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## 6 **Comparative analysis of the flow control over** 7 **a circular cylinder with detached flexible and** 8 **rigid splitter plates**

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### 21 **Abstract**

22 A comparative study is performed on a circular cylinder with both flexible and  
23 rigid splitter plates (SPs). This study has the novelty of using single and dual  
24 detached SPs located downstream of the cylinder. The dimensionless gap  
25 distance between the first splitter plate and the cylinder as well as the distance  
26 between the SPs are varied. The strain of flexible SPs can be used for energy  
27 harvesting from the flow. Therefore, a parametric study is performed to find the  
28 optimal design for placing piezoelectric polymers. The two-dimensional fluid  
29 structure-interaction analysis is performed based on the arbitrary Lagrangian–  
30 Eulerian scheme using COMSOL Multiphysics. Flow characteristics quantities,  
31 tip amplitude, and strain are evaluated at different arrangements of the SPs. The  
32 results reveal that wake control enhances effectively by doubling the number of  
33 SPs. The amplitude of the dual SPs increases by a remarkable ratio of 18.29  
34 compared to the single plate. In the case of rigid and flexible SPs at a certain  
35 arrangement, dramatic reductions of 97.8% and 76.35% in the Strouhal number  
36 are obtained compared to a bare cylinder. In addition, 18% drag reduction  
37 compared to the bare cylinder is recorded for the rigid SPs. The presented passive  
38 method can be used as an attractive approach in flow control as well as energy  
39 harvesting from ocean waves and sea currents.

40 **Keywords:** cylinder; splitter plate; piezoelectric; fluid-solid interaction (FSI).

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Abbreviations			
ALE	arbitrary Lagrangian-Eulerian	$L$	length of the SP [m]
FFT	fast Fourier transform	$P$	gap between the SPs [m]
FSI	fluid structure interaction	$p$	fluid pressure [Pa]
RMS	root mean square	$p_b$	pressure at the rear stagnation point [Pa]
Re	Reynolds number	$p_\infty$	free stream pressure [Pa]
SP	splitter plate	$p_s$	static pressure at the cylinder surface [Pa]
St	Strouhal number	$t$	time [s]
VIV	vortex induced vibration	$u_f$	fluid velocity [m/s]
VS	vortex shedding	$u_m$	fluid velocity (moving coordinate) [m/s]
Nomenclature		$u_{rms}^*$	non-dimensional RMS of streamwise velocity
$A$	SPs tip amplitude [m]	$U_\infty$	freestream velocity [m/s]
$C_D$	drag coefficient	$v_s$	velocity of SP [m/s]
$C_L$	lift coefficient	$v_{rms}^*$	non-dimensional RMS of traverse velocity
$C_P$	pressure coefficient	$W_Z^*$	non-dimensional spanwise vorticity
$C_{Pb}$	base pressure coefficient	$X, Y$	reference coordinates of the material frame
$D$	cylinder diameter [m]	$x, y$	spatial coordinates of the spatial frame
$F_D$	drag force [N]	$S$	gap between the cylinder and first SP [m]
$F_L$	lift force [N]	Greek symbols	
$f_s$	frequency of VS [Hz]	$\varepsilon$	strain
$h$	thickness of the SP [m]	$\theta$	angle
$I$	unit diagonal matrix	$\mu$	dynamic viscosity [Pa.s]
		$\rho$	fluid density [kg/m <sup>3</sup> ]
		$\rho_s$	solid density [kg/m <sup>3</sup> ]

42

43 

## 1. Introduction

44 The topic of fluid flow past a circular cylinder has been extensively studied in literature due to  
45 its importance in the industry [1]. Examples include submarines [2], wind industry [3], heat  
46 exchangers [4], automobiles [5], transmission lines [4], tall buildings [6], and bridges [5].  
47 Vortex shedding (VS) is a well-known phenomenon that occurs on the back of a bluff body in  
48 the flow field [7, 8]. It causes oscillations in drag and lift forces on the structure and  
49 consequently induces vibration, which is known as vortex-induced vibration (VIV) [9]. The  
50 VIV may cause destructive effects on the structure such as fatigue failure, structural clashing,  
51 and lifetime reduction [10]. Hence, the reduction of VIV through wake modification has  
52 received prominent consideration in engineering within the past few decades [11-13]. The wake  
53 structure downstream of a cylinder can be modified using active or passive methods. In the  
54 active methods, external energy is used to weaken the flow wake, such as rotation [14, 15],  
55 blowing and suction [16-19], electromagnetic force [20], and synthetic jets [21-23]. In contrast,  
56 in the passive methods, improvement of the structure surface or adding additional parts is taken  
57 into account. Examples include slotted circular cylinder [24, 25], splitter plates (SPs) [26-29],  
58 shape modification [30, 31] and surface bumps [32-34]. The significant advantages of the  
59 passive strategies are their low costs of implementation and maintenance because they do not  
60 need additional energy [35]. Among passive methods, the implementation of SPs in the wake  
61 region of bluff bodies has been one of the most successful methods to suppress VS [36, 37]. It  
62 can effectively modify the key flow characteristics by inhibiting the interaction between the  
63 two shear layers that form in the wake region [38]. Using SPs can lead to wake stabilization,  
64 the extension of vortex formation length, elongation of vorticities, suppression of VS, reduction  
65 of hydrodynamic forces, and the Strouhal number [36, 39]. The influence of multiple rigid SPs

