

1 Experimental and Numerical Study on Vortex-Induced 2 Motions of a Deep-Draft Semi-Submersible

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10 Abstract

11 An experimental study on Vortex-Induced Motions (VIM) of a Deep-Draft Semi-Submersible (DDS)
12 was carried out in a towing tank, with the aim to investigate the VIM effects on the overall
13 hydrodynamics of the structure. In order to study the fluid physics associated with VIM of the DDS, a
14 comprehensive numerical simulation was conducted to examine the characteristics of vortex shedding
15 processes and their interactions due to multiple cylindrical columns. The experimental measurements
16 were obtained for horizontal plane motions including transverse, in-line and yaw motions as well as
17 drag and lift forces on the structure. Spectral analysis was further carried out based on the recorded
18 force time history. These data were subsequently used to validate the numerical model. Detailed
19 numerical results on the vortex flow characteristics revealed that during the “lock-in”, the vortex
20 shedding processes of the upstream columns enhance the vortex shedding processes of the
21 downstream columns leading to the rapid increase of the magnitude of the VIM. In addition to the
22 experimental measurements, for the two uniform flow incidences (0° and 45°) investigated,
23 comprehensive numerical data of the parametric study on the VIM characteristics at wide range of
24 current strength will also serve as quality benchmarks for future study and provide guidance for
25 practical design.

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26 Keywords

27 Vortex-Induced Motions (VIM); Deep-Draft Semi-Submersible (DDS); Model Test; Computational
28 Fluid Dynamics (CFD)

29 Nomenclature

30	A	Projected area
31	A_x/L	Non-dimensional characteristics amplitude of in-line motion
32	A_y/L	Non-dimensional characteristics amplitude of transverse motion
33	$A_{1/3}/L$	Non-dimensional significant values of the transverse peaks
34	B_L	Platform width
35	B_T	Platform draft
36	C	Structural damping
37	C_D	Drag force coefficient
38	C_L	Lift force coefficient
39	D	Column projected width
40	f_s	Vortex shedding frequency
41	f_0	Natural frequency in clam water
42	Fr	Froude number
43	F_D, F_x	Hydrodynamic drag force acting on the structure
44	F_L, F_y	Hydrodynamic lift force acting on the structure
45	g	Acceleration of gravity
46	H	Immersed column height above the pontoon
47	K_x	Linear spring constant in the in-line direction

48	K_y	Linear spring constant in the transverse direction
49	L	Column width
50	P	Pontoon height
51	Re	Reynolds number
52	rms	Root mean square
53	S	Distance between centre columns
54	St	Strouhal number
55	T_0	Natural periods in calmwater
56	Δt	Numerical simulation time step
57	U, U_c	Current speed
58	u^*	Friction velocity at the nearest wall
59	Ur	Reduced velocity
60	ρ	Fresh water density
61	Δ	Displacement
62	Δy_1	First layer thickness
63	λ	Scale ratio
64	θ	Attack angle; Flow incidence
65	ν	Kinematic viscosity of the fresh water
66	ω	Vorticity magnitude
67	x, X	In-line motion
68	y, Y	Transverse motion
69	y^+	Y plus value

70 1. Introduction

71 Along with the continuing developments in the field of offshore technology, an increasing number of
72 deep-draft floating structures have been fabricated and installed in different deep-water regions
73 around the world such as the Gulf of Mexico (GoM). Deep-draft floating structures have favourable
74 behaviour in vertical plane motions and therefore are easy to accommodate steel risers. Most of the
75 deep-draft floating structures consist of four vertical cylindrical columns with connecting deck and
76 lower pontoon type members. When a current flows past the columns, a complex issue named VIM
77 can generate strong cyclic dynamic effects on the floaters, especially when the vortex shedding
78 frequency is approaching the natural frequency of the structure leading to the so-called “lock-in”
79 phenomenon. VIM is a cyclic rigid body motion induced by vortex shedding on a large floating
80 structure. It is a common practice to increase the draft of the columns in order to achieve the desired
81 hydrodynamic characteristics in vertical plane motions. However, the increase in columns’ draft can
82 also lead to more severe VIM. In this context, both experimental and numerical methods are used to
83 investigate the mechanism of VIM and the effects on overall hydrodynamics of the DDS.

84 In deep-water developments, a favourable motion response of the floater is critical to the safe
85 operations of top-tensioned facilities, as well as the fatigue life of the mooring system and the risers.
86 In the GoM, due to the strong loop currents, VIMs have been often observed since the Genesis Spar
87 platform commissioned in 1997 [1, 2]. Finn et al. [3] and van Dijk et al. [4] investigated VIM effects
88 on different designs of Spar platform. To reduce the potential problems, spiral strakes attached to the
89 hull were examined as an acceptable design approach in order to minimize the VIM phenomenon.
90 Several experiments on Spar VIM were carried out to mitigate VIM, such as Irani and Finn [5],
91 Halkyard et al. [6], Wang et al. [7] and Wang et al. [8]. In the last decade, Computational Fluid
92 Dynamics (CFD) provided a reasonable alternative way to predict VIM on Spar platforms. Halkyard
93 et al. [9], Oakley and Constantinides [10] combined the results from experimental and numerical
94 studies in order to compare the VIM effects on Spar from experimental measurements and CFD
95 predictions. Thiagarajan et al. [11] further investigated a bare cylinder and a cylinder with strakes to
96 study the VIM phenomenon. A guideline of numerical simulation of the VIM on the Spar platform
97 was proposed by Lefevre et al. [12].

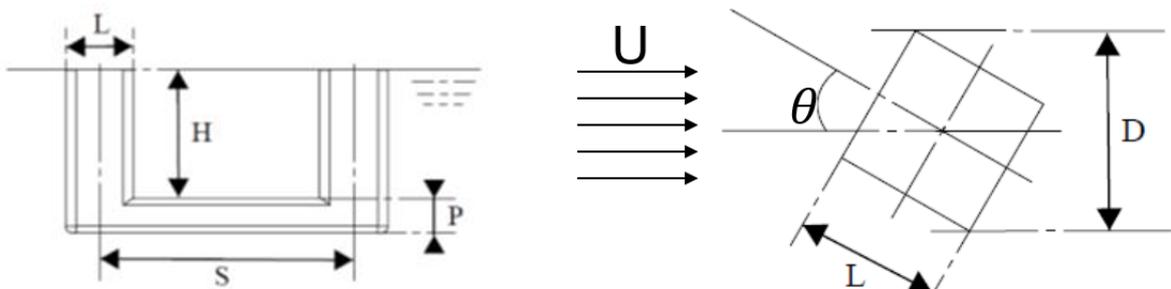
98 The presence of the VIM phenomenon on more complex multiple cylindrical structures, such as
99 Tension-Leg Platforms (TLP) and DDS, is confirmed from field measurements made by Rijken and
100 Leverette [13]. Waals et al. [14] studied the draft effects on VIM. When the draft changed from a
101 typical conventional semi-submersible to a DDS, significant increases of VIM were observed. Hong
102 et al. [15] also reported that deep-draft floaters experience strong VIM. Gonçalves et al. [16] found
103 that even the conventional semi-submersible with appendages can also suffer from VIM. For most of

104 the multiple cylindrical structures, VIM was predicted by undertaking the aforementioned
 105 experiments. CFD is still rarely applied for the study on VIM of multiple cylindrical structures at
 106 present time due to its computational intensity. Among very limited recent studies reported in the
 107 literature, Tan et al. [17] numerically predicted VIM on a multi-column floater. Lee et al. [18]
 108 investigated the VIM responses on both model and prototype DDSs by using CFD tools. Tan et al.
 109 [19] conducted that model tests are necessary in order to validate the numerical model by using
 110 experimental results obtained from a towing tank.

111 As pointed out by Fujarra et al. [2] in their comprehensive review, after one decade of experimental
 112 investigations, VIM on single or multiple cylindrical structures are now much better understood.
 113 Details about the deep-draft structures, which were studied during the last decade, are summarised in
 114 Table 1 and compared with the outcomes from the present study to emphasize and confirm the results.
 115 Fig. 1 shows the definition of the dimensions for the configurations.

116 Table 1. Summary of the studies on VIM of deep-draft structures (“*” is the numerical result).

	λ	<i>Mass ratio</i>	<i>H/L</i>	<i>S/L</i>	<i>H/P</i>	<i>Re</i>	<i>Ur</i>	<i>A_y/L at 45°</i>
Waals et al. [14]	1:70	0.83	1.75	4.14	2.33	$6 \times 10^3 \sim 7 \times 10^4$	4.0 ~ 40.0	0.32
Rijken and Leverette [20]	1:50	--	2.18	3.75	4.83	$\sim 10^5$	1.0 ~ 15.0	0.48
Rijken et al. [21]	1:48	--	1.71	4.04	3.04	$3 \times 10^4 \sim 3 \times 10^5$	5.0 ~ 9.0	0.64 [16]
Tahar and Finn [22]	1:56	0.77	1.74	3.20	4.00	$\sim 5 \times 10^5$	2.0 ~ 15.0	0.33
Lee et al. [18]	1:67	--	1.78	3.50	3.62	$2 \times 10^4 \sim 9 \times 10^4$	4.0 ~ 20.0	0.4*
Present study	1:64	0.91	1.90	3.72	3.70	$2 \times 10^4 \sim 1 \times 10^5$	3.4 ~ 20.2	0.742/0.751*



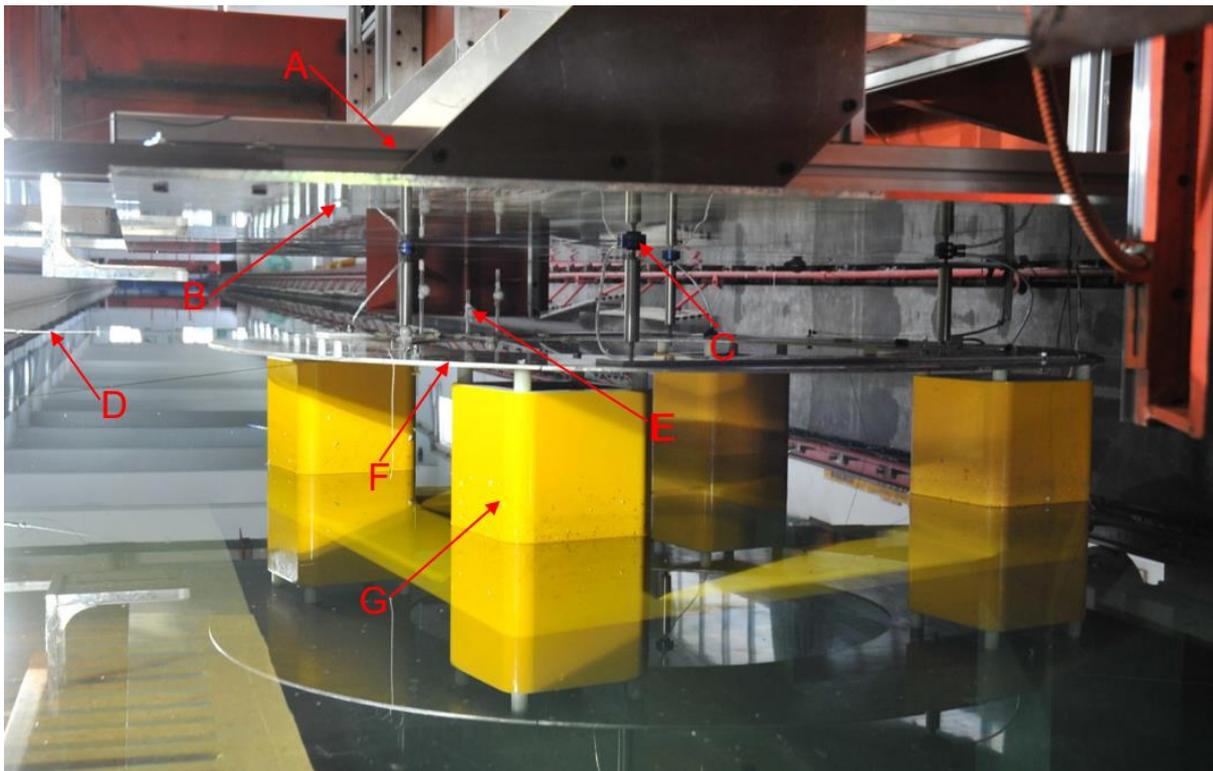
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118 Fig. 1. Characteristic dimensions of a DDS.

119 2. Model test

120 2.1. Model set-up

121 The experimental set-up is characterized by a DDS model supported above the waterline by four low
122 friction air bearings and a set of equivalent horizontal mooring springs in the Zhejiang Ocean
123 University towing tank with dimension of $130 \times 6 \times 3\text{m}$ (length \times width \times depth). The DDS model
124 and experimental set-up in the towing tank are shown in Fig. 2 and Fig. 3.

