulations. Figure 1(a) shows the TJ-5 multi-fan wind tunnel at
 193 Tongji University, featuring a cross-section size of 1.5 m (width) \times 1.8 m (height) and a total
 194 length of 10 m. Such facility is capable of simulating various accelerating inflows [19, 21, 35,
 195 36, 63, 64]. Figure 1(b) shows the rigid rectangular cylinder model with aspect ratio of 5:1,
 196 measuring 0.3 m (B) \times 0.06 m (D) and a length of 1.2 m. [56]. Wind speed is measured using a
 197 three-components Cobra probe, and reference pressure is obtained with a Pitot tube. A total of
 198 250 pressure tapes are arranged along 5 sections of the rectangular cross-section model to
 199 measure the non-stationary aerodynamic forces. To avoid discrepancies caused by
 200 synchronized measurements of wind speed and aerodynamic force, the instantaneous drag and
 201 pressure coefficients are normalized by the acceleration end speeds:

$$C_{D,e}(t) = \frac{2F_D(t)}{\rho U_e^2 D}, \quad C_{p,s}(t) = \frac{2(p(t) - p_\infty)}{\rho U_e^2}, \tag{10}$$

203 where $p(t)$ is the instantaneous pressure, and p_∞ is the static pressure.



204 Figure 1. Active WTT setup: (a) multi-fan array; (b) schematic of rectangular cylinder in accelerating
 205 flows [56].

206 4. Numerical setup and validation

207 4.1 Target accelerating inflow conditions

208 Table. 1 provides the parameters for the four types of considered accelerating inflows. The
 209 non-dimensional acceleration parameter a_p is within the range 0.002 to 0.05, which is close to
 210 the measured values for typhoons and downbursts [6, 57, 65-68]. In particular, for *Linear*-type
 211 inflows (*L-1*, *L-2* and *L-3*), the acceleration speeds are the same while shortening the
 212 acceleration duration results in a_{ps} values of 0.009, 0.018, and 0.036, respectively. For *L-4*, only
 213 a_{ps} is the same as *L-3*, but the start, end speed and duration are different. Similarly, for
 214 *Hyperbolic*-type inflows (*H-1*, *H-2* and *H-3*), the acceleration speeds are the same while
 215 shortening the acceleration duration adjusts a_p to 0.009, 0.018, and 0.036, respectively. For *H-*
 216 4, only the non-dimensional parameters a_p is same as *H-3* but other parameters are different.
 217 For the *Sinusoidal*-type inflows (*S-1*, *S-2* and *S-3*), both a_p and a_{ps} vary over time. By adjusting
 218 end speed and duration, the maximum a_p values of *H-i*, *L-i* and *S-i* ($i=1, 2, 3$) are consistent.
 219 These setups allow the effects of acceleration, start speed, end speeds, as well as non-
 220 dimensional acceleration parameters a_p and a_{ps} to be separately investigated.

221 Table. 1 Parameter settings for the four types of accelerating inflows numerical simulations

Case	U_s (m/s)	U_e (m/s)	ΔT (s)	B/D	a_p	a_{ps}
<i>L-1</i>	$3.0(\bar{U})$	5.0	6.1728	4	0.003-0.009	0.009
<i>L-2</i>	3.0	5.0	3.0864	4	0.006-0.018	0.018
<i>L-3</i>	3.0	5.0	1.5408	4	0.013-0.036	0.036
<i>L-4</i>	3.5	7.0	1.9830	4	0.009-0.036	0.036

<i>H-1</i>	3.0	5.28	4.0	4	0.009	0.009-0.028
<i>H-2</i>	3.0	5.28	2.0	4	0.018	0.018-0.056
<i>H-3</i>	3.0	5.28	1.0	4	0.036	0.036-0.112
<i>H-4</i>	3.5	7.06	1.0	4	0.036	0.036-0.146
<i>S-1</i>	3.0	6.0	8.0	4	0-0.009	0-0.016
<i>S-2</i>	3.0	6.0	4.0	4	0-0.018	0-0.033
<i>S-3</i>	3.0	6.0	2.0	3、4、5、8、10、12、16	0-0.036	0-0.065
<i>S-WT-1</i> [56]	6.2	10.5	2.0	5	0-0.0033	0-0.0053
<i>S-WT-2</i> [22]	2.3	25.8	3.0	3	0-0.028	0-0.0011
<i>S-3+5%<i>Tu</i></i>	3.0	6.0	2.0	4	0-0.036	0-0.065
<i>S-3+10%<i>Tu</i></i>	3.0	6.0	2.0	4	0-0.036	0-0.065
<i>S-3+15%<i>Tu</i></i>	3.0	6.0	2.0	4	0-0.036	0-0.065

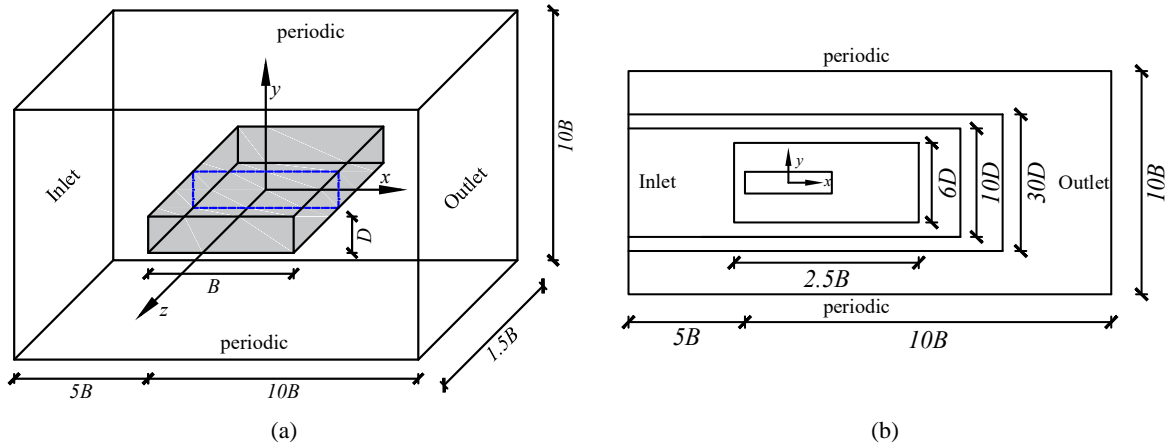
222 Furthermore, the aforementioned cases mainly focus on the rectangular cylinder with
223 aspect ratio 4 (denoted as *R4*), while cases *R3*, *R5*, *R8*, *R10*, *R12*, and *R16* under *S-3* inflow are
224 used to investigate the effects of aspect ratio and validate the Morison equation. In addition,
225 two *Sinusoidal*-type inflows, *S-WT-1* and *S-WT-2*, correspond to the WTTs in literatures [22,
226 56] are used to validate the CFD results. Finally, *Turbulent*-type accelerating inflows, based on
227 *S-3* with added synthetic turbulence intensity 5%, 10% and 15%, and turbulence integral scale
228 of $0.34B$, are adopted to investigate the effects of turbulence.

229 4.2 Domain, mesh and numerical settings

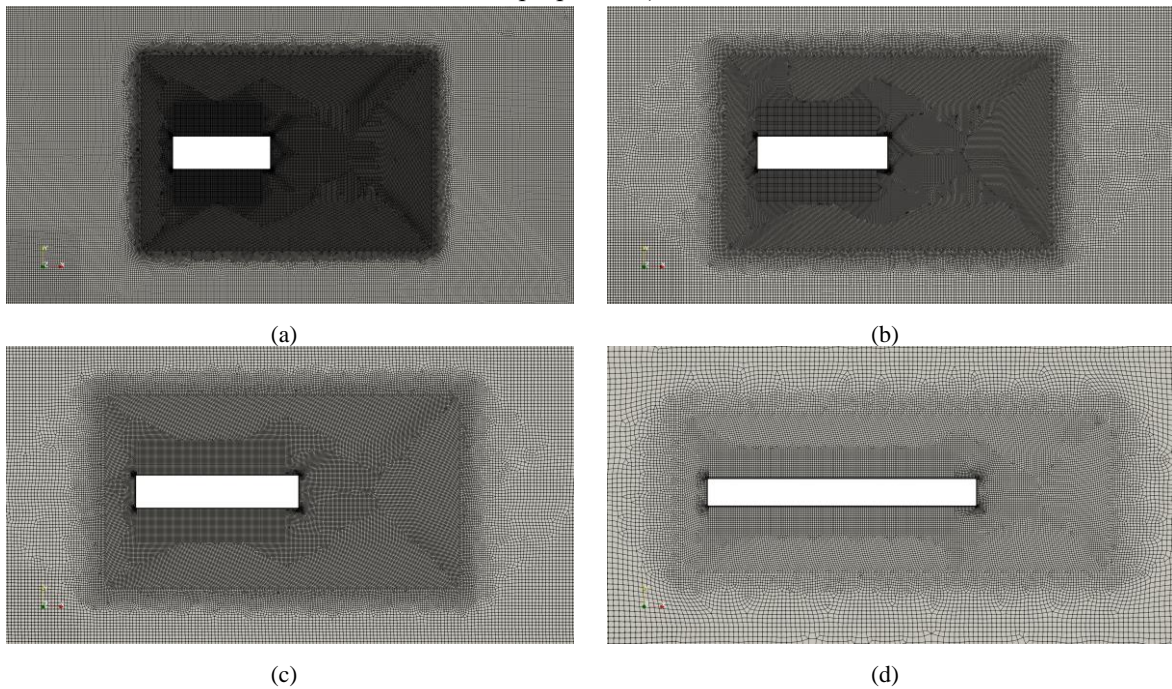
230 2D URANS with *k- ω* SST turbulence model are adopted for rectangular cylinders with
231 *Linear*, *Hyperbolic* and *Sinusoidal*-type accelerating inflows without synthetic turbulent
232 components, while 3D LES with One-Equation turbulence model is used for *R4* under
233 *Turbulent*-type accelerating inflows. These two turbulence models are well-established in the
234 literature for the CFD simulation of bluff sections[69-73].

235 Figure 2 shows the computational domain followed the guidelines of BARC project for
236 the 5:1 rectangular cylinder [74], with the domain dimensions are $15B(x) \times 10B(y)$ and a
237 maximum vertical blockage ratio of 2.9%. The computational mesh consists of four different
238 refinement regions. The finest mesh near the rectangular cylinder is structured and the size is
239 approximately $0.0049B(x) \times 0.0009B(y)$, while the mesh size gradually increases in the other

240 three regions. The total number for 2D URANS is 180k cells, while 3D LES with a spanwise
 241 length of $1.5B$ and 20 layers in the extrusion directions uses about 3.6M cells, meeting the
 242 spanwise requirements of LES [75, 76]. An overview of the meshes adopted near the cylinders
 243 is provided in Figure 3.



244 Figure 2. Numerical model: (a) computational domain; (b) mesh zones (the figure does not respect real
 245 proportions).



246 Figure 3. Detailed meshes around rectangular cylinders: (a) $R3$; (b) $R4$; (c) $R5$; (d) $R10$.

247 Regarding the numerical schemes, a centered second-order accurate scheme is employed
 248 to discretize the diffusion terms, while a linear upwind scheme is selected for solving the
 249 convection terms. Time integration is performed using a transient second-order Crank-
 250 Nicolson scheme, while Pressure-velocity coupling using the transient PISO algorithm.
 251 Regarding the boundary conditions, a time-varying Dirichlet condition is applied at the inlet to

252 impose synthetic accelerating inflows, while a Neumann condition is imposed on the pressure
 253 field. At the outlet, a null-pressure boundary condition is applied and an inlet-outlet boundary
 254 condition for velocity. Periodic boundary conditions are used on top, bottom and sides surfaces.

255 The maximum Courant number are between 1.2 to 2.5 for URANS and 1.2 to 2.9 for LES,
 256 occurring in a few small cells. The average value of y^+ are below 2.1. All simulations were
 257 conducted using OpenFOAM-v2112 on a workstation equipped with AMD EPYC 7763 CPU.