66 with varying angles attached to the rear surface of a cylinder at  $Re=100$  was studied by Abdi  
67 et al. [7]. The results revealed that two and three attached SPs were more effective than one SP  
68 in drag reduction. Furthermore, it was found that the attachment angle had a significant effect  
69 on the wake control and the maximum drag reduction occurred for two SPs case at an angle of  
70  $45^\circ$ . Hwang et al. [40] examined the influence of two detached rigid SPs placed upstream and  
71 downstream of a cylinder on drag reduction. Their numerical study showed that the SP located  
72 upstream of the cylinder reduced the stagnation pressure and the SP located downstream of the  
73 cylinder increased the base pressure of the cylinder. The combination of both led to 38.6%  
74 reduction in the drag coefficient. Bao and Tao [41] investigated the influence of two rigid SPs  
75 attached symmetrically at the rear of cylinder. They found that the attachment angle influenced  
76 the wake control, and the maximum efficiency of suppression was achieved for the range of  
77  $40^\circ \leq \theta_f \leq 50^\circ$ . Gerrard [27] investigated the influence of the length of a rigid SP on flow  
78 structure at Reynold number of  $2 \times 10^4$ . The results revealed that the best length to achieve the  
79 lowest Strouhal number ( $St$ ) was equal to the cylinder diameter. In an experimental study by  
80 Roshko [28], it was demonstrated that when the ratio of the rigid SPs length to the cylinder  
81 diameter was equal to 5, the VS was completely suppressed. An attached hinged rigid SP was  
82 investigated by Shukla et al. [38]. It was observed the communication between the shear layers  
83 was not completely disrupted since the SP rotated about the hinged point. Other studies have  
84 investigated the effect of permeable and inclined SPs [42], an attached rigid wavy SP [43], and  
85 an upstream rod [44] on the flow structure around a cylinder.

86 Recently the application of flexible SPs has become popular for the flow control.  
87 Because in addition to high capability in control, it also can be used for energy harvesting from  
88 the flow. For instance, the SPs deformation due to VS can be utilized to harvest energy from  
89 the flow using piezoelectric polymers. These polymers are able to generate electric charges  
90 when they are under pressure or strain by converting mechanical energy into electrical energy  
91 [45]. Shukla et al. [46] have carried out experimental studies with a flexible SP and examined  
92 the influence of the SP's flexural rigidity, length of SP, and Reynolds number on the flow  
93 characteristics of a cylinder. Results showed that that at high values of Reynolds number, two  
94 different oscillation regimes for the SP can be observed. The frequency of both regimes was  
95 close to the cylinder frequency. Moreover, it was found that the SPs that were considerably  
96 larger than the wake length had similar responses, whereas shorter SPs had significantly  
97 different responses. Wu et al. [47] numerically studied a detached flexible SP, which was  
98 placed at the downstream or upstream of a fixed cylinder using the immersed boundary-Lattice  
99 Boltzmann method. The SP was under a forced oscillation and was deformed in a fish-like  
100 movement at  $Re=100$ . The results indicated that the flexible downstream SP has more effect  
101 on drag reduction compared to the rigid one due to the fish-like motion of the SP. In addition,  
102 a further drag reduction was achieved using upstream flexible SP compared to downstream  
103 one. Sun et al. [48] investigated flow-induced-vibration of a flexible SP attached to a cylinder  
104 at  $Re=100$ . It was observed that the cylinder with the SP has less drag, but a higher oscillation  
105 amplitude compared to a bare cylinder. Chehreh and Javadi [49] numerically studied the effect  
106 of two SPs that were attached at specific angles ( $\pm 55$  degrees) behind a cylinder at  $Re=100$  and  
107 200. The SPs were under forced oscillation at various ratios of the natural VS frequencies.  
108 Results showed that by increasing the frequency ratio and the oscillation amplitude, an in-phase  
109 VS pattern in the wake structure was observed resulting in complete VS suppression. In another  
110 work, Abdi et al. [8] studied the effect of adding single and multiple attached flexible SPs  
111 downstream of a cylinder at  $Re=100$  using Arbitrary Lagrangian–Eulerian (ALE) scheme.  
112 They evaluated the effect of SP flexibility and attachment angle on drag, lift, and the Strouhal  
113 number. Results showed that in contrast to rigid cases, a slight increase in the Strouhal  
114 number ( $St$ ) was observed in flexible cases. The increase in  $St$  originated from formation of a tiny



115 vortex in the tip of SP, which was called tip vortex. Pfister and Marquet [50] numerically  
116 studied the dynamics of a hyperplastic attached SP subjected to a laminar flow at  $Re=80$ .  
117 Numerical approach was based on the ALE formulation of the incompressible Navier–Stokes  
118 equations (flow modeling), coupled with a Saint-Venant Kirchhoff model (SP modeling).