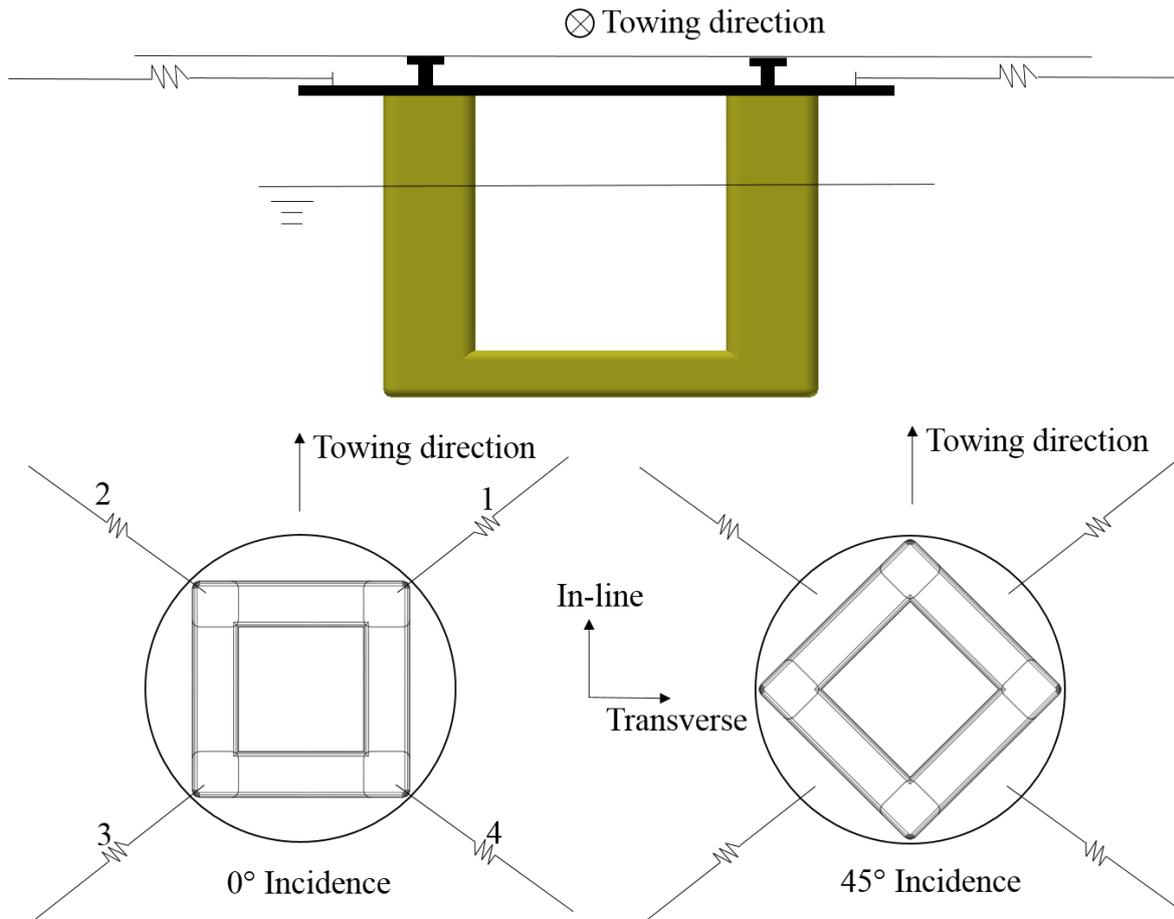


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- A) Adjustable support structure
- B) Smooth horizontal table
- C) Low friction air bearing
- D) Horizontal spring with load cell
- E) Locomotion measure device with 6 degree of freedom
- F) Top frame
- G) DDS model in scale ratio $\lambda = 1 : 64$

126

127 Fig. 2. Experimental set-up in the towing tank.



128

129 Fig. 3. Schematic of the experimental set-up.

130 Table 2. Main characteristics of the DDS unit.

	Prototype (m)	Model (m)
Distance between centre columns (S)	72.5	1.133
Column width (L)	19.5	0.305
Immersed column height above the pontoon (H)	37.0	0.578
Pontoon height (P)	10.0	0.156

131 It is important for keeping the similarity between prototype and model. Thus, the Froude scaling
 132 approach recommended by van Dijk et al. [23] was used. It is essential to note that the Reynolds
 133 number ($Re = UD/\nu$, where U is the current velocity, D is the projected width of the column and ν is
 134 the kinematic viscosity of the fresh water) for the prototype DDS is in the order of 10^7 while the
 135 Reynolds number at model scale is significantly lower. Since the DDS model is a relatively bluff
 136 body, the flow is expected to separate at the corners of the columns. The vortex shedding
 137 phenomenon is mostly independent of the Reynolds number from the transcritical region to the
 138 subcritical region. The scale effects for square section shaped structure are less than that for circle

139 section shaped structures [2]. The main characteristics of the DDS model are shown in Table 2 with
140 the dimensions defined in Fig. 1.

141 2.2. Mooring system

142 Four horizontal mooring lines with load cells are attached at the top frame to restrain the horizontal
143 motions of the DDS model. An additional set of four low friction air bearings were developed in order
144 to limit the vertical motions of the DDS model. Only three degrees of freedom motions in horizontal
145 plane (namely transverse, in-line and yaw) were allowed in the test. The horizontal mooring system
146 consists of four horizontal lines with soft springs being employed to provide the horizontal restoring
147 force for the model and match the natural periods in the horizontal plane motions. The mooring lines
148 were set above the water level to avoid disturbing the vortex shedding process. Each mooring line
149 with a load cell was attached to an anchor post on the carriage at one end and to the top deck of the
150 model at the other end. The top deck featuring studs were arranged circumferentially with 15° spacing
151 interval. When the current incidences need to be changed, the model with the top deck can be rotated
152 accordingly and the horizontal lines are attached to the appropriate studs, allowing the same mooring
153 configuration for the two different current incidence angles. Therefore, the mooring stiffness was kept
154 the same for the two current incidences, aiming to facilitate result comparison [24].

155 2.3. Test programme

156 In order to investigate the effects of VIM on the DDS model under a reduced velocity ranging from
157 3.5 to 20.3, two incidences (0° and 45°) relative to the towing direction were tested. The definition of
158 motions and towing directions are shown in Fig. 3. A minimum of fifteen oscillation cycles were
159 allowed to occur in order to reflect the quasi-steady state of the experimental VIM phenomenon.

160 2.4. Reduced velocity

161 The reduced velocity (Ur) is defined as:

$$162 \quad Ur = \frac{(UT_0)}{D} \quad (1)$$

163 where U is the current speed, T_0 is the natural period in calm water and D is the projected width of the
164 column.

165 Table 3. Natural periods of the motions in calm water.

Incidences (°)	Natural period of transverse motion, $T_{0transverse}$ (s)	Natural period of in-line motion, $T_{0in-line}$ (s)	Natural period of yaw motion, T_{0yaw} (s)
0°	19.4	19.6	17.1
45°	20.1	19.2	18.3

166

167 3. Numerical (CFD) simulation

168 3.1. Computational overview

169 To further investigate the fluid physics associated with VIM, a comprehensive numerical study is
170 conducted to examine the vortex shedding characteristics and the vortex dynamics leading to the
171 motions of DDS. A mesh and time step sensitivity assessment has been carried out on the numerical
172 model in order to develop an efficient process followed by the actual VIM simulations.

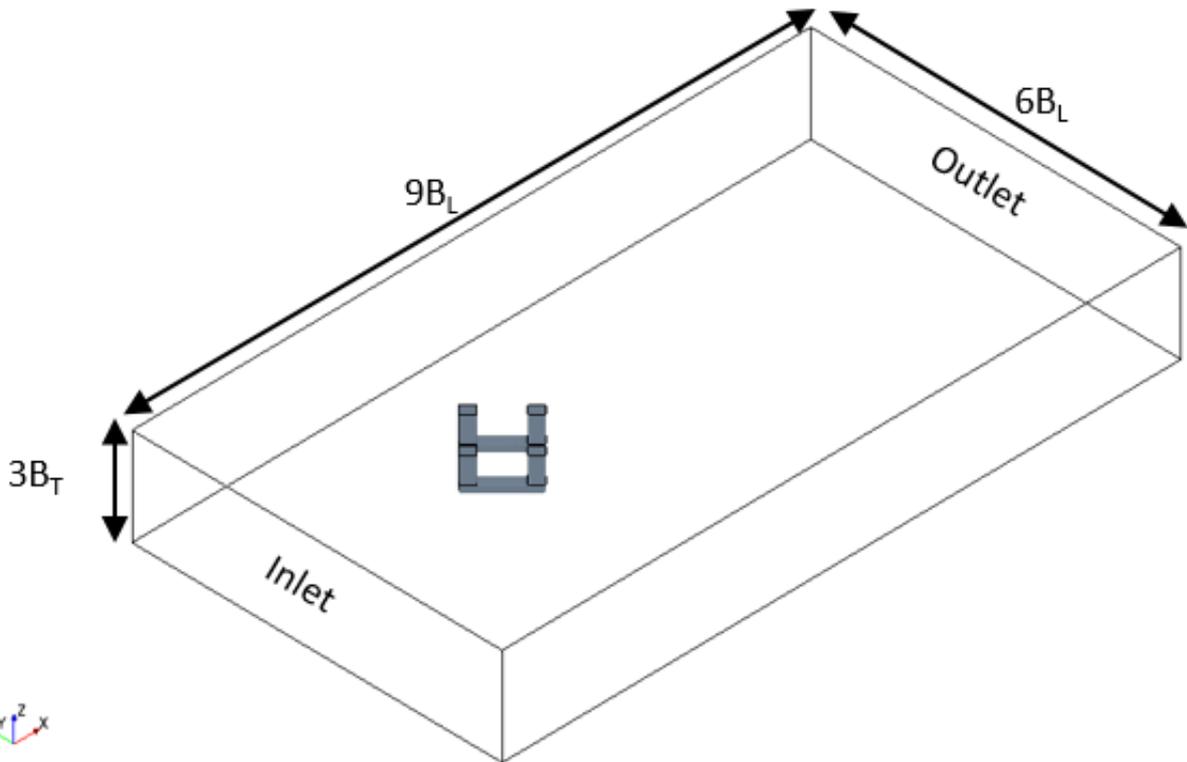
173 The detached eddy simulation (DES) was used in this study. For the DES model, the improved
174 delayed detach eddy simulation (IDDES) model [25] with the Spalart-Almaras (SA) [26] was used.
175 Delayed detached eddy simulation (DDES) [27] is a recent modification of detached eddy simulation
176 (DES) [26]. IDDES is a capable model which builds a single set of formulas both for natural (D)DES
177 applications and for wall-modelling in large eddy simulation (WMLES) [25]. In this case, the
178 boundary layers and irrotational regions are solved using SA model. However, when the grid is fine
179 enough, it will emulate a basic large eddy simulation (LES) subgrid scale model in detached flow
180 regions [28]. This approach can improve the boundary layer simulation and in the meantime reduce
181 the computational cost. It is noted that the SA model requires $y^+ < 1$ (where $y^+ = u_*\Delta y_l/\nu$, and where
182 u_* denotes the friction velocity at the nearest wall, Δy_l is the first layer thickness and ν is the
183 kinematic viscosity) indicating that the viscous sublayer is properly resolved. All the simulations are
184 carried out using Star-CCM+ 9.

185 The main characteristics of the DDS design analysed in this section are given in Table 2.
186 Additionally, a MARIN DDS design [14] was also simulated, aiming to further validate the present
187 numerical model with previously published experiment data. The main characteristics of the MARIN
188 model are shown in Table 4. The scale ratio λ for this particular model is 1:70 (the flow velocity is set
189 as 0.17m/s which is the same as in the experiment undertaken by Waals et al. [14]).

190 Table 4. The main characteristics of the MARIN DDS.

	Prototype (m)	Model (m)
Distance between centre columns (S)	58.7	0.838
Column width (L)	14.0	0.200
Immersed column height above the pontoon (H)	35.0	0.500
Pontoon height (P)	10.5	0.150

191 For all the simulations, the computational domain $9B_L \times 6B_L \times 3B_T$ was used (where B_L is the hull
192 width of the DDS and B_T is the draft of the DDS, see Fig. 4). It is noted that the computational
193 domains were $6B_L \times 4.5B_L \times 2.8B_T$ and $5B_L \times 4B_L \times 2.2B_T$ in the study by Lee et al. [18]. Tan et al.
194 [17] performed simulation with a domain $27B_L \times 18B_L \times 6.5B_T$ and Liu et al. [29] used a domain of
195 $11B_L \times 6B_L \times 3B_T$. Compared with aforementioned computational domain settings, a $9B_L \times 6B_L \times 3B_T$
196 domain is considered to be large enough to eliminate the far field effects from the boundaries
197 affecting the flow around the model and the three-dimensional effects from a spanwise cross flow
198 direction.



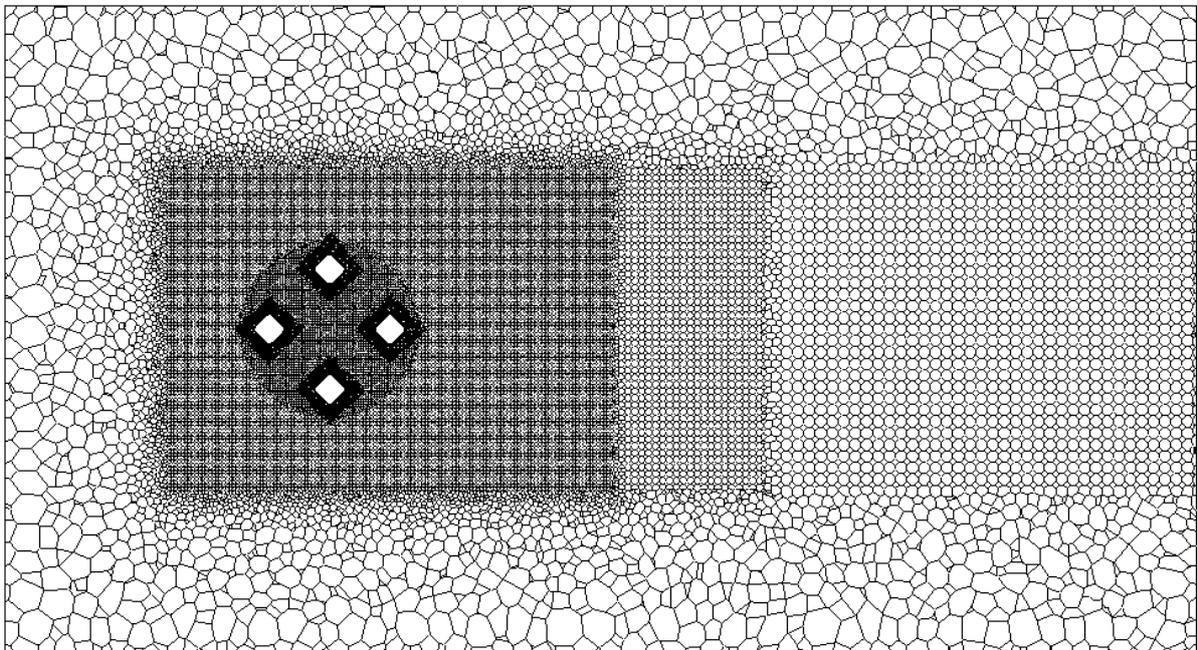
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200 Fig. 4. Computational domain.

201 The computational domain is modelled with a three-dimensional mesh of elements. A polyhedral
202 mesh [28] is used in this study. The overall element mesh domain is shown at a mid-depth horizontal
203 layer in Fig. 5. In the present study, a near wall refinement method named “Prism Layer Mesher [28]”
204 is adopted. The “Prism Layer Mesher” model is used with a core volume mesh to generate orthogonal

205 prismatic cells next to wall surfaces. This layer of cells is necessary to improve the accuracy of the
206 flow solution [28]. The y^+ values are smaller than 1 in all simulations. Another five regional
207 refinements are added in the domain in order to refine both the near wake and the far wake region (see
208 Fig. 5).