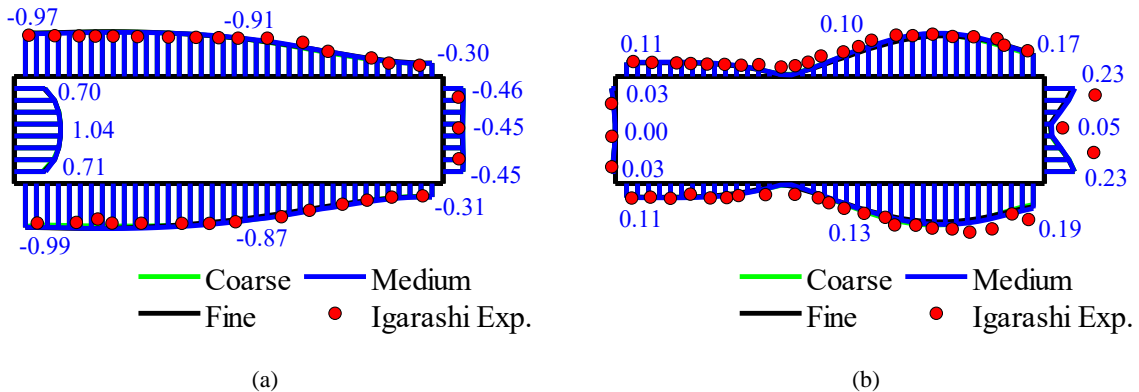
258 4.3 Validation

259 Three different meshes, denoted as Coarse, Medium, and Fine, are used for $R4$ to assess
 260 mesh independence. The length of the finest mesh δ_x near $R4$ decrease from 6.03×10^{-3} to
 261 $2.45 \times 10^{-3} B$, while the height δ_y decrease from 1.21×10^{-3} to $4.88 \times 10^{-4} B$. The total number of
 262 cells increase from 163.3k to 375.8k. Detailed mesh properties are provided in Table. 2.

263 Table. 2 Mesh properties of $R4$ for 2D URANS.

Case	δ_x/B	δ_y/B	Boundary layers	Total cells (k)
Coarse	6.03×10^{-3}	1.21×10^{-3}	30	163.3
Medium	4.90×10^{-3}	9.40×10^{-4}	40	180.0
Fine	2.45×10^{-3}	4.88×10^{-4}	80	375.8

264 Figure 4 shows pressure coefficient distributions for $R4$ under steady inflow for the three
 265 considered meshes. A good agreement is observed between the meshes, which also matches
 266 well with the experimental data [77]. To balance computational efficiency and accuracy, the
 267 medium mesh is used for simulating accelerating inflow cases.



268 Figure 4. Pressure coefficients for $R4$ using URANS: (a) time-average; (b) standard deviation.

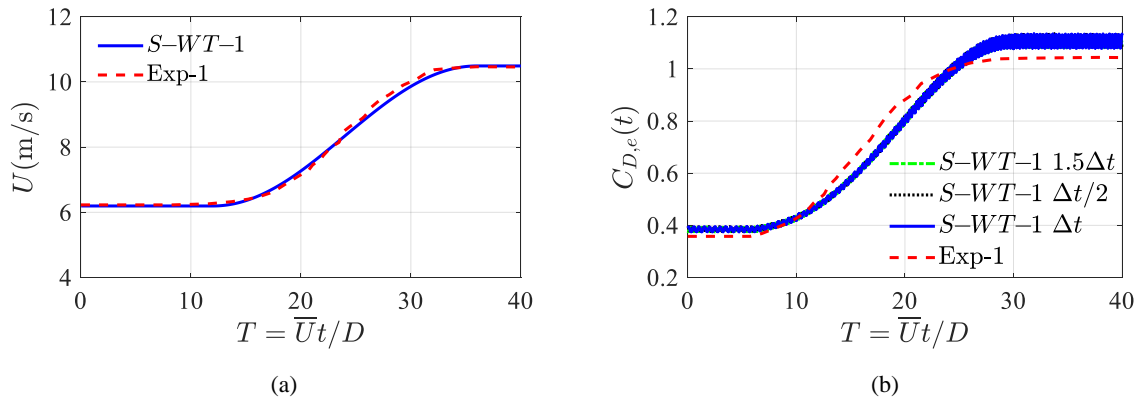
269 Table. 3 summarizes aerodynamic coefficients for considered rectangular cylinders. The
 270 mean drag coefficient, standard deviation of lift coefficients and Strouhal number show good
 271 agreement with the reference data, except for a large deviation for the standard deviation of C_L
 272 for $R3$, which is however known to be sensitive to the Reynolds number. Overall, the obtained
 273 results confirm the suitability of the adopted model for present investigations.

274 Table. 3 Summary of aerodynamic coefficients and comparison with results present in the literature. All
 275 data calculated with respect to D , except $t - std (C_L)$ and St using B .

Case	Source	Re ($\times 10^4$)	$t - avg (C_D)$	$t - std (C_L)$	St
R3	Current URANS	1.38~15.48	1.182~1.364	0.1989~0.4059	0.1667~0.1826
	Exp. [22]	0.93-12.3	1.240	0.2900	0.1620
	Exp. [78]	5.16	1.470	0.1400	0.1630
	Exp. [79]	1.30	1.330	-	0.1620
R4	Current URANS	7.50	1.246	0.2677	0.1500
	Current LES	7.50	1.108	0.1925	0.1333
	URANS. [80]	2.50	1.227	-	-
	Exp. [77]	6.00	1.213	0.2890	0.1350
	Exp. [81]	7.00	-	0.2370	0.1480
R5	Current URANS	7.50	1.109	0.1716	0.1167
	Exp. [82]	2.64	1.029	0.0800	0.1110
	Exp. [83]	5.70	1.042	0.0700	0.1140
	LES. [84]	6.70	1.015	0.0880	0.1120
	Exp. [85]	1.30	1.108	0.0900	0.1110
	URANS. [86]	2.70	1.120	0.1600	0.1120
R8	Current URANS	7.50	0.979	0.0255	0.1333
R10	Current URANS	7.50	1.066	0.0334	0.1333
	RANS. [87]	1.40	1.040	0.0340	0.1310
R12	Current URANS	7.50	1.079	0.0260	0.1333
R16	Current URANS	7.50	1.198	0.0310	0.1500

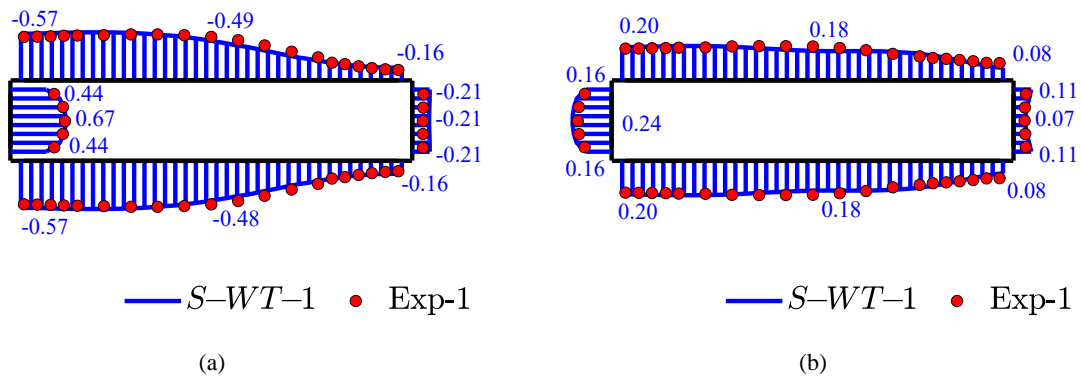
276 Figure 5 compares the accelerating wind speeds and drag coefficients between CFD and
 277 WTTs [56] for $R5$ under $S-WT-1$ inflows (see in Table. 1). Considering that the abrupt increase
 278 in wind speed cause significant changes in the Courant number, a time-step independence study
 279 was conducted using $1.5\Delta t$, Δt and $\Delta t/2$ with maximum Courant numbers of 2.08, 1.35, and
 280 0.64, respectively. Results shows that the drag coefficients calculated using Eq. (10) show good

281 agreement across different time steps and aligns well with the WTTs, with a maximum
 282 deviation of less than 12%.



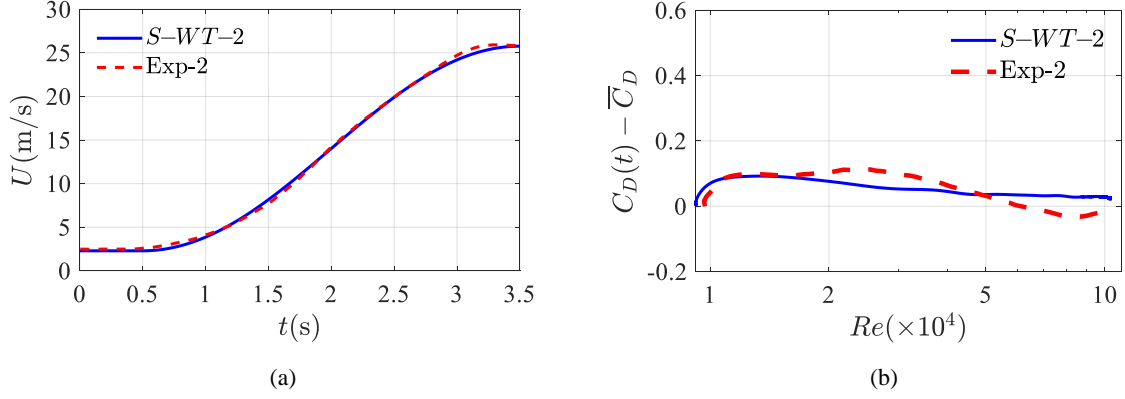
283 Figure 5. Time step independence check under $S-WT-1$ conditions: (a) U ; (b) $\bar{C}_{D,e}(t)$.

284 Figure 6 further presents the comparison between the CFD and WTTs [56] in terms of
 285 pressure coefficients distribution of $R5$ under $S-WT-1$ during the acceleration phase. Overall,
 286 the mean and standard deviation of pressure coefficients obtained from present simulations are
 287 in good agreement with the WTTs.



288 Figure 6. Pressure coefficients for $R5$ under $S-WT-1$ conditions: (a) time-average; (b) standard deviation.

289 Figure 7 shows the time-varying speed and drag coefficients of $R3$ under $S-WT-2$ inflows
 290 (see Table. 1) between CFD and WTTs [22]. It can be observed that CFD can well reproduce
 291 the target acceleration winds and the trend of the corresponding drag coefficients. This
 292 indicates that the present CFD setting can effectively simulate the aerodynamic characteristics
 293 of the rectangular cylinders under accelerating inflows.