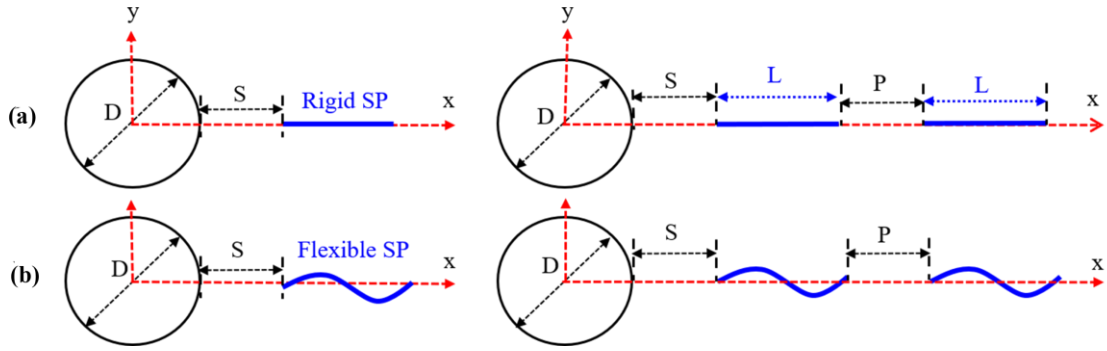
119 As discussed above, several studies have focused on the rigid SPs. Some others focused on  
120 the attached flexible SPs. The usage of detached SPs and the possible advantages of using  
121 several SPs should be studied further. In addition, electricity generation from flexible SPs by  
122 piezoelectric polymers requires more information related to the SPs' strain. To this aim, a  
123 comparative study is done on a circular cylinder with both rigid and flexible SPs. One and two  
124 detached SPs are considered downstream of a circular cylinder. The distance between the first  
125 SP and cylinder as well as between the SPs are varied. For flexible SPs, the tip amplitude and  
126 strain were measured to harvest energy from the flow. The optimum arrangements of the SPs  
127 for placing piezoelectric polymers in terms of both flow control and electricity generation are  
128 obtained. This study focuses only on  $Re=100$  in a two-dimensional FSI problem to avoid the  
129 three-dimensional flow nature that occurs at  $Re > 160$  [49]. Considering the current worldwide  
130 energy demands, and transition into clean energy, the use of such flexible SPs provides  
131 significant benefits over the conventional cylindrical structure which include benefit of energy  
132 harvesting along with reducing structural fatigue failure and increasing the lifetime.

133 The remainder of this paper is structured in four sections. The numerical methodology and  
134 validation of the simulation model are described in section 2. The results that include amplitude  
135 and strain of the SPs during fluctuation and flow characteristic variables are provided in section  
136 3. Eventually, the summary and conclusions are discussed in section 4.

## 137 2. Materials and methods

### 138 2.1. Problem statement

139 As illustrated in Fig. 1(a), in this study a circular cylinder with one and two detached rigid SPs  
140 was modeled. A similar geometry with flexible SPs was modeled as well (Fig. 1(b)). The SPs  
141 are located downstream of the cylinder in a horizontal line crossing center of the cylinder. The  
142 ratio of the gap between the cylinder and the first SP (S), to the cylinder diameter (D) varies in  
143 the range of  $0 \leq S/D \leq 2.5$ , and the ratio of the gap between the SPs (P) to the cylinder  
144 diameter (D) is in the range of  $0 \leq P/D \leq 3$ . It should be noted that the first SP can be attached  
145 to the cylinder as well. The lengths of the SPs are the same and equal to the cylinder diameter  
146 ( $L/D=1$ ) to minimize the Strouhal number [27]. The thickness (h) of the SPs is set at  $0.03D$ .  
147 The computational domain size and the related boundary conditions are displayed in Fig. 2.  
148 The dimension of the computational fluid domain is  $80D \times 60D$  [8]. The distance between the  
149 inlet to the center of the cylinder is  $20D$ . The upper and lower boundaries are located at  $30D$   
150 from the cylinder's center. Hence, the dimension of the computational domain is sufficiently  
151 large, so that the effect of the blockage ratio is negligible. No-slip boundary condition is applied  
152 to the surface of the cylinder and SPs. Therefore, the fluid velocity ( $u_f$ ) on the cylinder is equal  
153 to zero, and on the flexible SPs  $u_f = v_s$  ( $v_s$  is the SP velocity).



154

155

**FIG. 1.** Configuration of the cylinder with one and two SPs: (a) rigid, (b) flexible.

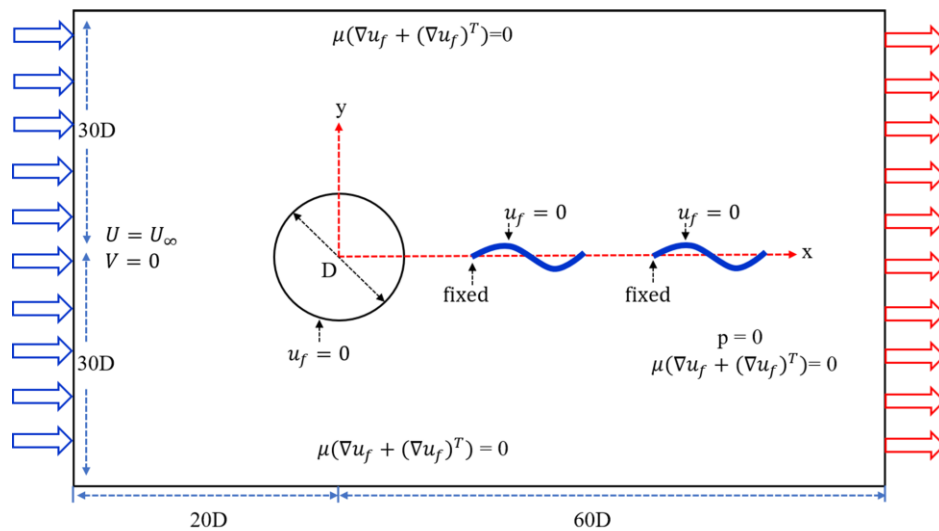
156 The fluid flow enters the computational domain from the inlet boundary with a velocity of  $U_\infty$   
 157 and exits from the outlet boundary with zero gradient pressure. The open boundary condition  
 158 with no viscous stress is applied to the upper and lower boundaries. The cylinder and the front  
 159 edge (left side) of the detached flexible SPs are fixed. Table 1 presents the material properties  
 160 for fluid and solid domains. The choice of material for this study is based on several  
 161 requirements. The flow must be able to deform the SPs and the typical fluid candidate for such  
 162 a numerical study is glycerin which has a relatively high viscosity [51]. For solid domain, the  
 163 stiffness of SPs must be low enough to oscillate at reasonable amplitude. For this reason, the  
 164 SPs are made of cork which has a high elasticity.