209 The boundary conditions are kept same in all simulations. At the inlet, a uniform and constant
210 velocity of 0.25m/s is specified directly for all sensitivity studies. Along the outlet boundary, the
211 pressure is prescribed to be equal to zero. The velocity at the boundary is extrapolated from the
212 interior using reconstruction gradients [28]. For the body surface of the DDS, a no-slip boundary
213 condition is specified in terms of the tangential velocity which is explicitly set to be zero and the
214 pressure at the boundary is extrapolated from the adjacent cells using reconstruction gradients [28]. It
215 is noted that for the Froude number being quite small ($Fr < 0.2$, $Fr = U/\sqrt{gD}$, where U is the current
216 velocity, g is the acceleration of gravity and D is the projected width of the column) in all simulations
217 of the present investigation. As observed in the model tests, the free surface effects are rather limited
218 and can be ignored. Therefore, only the submerged geometry is considered, and the geometry of the
219 structure above the waterline will not affect the simulation results. However, the gravity centre, the
220 mass of the structure and the moment of inertia are still using the values from the entire structure
221 design. Thus, the free surface boundary is prescribed as being a symmetry boundary.



222

223 Fig. 5. Visualization of the mesh at the middle draft level of the DDS (XY plane at the middle draft of
224 the DDS).

225 To verify the numerical model, a mesh sensitivity study and a time step study were carried out. These
 226 studies aimed to obtain the numerical results independent of mesh and time step variations. Details are
 227 presented in Table 5 for a stationary DDS under 45° flow incidence. Results for all cases are obtained
 228 by averaging after more than fifteen vortex shedding cycles.

229 3.2. Convergence Studies

230 The convergence studies, based on the effects of mesh refinement and time step variations, provided
 231 results for time-averaged drag force coefficient (\bar{C}_D) and Strouhal number (St). The Strouhal number
 232 ($St = f_s L / U_c$, where f_s is the vortex shedding frequency, L is the width of the column and U_c is the free
 233 stream flow velocity) is obtained from the power spectra of the fluctuating lift force coefficient as
 234 suggested by Schewe [30].

235 The force coefficients (C_D , C_L) are defined as:

$$236 \quad C_D = \frac{F_D}{\frac{1}{2}\rho U_c^2 A}, \quad (2)$$

$$237 \quad C_L = \frac{F_L}{\frac{1}{2}\rho U_c^2 A}, \quad (3)$$

238 where, F_D is the drag force on the structure, F_L is the lift force on the structure, ρ is the fresh water
 239 density, U_c is the free stream velocity and A is the projected area.

240 Firstly, five tests at $Re = 7.6 \times 10^4$ were carried out with different mesh especially in the near wake
 241 region of the structure. The DDS_M1 case is presented as relatively coarse mesh in the test. In this
 242 model, the computational domain consists of 0.15 million elements. Further cases ranged from 0.56
 243 million to 6.86 million elements (see Table 5). All cases firstly used the same non-dimensional time
 244 step of 0.008.

245 Finally, a time step sensitivity study was carried out for the convergence evaluation. The geometric
 246 model chosen for initial time step sensitivity study is the case DDS_M3, which was then repeated for
 247 two further cases with different time steps. A summary of these seven different sets of analyses is
 248 given in Table 5, and the results are presented in Table 6 and Table 7.

249 Table 5. Numerical set-up information.

Case	Elements (million)	Non-dimensional time step ($\Delta t U/L$)
------	--------------------	--

DDS_M1	0.15	0.008
DDS_M2	0.56	0.008
DDS_M3	3.43	0.008
DDS_M4	5.08	0.008
DDS_M5	6.86	0.008
DDS_T1	3.43	0.016
DDS_T2	3.43	0.004

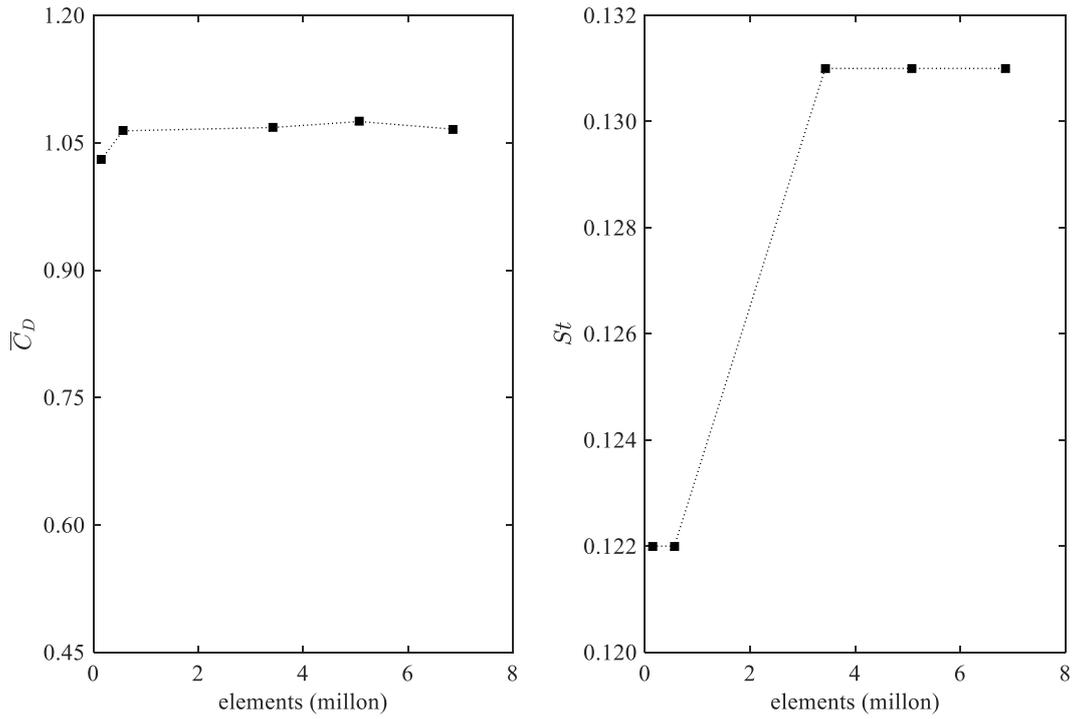
250 Table 6. The mesh refinement tests.

Case	Elements (million)	\bar{C}_D	Relative variation (%)	St	Relative variation (%)
DDS_M1	0.15	1.030		0.122	
DDS_M2	0.56	1.064	3.301	0.122	0
DDS_M3*	3.43	1.068	0.376	0.131	7.377
DDS_M4	5.08	1.075	0.655	0.131	0
DDS_M5	6.86	1.066	0.837	0.131	0

251 Table 7. The time step sensitivity study.

Case	Non-dimensional time step ($\Delta t U/L$)	\bar{C}_D	Relative variation (%)	St	Relative variation (%)
DDS_T1	0.016	1.020		0.131	
DDS_M3*	0.008	1.068	4.706	0.122	11.486
DDS_T2	0.004	1.068	0	0.122	0

252 As shown in Table 6 and Table 7, the DDS_M3 case is considered to be fine enough for both mesh
253 refinement effects and a suitable time step. Case DDS_M3 has been chosen for the further validation
254 of the numerical model against experimental data.



255

256 Fig. 6. Convergence line for both \bar{C}_D and St .

257 *3.3. Model validation*

258 Experimental data available from MARIN [14] is the main reference for validating the present
 259 numerical simulation. The resulting \bar{C}_D from the present numerical calculation and the experimental
 260 measurements are presented in Table 8.

261 Table 8. Comparison of \bar{C}_D from the present numerical calculation and the MARIN experimental
 262 measurements.

Case	\bar{C}_D	Relative variation (%)
Present numerical model	1.127	8.78
MARIN test [14]	1.036	

263 Compared with the experimental data, the results from the present numerical model show good
 264 agreement with a relative variation 8.78%. Therefore, the present numerical model can be used with
 265 confidence in future VIM motion simulations.

266 Table 9. Comparison of results from the present numerical calculations and experimental measurements
 267 for 45° incidence.

Ur	\bar{C}_D (num.)	\bar{C}_D (exp.)	Relative variation (%)	C_{Lrms} (num.)	C_{Lrms} (exp.)	Relative variation (%)	A_y/L (num.)	A_y/L (exp.)	Relative variation (%)
3.9	2.210	2.399	7.9	0.931	0.751	23.9	0.236	0.166	41.9
6.6	2.619	2.614	0.2	0.540	0.497	8.5	0.760	0.742	2.5
8.9	2.292	2.429	5.7	0.190	0.230	17.3	0.378	0.398	5.0
12.1	2.099	2.154	2.6	0.194	0.177	9.8	0.345	0.318	8.5

268 In addition to the experimental data from MARIN, further comparison of \bar{C}_D , C_{Lrms} and A_y/L with the
269 present experimental and numerical investigations are provided in Table 9 showing good agreements,
270 hence providing another means of validating the numerical model in this study. Most of the relative
271 variations are less than 10%, especially for the predictions of \bar{C}_D . However, it is noted that at $Ur = 3.9$,
272 the numerical results have a relatively large discrepancy when compared with the experimental data.
273 The detailed discussions will be presented in 4.2. *Force analysis*.

274 4. Results and discussion

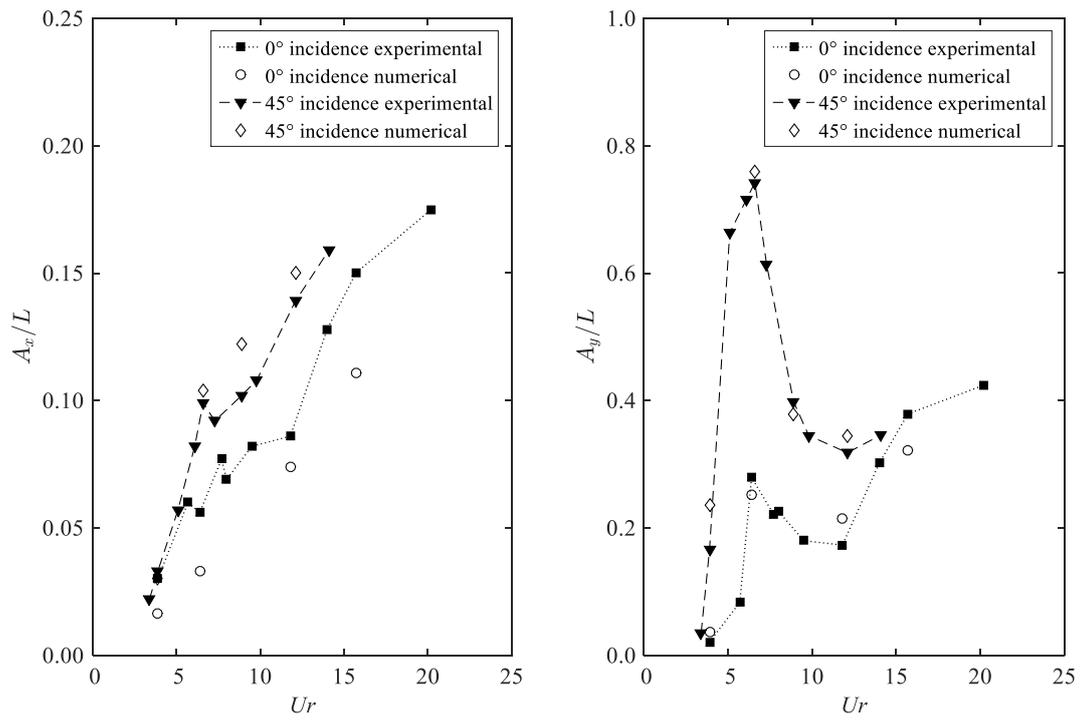
275 The motion response of a typical moored DDS under four current velocities for each of the two
276 headings were investigated using the present numerical model and their results are further compared
277 with the measurements conducted in the towing tank. The motion measurements for more than ten
278 cycles of the VIM oscillation period are collected in the present study.

279 4.1. Motion characteristics

280 4.1.1. Motions in transverse and in-line directions

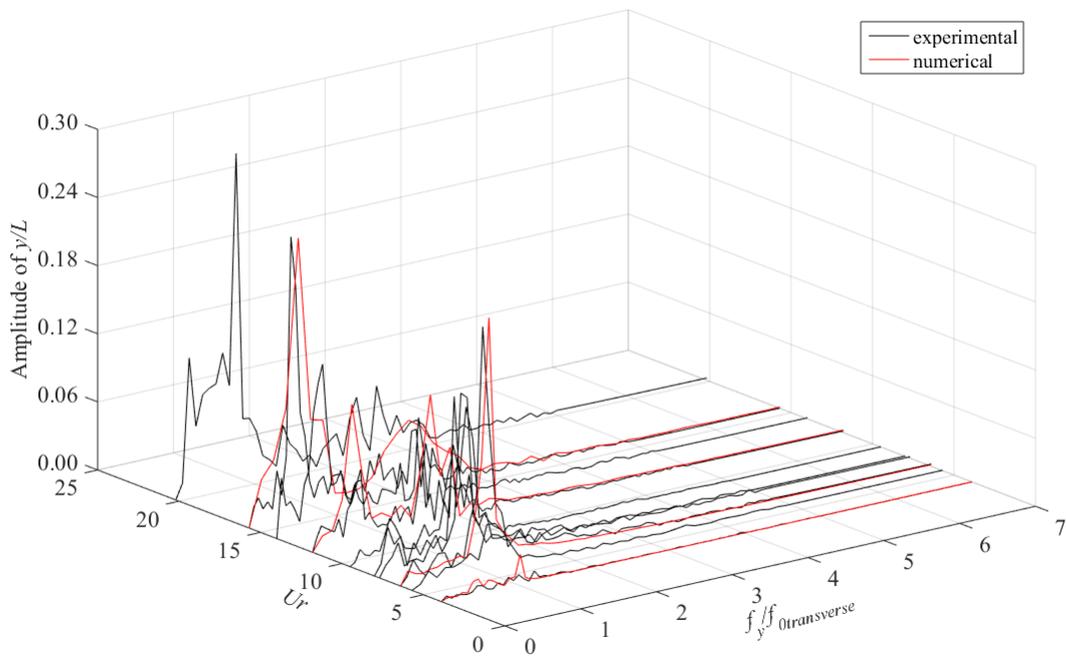
281 Fig. 7, which compares the results from the numerical simulation with those from the model tests,
282 presents the non-dimensional characteristic amplitude (A_x/L , A_y/L , where Ur is defined based on
283 $T_{0transverse}$) for motions in both the in-line and the transverse directions under flow incidences of 0°
284 and 45° . The non-dimensional amplitude is defined as $\sqrt{2} \times \sigma\left(\frac{y(t)}{L}\right)$ (where σ is the standard deviation
285 of the time series $y(t)/L$, and $y(t)$ represents the time series of in-line, transverse and yaw motions. For
286 yaw motions the non-dimensional amplitude is defined as $\sqrt{2} \times \sigma(y(t))$). As can be seen in Fig. 7, the
287 45° incidence cases showed larger VIM in magnitude in both the in-line and the transverse directions.
288 Moreover, the largest A_x/L for both incidences occurred at the same range around $Ur = 6.5$. The
289 “lock-in” region for 0° incidence happens in the range of $6.0 \leq Ur \leq 9.5$, while for 45° incidence, the
290 “lock-in” region occurs between $5.0 \leq Ur \leq 9.0$. It is also to be noted that the motion in the in-line
291 direction for both incidences keeps increasing with increasing Ur . In this context, the present
292 numerical model predicts the motions in both the transverse and the in-line directions well. At low Ur