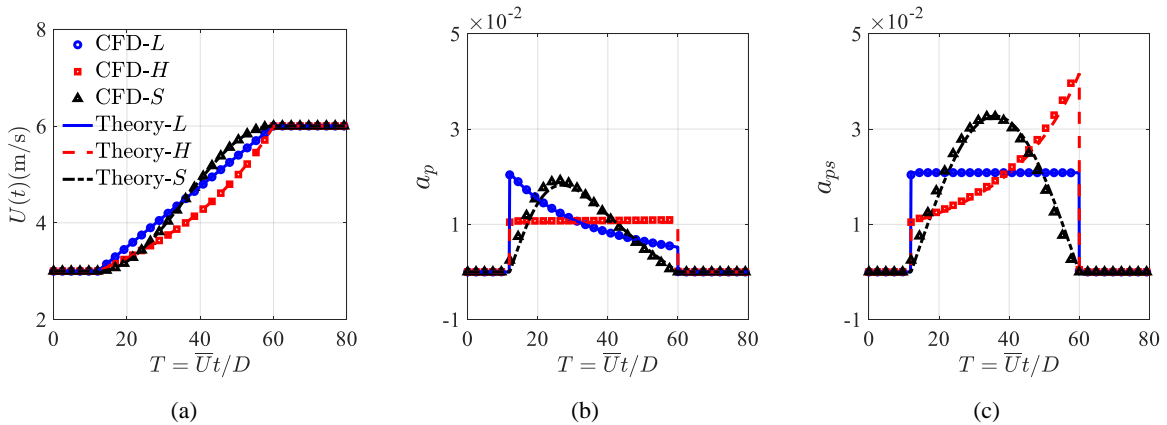


294 Figure 7. Time-varying drag coefficients of R3 for acceleration case *S-WT-2*: (a) U ; (b) $C_D(t) - \bar{C}_D$.

295 5. Results and discussions

296 5.1 Accelerating inflows characteristics

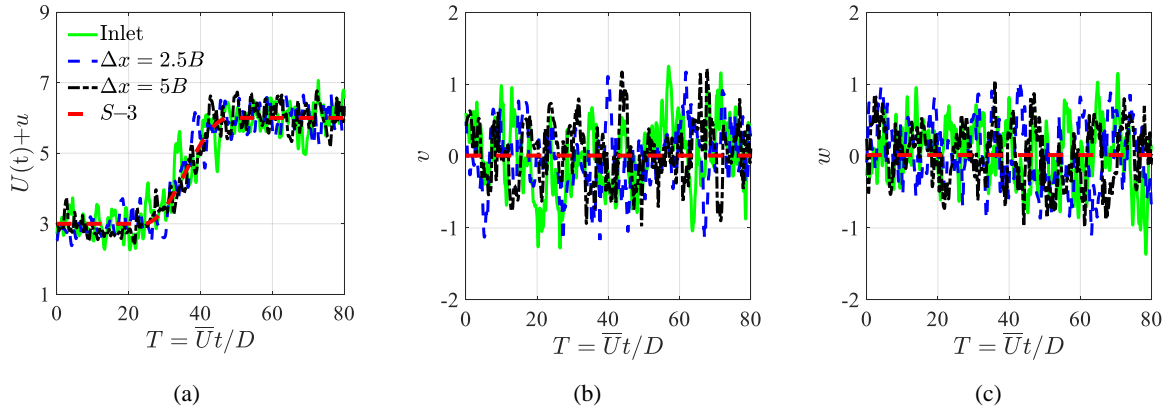
297 Figure 8 shows URANS results for instantaneous velocity, non-dimensional parameter a_p
 298 and a_{ps} for the *Linear*, *Hyperbolic* and *Sinusoidal*-type accelerating inflows. In particular, we
 299 remind that a_p is normalized by the instantaneous velocity using Eq. (2), and a_{ps} by the start
 300 velocity using Eq. (4). It can be found that CFD results match well with target theoretical values
 301 using Eq (5), (6) and (7), respectively. As expected, For *Linear*-type inflow, a_p peaks at the
 302 acceleration start point and then ramp down rapidly, while a_{ps} stays constant. For the
 303 *Hyperbolic*-type inflow, a_p remains constant while a_{ps} ramp up with acceleration time. For
 304 *Sinusoidal*-type inflow, both a_p and a_{ps} first ramp up and then ramp down.



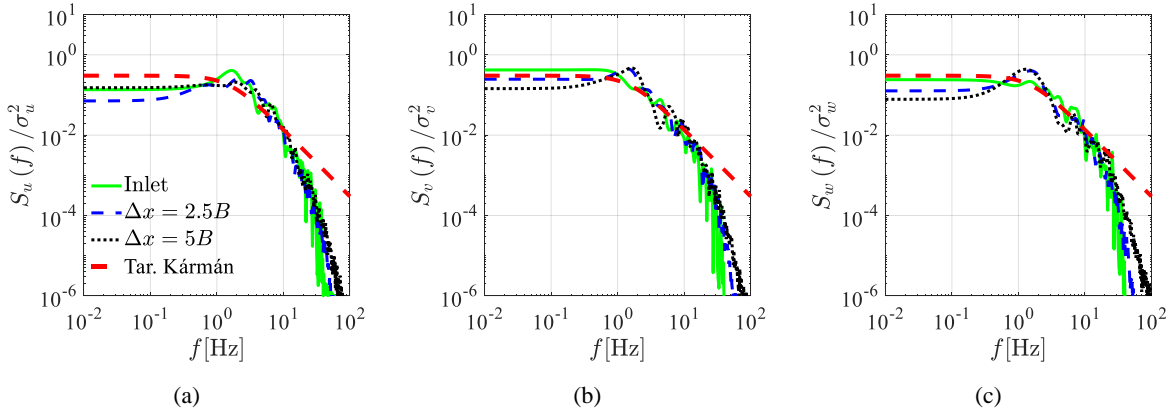
305 Figure 8. Comparison of three types of accelerating inflows wind fields: (a) $U(t)$; (b) a_p ; (c) a_{ps} .

306 Coming now to the characterization of *Turbulent*-type accelerating inflow used in
 307 conjunction with LES, Figure 9 present the time-history of the accelerating flow, while Figure
 308 10 presents the spectra of fluctuating turbulence components. Results at the inlet, $2.5B$ and $5B$

309 from the inlet are in agreement with the target value, indicating that the synthetic turbulence is
 310 correctly transported in the LES domain.



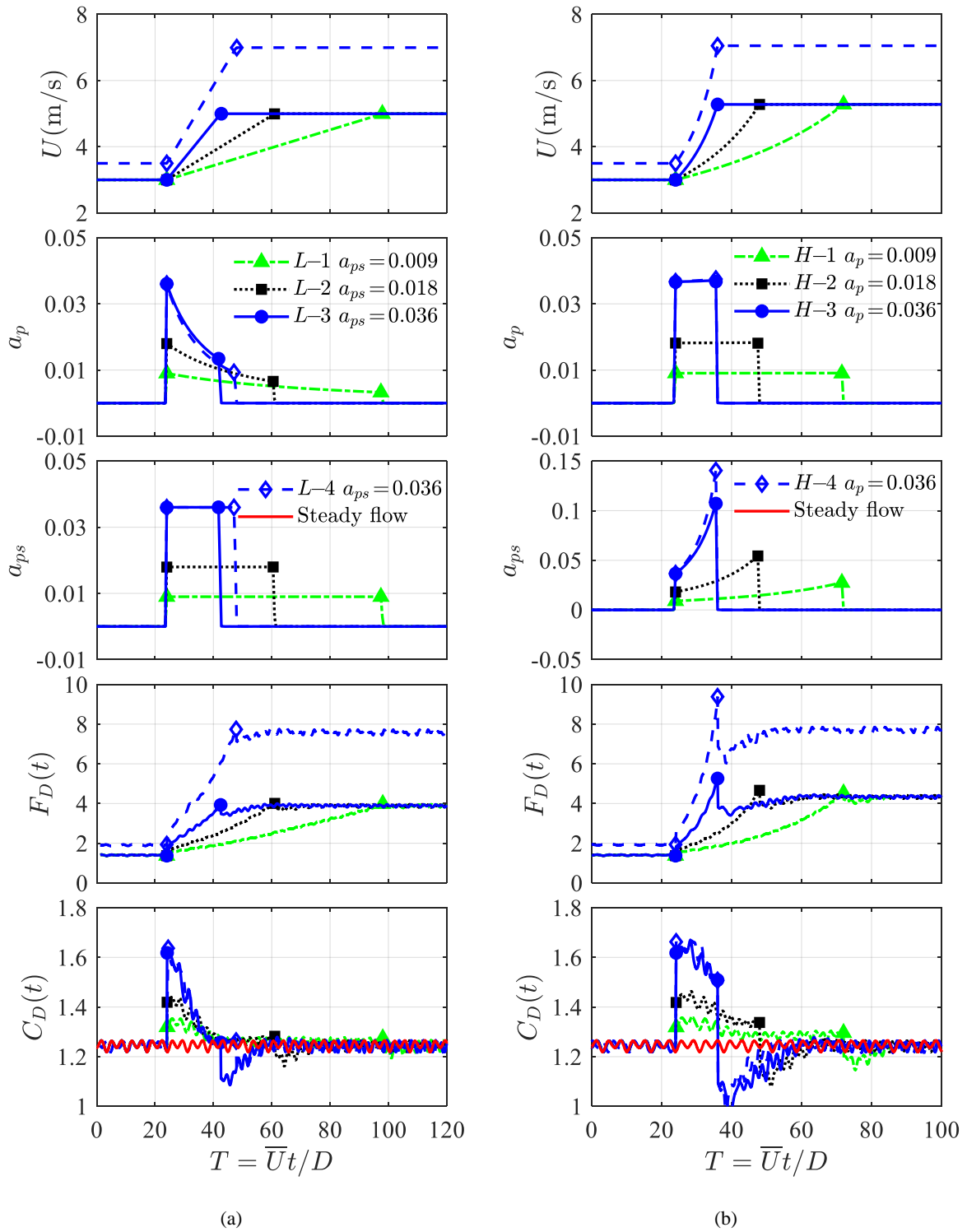
311 Figure 9. Time history of wind speed for *Turbulent*-type accelerating inflow: (a) $U(t)+u$; (b) v ; (c) w .



312 Figure 10. Spectra of fluctuating components of *Turbulent*-type accelerating inflow: (a) u ; (b) v ; (c) w .

313 5.2 Effects of acceleration parameters

314 Figure 11 provides the drag force for *R4* under *Linear* and *Hyperbolic*-type accelerating
 315 inflows. In particular, the force coefficients are normalized by the instantaneous velocity using
 316 Equation (3). For the *Linear*-type inflows shown in Figure 11(a), a_{ps} is constant but a_p ramps
 317 down over time. As the a_{ps} increase from 0.009 to 0.036, the drag coefficients exhibit a notable
 318 overshoot, with maximum values approximately 6.7%, 14.2%, 28.2% higher than those under
 319 steady inflows. Comparing Cases *L-3* and *L-4*, where have the same a_{ps} and maximum a_p , but
 320 different initial and end accelerations, the curve of drag coefficients are found to almost overlap.

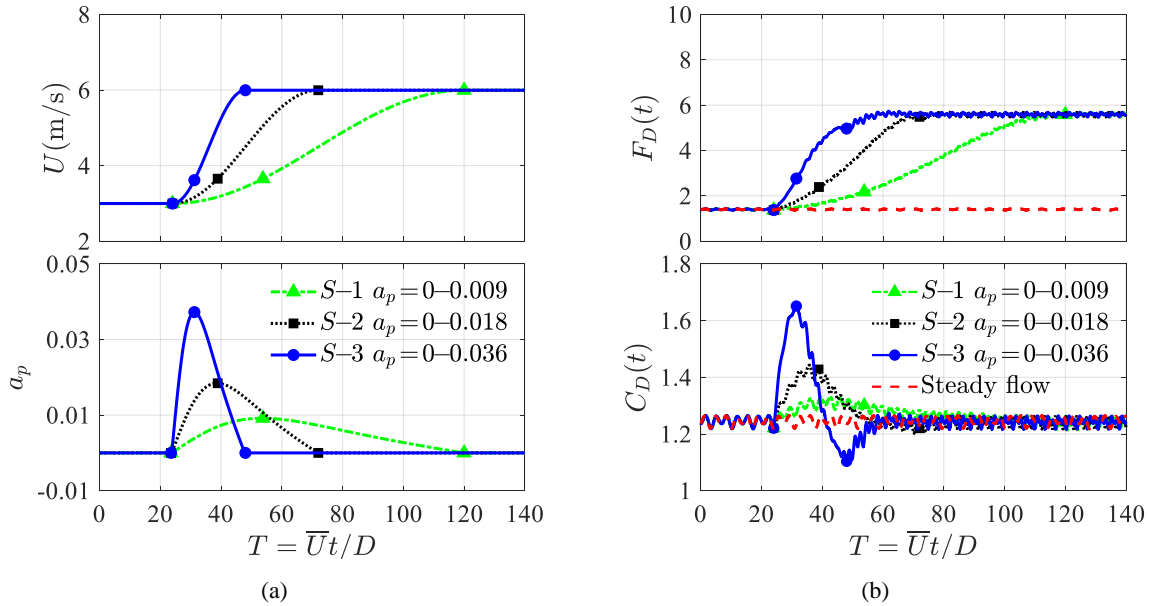


321 Figure 11. Drag coefficient of $R4$ for different accelerating flows: (a) *Linear* type; (b) *Hyperbolic* type.

322 For the *Hyperbolic*-type inflows shown in Figure 11(b), a_p is constant but a_{ps} ramp up
 323 over time. It can be found that the drag coefficients exhibit a flat trend, which aligns with a_p
 324 but opposes that of a_{ps} during the acceleration phase. Comparing Case $H-1$, $H-2$ and $H-3$, as a_p
 325 increases from 0.009 to 0.036 and the maximum a_{ps} rises from 0.028 to 0.112, the maximum

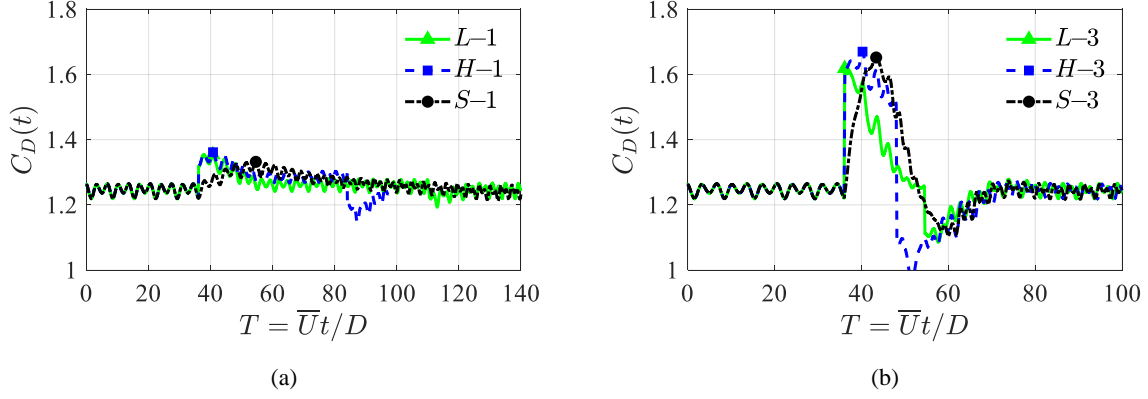
326 C_D values are approximately 6.7%, 14.5%, 29.4% higher than those under steady inflows. Such
 327 results are consistent with those observed in $L-1$, $L-2$ and $L-3$, respectively. Comparing Case
 328 $H-3$ and $H-4$, where have the same a_p but different a_{ps} , acceleration start and end speeds, the
 329 curve of drag coefficients are almost overlap.