165

**Table 1.** Material properties used in the computational domain.

166

	Material	Density	Poisson's ratio	Young's modulus	Dynamic viscosity
Fluid domain	Glycerin	$1260 \text{ kg/m}^3$	-	-	$1.42 \text{ Pa}\cdot\text{s}$
Solid domain	Cork	$180 \text{ kg/m}^3$	0.3	$32 \text{ MPa}$	-



167

168

**FIG. 2.** The computational domain and boundary conditions.

169

## 2.2. Governing equations

170 The numerical procedure is based on the finite element method using the COMSOL  
 171 Multiphysics software (version 5.4, COMSOL Inc., Burlington, MA). The Arbitrary

172 Lagrangian-Eulerian (ALE) scheme is used to simulate this fluid-structure interaction problem  
 173 with a fully coupled approach. In the ALE scheme, the equations of the fluid domain are  
 174 formulated based on the Eulerian description at a spatial frame, and the deformation equations  
 175 of the solid material are formulated based on the Lagrangian description at a material  
 176 (reference) frame. Due to the flexibility of the grid in the ALE method, it is beneficial in  
 177 problems with large deformations [52]. The governing equations of fluid flow, solid mechanics,  
 178 coupling interface, and moving mesh are described in the following sections.

### 179 2.2.1. Fluid dynamics

180 The fluid flow is considered to be incompressible and Newtonian. The Navier-Stokes equations  
 181 in the spatial coordinate system are as follows [53]:

$$\nabla \cdot u_f = 0 \quad (1)$$

$$\rho \frac{\partial u_f}{\partial t} - \nabla \cdot [-pI + \mu(\nabla u_f + (\nabla u_f)^T)] + \rho(u_f - u_m) \cdot \nabla u_f = 0 \quad (2)$$

182 where  $(\bullet)^T$  represents a transpose,  $I$  denotes the unit diagonal matrix,  $p$  is the pressure,  $\mu$  is the  
 183 dynamic viscosity,  $\rho$  is the density of the fluid,  $u_m$  is the fluid velocity corresponding to a  
 184 moving coordinate system, and  $t$  is time. The initial conditions for the fluid domain are:

$$p = 0 \text{ and } u_f = 0 \quad (3)$$

185 Furthermore, a force transformation is required due to the adoption of different coordinate  
 186 systems in the ALE method [8]:

$$F = f \cdot \left(\frac{dv}{dV}\right) \quad (4)$$

188 Here,  $f$  and  $F$  denote the force in the spatial and the material frames, respectively, and  $dv$  and  
 189  $dV$  are the scale factors for the spatial frame and the material frame, respectively.

### 190 2.2.2. Solid mechanics

191 Numerical formulation of the SPs in the material frame (undeformed) coordinate system is as  
 192 follows:

$$(S - S_0) = C : (\varepsilon - \varepsilon_0) \quad (5)$$

194 Here,  $S$  is the second Piola–Kirchhoff stress tensor and  $C$  is the fourth-order elasticity tensor,  
 195  $\varepsilon$  is the Green–Lagrange strain, “:” is the double-dot tensor product (double contraction),  $S_0$   
 196 and  $\varepsilon_0$  stand for the initial quantities. In the above equation,  $\varepsilon$  is given by:

$$\varepsilon = 0.5 [(\nabla u_s)^T + \nabla u_s + (\nabla u_s)^T \nabla u_s] \quad (6)$$

199 where  $u_s$  is the displacement vector. Based on linear elastic assumption, the deformation of SP  
 200 is calculated by:

$$\rho_s \frac{\partial^2 u_s}{\partial t^2} - \nabla \cdot \sigma = F_V \quad (7)$$

202 where  $\rho_s$  is density of solid domain,  $F_V$  is the force per unit volume at the SPs surface, and  $\sigma$   
 203 is the Cauchy stress. The initial conditions for the solid domain are adjusted as:

$$u_s = 0 \text{ and } \frac{\partial u_s}{\partial t} = 0 \quad (8)$$

### 204 2.2.3. Coupling and interface consideration

205 In the coupling process of the fluid domain with the solid one, it is essential to satisfy the  
 206 boundary conditions related to the contact interface. The  $u_f$  is obtained from the flexible SPs  
 207 velocity ( $v_s$ ) at the interface:

$$u_f = v_s \quad (9)$$

208 The stress on the SPs at the interface of the two domains is computed from the following  
 209 equation:

$$\Gamma \cdot n^f + \sigma \cdot n^s = 0 \quad (10)$$

210 where  $\Gamma$  and  $\sigma$  are the stress tensors and  $n^f$  and  $n^s$  are the normal vectors of the fluid and SPs,  
 211 respectively. The  $\Gamma$  is the sum of pressure and viscous stresses of the fluid:

$$\Gamma = -pI + \mu(\nabla u_f + (\nabla u_f)^T) \quad (11)$$

### 212 2.2.4. Moving mesh

213 The computational mesh deforms to adjust to the deformation of the flexible SPs. In the moving  
 214 mesh interface, the Winslow smoothing equations are applied [54].

$$\frac{\partial^2 \partial X}{\partial x^2 \partial t} + \frac{\partial^2 \partial X}{\partial y^2 \partial t} = 0 \quad (12)$$

$$\frac{\partial^2 \partial Y}{\partial x^2 \partial t} + \frac{\partial^2 \partial Y}{\partial y^2 \partial t} = 0 \quad (13)$$

215 where,  $X$  and  $Y$  denote the reference coordinates of the material frame (solid domain), and  $x$   
 216 and  $y$  are related to the spatial coordinates of the spatial frame (fluid domain) [8].