293 values, the numerical model predicts a larger response than the experimental results in the transverse
 294 direction. When the towing speed for Ur is extremely low (0.062m/s for 0° incidence at $Ur = 3.9$) in
 295 the towing tank test, it is likely that the “friction” of the whole physical facilities tends to affect the
 296 experimental measurements. However, at high Ur , such effect become insignificant, especially in the
 297 “lock-in” region where the numerical predictions agree well with the experimental data. Fig. 8 and
 298 Fig. 9 present the results of the motion in the transverse direction for 0° and 45° flow incidences in the
 299 frequency domain. It is clearly seen that the motion responses very much concentrate around the
 300 natural transverse frequency ($f_{0transverse}$) in the “lock-in” region. Moreover, as can be seen in Fig. 10
 301 and Fig. 11, both incidences show that in the “lock-in” region, the structure’s response frequency (f_y)
 302 is approximately the same as the vortex shedding frequency (f_s) (also seen in Fig. 12 and Fig. 13). It is
 303 further observed in both experiments and numerical simulations that, for 0° incidence, in the “post
 304 lock-in” region f_s increases and becomes larger than f_y . This phenomenon was also observed by Waals
 305 et al. [14] and termed as galloping. Galloping is different from VIM. It describes a low frequency
 306 response and is not self-limiting. When Galloping happens, f_s is much larger than the structural
 307 response frequency [14]. The transverse motion tends to increase with increasing Ur . This can be
 308 found in Fig. 8 and Fig. 10. In the “post lock-in” region, the peak f_y is still around $f_{0transverse}$.
 309 Additionally, a high f_y appeared with increasing Ur (see Fig. 8). However, in the vortex shedding
 310 frequency domain, at $Ur = 15.7$, there are two nearly equal weight peak transverse forces occurring at
 311 two vortex shedding frequencies (as shown in Fig. 14b). In addition, it is more clear that f_s is three
 312 times as the peak f_y at $Ur = 20.2$ in the experimental measurements (see Fig. 8 and Fig. 10). Thus, the
 313 motion response in the “post lock-in” region is an oscillation phenomenon which combines VIM and
 314 the galloping phenomena. In this situation, A_x/L keeps increasing in the “post lock-in” region.



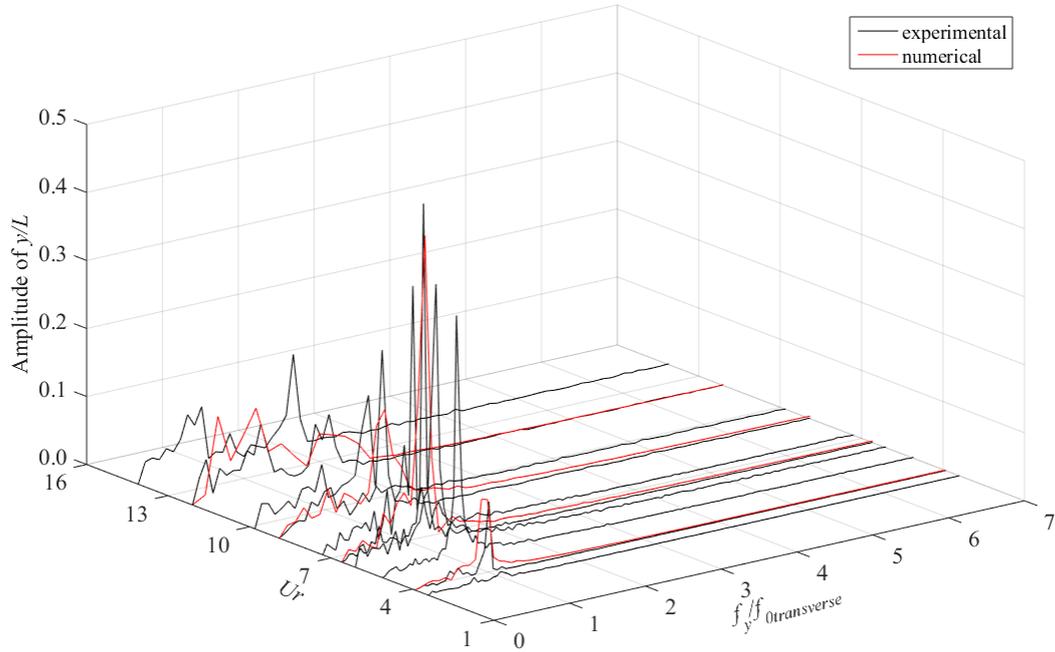
315

316 Fig. 7. Non-dimensional in-line and transverse characteristics amplitudes (A_x/L , A_y/L), the U_r is
 317 defined based on $T_{0transverse}$.



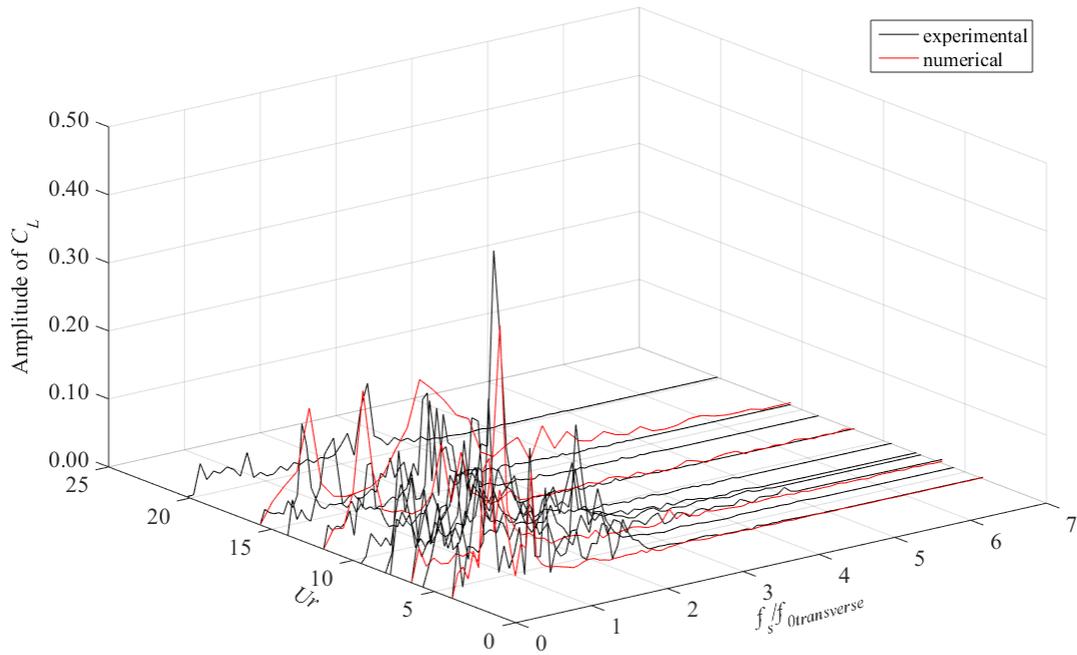
318

319 Fig. 8. FFT of the motions in the transverse direction as a function of Ur and f_y for 0° incidence (the
320 Ur is defined based on $T_{0(transverse)}$).



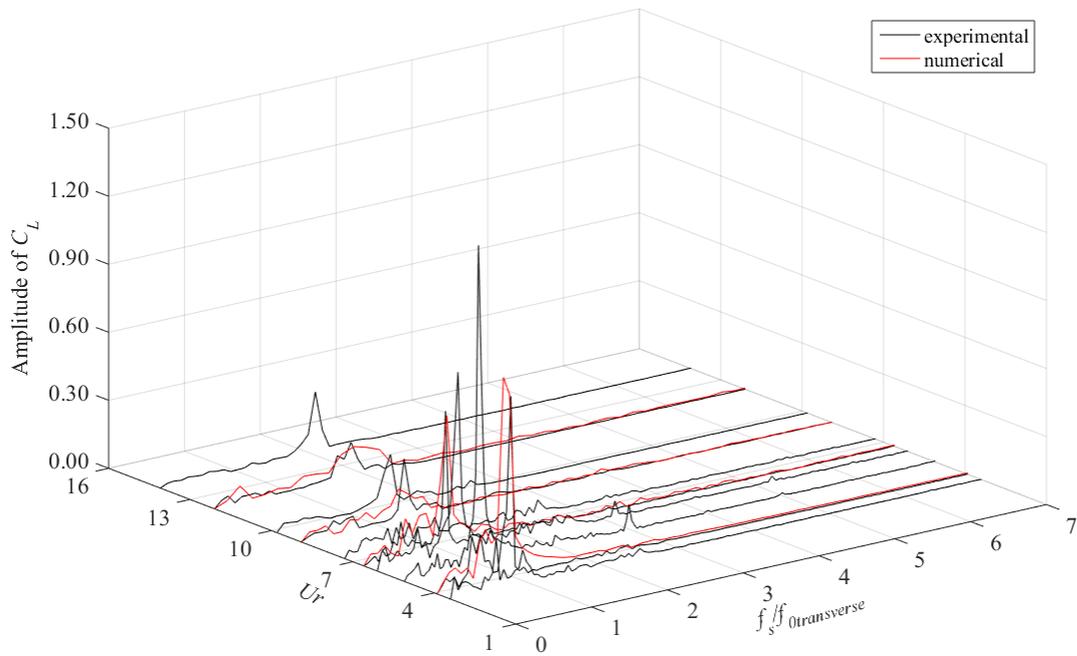
321

322 Fig. 9. FFT of the motions in the transverse direction as a function of Ur and f_y for 45° incidence (the
323 Ur is defined based on $T_{0(transverse)}$).



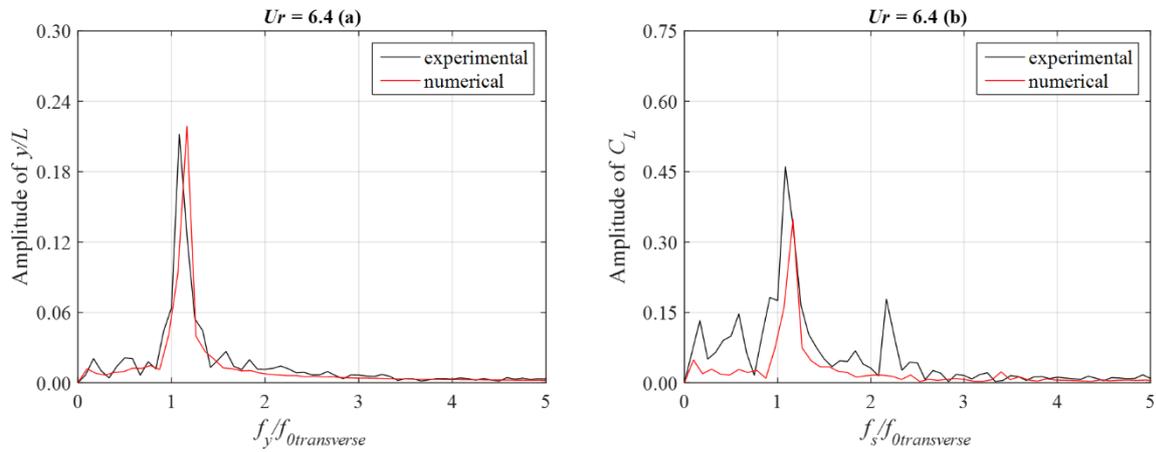
324

325 Fig. 10. FFT of lift force coefficient as a function of U_r and f_s for 0° incidence (the U_r is defined
 326 based on $T_{0transverse}$).



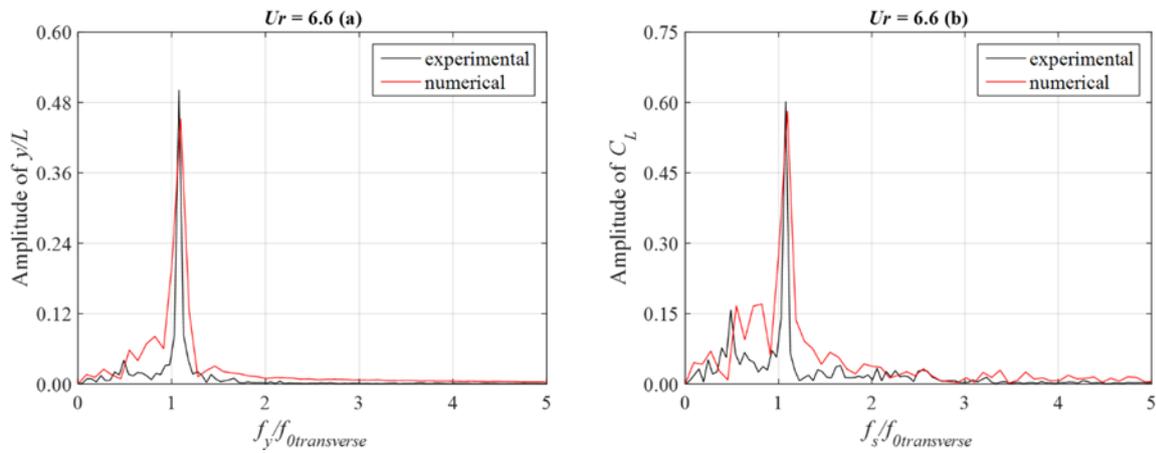
327

328 Fig. 11. FFT of lift force coefficient as a function of Ur and f_s for 45° incidence (the Ur is defined
 329 based on $T_{0transverse}$).