330 For the *Sinusoidal*-type inflows $S-1$, $S-2$ and $S-3$ shown in Figure 12, a_p first ramps up and
 331 then ramps down over time. Comparing Case $S-1$, $S-2$ and $S-3$, as maximum a_p increases from
 332 0.009 to 0.036, the maximum C_D values are approximately similar, 6.4%, 14.0%, 30.4% higher
 333 than those under steady inflows. As expected, these increases are consistent with those
 334 observed in *Linear* and *Hyperbolic* inflows.



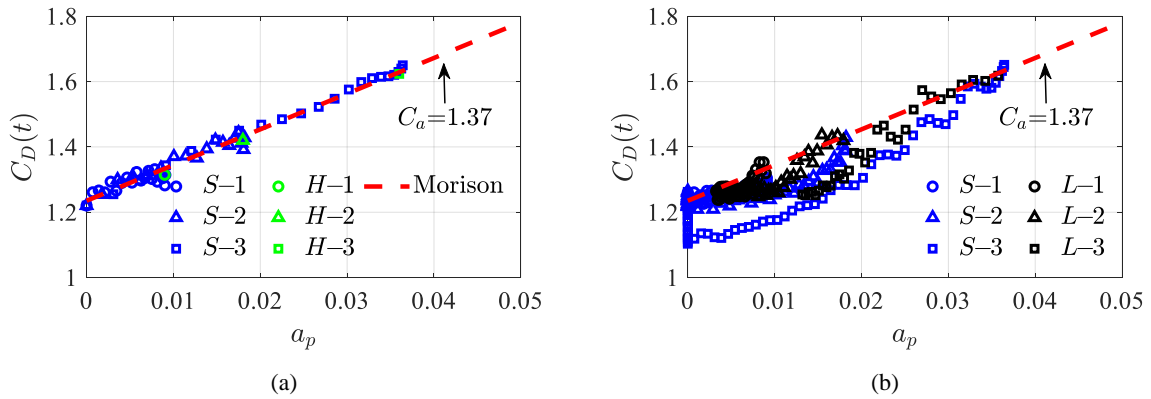
335 Figure 12. Drag coefficients of R4 for *Sinusoidal*-type accelerating flows: (a) U and a_p ; (b) $F_D(t)$ and
 336 $C_D(t)$.

337 Figure 13 further summarizes the drag coefficients obtained by different accelerating flow
 338 types, but with the same a_p . It can be found that the maximum drag coefficients are almost the
 339 same for different acceleration types. Therefore, the acceleration parameter a_p , made non-
 340 dimensional by the instantaneous wind speed, is the most suitable parameter in determining the
 341 drag overshoot, with the simplified formulation not always giving comparably accurate results.



342 Figure 13. Drag coefficient of R4 under different accelerating flows with $a_{p,max}$ of: (a) 0.009 and (b) 0.036.

343 Figure 14 clarifies the relationship between instantaneous drag coefficients and the non-
 344 dimensional parameters a_p to validate the Morison theory. In particular, Figure 14 (a) shows
 345 the results during the a_p ramp-up phase. The drag coefficients for both *Sinusoidal* and
 346 *Hyperbolic* type inflows exhibits a linear relation with a_p and are well-described by the Morison
 347 theory using Eq.(3) with the added mass coefficient C_a of 1.37. In contrast, Figure 14 (b) shows
 348 that during a_p ramp-down phase, the drag coefficients are lower than in the ramp-up phase and
 349 influenced by a_p , acceleration duration and inflow type. When a_p drops below 0.01, the drag
 350 coefficients fall below the quasi-steady value.



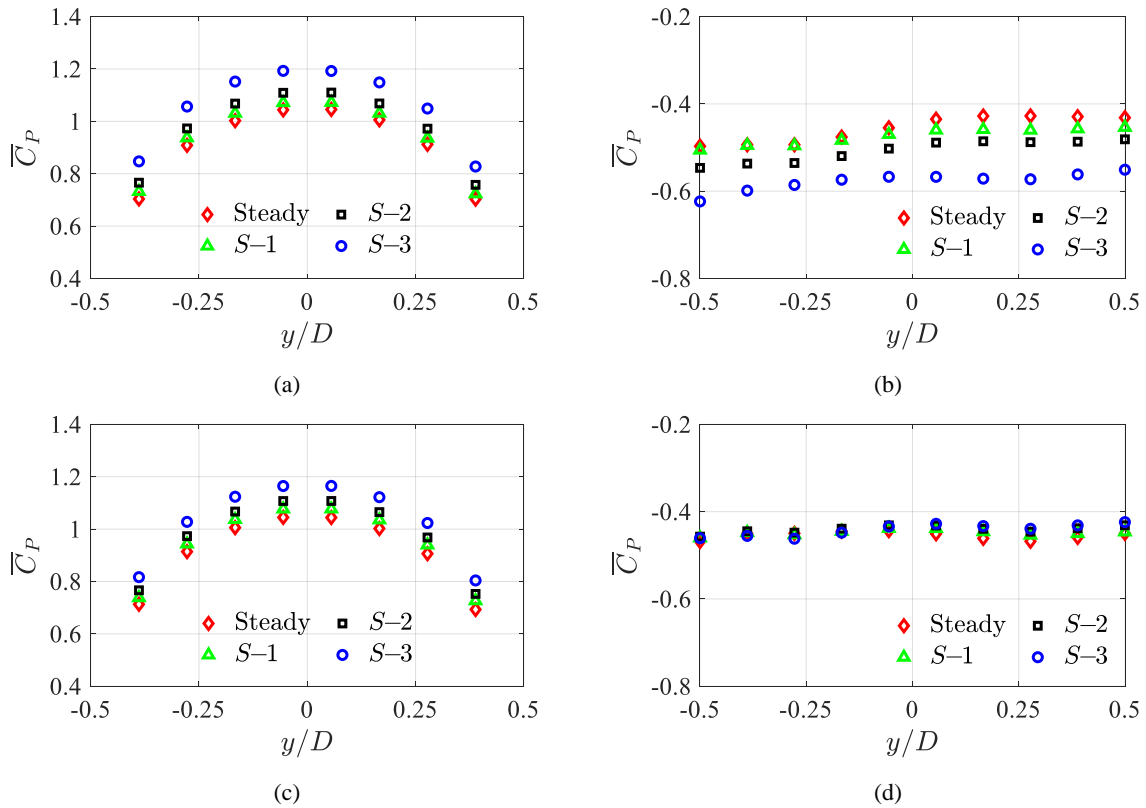
351 Figure 14. Instantaneous drag coefficients of R4 vs a_p : (a) ramp-up; (b) ramp-down.

352 In order to explain the mechanism of drag overshoot, the instantaneous pressure
 353 coefficients under accelerating inflows are calculated as:

$$354 \quad C_p(t) = \frac{2(p(t) - p_\infty)}{\rho U(t)^2}. \quad (11)$$

355 Figure 15 shows mean pressure coefficients \bar{C}_p acting on the vertical windward and
 356 leeward sides of R4 under *Sinusoidal*-type inflows. For the a_p ramp-up phase shown in Figure

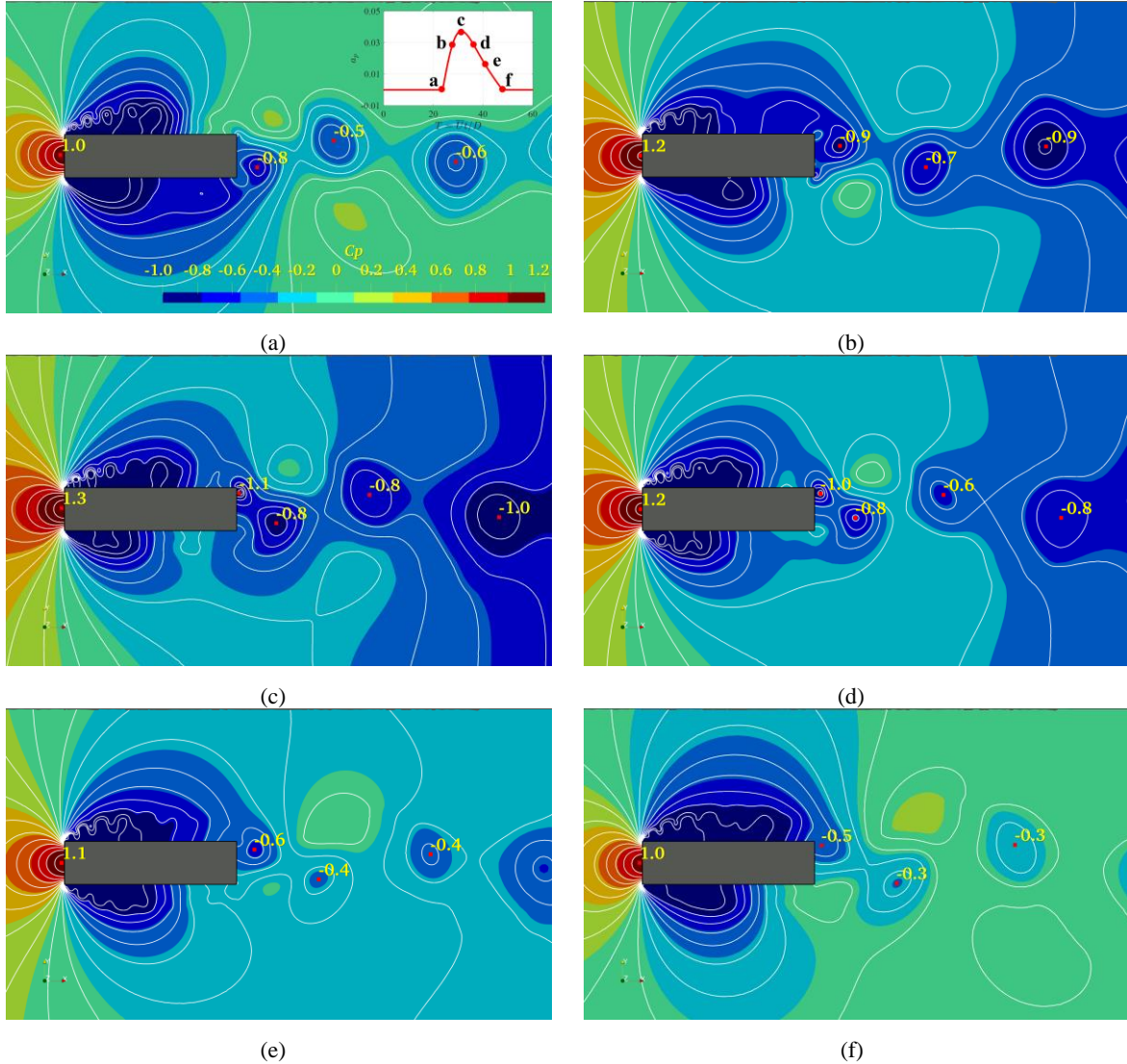
357 15 (a) and (b), as a_p increase from 0 to 0.036, the positive \bar{C}_p on the windward side increases
 358 by approximately 14%, while the negative \bar{C}_p on the leeward side decrease by about 34%.
 359 This leads to an increase in the net pressure coefficients and cause drag coefficient overshoot.
 360 In contrast, for the a_p ramp-down phase shown in Figure 15 (c) and (d), only \bar{C}_p on the
 361 windward side increase while the negative \bar{C}_p on the leeward side remains constant, resulting
 362 in a lower overshoot compared to the ramp-up phase.