## 217 2.3. Non-dimensional flow parameters

218 It is a common approach to describe physical phenomena in non-dimensional forms in order to  
 219 achieved generalized results comparable with other studies. Accordingly, important non-  
 220 dimensional parameters associated with flow characteristics are defined by equations (14) to  
 221 (23):

### 222 2.3.1. Strouhal number

223 The frequency of VS is characterized by a dimensionless parameter known as the Strouhal  
 224 number (St), which is defined as follow:

$$St = \frac{f_s D}{U_\infty} \quad (14)$$

225 where  $f_s$  is the frequency of VS,  $D$  is the cylinder diameter and  $U_\infty$  is the free stream velocity  
226 of flow.

### 227 2.3.2. Hydrodynamic coefficients

228 The most frequently used flow quantities in an unsteady flow regime are lift coefficient ( $C_l$ )  
229 and drag coefficient ( $C_d$ ), which are defined by:

$$C_l = \frac{F_l}{0.5\rho U_\infty^2 D} \quad (15)$$

$$C_d = \frac{F_d}{0.5\rho U_\infty^2 D} \quad (16)$$

230 Here,  $F_l$  and  $F_d$  are lift and drag forces, which are the force components that are applied to the  
231 bluff body perpendicular and parallel to the flow direction, respectively.  
232

### 233 2.3.3. Pressure coefficients

234 The drag force is a combination of pressure and viscous forces applied to the surface by the  
235 fluid. Meanwhile, the pressure force is the dominant part of the drag, which is highly dependent  
236 on shape of bluff bodies. Due to the importance of pressure drag, the pressure coefficient is  
237 introduced, which describes the pressure difference between reference pressure and surface  
238 pressure as follows:

$$C_p = \frac{p_s - p_\infty}{0.5\rho U_\infty^2} \quad (17)$$

239 where  $p_s$  is the static pressure on the cylinder surface,  $p_\infty$  is the free-stream static pressure far  
240 from the bluff body and  $0.5\rho U_\infty^2$  is the dynamic pressure. If the pressure of the rear stagnation  
241 point ( $p_b$ ) is used in equation (17), the base pressure coefficient ( $C_{pb}$ ) can be obtained [55,  
242 56]:

$$C_{pb} = \frac{p_b - p_\infty}{0.5\rho U_\infty^2} \quad (18)$$

### 243 2.3.4. Root-mean-square (RMS) of velocity

244  
245 In the wake region of a bluff body, the root-mean square of streamwise velocity ( $u_{rms}$ ) and  
246 transverse velocity ( $v_{rms}$ ) show the roll-up position of shear layers and the interaction between  
247 them, which are defined by:  
248

$$u_{rms} = \sqrt{\frac{1}{N} \sum_{i=1}^N (u_i - \bar{u})^2} \quad (19)$$

$$v_{rms} = \sqrt{\frac{1}{N} \sum_{i=1}^N (v_i - \bar{v})^2} \quad (20)$$



249 In these relations,  $\bar{u}$  and  $\bar{v}$  are the time averaged of streamwise and transverse velocities,  $N$  is  
 250 the number of samples in the time history, and  $u_i$  and  $v_i$  denote the temporal series. The  
 251 dimensionless forms of them are as follow:

$$252 \quad u_{rms}^* = \frac{u_{rms}}{U_\infty} \quad (21)$$

$$v_{rms}^* = \frac{v_{rms}}{U_\infty} \quad (22)$$

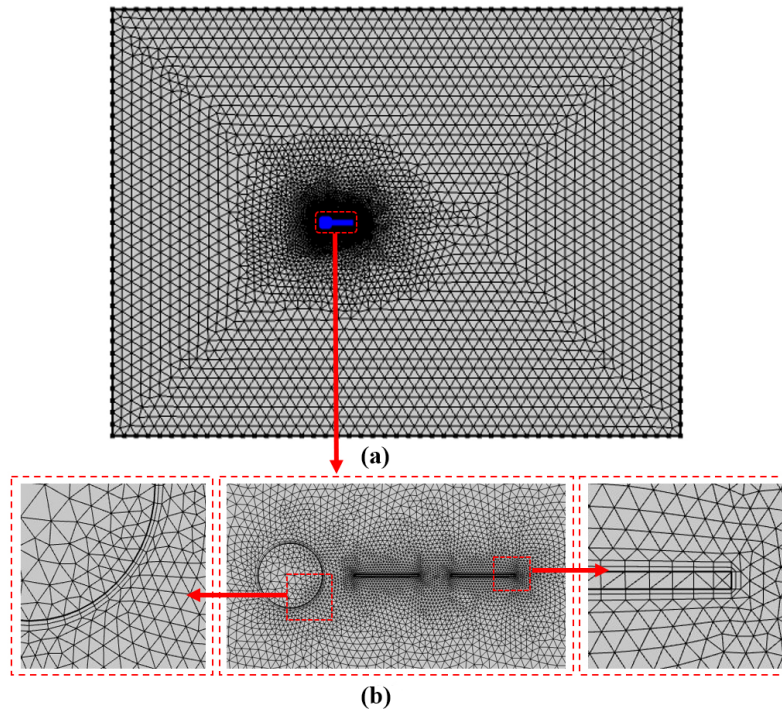
### 253 2.3.5. Spanwise vorticity

254 Vorticity is rotation of the fluid particles around a fixed axis. It can represent the boundary  
 255 layer, the shear layer growth, and VS phenomena. The dimensionless spanwise vorticity ( $W_z^*$ )  
 256 is given by [57]:  
 257

$$258 \quad W_z^* = \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) \frac{D}{U_\infty} \quad (23)$$