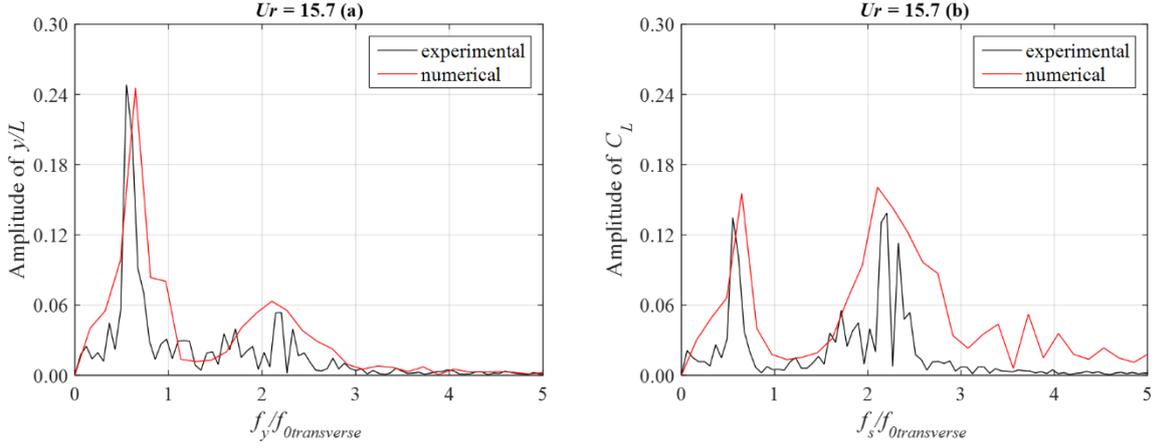
330

331 Fig. 12. FFT of the transverse motions and the lift force coefficients at $Ur = 6.4$ for 0° incidence, (a)
 332 transverse motion (y/L); (b) lift force coefficient (C_L).



333

334 Fig. 13. FFT of the transverse motions and the lift force coefficients at $Ur = 6.6$ for 45° incidence, (a)
 335 transverse motion (y/L); (b) lift force coefficient (C_L).



336

337 Fig. 14. FFT of the transverse motions and the lift force coefficients at $Ur = 15.7$ for 0° incidence, (a)
 338 transverse motion (y/L); (b) lift force coefficient (C_L).

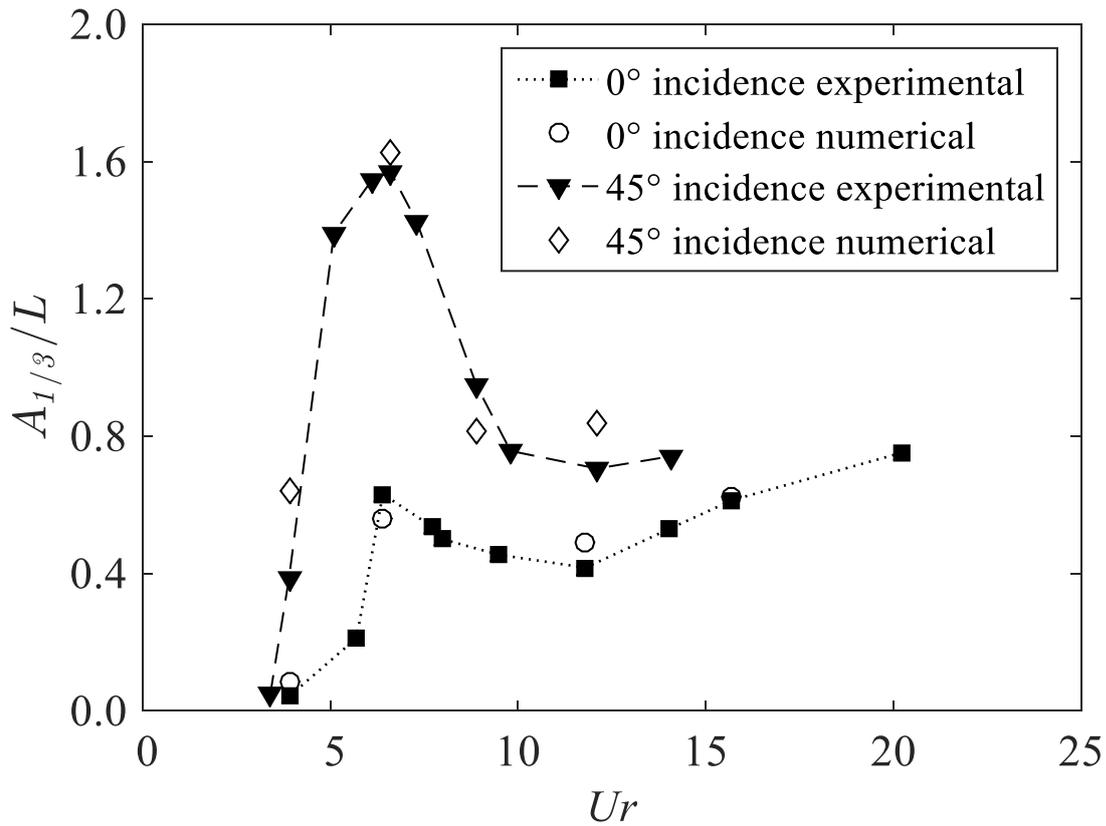
339 It is noted that the transverse motions are somewhat sinusoidal with near constant amplitude as would
 340 be expected at “lock-in”. However, in the “pre lock-in” and “post lock-in” region, the time history of
 341 the non-dimensional transverse amplitude shows considerable variability. Thus, a new variable called
 342 the significant value of transverse peaks ($A_{1/3}/L$) is introduced in the present study in order to examine
 343 the irregular characteristics of the transverse motions.

344
$$A_{1/3}/L = \frac{1}{\frac{1}{3}N} \sum_{m=1}^{\frac{1}{3}N} A_m/L, \quad (4)$$

345 where N is the number of the oscillations and L is the columns’ width, the largest A_m has $m = 1$ and the
 346 lowest A_m is for $m = N$, A_m is the individual oscillation height which is defined as:

347
$$A_m = A_{peak} - A_{bottom} \quad (5)$$

348 where A_{peak} and A_{bottom} are the points when $\frac{dy}{dt} = 0$ within one oscillation period.



349

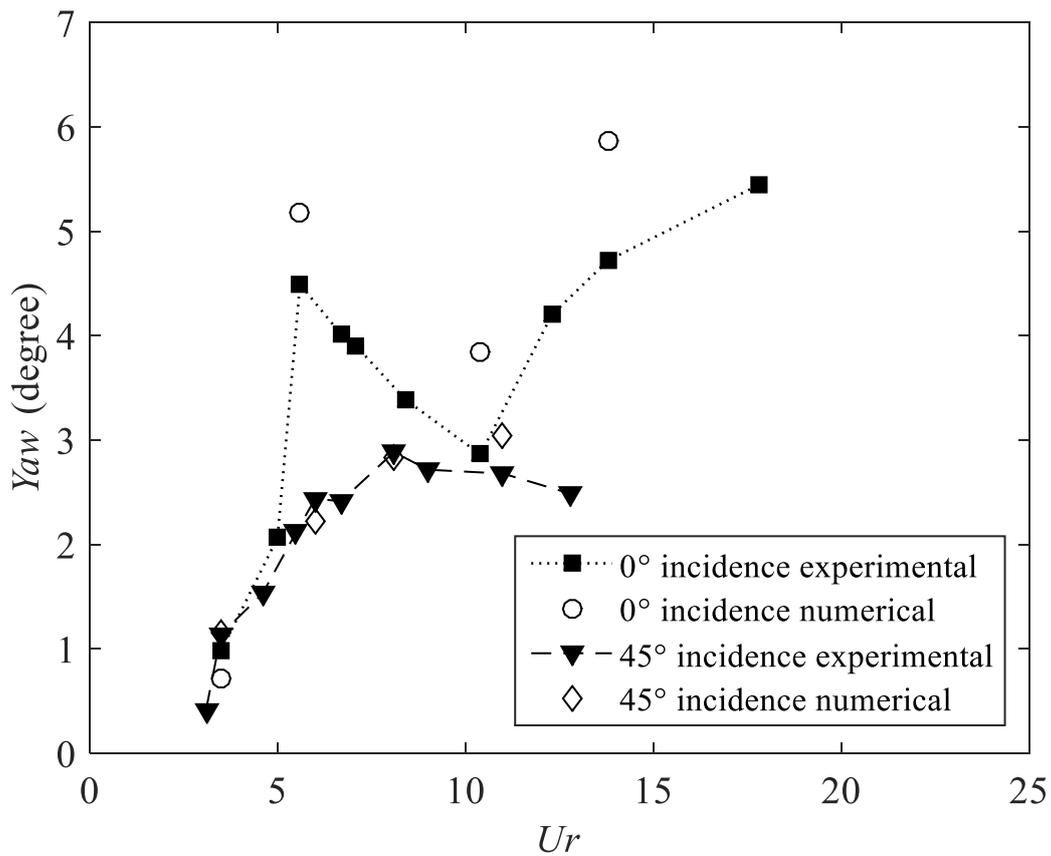
350 Fig. 15. Significant values of the transverse peaks ($A_{1/3}/L$). The Ur is defined based on $T_{0transverse}$.

351 Fig. 15 presents $A_{1/3}/L$ as a function of Ur . It shows that, in the “pre lock-in” and “post lock-in” region,
 352 the present numerical model predicts the characteristics of the transverse motions well when compared
 353 with the experimental results.

354 *4.1.2. Yaw motions*

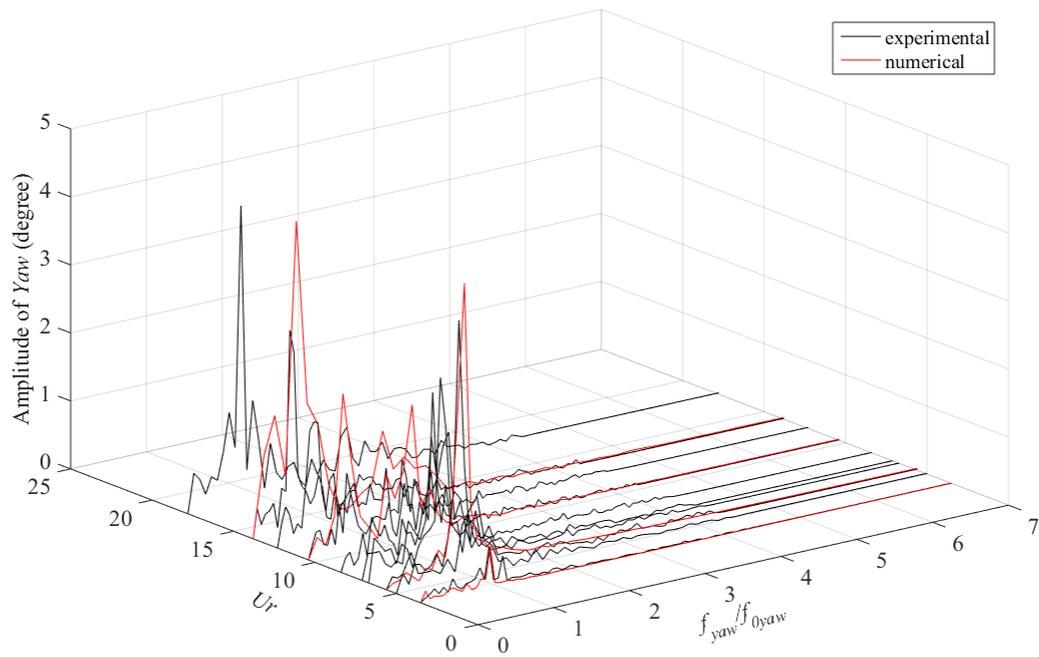
355 Fig. 16 presents the non-dimensional yaw amplitude. Fig. 17 and Fig. 18 present the yaw motions in
 356 the frequency domain as a function of Ur . In the current study, it is observed that the in-line,
 357 transverse and yaw natural frequencies are relatively close to each other. The non-dimensional
 358 amplitude for the 0° incidence yaw motion shows the same trend as A_y/L . However, for 45° incidence,
 359 the yaw motion response is different from the transverse motion response. In the “lock-in” region, the
 360 non-dimensional yaw amplitudes at 0° incidence are larger than those at 45° incidence. For both flow
 361 incidences, the numerical method predicts the motion response trend well comparing with the
 362 experimental results. It is noted that in the numerical simulations, the mooring lines are idealised
 363 springs’ arrangement which are exactly symmetrical. However, in the experiments, slight differences

364 can be observed in the forces on each side of the mooring lines possibly owing to the mooring lines
 365 being not exactly the same and the effects of spring bending due to the gravity on springs in the
 366 experimental set-up. The slight differences on the mooring lines causes the structure to have a small
 367 attack angle with the current flow during VIM. Especially for 0° incidence, the small attack angle
 368 makes the columns at the balance position not exactly perpendicular to the current leading to a slight
 369 variation in the hydrodynamic moment measurements. This may contribute to the discrepancies
 370 between the numerical predictions and the experimental data for the yaw motion.