363 Figure 15. Mean pressure coefficients in *Sinusoidal*-type inflows: (a) and (b) windward and leeward sides
 364 during a_p ramp-up; (c) and (d) during a_p ramp-down.

365 Figure 16 provides the instantaneous pressure flow fields of $R4$ under $S-3$ condition at
 366 different time instants. Comparing Figure 16 (a)~(c), as a_p ramp up from 0 to 0.036, the
 367 windward pressure rises from 1.0 to a maximum of 1.3 due to flow acceleration. Meanwhile,
 368 the lowest negative pressure in the wake region of Kármán's vortex street drops from -0.8 to -
 369 1.1, leading to an increase in net pressure and a drag overshoot. Conversely, as a_p ramps down
 370 from 0.036 back to 0 in Figures 16(c)~(f), the windward pressure decreases from 1.3 to 1.0.
 371 Furthermore, the lowest negative pressure in the wake region of Kármán's vortex street rises

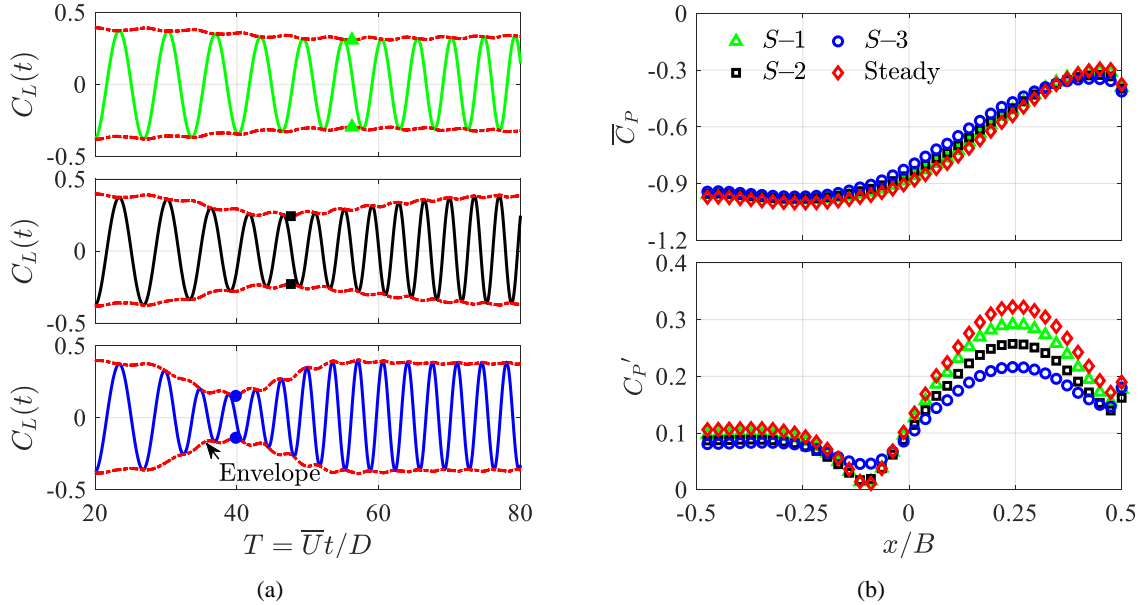
372 from -1.1 to -0.3, even exceeding the steady value when a_p returns 0. This results in a reduction
 373 of the drag overshoot, eventually causing aerodynamic forces to drop below the quasi-steady
 374 values as acceleration comes to an end and a_p approaches 0.



375 Figure 16. Pressure flow fields for R4 under S-3 conditions at different time instants: (a) $T=24$; (b)
 376 $T=27.6864$; (c) $T=31.3752$; (d) $T=36$; (e) $T=40.8$; (f) $T=48$.

377 Figure 17 (a) presents the time-varying lift coefficients $C_L(t)$ and their respective envelope
 378 curves of R4 under S-1, S-2 and S-3 accelerating inflows. As $a_{p,max}$ increases from 0.009 to
 379 0.036, the amplitude of $C_L(t)$ decreases by approximately 17.8%, 35.2% and 59.4%,
 380 respectively, compared to the steady case. This indicates that accelerating inflows can decrease
 381 the VIV forces, which is consistent with the experimental results by [24, 25, 53]. Figure 17 (b)
 382 presents the corresponding mean and standard deviation distributions. As $a_{p,max}$ increases from
 383 0 to 0.036, the accelerating flows have minimal effects on the mean value, but significantly

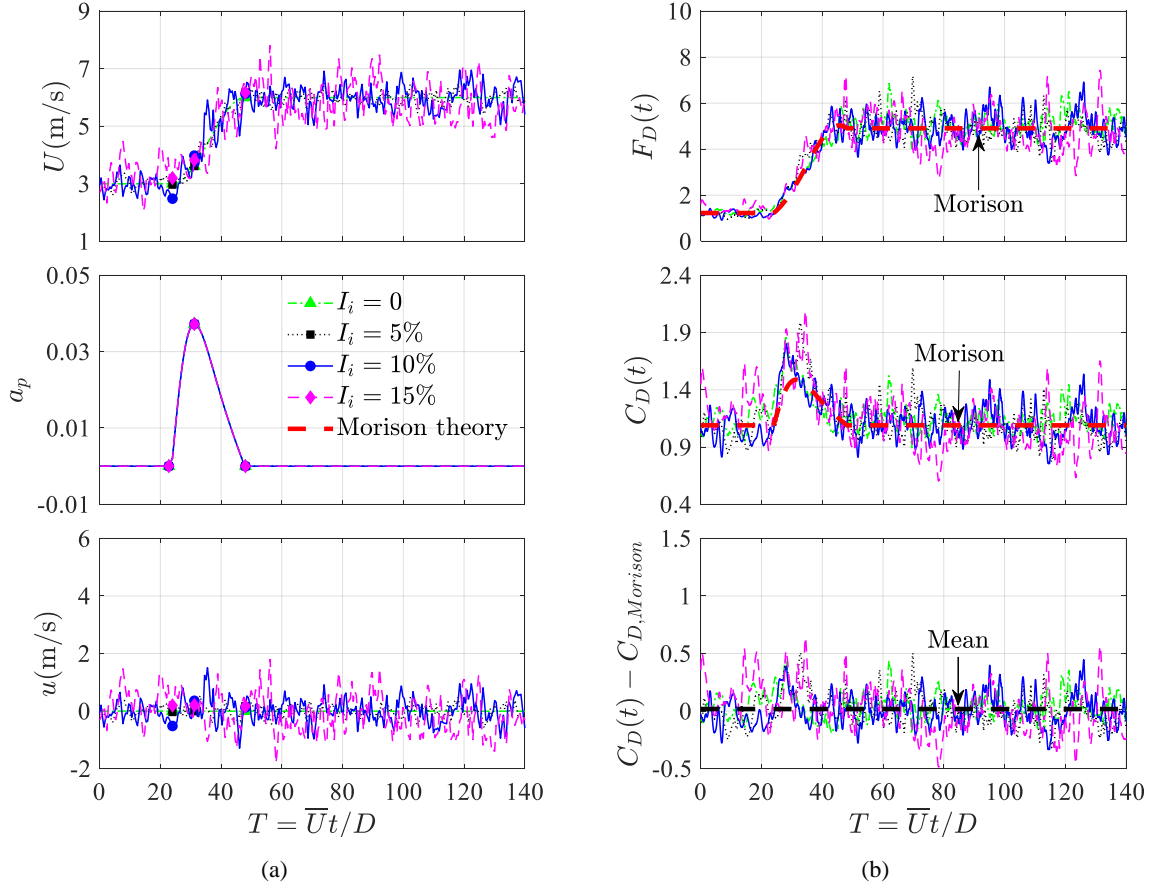
384 reduce the standard deviation of the pressure coefficients. Compared to the steady case, the
 385 peak value of C_p' decrease by approximately 8.8%, 17.2%, and 32.9%, respectively, leading to
 386 a reduction in the fluctuation amplitude of lift coefficients.



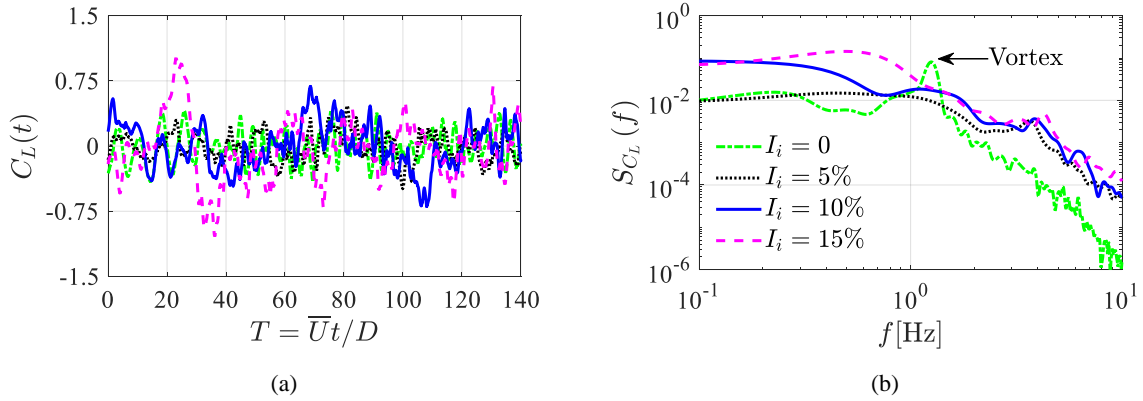
387 Figure 17. Lift Statistics of R4 in different *Sinusoidal*-type inflows: (a) time history of lift coefficients; (b)
 388 mean and stand deviation of pressure distributions during acceleration.

389 5.3 Effects of turbulence components

390 In order to clarify the turbulence effect in accelerating inflows, Figure 18 presents the LES
 391 results for R4 under *Turbulent*-type accelerating inflows, with turbulence intensity 0%, 5%, 10%
 392 and 15%. The Morison values, calculated using Eq.(3) with the added mass coefficient C_a of
 393 1.37 from URANS, are also compared. Significant overshoot phenomena are observed also in
 394 this case, consistently with the previously presented results. The time-varying-mean drag
 395 coefficients obtained under the four accelerating inflows with different turbulence intensities
 396 are well-described by Morison equation. This indicates that turbulence have limited effects on
 397 the drag overshoot and the Morison equation is also suitable for accelerating turbulent inflows.



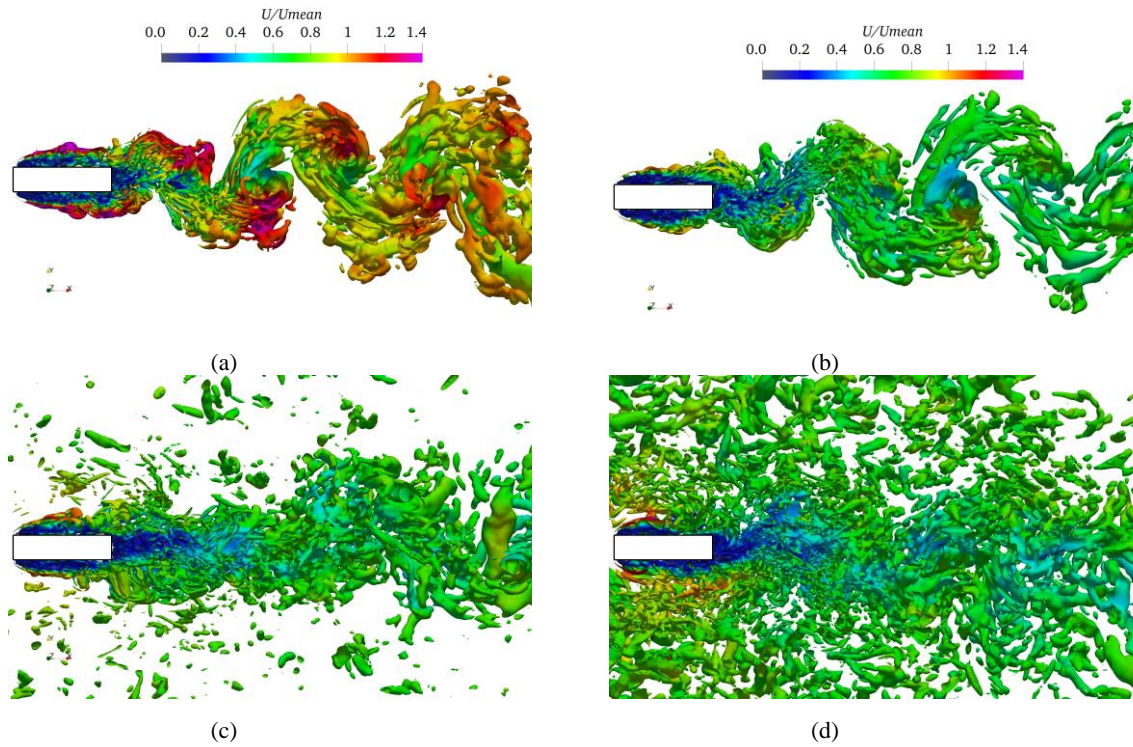
398 Figure 18. Drag forces of R4 from LES under *Turbulent*-type accelerating flows with varying turbulence
 399 intensities: (a) U and a_p ; (b) $F_D(t) - \bar{F}_D$ and $C_D(t) - \bar{C}_D$.