## 259 2.4. Mesh description

260 As displayed in Fig. 3 (a), an unstructured mesh is employed for the computational domain due  
 261 to the high adaptability of the triangular elements with the fluid domain. The circumferences  
 262 of the cylinder and SPs are discretized by extremely fine cells. For accurate estimation of  
 263 velocity and pressure gradients, two layers of structural cells are utilized for the SPs and  
 264 cylinder surfaces (Fig. 3(b)). Table 2 demonstrates the dependence of the Strouhal number and  
 265 time average of the drag coefficient ( $\overline{C_d}$ ) on the mesh resolution for the cylinder with two SPs  
 266 ( $S = P = 0.5D$ ). According to the results, the setting of case “c” is selected.  
 267



268 **FIG. 3.** Meshing of the computational domain, (a) view of the whole domain, (b) zoomed view of the mesh  
 270 around the cylinder and SP.

271 **Table 2.** Grid independence study for a fixed cylinder with two detached flexible SPs ( $S = P = 0.5D$ ).

Case	Number of elements	St	$\overline{C_d}$
a	8001	0.157	1.152
b	10673	0.158	1.153
c	15556	0.159	1.157
d	30830	0.159	1.158

272

273 **2.5. Validation of the model**

274 The model is validated by the numerical and experimental results of flow past a circular  
 275 cylinder as well as flow past a cylinder with one attached rigid SP at  $Re=100$  in the literature.  
 276 As can be seen in Table 3, the results of  $St$ ,  $\overline{C_d}$ , and RMS of the lift coefficient ( $C_{l_{rms}}$ ) are in  
 277 good agreement with the corresponding results of other studies. Furthermore, the results of one  
 278 attached flexible SP case are compared with the numerical results of Turek and Hron [51] in  
 279 Table 4. In this case,  $Re=200$  and the length and thickness of the SP are 0.35 m and 0.02 m,  
 280 respectively. Both frequency and magnitude of  $F_L$  and  $F_D$  on the cylinder and SP are compared  
 281 in Table 4. The results again show a good agreement with the corresponding ones.

282

283 **Table 3.** Validation of the results of a cylinder with and without attached rigid SP at  $Re=100$ .

Test case	Bare cylinder ( $Re=100$ )			One attached rigid SP ( $Re=100, L/D=1$ )	
	$St$	$\overline{C_d}$	$C_{l_{rms}}$	$St$	$\overline{C_d}$
Sudhakar and Vengadesan [4]	0.165	1.37	-	0.139	1.174
Norberg [58]	0.164	-	0.22	-	-
Williamson [59]	0.164	-	-	-	-
Hwang and Yang [40]	0.167	1.34	-	0.137	1.17
Present study	0.164	1.33	0.228	0.136	1.161

284

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286

287

**Table 4.** Validation of the results of a cylinder with one flexible SP at  $Re=200$ .

Test case	Drag force		Lift force	
	Magnitude (N)	Frequency (Hz)	Magnitude (N)	Frequency (Hz)
Turek and Hron [51]	149.78±2.22	10.9	457.3±22.66	5.3
Present study	150±4.49	10.43	454±24.78	5.33

289

290

### 3. Results and discussion

291

In this section, flow characteristics including contours of vorticity, streamlines, velocities, and values of  $St$ ,  $\overline{C_d}$ ,  $\overline{C_p}$ ,  $\overline{C_{pb}}$  and  $Cl_{rms}$  at different arrangement of SPs are studied. The results are evaluated as a function of  $S/D$  and  $P/D$ .

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#### 3.1. Contours of vorticity and streamlines