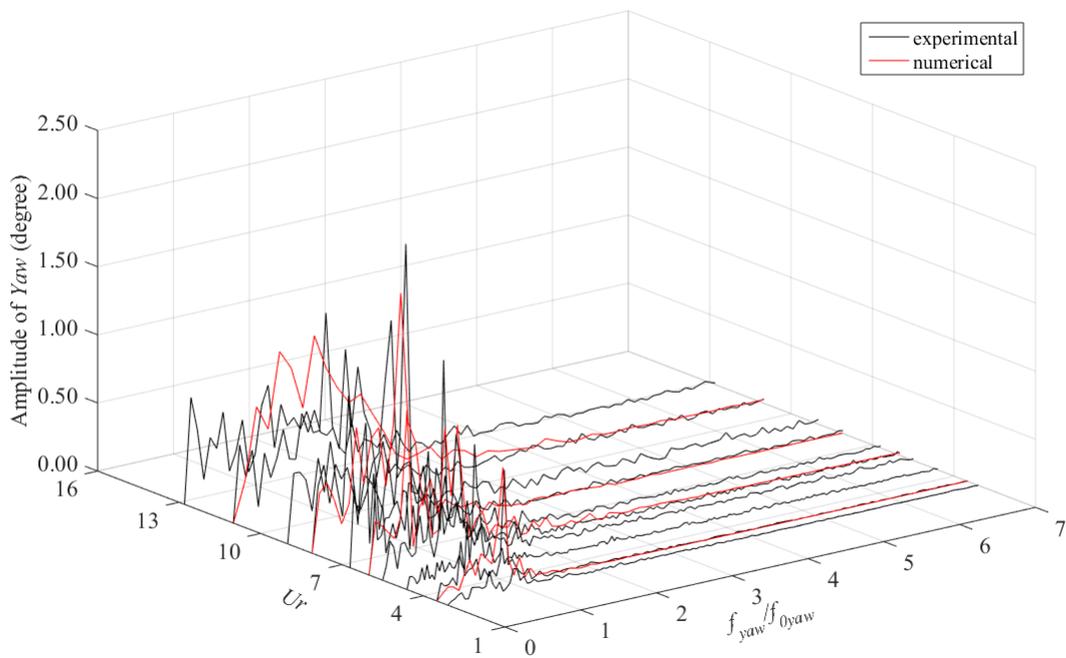
371

372 Fig. 16. Non-dimensional yaw characteristics amplitude (the Ur is defined based on T_{0yaw}).



373

374 Fig. 17. FFT of the yaw motion as a function of U_r and f_{yaw} for 0° incidence (the U_r is defined based
 375 on T_{0yaw}).



376

377 Fig. 18. FFT of the yaw motion as a function of Ur and f_{yaw} for 45° incidence (the Ur is defined based
378 on T_{0yaw}).

379 4.2. Force analysis

380 The fluid forces on the structure are calculated by the equation given by Sarpkaya [31] as:

$$381 \quad m\ddot{X}(t) + C\dot{X}(t) + K_x(t) = F_x(t) \quad (6)$$

$$382 \quad m\ddot{Y}(t) + C\dot{Y}(t) + K_y(t) = F_y(t) \quad (7)$$

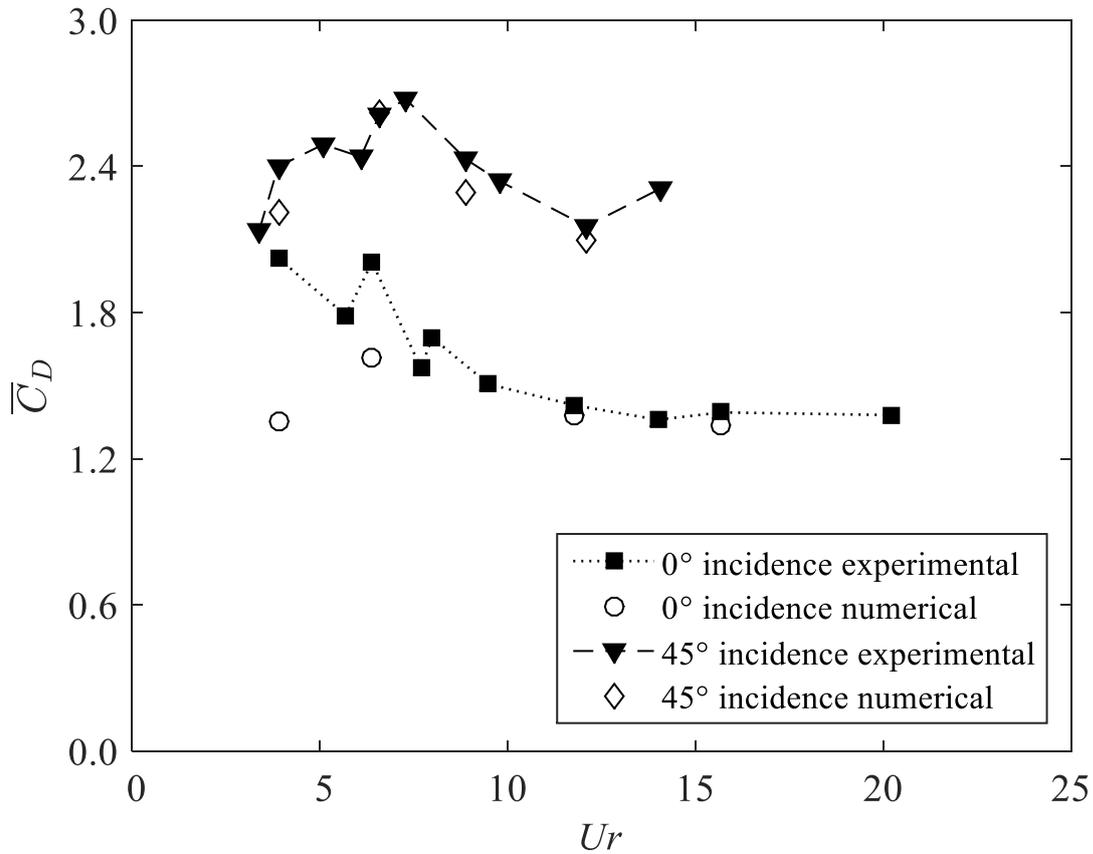
383 where m is the platform mass; C is the structural damping coefficient; K_x and K_y are the linear spring
384 constant in the in-line and transverse directions; $F_x(t)$ and $F_y(t)$ represent the in-line and transverse
385 hydrodynamic forces acting on the structures.

386 As the structural damping coefficient is very small and can be disregarded. The hydrodynamic forces
387 which include added mass and hydrodynamic damping forces due to fluid are placed on the right side
388 of the equations. Thus, the Equation (6) and (7) can be written as:

$$389 \quad m\ddot{X}(t) + K_x(t) = F_x(t) \quad (8)$$

$$390 \quad m\ddot{Y}(t) + K_y(t) = F_y(t) \quad (9)$$

391 In the present study, the total hydrodynamic forces in the experiments are measured indirectly by
392 using the equations given by Sarpkaya [31]. However, the total hydrodynamic forces of the numerical
393 predictions are obtained directly from the CFD simulations.



394

395 Fig. 19. Mean drag coefficient (\bar{C}_D), where A is the projected area at 0° incidence.

396 The drag coefficients for both 0° and 45° flow incidences are shown in Fig. 19. For 0° incidence, the
 397 numerical results show a large discrepancy to experimental measurements at low Ur . This is possibly
 398 due to the extremely low towing speed (0.062m/s for reduced velocity at $Ur = 3.9$) in the experiment
 399 where the mechanical friction in the system set-up affects the force measurements especially at the
 400 very low towing speed. In addition, the mooring lines can have the most striking effects on the results.
 401 To investigate this further, the mooring line forces have been examined in both the experiment
 402 measurement and the numerical simulation. As shown in Table 10, the numerical predictions show
 403 that the forces on the mooring lines are symmetrical along the in-line direction. However, in the
 404 experiments, slight differences can be observed in the forces on each sides of the mooring lines
 405 possibly owing to the mooring lines being not exactly same and the effects of spring bending by the
 406 gravity in the experimental set-up. The differences of the mooring force between the upstream
 407 mooring lines (Mooring line 1 and Mooring line 2) are smaller than the downstream mooring lines
 408 (Mooring line 3 and Mooring line 4). The asymmetrical forces on the mooring lines make the motions
 409 of the structure asymmetrical. Especially for 0° incidences cases, the asymmetrical forces on the
 410 mooring line make the structure to have a small attack angle with the current flow. This rotational

411 offset is the main contributor to the differences between numerical predictions and experimental data.
 412 When the Ur increases, the offset of the platform relative to the in-line direction also increases leading
 413 to the forces on the downstream mooring line decreasing. Consequently, the effect of the force
 414 difference in the downstream mooring lines is weakened with increasing Ur . Therefore, the numerical
 415 results agree well with experimental measurements for high Ur for 0° incidence. As shown in Fig. 19,
 416 \bar{C}_D increases when “lock-in” occurs. This is because the fluctuations of the force on the structure is
 417 excited by resonance. As can be seen in Fig. 19, \bar{C}_D at 45° incidence is higher than that at 0°
 418 incidence. Similar observation was also reported by Sumer and Fredsøe [32] for flow past a sharp-
 419 corner square cylinder.

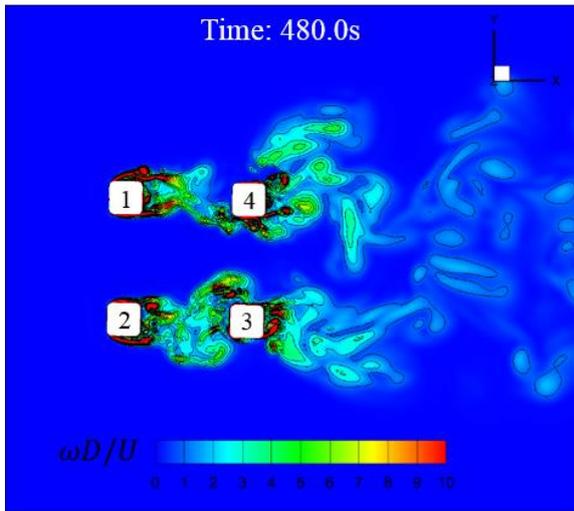
420 Table 10. Comparison of the mooring line mean forces for 0° incidence at $Ur = 3.9, 6.4$ (The mooring
 421 lines arrangement is shown in Fig. 3).

Mean mooring force	Mooring line 1 (N)	Mooring line 2 (N)	Mooring line 3 (N)	Mooring line 4 (N)
$Ur = 3.9$ numerical	7.365	7.375	6.425	6.415
$Ur = 3.9$ experimental	7.489	7.745	6.445	5.896
$Ur = 6.4$ numerical	8.481	8.405	5.523	5.601
$Ur = 6.4$ experimental	8.617	8.934	5.417	4.859

422 *4.3. Vortex shedding characteristics*

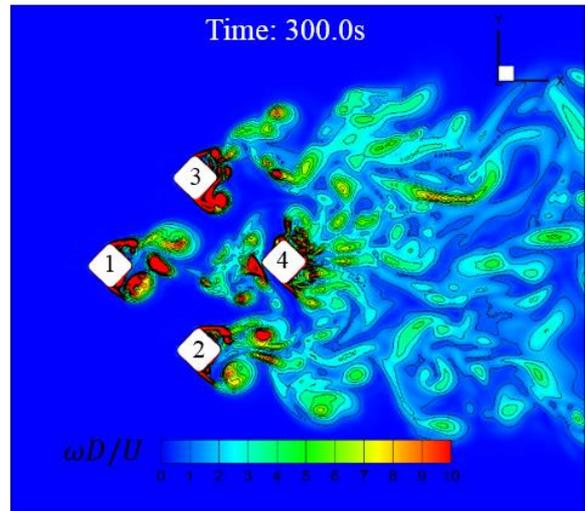
423 To have a general visual appreciation of the vortex shedding pattern, the vorticity magnitude contours
 424 obtained from the numerical simulations for “pre lock-in”, “lock-in” and “post lock-in” regions are
 425 plotted in Fig. 20.

0° incidence

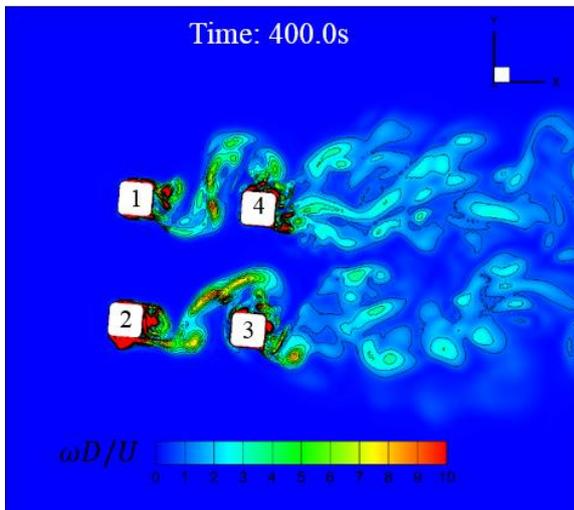


a) "pre lock-in" ($Ur = 3.9$)

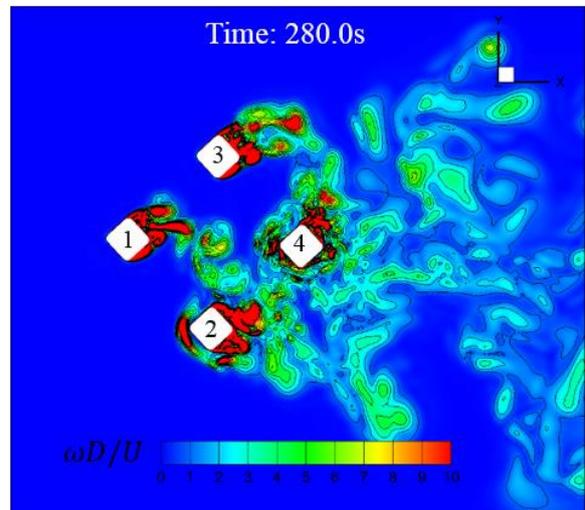
45° incidence



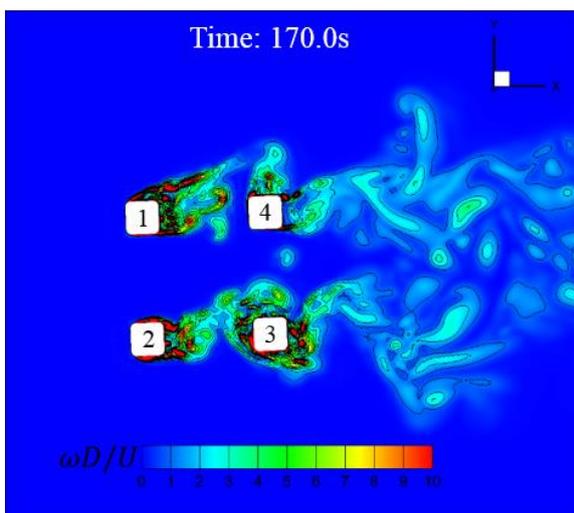
d) "pre lock-in" ($Ur = 3.9$)