400 Figure 19 Lift coefficients from LES under *Turbulent*-type accelerating inflows with varying turbulence
 401 intensities: (a) time history; (b) spectrum.

402 Figure 19 presents the time history and spectrum of lift coefficients of R4 under *Turbulent*-
 403 type accelerating inflows with turbulence intensity of 0~15%. It can be found that turbulence
 404 clearly reduces the vortex induced forces, while obviously increasing buffeting forces. Figure
 405 20 further compares the corresponding coherent structure of R4. Similar to URANS results,
 406 vortex shedding in accelerating inflows without turbulence is slightly weaker than in steady

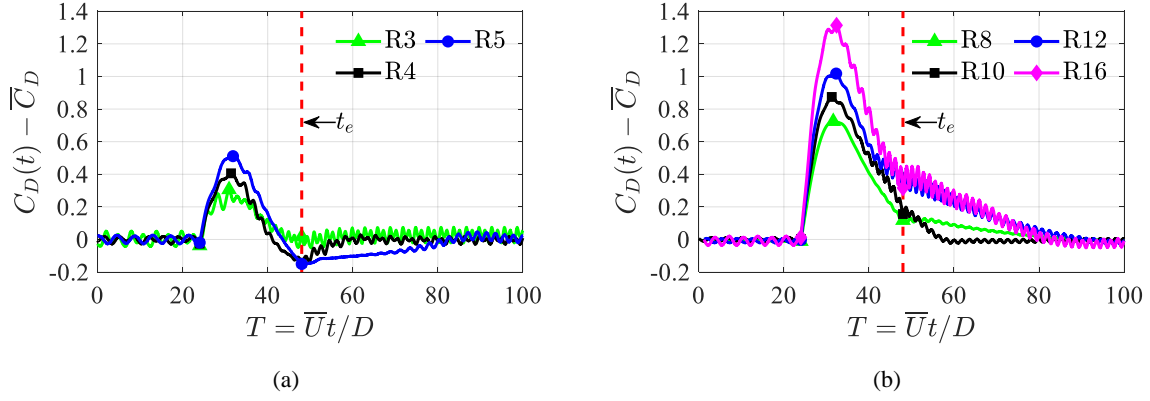
407 cases. Once more, increasing turbulence intensity diminish the vortex shedding intensity, which
 408 is similar to its effects on the VIV in steady case [88].



409 Figure 20 Q criterion of the instantaneous coherent structure for different turbulence intensity($Q=0.50 \text{ s}^{-2}$): (a)
 410 Steady flow (b) $I_t=0\%$; (c) $I_t=5\%$; (d) $I_t=10\%$.

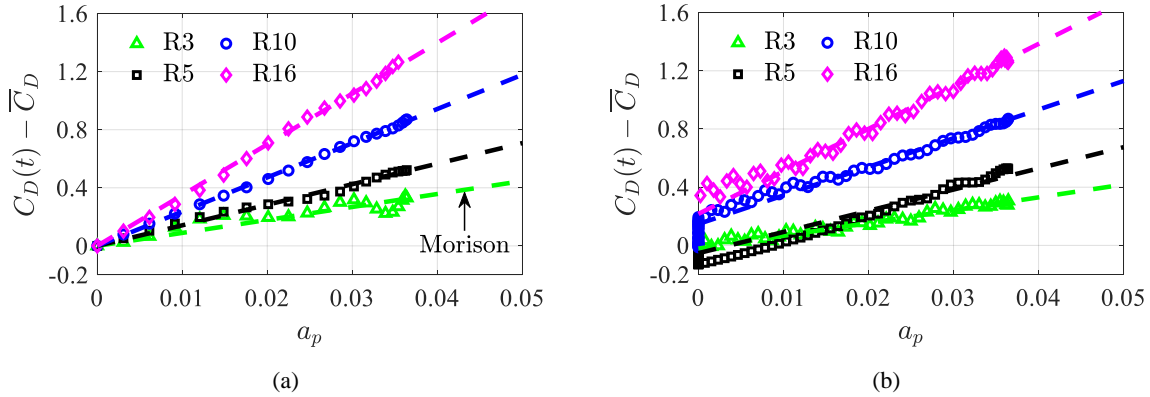
411 5.4 Effects of aspect ratio

412 Next, we report the effects of the aspect ratio on the drag overshoot of rectangular
 413 cylinders. Figure 21 shows the drag coefficients for $R3$, $R4$, $R5$, and $R8$, $R10$, $R12$, $R16$ under
 414 the $S-3$ accelerating flow condition. The overshoot of drag coefficient increases rapidly with
 415 the aspect ratio. For $R3$, $R4$, and $R5$, the maximum drag coefficients exceed the quasi-steady
 416 values by 22.4%, 32.6%, and 46.1%, respectively, while for $R8$, $R10$, $R12$, and $R16$, the
 417 increases are 74.0%, 82.0%, 94.3%, and 109.7%, respectively. Notably, at the end of the
 418 acceleration phase ($t=t_c$), the drag coefficients for the investigated rectangular cylinders, except
 419 $R3$, do not immediately return to the quasi-steady values. For $R4$ and $R5$, they are 11.5% and
 420 13.5% lower, while for $R8$, $R10$, $R12$, and $R16$, they are 12.0%, 14.6%, 32.9%, and 26.4%
 421 higher than the quasi-steady values, respectively.



422 Figure 21. Drag coefficients for different rectangular cylinders for *Sinusoidal*-type inflow *S-3*: (a) *R3*, *R4*,
 423 *R5*; (b) *R8*, *R10*, *R12* and *R12*;

424 Figure 22 further presents drag coefficients versus the acceleration parameters a_p for
 425 rectangular cylinders under the *S-3* accelerating inflows. The results are fitted using the
 426 Morison theory in Eq.(3). The added mass coefficients C_a for *R3*, *R5*, *R10*, and *R16* are 1.49,
 427 1.42, 1.18, and 1.09, respectively. During the a_p ramp-up phase, the drag coefficients closely
 428 match the Morison values. However, during the ramp-down phase, especially when a_p is
 429 between 0 to 0.01, the drag coefficients does not return to the quasi-steady state, causing
 430 deviations from Morison theory.



431 Figure 22. Drag coefficients vs accelerate parameter a_p for different rectangular cylinders: (a) a_p ramp-up
 432 phase; (b) a_p ramp-down phase.

433 Figure 23(a) shows the added mass coefficient C_a versus the aspect ratio R obtained from
 434 CFD. In particular, the fitted empirical formula is given as follows:

$$435 \quad C_a = aR^{-b}, \quad (12)$$

436 where $a=1.90$, $b=0.20$ are the empirical coefficients. Substituting Eq.(12) into Eq.(3), the drag
 437 coefficients for rectangular cylinders under accelerating inflows can be evaluated as:

438

$$C_D(t) = \bar{C}_D + 2aR^{1-b}a_p. \quad (13)$$

439

440

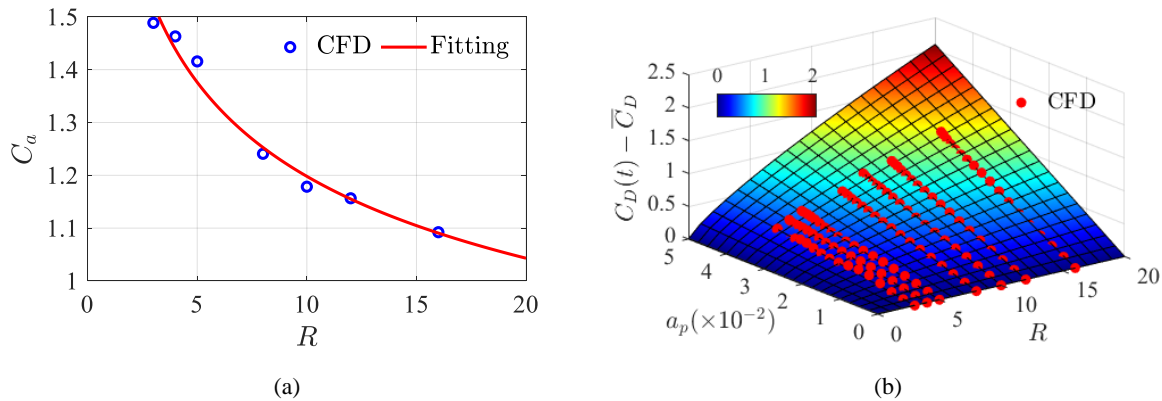
441

442

443

444

Based on the above proposed empirical formula, Figure 23(b) shows the surface plot of drag coefficient as a function of the non-dimensional parameters a_p and aspect ratio R . The proposed formula agrees well with the CFD results, showing that the drag overshoot increases with a_p and becomes more significant as the aspect ratio increases. Notably, streamlined bridge decks with large aspect ratios are commonly used in long-span bridges. Therefore, the drag overshoot caused by accelerating flows with high a_p should be considered in their design.



445

446

Figure 23. Drag coefficients for rectangular cylinders: (a) identified added mass coefficients vs. aspect ratio; (b) empirical formula surface plot vs. a_p and aspect ratio.

447

448

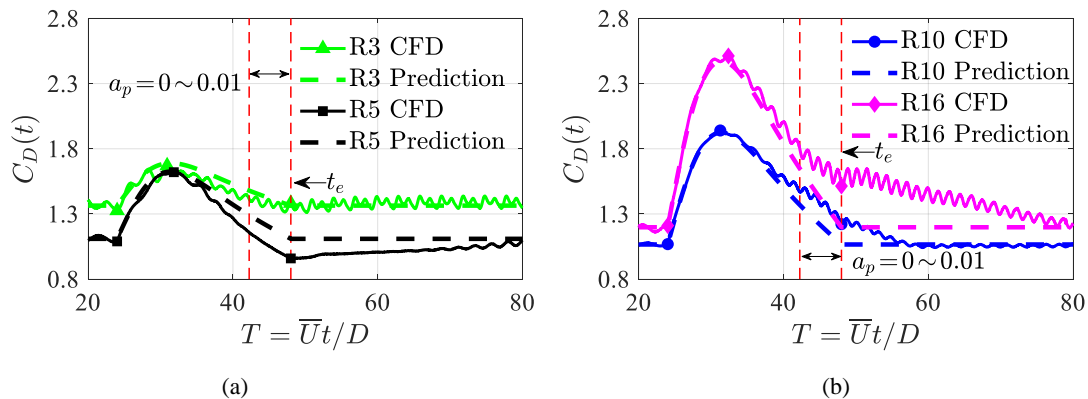
449

450

451

452

Finally, Figure 24 compares the time history of drag coefficients from CFD with predictions using the proposed empirical formula in Eq.(13). The formula accurately predicts drag coefficients during the a_p ramp-up phase. However, the drag overshoot during a_p ramp-down phase depends on both a_p and the type of accelerating inflow. When a_p decrease below 0.01, the formula overestimates drag coefficients by up to 13.6% for $R3$ and $R5$, and underestimates them by up to 26.6% for $R10$ and $R16$ during the a_p ramp-down phase.