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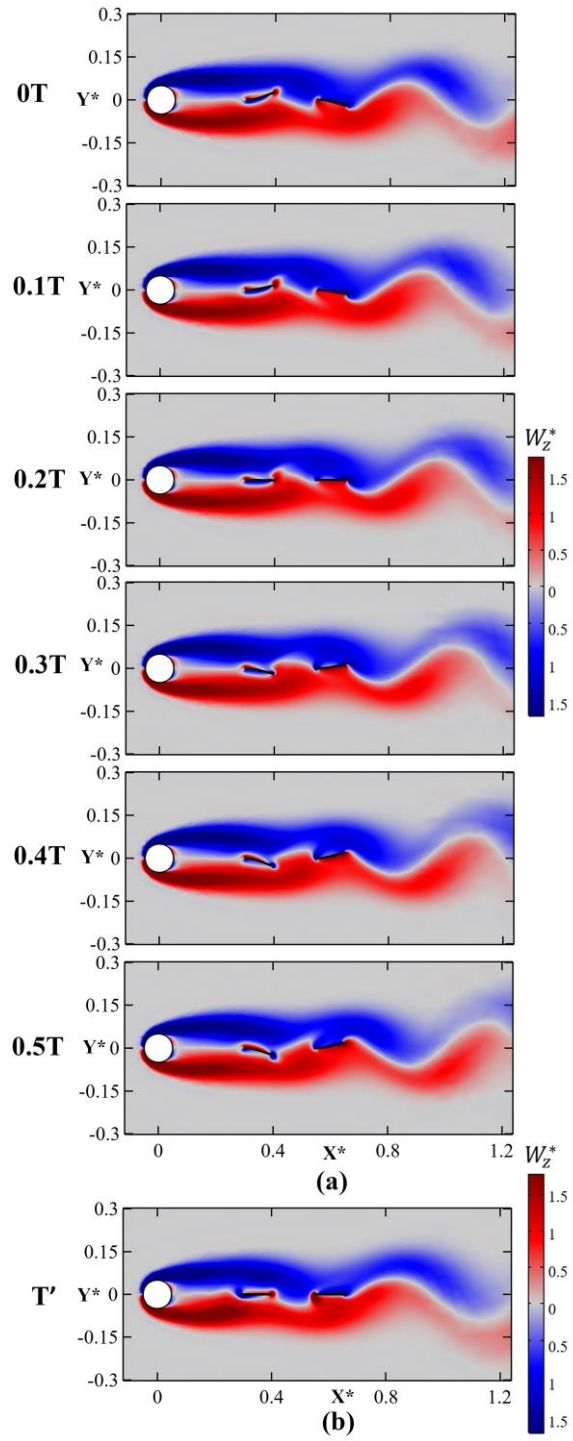
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Figure 4(a) demonstrates an example of instantaneous dimensionless spanwise vorticity contours ( $W_z^*$ ) for a half cycle of SPs oscillation in the case of two flexible SPs ( $S/D = 2.5$  and  $P/D = 1.5$ ). The x and y coordinates become dimensionless with the cylinder diameter (D). The beginning of the cycle (0T) is attributed to the highest displacement of the first SP. Two shear layers consisting of positive vorticity (counterclockwise) and negative vorticity (clockwise) can be observed in the vorticity contours [60]. These shear layers roll up simultaneously with the SPs flapping movement. Under the shedding mechanism, the first SP (the SP close to the cylinder) interacts with shear layers of the cylinder. Then, the second SP experiences the shear layers affected by the first SP. The movement of the SPs has a phase difference of  $180^\circ$  and they deform in the opposite directions to each other. When the first SP is at the maximum displacement in the +y direction, the second SP is at the maximum displacement in the -y direction. In addition to the main shear layers of the cylinder, small shear layers extend over and below of the SPs. The small shear layers slip at the SPs surfaces and roll up at the tip of the plate. The interaction between the main shear layers of the cylinder and the small shear layers at the tip of SPs results in two different mechanisms which will be called here after destructive mechanism and constructive mechanism. When the shear layers (from the cylinder and from the SPs) have the same sign, vorticities merge with each other and produce a shear layer with higher strength and if they have opposite sign, they weaken each other. It can be seen that the shear layers of the first and the second SPs have destructive and constructive mechanisms, respectively. The displacement of the first SP is more than the second SP. Because the cylinder shear layers that interact with the first SP are strong and after contacting with the first SPs shear layer, they become weak. Figure 4(b) indicates the corresponding contour for the case of rigid SPs. Similar to the flexible case, the shear layers of the first and the second SPs have destructive and constructive mechanisms, respectively. However, in the second SP of the rigid case, a new destructive mechanism appears at the fixed edge of the SP. In both rigid and flexible cases, the SPs prevent the main shear layers to interact with each other. Consequently, they expand and interact with each other after the second SP. In this arrangement of SPs, the elongation of vortices along two flexible and rigid SPs leads to 15% and 29.55% reduction in the  $St$  compared to the bare cylinder, respectively. The reason

326 for the higher wake suppression in the case of rigid SPs compared to the flexible ones in this  
327 arrangement of SPs is attributed to the flexibility of the SPs which is discussed in the following  
328 paragraph.