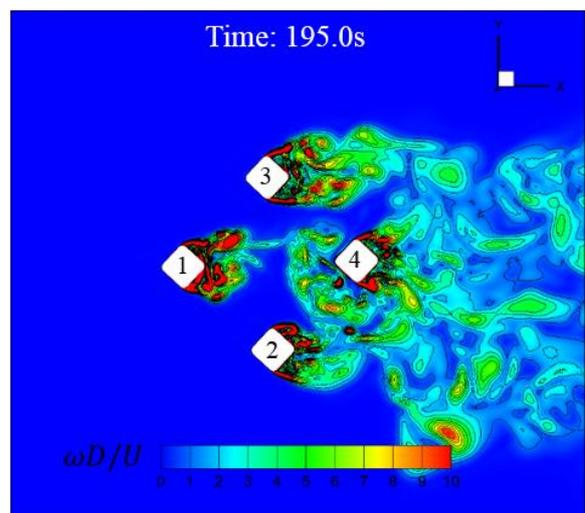
b) "lock-in" ($Ur = 6.4$)



e) "lock-in" ($Ur = 6.6$)



c) "post lock-in" ($Ur = 11.8$)



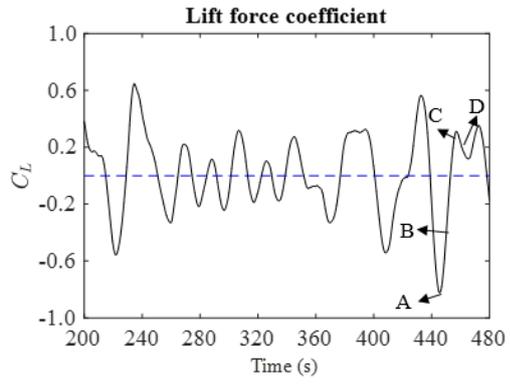
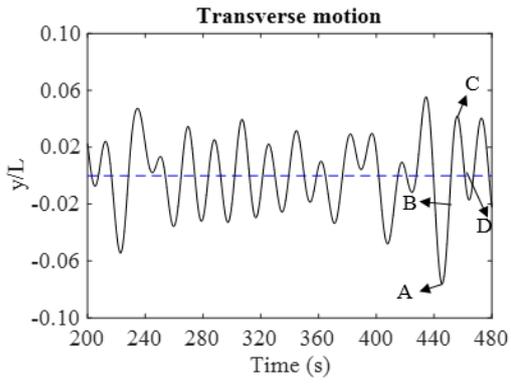
f) "post lock-in" ($Ur = 12.1$)

427 Fig. 20. Non-dimensional vorticity magnitude ($\omega D/U$) contours of the DDS model for “pre lock-in”,
428 “lock-in” and “post lock-in” regions for 0° and 45° incidence, XY plane at middle draft location of the
429 DDS.

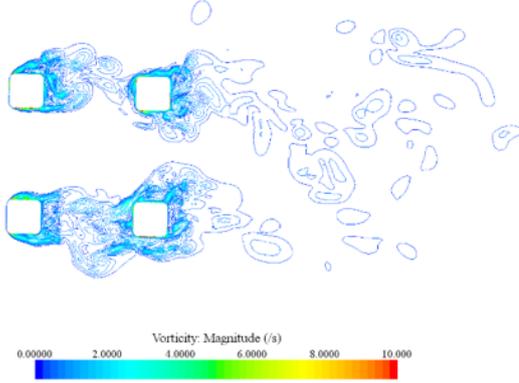
430 Fig. 20 presents the three-dimensional vorticity magnitude ($\omega D/U$, where $\omega = \sqrt{(\omega_x^2 + \omega_y^2 + \omega_z^2)}$). As
431 can be seen, under 45° incidence, in the “pre lock-in” region, the vortices that form and then detach
432 from column 1 can only impinge directly on column 3 located downstream. However, in the “lock-in”
433 region, it can be clearly seen that the vortices detached from column 1 directly act on column 2. As
434 the vortex shedding frequency at this reduced velocity is equal to the natural frequency of the
435 structure, the vortices acting on the structure become synchronised with the model oscillation
436 frequency. This is the reason that causes “lock-in” to occur. In the “post lock-in” region, the vortices
437 detached from column 1 strongly act on the column 3 again, and the vortex shedding frequency starts
438 to move away from the natural frequency of the structures resulting in the decreased structure motion.

439 At 0° incidence, the phenomenon of VIM are similar to that at 45° incidence. Since the column
440 leading surfaces are vertically faced to the current, the vortices that are detached from the upstream
441 columns are not as significant as in the 45° incidence cases. However, it can still be clearly seen that
442 in the “lock-in” region, that the vortices detached from the upstream columns directly act on the
443 downstream columns.

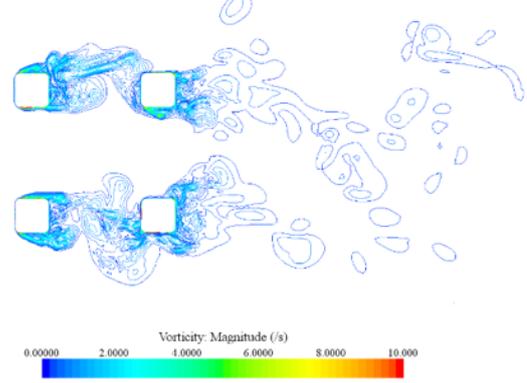
444 *4.4. Correlation of vortex shedding, force and VIM*



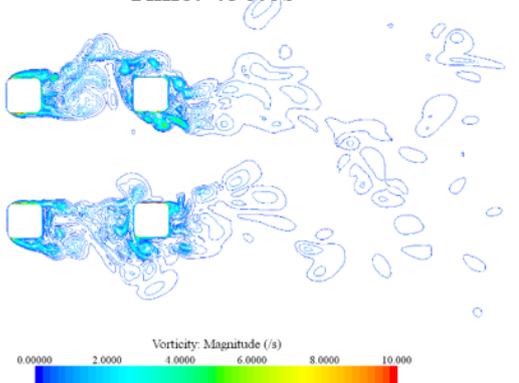
(A) Time: 445.6s



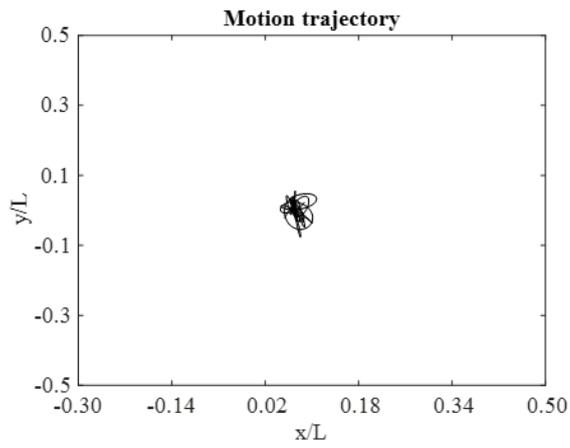
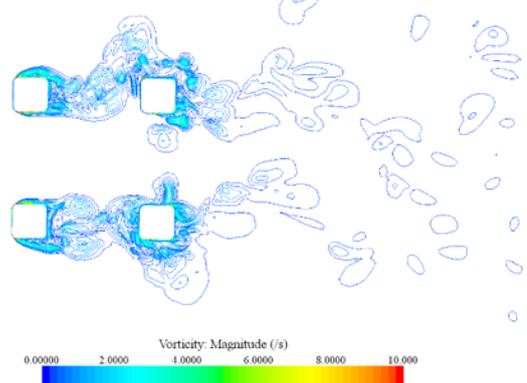
(B) Time: 450.4s



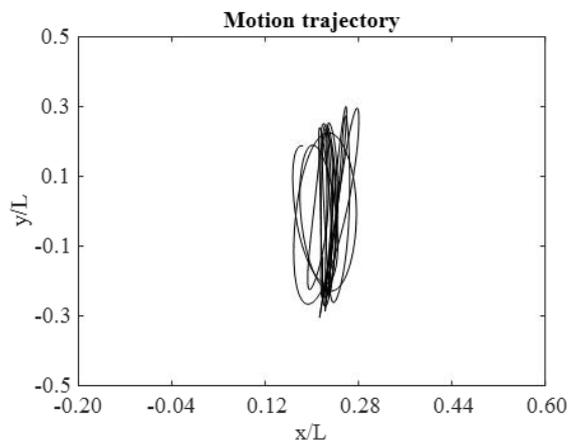
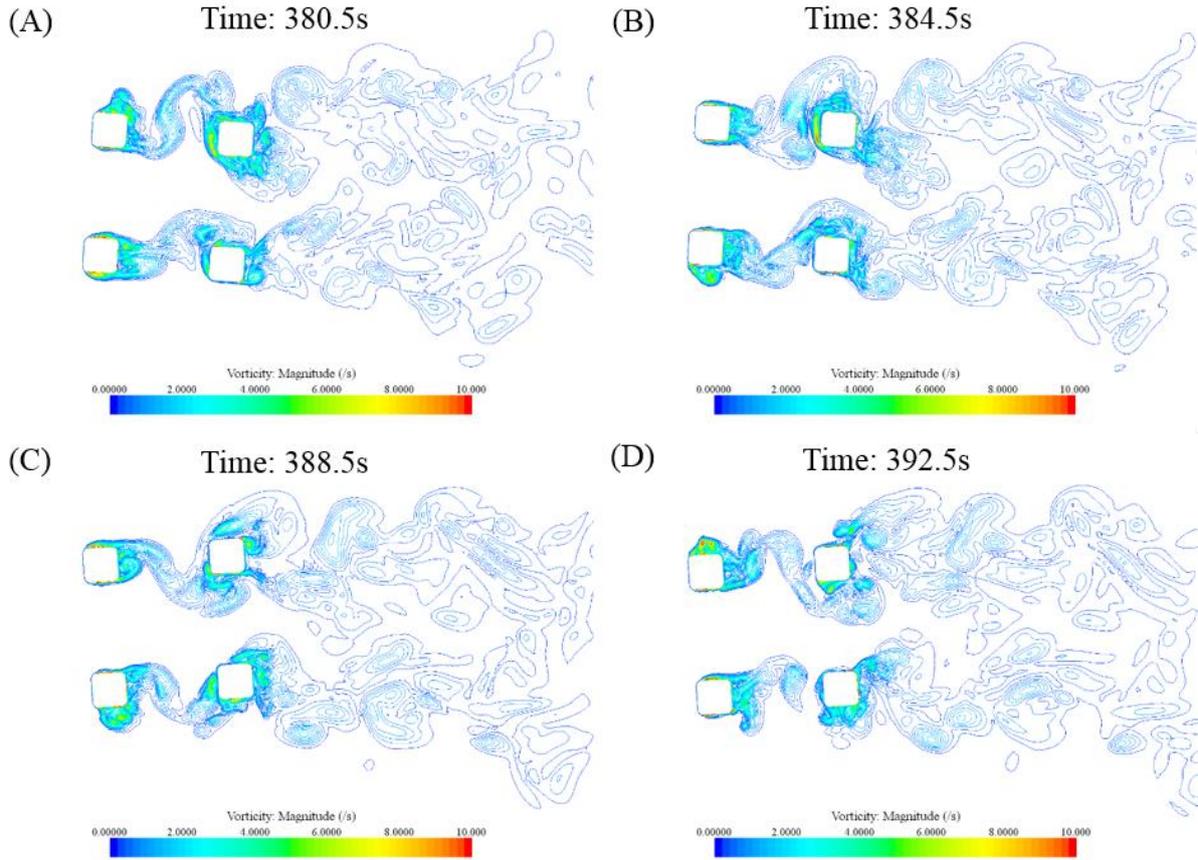
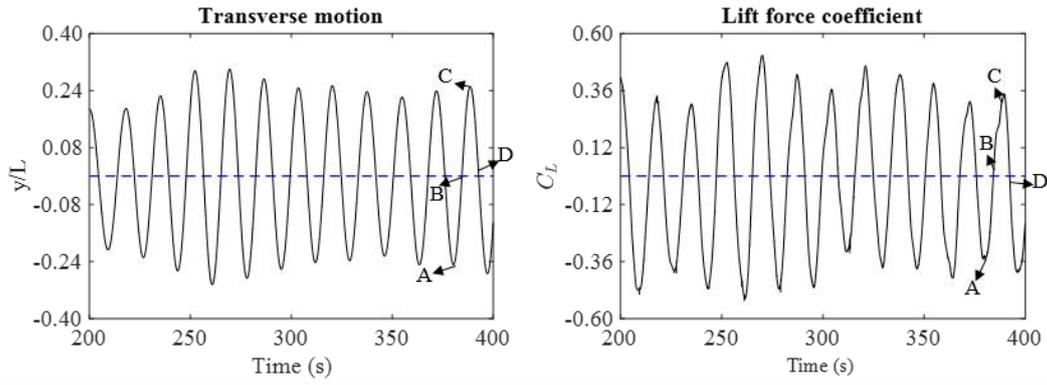
(C) Time: 456.0s