453

454

Figure 24. Comparison between empirical formula predictions and CFD for the drag coefficients of rectangular cylinders: (a) $R3$ and $R5$ (b) $R10$ and $R16$

455 6. Conclusions

456 This paper employs URANS and LES to investigate the aerodynamic drag overshoot of
457 rectangular cylinders with aspect ratios from 3 to 16 under four types of accelerating inflows.
458 Sixteen acceleration cases, varying in acceleration start and end speeds, duration, non-
459 dimensional parameters $a_p(D(dU/dt)/U^2)$, turbulence intensity and aspect ratio, are analyzed to
460 identify key factors influencing aerodynamic overshoot. The accuracy of CFD simulations is
461 confirmed by their good agreement with WTTs [22, 56]. The main conclusions are as follows:

462 (1) All investigated rectangular cylinders exhibit drag overshoot under accelerating
463 inflows. According to the Morrison model, the parameter $a_p(D(dU/dt)/U^2)$, non-dimensional
464 by instantaneous speeds, determines the overshoot. During the a_p ramp-up phase, both
465 windward positive and leeward negative pressures increase, causing the overshoot to rise
466 linearly with a_p . During a_p ramp-down phase, drag overshoot is not only influenced by a_p but
467 also by acceleration duration and inflow type.

468 (2) The drag overshoot increases with aspect ratio. For rectangular cylinders with aspect
469 ratios from 3 to 16 under acceleration inflows with a_p of 0.036, the drag coefficients increase
470 by 22.4%~109.7% compared to the quasi-static case. Therefore, drag overshoot must be
471 considered for long-span bridges with large aspect ratio decks exposed to non-synoptic winds
472 with high a_p .

473 (3) No vortex-shedding induced lift coefficient overshoot is observed for investigated
474 acceleration cases. Instead, it appears that accelerating inflows reduce fluctuating lift
475 coefficients by lowering fluctuating pressures at the trailing edge.

476 (4) As the turbulence intensity of the accelerating inflows increases from 0 to 15%, the
477 drag overshoot of rectangular cylinder with an aspect ratio 4 is substantially unaffected.
478 Therefore, turbulence has limited effects on drag overshoot, being the main effect to reduce
479 vortex-induced forces as in stationary cases.

480 (5) The proposed empirical formula based on Morison theory and identified added mass
481 coefficients can well estimate the drag overshoot for rectangular cylinders during a_p ramp-up
482 phase. However, for a_p ramp-down phase that involves complex overshoot, the formula

483 overestimates drag coefficients by approximately 13.6% for smaller aspect ratios (3 to 5) and
484 underestimates them by about 26.6% for larger aspect ratios (10~16). Despite these
485 discrepancies, the formula provides useful guidelines for estimating drag loads on bluff bodies
486 in accelerating inflows.

487 **Acknowledgments**

488 The authors express their gratitude for financial support from National Key Research and
489 Development Program of China (2022YFC3005302), National Natural Science Foundation of
490 China (52408514), China Postdoctoral Science Foundation (2023M740786 & 2024T170188),
491 Natural Science Foundation of Guangxi (2025GXNSFBA069139) and Guangxi Science and
492 Technology Base and Talent Project (AA23026011 & AD23026185).

493 **Data availability**

494 The data that support the findings of this study are available from the corresponding author
495 upon reasonable request.

496 **Author Contributions**

497 All authors contributed to this work.

498 **Conflicts of Interest**

499 The authors declare no conflict of interest.

500 **References:**

- 501 [1] H. Zhang, H. Wang, Z. Xu, Numerical study of wind loads on the streamlined bridge deck in the translating
502 tornado-like vortex, *Physics of Fluids*, 35 (2023).
- 503 [2] R.-D. Xue, G. Chen, X.-H. Xiong, Aerodynamic characteristics of the train under real wind gust, *Physics of*
504 *Fluids*, 36 (2024).
- 505 [3] P. Hu, F. Zhang, Y. Han, C. Cai, Z. Wang, J. Long, Aerodynamic characteristics of the train under the stationary
506 thunderstorm downburst wind, *Physics of Fluids*, 36 (2024).
- 507 [4] T.T. Fujita, Downbursts: meteorological features and wind field characteristics, *Journal of Wind Engineering*
508 *and Industrial Aerodynamics*, 36 (1990) 75-86.
- 509 [5] H. Wang, A. Li, J. Niu, Z. Zong, J. Li, Long-term monitoring of wind characteristics at Sutong Bridge site,
510 *Journal of Wind Engineering and Industrial Aerodynamics*, 115 (2013) 39-47.

511 [6] H. Wang, T. Wu, T. Tao, A. Li, A. Kareem, Measurements and analysis of non-stationary wind characteristics
512 at Sutong Bridge in Typhoon Damrey, *Journal of Wind Engineering and Industrial Aerodynamics*, 151 (2016)
513 100-106.

514 [7] M. Burlando, D. Romanic, G. Boni, M. Lagasio, A. Parodi, Investigation of the weather conditions during the
515 collapse of the Morandi Bridge in Genoa on 14 August 2018 using field observations and WRF model,
516 *Atmosphere*, 11 (2020) 724.

517 [8] Y. Feng, Q. Su, J. Hao, W. Han, H. Wang, A comparative study on the transient wind-induced response of long-
518 span bridges subject to downbursts and typhoons, *Engineering Structures*, 280 (2023) 115649.

519 [9] X. Chen, Analysis of multimode coupled buffeting response of long-span bridges to nonstationary winds with
520 force parameters from stationary wind, *Journal of Structural Engineering*, 141 (2015) 04014131.

521 [10] T. Tao, H. Wang, P. Shi, H. Li, Stationary and non-stationary buffeting analyses of a long-span bridge under
522 typhoon winds, *Wind and Structures*, 31 (2020) 445-457.

523 [11] Y. Su, G. Huang, Y.-l. Xu, Derivation of time-varying mean for non-stationary downburst winds, *Journal of*
524 *Wind Engineering and Industrial Aerodynamics*, 141 (2015) 39-48.

525 [12] L. Hu, Y.-L. Xu, W.-F. Huang, Typhoon-induced non-stationary buffeting response of long-span bridges in
526 complex terrain, *Engineering Structures*, 57 (2013) 406-415.

527 [13] Z. Xu, G. Dai, L. Zhang, Y.F. Chen, R.G. Flay, H. Rao, Effect of non-Gaussian turbulence on extreme
528 buffeting response of a high-speed railway sea-crossing bridge, *Journal of Wind Engineering and Industrial*
529 *Aerodynamics*, 224 (2022) 104981.

530 [14] T. Sarpkaya, C. Ihrig, Impulsively started steady flow about rectangular prisms: experiments and discrete
531 vortex analysis, *Journal of Fluids Engineering*, DOI (1986).

532 [15] T. Sarpkaya, H. Kline, Impulsively-started flow about four types of bluff body, *Journal of Fluids Engineering*,
533 DOI (1982).

534 [16] T. Sarpkaya, Separated flow about lifting bodies and impulsive flow about cylinders, *AIAA Journal*, 4 (1966)
535 414-420.

536 [17] T. Sarpkaya, Lift, drag, and added-mass coefficients for a circular cylinder immersed in a time-dependent
537 flow, *Journal of Applied Mechanics*, 30 (1963) 13-15.

538 [18] T. Takeuchi, J. Maeda, Unsteady wind force on an elliptic cylinder subjected to a short-rise-time gust from
539 steady flow, *Journal of Wind Engineering and Industrial Aerodynamics*, 122 (2013) 138-145.

540 [19] X. Dong, L. Zhao, W. Cui, Y. Peng, Y. Ge, Aerodynamics and aeroelastic performance of a rigid-frame bridge
541 with a bluff body girder subjected to short-rise-time gusts, *Engineering Structures*, 263 (2022) 114376.

542 [20] B. Yan, Y. Yuan, X. Zhou, Y. Li, Q. Yang, Q. Liu, W. Yang, J. Han, Experimental study of non-stationary
543 aerodynamic effects on the wind turbine nacelles under extreme wind events, *Physics of Fluids*, 36 (2024).

544 [21] S. Li, X. Li, Y. Jiang, T. Li, Y. Wang, Non-stationary aerodynamic characteristics of the rectangular cylinder
545 in downburst-like flow, *Physics of Fluids*, 37 (2025).

546 [22] T. Yang, M.S. Mason, Aerodynamic characteristics of rectangular cylinders in steady and accelerating wind
547 flow, *Journal of Fluids and Structures*, 90 (2019) 246-262.

548 [23] V. Le, L. Caracoglia, Experimental investigation on non-stationary wind loading effects generated with a
549 multi-blade flow device, *Journal of Fluids and Structures*, 96 (2020) 103049.

550 [24] S. Brusco, H.-Y. Bin, Y.-L. Lo, G. Piccardo, Transient aerodynamics of a square cylinder under downburst-
551 like accelerating flows reproduced in a multiple-fan wind tunnel, *Journal of Fluids and Structures*, 124 (2024)
552 104038.

553 [25] X.-Y. Chen, L.-D. Zhu, Z.-X. Tan, Experimental investigation on key parameters influencing unsteady
554 aerodynamics of a 3: 2 rectangular prism in accelerating flow, *Physics of Fluids*, 36 (2024).

555 [26] T. Takeuchi, J. Maeda, Overshoot of wind forces on a body under step-function-like gusty winds, *Journal of*
556 *Structural and Construction Engineering: Transactions of AIJ*, 681 (2012) 1629-1635.

557 [27] S. Zhang, Q. Yang, G. Solari, B. Li, G. Huang, Characteristics of thunderstorm outflows in Beijing urban
558 area, *Journal of Wind Engineering and Industrial Aerodynamics*, 195 (2019) 104011.

559 [28] S. Zhao, Y. Ge, G. Kopp, Assessment of gust factors and wind speed decomposition methods for
560 thunderstorms, *Journal of Wind Engineering and Industrial Aerodynamics*, 223 (2022) 104953.

561 [29] K. Cai, M. Huang, Y. Dong, S. Liao, Y.-Q. Ni, P. Chan, Nonstationary Turbulent Wind Speed Models and
562 Their Effects on Wind-Induced Responses of Tall Buildings, *Journal of Structural Engineering*, 151 (2025)
563 04025003.

564 [30] F. Jiang, M. Zhang, Y. Li, T. Yan, J. Zhang, Field measurement analysis of wind parameters and nonstationary
565 characteristics in mountainous terrain: focusing on cooling windstorms, *Journal of Wind Engineering and*
566 *Industrial Aerodynamics*, 230 (2022) 105175.

567 [31] M. Chay, C. Letchford, Pressure distributions on a cube in a simulated thunderstorm downburst—Part A:
568 stationary downburst observations, *Journal of Wind Engineering and Industrial Aerodynamics*, 90 (2002) 711-732.

569 [32] D. Romanic, A. Kassab, J. Chowdhury, H. Hangan, L. Doddipatla, An analysis of the influence of a generic
570 building on tornadic flow fields using high-frequency PIV and point velocity measurements, *Journal of Fluids and*
571 *Structures*, 123 (2023) 104010.

572 [33] J. Žužul, A. Ricci, M. Burlando, B. Blocken, G. Solari, CFD analysis of the WindEEE dome produced
573 downburst-like winds, *Journal of Wind Engineering and Industrial Aerodynamics*, 232 (2023) 105268.

574 [34] F. Canepa, M. Burlando, D. Romanic, G. Solari, H. Hangan, Downburst-like experimental impinging jet
575 measurements at the WindEEE Dome, *Scientific Data*, 9 (2022) 243.

576 [35] S. Brusco, G. Buresti, Y.-L. Lo, G. Piccardo, I. Aerodynamics, Constant-frequency time cells in the vortex-
577 shedding from a square cylinder in accelerating flows, *Journal of Wind Engineering*, 230 (2022) 105182.

578 [36] X. Li, S. Li, Q. Yang, Y. Hui, S. Cao, Time-varying up-crossing theory-based non-stationary extreme
579 estimation of gust-loading on rectangular cylinder due to thunderstorm-like wind, *Probabilistic Engineering*
580 *Mechanics*, 74 (2023) 103506.

581 [37] Y. Yuan, B. Yan, X. Zhou, X. Li, Y. Dong, Q. Yang, Q. Liu, Evolution of downburst-like flows produced by
582 an active-controlled multi-blade facility, *Physics of Fluids*, 36 (2024).

583 [38] S. Zou, X. He, Generation of a mountain-valley wind in an atmospheric boundary wind tunnel: a gust-wind
584 generator study, *Advances in Bridge Engineering*, 4 (2023) 4.