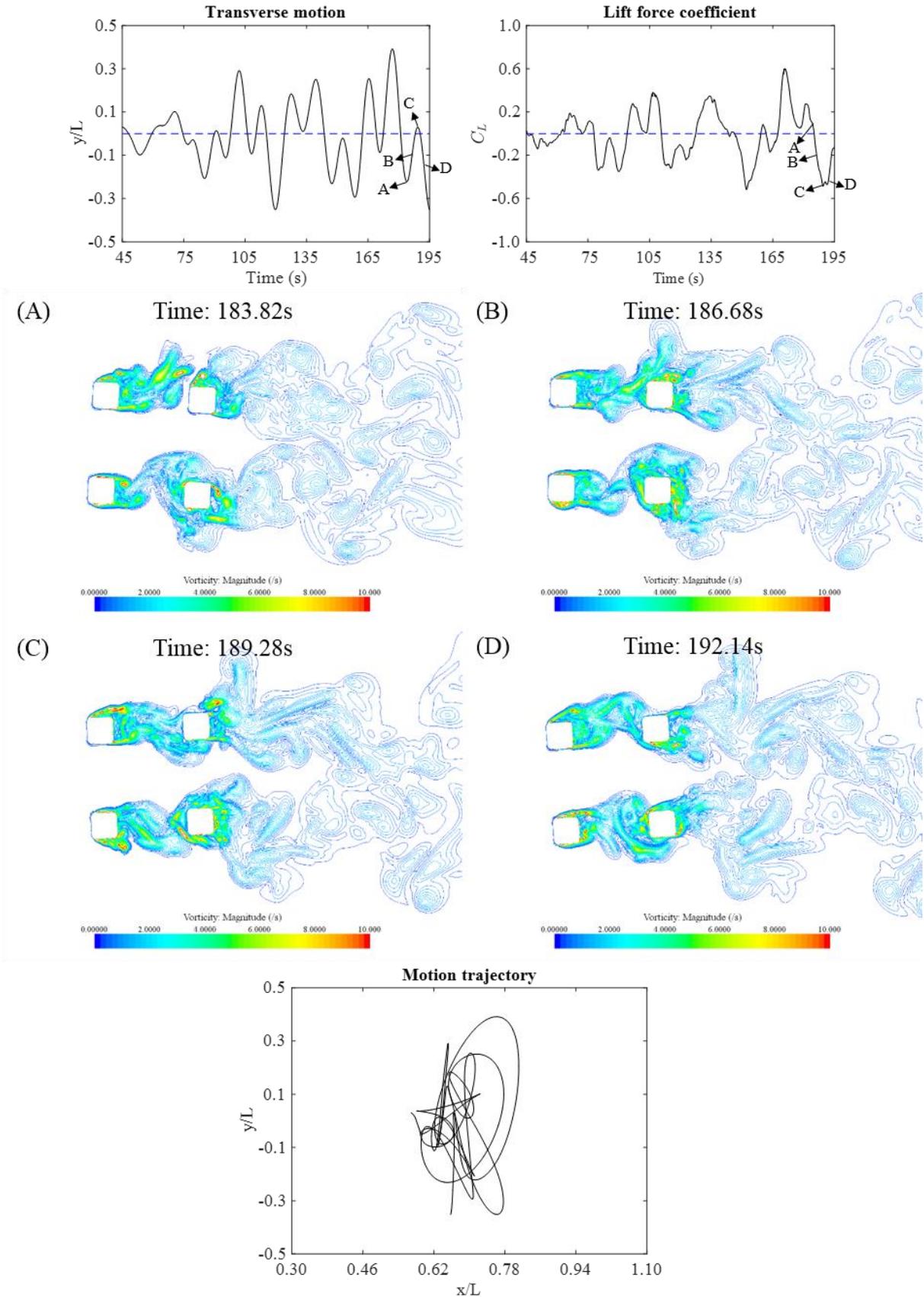
(D) Time: 460.8s



446 Fig. 21. Time history of the motion in the transverse direction (y/L), lift force coefficient (C_L) for 0°
447 incidence at $Ur = 3.9$ (pre lock-in), the vorticity contours in the XY plane at middle draft of the DDS
448 (A and C refer to the point close to the transverse motion peak value within one oscillation period, B
449 is the vortex shedding process between A and C, D is the vortex shedding process after C,
450 corresponded simulation time are shown in the figure), and the motion trajectory in the XY plane.



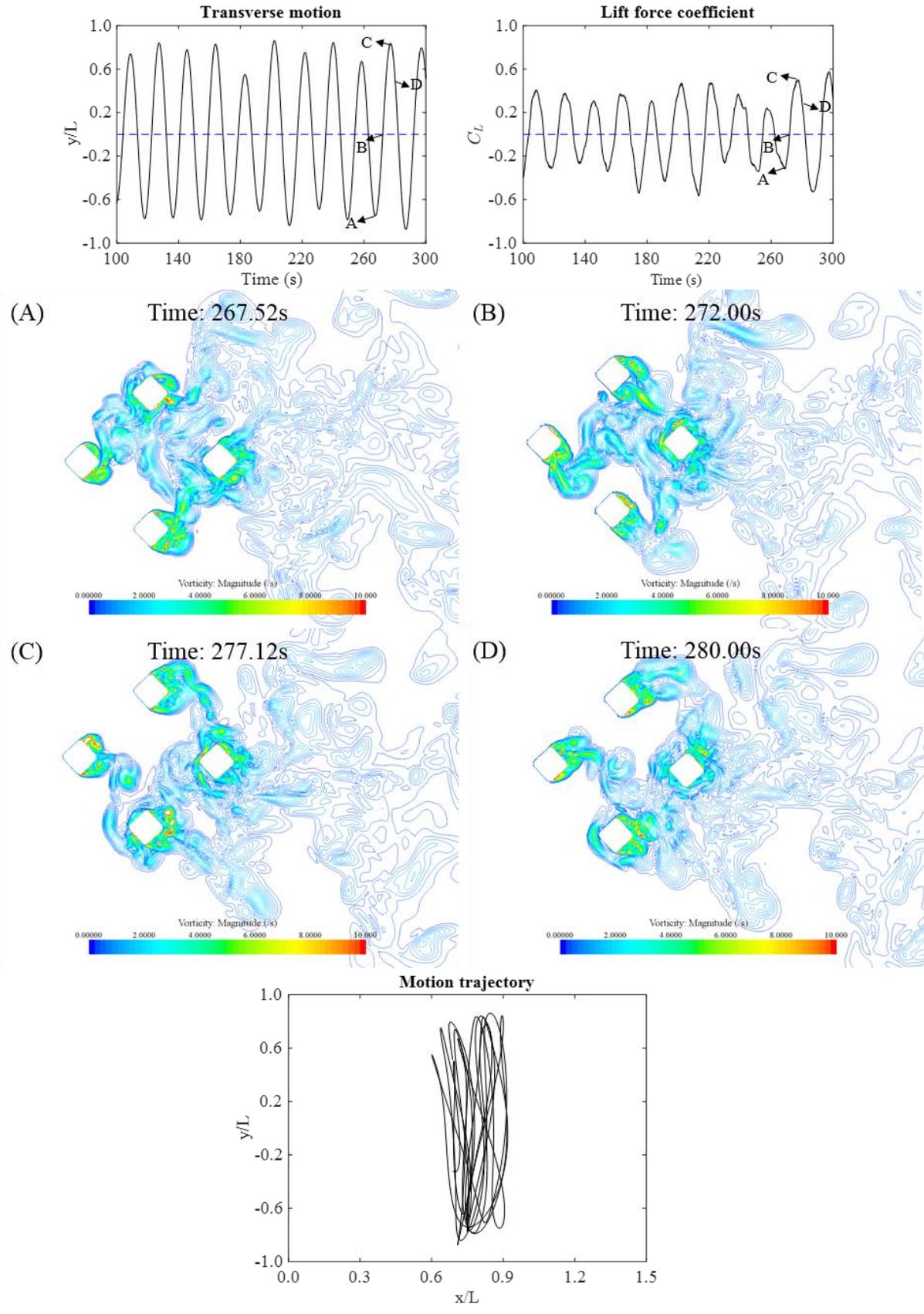
452 Fig. 22. Time history of the motion in the transverse direction (y/L), lift force coefficient (C_L) for 0°
453 incidence at $Ur = 6.4$ (lock-in), the vorticity contours in the XY plane at middle draft of the DDS (A
454 and C refer to the point close to the transverse motion peak value within one oscillation period, B is
455 the vortex shedding process between A and C, D is the vortex shedding process after C, corresponded
456 simulation time are shown in the figure), and the motion trajectory in the XY plane.



457

458 Fig. 23. Time history of the motion in the transverse direction (y/L), lift force coefficient (C_L) for 0°
 459 incidence at $Ur = 11.8$ (post lock-in), the vorticity contours in the XY plane at middle draft of the DDS

460 (A and C refer to the point close to the transverse motion peak value within one oscillation period, B
461 is the vortex shedding process between A and C, D is the vortex shedding process after C,
462 corresponded simulation time are shown in the figure), and the motion trajectory in the XY plane.



463

464 Fig. 24. Time history of the motion in the transverse direction (y/L), lift force coefficient (C_L) for 45°
 465 incidence at $Ur = 6.6$ (lock-in), the vorticity contours in the XY plane at middle draft of the DDS (A

466 and C refer to the point close to the transverse motion peak value within one oscillation period, B is
467 the vortex shedding process between A and C, D is the vortex shedding process after C, corresponded
468 simulation time are shown in the figure), and the motion trajectory in the XY plane.

469 The flow pattern at the peak transverse motion point may reveal the key factor which induced the
470 VIM. The vortex shedding patterns, which are close to the transverse motion peak value within one
471 oscillation period, are shown in Fig. 21, Fig. 22, Fig. 23 and Fig. 24. Additionally, sub-picture (B)
472 presents the vortex shedding process between the two peak point and sub-picture (D) presents the
473 vortex shedding process after the peak point C (see Fig. 21, Fig. 22, Fig. 23 and Fig. 24), in order to
474 show the continuous vortex shedding process within one VIM oscillation period.

475 Fig. 21 presents the time history of the transverse motions, the lift force coefficient the vorticity
476 contours and the motion trajectory under 0° incidence at $Ur = 3.9$ (“pre lock-in”). The sub-pictures A,
477 B, C and D show the vorticity contours within one complete vortex shedding period. As can be seen
478 in Fig. 21, the vortices shed from the upstream columns directly impinge on the front faces of the
479 downstream columns. The downstream columns correspondingly break or degrade the vortices being
480 shed from the upstream columns. Unlike the vortices shed from the upstream columns, only relatively
481 small vortices can be seen in the wake region of the downstream columns. Thus the vortices are
482 broken into small elements with weak vortices by the downstream columns. As the small vortices are
483 asymmetrical, generated by breaking the vortices shed from the upstream columns, the corresponding
484 lift force are fluctuating asymmetrically as well. The time histories of the transverse motions and the
485 lift forces show the same trend in Fig. 21.

486 Similar to Fig. 21, Fig. 22 presents the time history of the transverse motions, the lift force
487 coefficients, the vorticity contours and the motion trajectory under 0° incidence at the higher reduced
488 velocity of $Ur = 6.4$ (“lock-in”). With the increase of Ur , in the “lock-in” region, the vortices shed
489 from the upstream columns act on the downstream columns as if vortices being “shed” of a significant
490 nature from the downstream column itself. The vortices are nearly symmetrically generated on the
491 downstream area of the platform and the vortex street can be clearly seen in the vorticity contours in
492 Fig. 22. This makes both the C_L variations and the time history of the transverse motions to become
493 more symmetrical. Because the vortex shedding frequency is close to the overall structure’s motion
494 frequency in the transverse direction, the structure’s motion trajectory in the transverse direction is
495 nearly same as the vortex shedding trajectory. Hence, the motions of the downstream columns do not
496 break apart the vortices shed from the upstream columns. The upstream formed vortices are acting
497 together with the downstream formed vortices thus to enhance the motions of the structure. Moreover,
498 as the vortices shed from the upstream columns are not effectively broken by the downstream
499 columns, the whole wake region of the structure is significantly enhanced. Similarly, the non-

500 dimensional force fluctuations and corresponding motions are induced by the enhanced wake region.
501 This can be clearly seen in Fig. 22. It is also to be noted that the trends of the lift force coefficient and
502 the transverse motions are nearly the same indicating that when the lift force reaches to a peak value,
503 the transverse motion also approaches a peak value.

504 In the “post lock-in” region, as shown in Fig. 23, the downstream columns break the vortices shed
505 from the upstream columns. Due to the vortex shedding frequency increasing more rapidly than the
506 structure’s motion frequency (this can be seen by comparing Fig. 8 and Fig. 10), the vortices shed
507 from the upstream columns are broken by the lateral motion of the downstream columns. However, as
508 the current speed increases, the strength of the vortices is stronger than in the “pre lock-in” region.
509 Although the vortices shed from the upstream columns are seen broken by the downstream columns,
510 “strong vortices” still can be found in the downstream area of the platform. However, the vortex street
511 is not clearly seen as the case in the “lock-in” region. The vortices show a disordered structure in the
512 downstream area. The time history of the lift force coefficient similarly becomes irregular and has less
513 correlation with the time history of the transverse motions. The transverse motion still however has a
514 general trend similarity to the lift force coefficient.

515 When the flow incidence changes to 45° , the attack angle of the columns makes the transverse
516 motions more pronounced than that for the 0° incidence condition. With the attack angle of 45° , the
517 columns are not vertically faced to the current. When the vortices shed from the upstream column hit
518 on the downstream column leading faces and edge, the vortex energy explodes and spreads far more
519 on the transverse direction compared with 0° incidence. Because three columns are on the
520 downstream area at 45° incidence, the vortex street is more complicated compared with the vortex
521 street at 0° incidence. Fig. 24 presents the time histories of the lift force coefficient, the motions, the
522 vorticity contours and the motion trajectory at 45° incidence. It is seen that the trends of the time
523 history of C_L and the transverse motions fluctuations are nearly the same. Good correlation between
524 the lift force and the transverse motions is also observed.

525 The motion trajectories are also plotted in Fig. 21, Fig. 22, Fig. 23 and Fig. 24. According to the 0°
526 incidence results, there are no eight-shaped trajectories appeared. However, at 45° incidence, the
527 eight-shaped trajectory can be found in the “lock-in” region as those typically presented for single
528 cylindrical structures.

529 5. Conclusions

530 This paper presents an experimental and numerical study focusing on various aspects of the VIM of a
531 DDS. While model tests conducted in towing tank served as a reliable benchmark for validating the

532 numerical model, it also provided comprehensive measurements on the motion responses and
533 associated forces acting on the structure. Numerical simulation on the other hand, provided substantial
534 details on the vortex shedding characteristics under different current incidence angles and wide range
535 of current strength which further adds to the in-depth analysis of the correlations between the vortex
536 shedding flow characteristics and motion induced.

537 For two flow incidences investigated, VIM behaviour of the DDS in the horizontal XY plane occurs in
538 a range of $4.0 \leq Ur \leq 11.0$, with peaks around $6.0 \leq Ur \leq 7.0$ corresponding to “lock-in”. When
539 $Ur \geq 15.0$, a high vortex shedding frequency appeared (galloping) is observed. In the “post lock-in”
540 region, the motion response may be dominated by both VIM and galloping. Both in-line and
541 transverse motions under 45° incidence are larger than that in the 0° incidence condition with yaw
542 motions showing opposite responses.

543 Good correlation has been demonstrated among the vortex shedding patterns, the fluctuation forces on
544 the structure, and the VIM trajectory in the present work. The “lock-in” phenomenon was found to
545 have the most striking effect on the vortex shedding processes, the force and the VIM trajectories.
546 During the “lock-in”, the vortices shed from the upstream columns of the DDS act on the downstream
547 columns as if vortices being “shed” of a significant nature from the downstream column itself.

548 It is worth noting that the differences of the mooring line settings between the experiments and
549 numerical simulations may affect the forces on the structures. In order to improve the accuracy of the
550 numerical simulations, a further study considering the gravity force on and the material characteristics
551 of the mooring lines is needed to examine their effects in the numerical model properly.

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