585 [39] N.D. Tiwari, P.P. Sarkar, Prediction of dynamic loads and responses of a tall building in tornado wind:
586 Numerical analysis and experimental validation, *Engineering Structures*, 326 (2025) 119510.

587 [40] L. Zhao, L. Zhang, W. Cui, S. Cao, Y. Ge, The reproduction of 2-D non-synoptic wind field in an actively
588 controlled wind tunnel, *Journal of Wind Engineering and Industrial Aerodynamics*, 251 (2024) 105786.

589 [41] T. Ghazal, M. Aboutabikh, H. Aboshosha, M. Abdelwahab, Thunderstorm wind load evaluation on storm
590 shelters using wind tunnel testing, *Engineering Structures*, 262 (2022) 114350.

591 [42] E.-S. Abd-Elaal, J.E. Mills, X. Ma, A coupled parametric-CFD study for determining ages of downbursts
592 through investigation of different field parameters, *Journal of Wind Engineering and Industrial Aerodynamics*,
593 123 (2013) 30-42.

594 [43] C. Li, Q. Li, Y. Xiao, J. Ou, A revised empirical model and CFD simulations for 3D axisymmetric steady-
595 state flows of downbursts and impinging jets, *Journal of Wind Engineering and Industrial Aerodynamics*, 102
596 (2012) 48-60.

597 [44] M. Haines, I. Taylor, Numerical investigation of the flow field around low rise buildings due to a downburst
598 event using large eddy simulation, *Journal of Wind Engineering and Industrial Aerodynamics*, 172 (2018) 12-30.

599 [45] L. Patruno, M. Ricci, A systematic approach to the generation of synthetic turbulence using spectral methods,
600 *Computer methods in applied mechanics and engineering*, 340 (2018) 881-904.

601 [46] T. Ma, C. Sun, P. Miller, Large eddy simulation of non-stationary highly turbulent hurricane boundary layer
602 winds, *Physics of Fluids*, 36 (2024).

603 [47] Z. Fang, Z. Wang, H. Huang, L. Yang, Y. Guo, Numerical simulations of downburst wind fields: A
604 comparative analysis of stationary and moving storms using the impinging jet model, *Physics of Fluids*, 36 (2024).

605 [48] P. Hu, Y. Tang, Y. Han, C. Cai, N. Yan, F. Zhang, Numerical study on self-excited forces and flow fields for
606 a thin plate under a sinusoidal non-stationary wind condition, *Physics of Fluids*, 35 (2023).

607 [49] Y. Pan, M. Liu, C. Zhang, Z. Xie, Temporal variability wind characterization analysis and model construction
608 of moving downbursts, *Physics of Fluids*, 37 (2025).

609 [50] W. Li, L. Patruno, H. Niu, S. de Miranda, X. Hua, Aerodynamic admittance of a 6: 1 rectangular cylinder: A
610 computational study on the role of turbulence intensity and integral length scale, *Journal of Wind Engineering and
611 Industrial Aerodynamics*, 218 (2021) 104738.

612 [51] Y. Zhang, S. Cao, J. Cao, J. Wang, Effects of turbulence intensity and integral length scale on the surface
613 pressure on a rectangular 5: 1 cylinder, *Journal of Wind Engineering and Industrial Aerodynamics*, 236 (2023)
614 105406.

615 [52] F. Guo, G. Wu, X. Du, M.S. Mason, Numerical investigation of flow around a square cylinder in accelerated
616 flow, *Physics of Fluids*, 33 (2021).

617 [53] G. Lunghi, S. Brusco, A. Mariotti, G. Piccardo, M. Salvetti, Influence of inflow acceleration on the
618 aerodynamic characteristics of a square cylinder, *Journal of Wind Engineering and Industrial Aerodynamics*, 252
619 (2024) 105814.

620 [54] T. Takeuchi, N. Takeuchi, J. Maeda, Y.C. Kim, Characteristics of local wind force and wind response of a
621 building under short-rise-time gusts, *9th Asia-Pacific Conference on Wind Engineering*, 2017.

622 [55] J. Xing, L. Patruno, S. de Miranda, F. Ubertini, Non-stationary winds effects over large partially-open roofs:
623 A CFD study regarding the role of unsteady aerodynamics, *Structures*, 65 (2024) 106728.

624 [56] Y. Xiao, *Aerodynamic Characteristics of 5:1 Rectangular Cylinder Subjected to Transient Flow*, Southwest
625 Jiaotong University, 2022.

626 [57] S. Brusco, G. Buresti, G. Piccardo, Thunderstorm-induced mean wind velocities and accelerations through
627 the continuous wavelet transform, *Journal of Wind Engineering and Industrial Aerodynamics*, 221 (2022) 104886.

628 [58] J. Morison, J.W. Johnson, M. O'Brien, Experimental studies of forces on piles, *Coastal Engineering
629 Proceedings*, DOI (1953) 25-25.

630 [59] J.R. Morison, J.W. Johnson, S.A. Schaaf, The force exerted by surface waves on piles, *Journal of Petroleum
631 Technology*, 2 (1950) 149-154.

632 [60] C. Clément, P. Bozonnet, G. Vinay, P. Pagnier, A.B. Nadal, J. Réveillon, Evaluation of Morison approach
633 with CFD modelling on a surface-piercing cylinder towards the investigation of FOWT Hydrodynamics, *Ocean
634 Engineering*, 251 (2022) 111042.

635 [61] K. Xu, Y. Shao, Z. Gao, T. Moan, A study on fully nonlinear wave load effects on floating wind turbine,
636 *Journal of Fluids and Structures*, 88 (2019) 216-240.

637 [62] R.H. Kraichnan, Diffusion by a random velocity field, *Physics of Fluids*, 13 (1970) 22-31.

638 [63] S. Li, R. Snaiki, T. Wu, Active simulation of transient wind field in a multiple-fan wind tunnel via deep
639 reinforcement learning, *Journal of Engineering Mechanics*, 147 (2021) 04021056.

640 [64] K. Butler, S. Cao, A. Kareem, Y. Tamura, S. Ozono, Surface pressure and wind load characteristics on prisms
641 immersed in a simulated transient gust front flow field, *Journal of Wind Engineering and Industrial Aerodynamics*,
642 98 (2010) 299-316.

643 [65] Z. Li, T. Chan, J. Ko, Evaluation of typhoon induced fatigue damage for Tsing Ma Bridge, *Engineering*
644 *Structures*, 24 (2002) 1035-1047.

645 [66] H. Wang, T. Tao, Y. Gao, F. Xu, Measurement of wind effects on a kilometer-level cable-stayed bridge during
646 Typhoon Haikui, *Journal of Structural Engineering*, 144 (2018) 04018142.

647 [67] X. Wang, H. Li, Z. Chen, Y. Qian, Y. Wang, X. Peng, Field measurement of near-surface typhoon
648 characteristics using a smart monitoring system on a long-span arch bridge site, *Advances in Structural*
649 *Engineering*, 22 (2019) 1977-1987.

650 [68] M. Mason, T. Yang, Unsteady pressures on a square cylinder subjected to transient wind fields, 12th UK
651 Conference on Wind Engineering, 2016.

652 [69] F. Nieto, D. Hargreaves, J. Owen, S. Hernández, On the applicability of 2D URANS and SST k- ω turbulence
653 model to the fluid-structure interaction of rectangular cylinders, *Engineering Applications of Computational Fluid*
654 *Mechanics*, 9 (2015) 157-173.

655 [70] A. Álvarez, F. Nieto, K. Kwok, S. Hernández, Aerodynamic performance of twin-box decks: A parametric
656 study on gap width effects based on validated 2D URANS simulations, *Journal of Wind Engineering and Industrial*
657 *Aerodynamics*, 182 (2018) 202-221.

658 [71] W. Li, L. Patruno, H. Niu, S. de Miranda, X. Hua, Identification of complex admittance functions using 2D-
659 URANS models: Inflow generation and validation on rectangular cylinders, *Journal of Wind Engineering and*
660 *Industrial Aerodynamics*, 208 (2021) 104435.

661 [72] A. Álvarez, F. Nieto, D. Nguyen, J. Owen, S. Hernández, 3D LES simulations of a static and vertically free-
662 to-oscillate 4: 1 rectangular cylinder: Effects of the grid resolution, *Journal of Wind Engineering and Industrial*
663 *Aerodynamics*, 192 (2019) 31-44.

664 [73] D.T. Nguyen, D.M. Hargreaves, J.S. Owen, Vortex-induced vibration of a 5: 1 rectangular cylinder: A
665 comparison of wind tunnel sectional model tests and computational simulations, *Journal of Wind Engineering and*
666 *Industrial Aerodynamics*, 175 (2018) 1-16.

667 [74] L. Bruno, M.V. Salvetti, F. Ricciardelli, Benchmark on the aerodynamics of a rectangular 5: 1 cylinder: an
668 overview after the first four years of activity, *Journal of Wind Engineering and Industrial Aerodynamics*, 126
669 (2014) 87-106.

670 [75] P. Zou, S. Cao, J. Cao, Spanwise correlation and coherent structures of separated flow around rectangular 5:
671 1 cylinder, *Journal of Wind Engineering and Industrial Aerodynamics*, 231 (2022) 105211.

672 [76] Z. Zhang, F. Xu, Spanwise length and mesh resolution effects on simulated flow around a 5: 1 rectangular
673 cylinder, *Journal of Wind Engineering and Industrial Aerodynamics*, 202 (2020) 104186.

674 [77] T. Igarashi, Characteristics of the flow around rectangular cylinders: the case of the angle of attack 0 deg,
675 *Bulletin of JSME*, 28 (1985) 1690-1696.

676 [78] H. Noda, A. Nakayama, Free-stream turbulence effects on the instantaneous pressure and forces on cylinders
677 of rectangular cross section, *Experiments in fluids*, 34 (2003) 332-344.

678 [79] C. Norberg, Flow around rectangular cylinders: pressure forces and wake frequencies, *Journal of Wind*
679 *Engineering and Industrial Aerodynamics*, 49 (1993) 187-196.

680 [80] L. Thiesemann, Zur Ermittlung von Flatterderivativa aus Versuchen und mittels numerischer
681 Strömungsmechanik, Shaker2008.

682 [81] X. Amandolese, Contribution à l'étude des chargements fluides sur des obstacles non profilés fixes ou mobiles:
683 application aux tabliers de pont, Marne-la-Vallée, ENPC, 2001.

684 [82] G. Schewe, Reynolds-number-effects in flow around a rectangular cylinder with aspect ratio 1: 5, *Journal of*
685 *Fluids and Structures*, 39 (2013) 15-26.

686 [83] C. Mannini, A.M. Marra, L. Pigolotti, G. Bartoli, The effects of free-stream turbulence and angle of attack
687 on the aerodynamics of a cylinder with rectangular 5: 1 cross section, *Journal of Wind Engineering and Industrial*
688 *Aerodynamics*, 161 (2017) 42-58.

689 [84] B. Wu, S. Li, S. Cao, Q. Yang, L. Zhang, Numerical investigation of the separated and reattaching flow over
690 a 5: 1 rectangular cylinder in streamwise sinusoidal flow, *Journal of Wind Engineering and Industrial*
691 *Aerodynamics*, 198 (2020) 104120.

692 [85] M. Li, Q. Li, H. Shi, Aerodynamic pressures on a 5: 1 rectangular cylinder in sinusoidal streamwise
693 oscillatory flows with non-zero mean velocities, *Journal of Wind Engineering and Industrial Aerodynamics*, 208
694 (2021) 104440.

695 [86] L. Patruno, M. Ricci, S. de Miranda, F. Ubertini, Numerical simulation of a 5: 1 rectangular cylinder at non-
696 null angles of attack, *Journal of Wind Engineering and Industrial Aerodynamics*, 151 (2016) 146-157.

697 [87] S. de Miranda, L. Patruno, F. Ubertini, G. Vairo, On the identification of flutter derivatives of bridge decks
698 via RANS turbulence models: Benchmarking on rectangular prisms, *Engineering Structures*, 76 (2014) 359-370.

699 [88] S.J. Daniels, I.P. Castro, Z.-T. Xie, Numerical analysis of freestream turbulence effects on the vortex-induced
700 vibrations of a rectangular cylinder, *Journal of Wind Engineering and Industrial Aerodynamics*, 153 (2016) 13-
701 25.

702