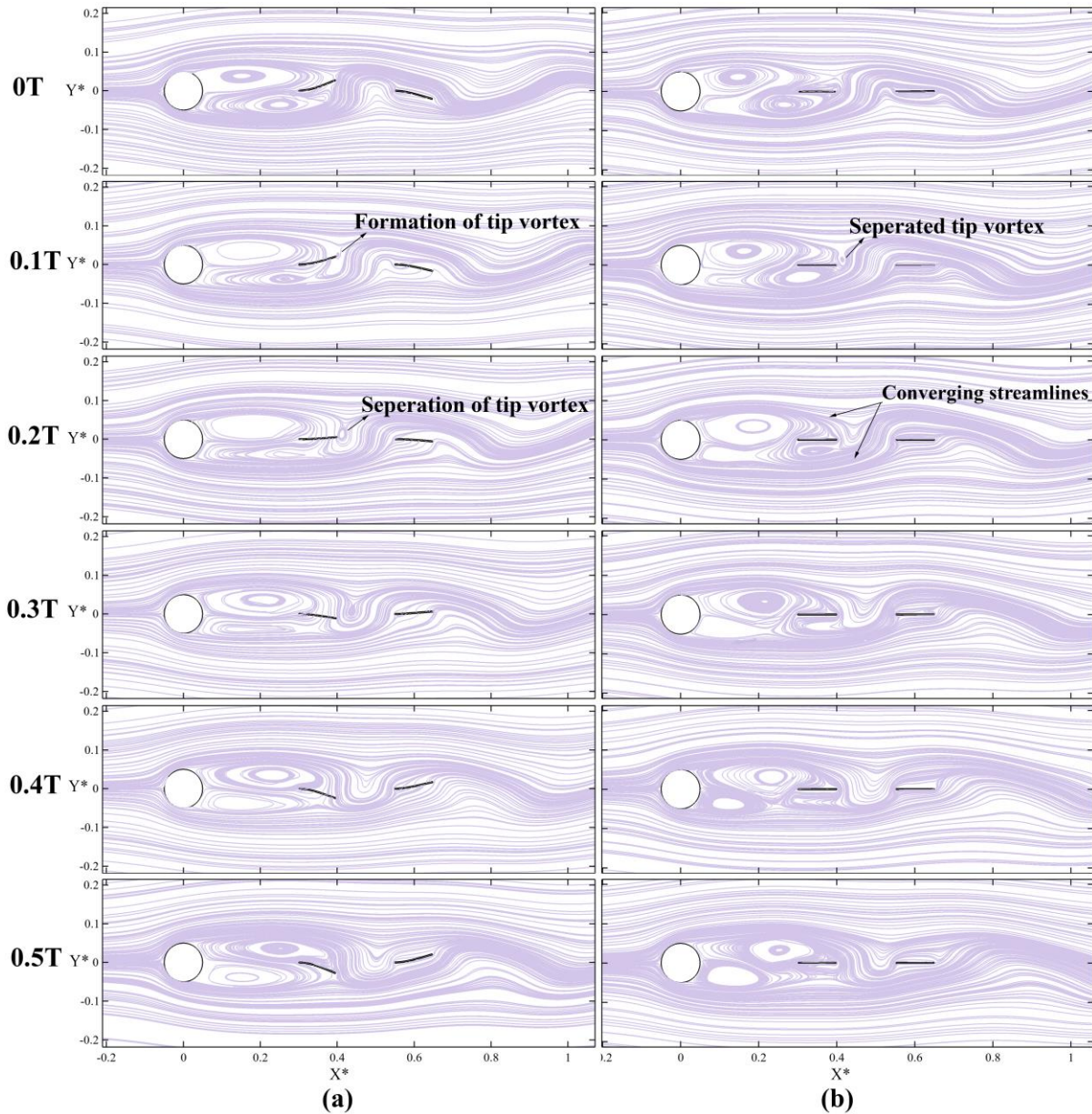
329 The streamlines pattern is provided for a half cycle of SPs oscillation in Fig. 5 for flexible SPs  
330 at  $S/D = 2.5$  and  $P/D = 1.5$ . The corresponding results of the rigid SPs are depicted on the  
331 right column of Fig. 5. The better performance of rigid SPs in  $St$  reduction compared to the  
332 flexible ones could be justified using three mechanisms that can be seen in streamlines. Firstly,  
333 the downward motion of the first flexible SP gives more space to the upper vortex near the  
334 cylinder to grow. Therefore, it grows faster than the corresponding vortex of the rigid SPs.  
335 Secondly, on the other side of the first SP, the lower vortex at the same period is bigger in the  
336 case of flexible SPs compared to the rigid ones. The third mechanism is related to the  
337 generation of a tiny vortex near the tip of the first SP (here after called “tip vortex”) in both  
338 rigid and flexible cases. This tip vortex develop more instability in the wake structure. As can  
339 be seen in Fig. 5(a) for flexible case, the “tip vortex” generates at the tip of the first SP in a  
340 time cycle of  $0.1T$ , and then separates at  $0.2T$ . However, in the rigid case, it forms between the  
341 time cycles of  $0T$  and  $0.1T$  and eventually, it is completely separated from the first SP at  $0.1T$ .  
342 In both cases, the separated tip vortices joins the converging streamlines. These observations  
343 confirm the better performance of rigid SPs compared to the corresponding flexible ones in  
344 terms of  $St$  reduction.

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**FIG. 4.** Instantaneous dimensionless spanwise vorticity contours ( $W_z^*$ ) for two detached SPs at ( $S/D = 2.5$  and  $P/D = 1.5$ ): (a) flexible SPs during a half cycle of SPs oscillation, (b) rigid SPs.



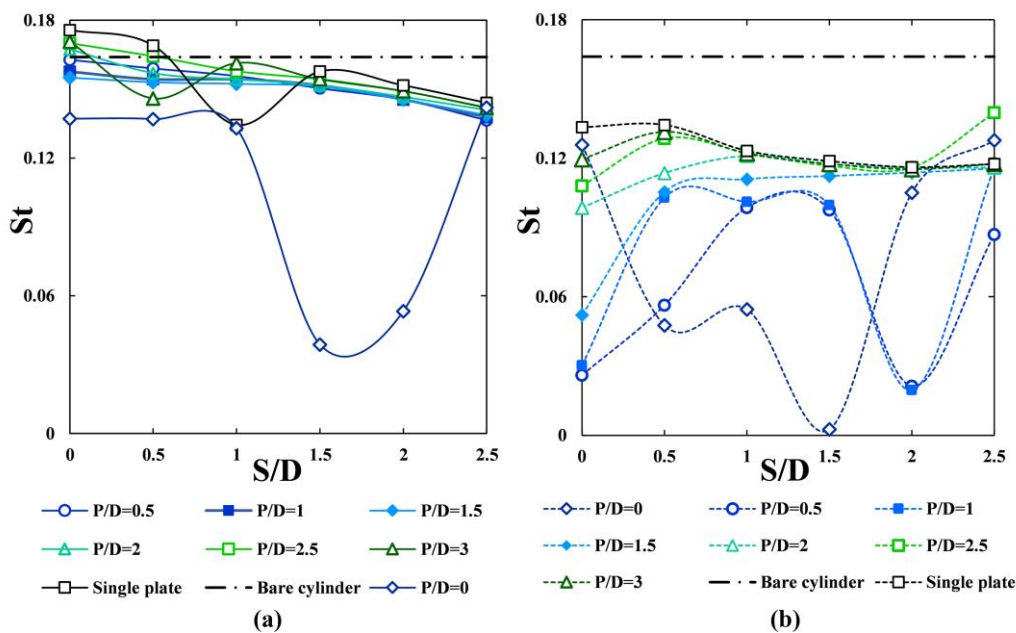
349  
350 **FIG. 5.** Streamline patterns for a half cycle of oscillation in the case of two SPs ( $S/D = 2.5$  and  $P/D = 1.5$ ):  
351 (a) flexible SPs (b) rigid SPs.  
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### 353 3.2. Strouhal number

354 In this section, the Strouhal number is evaluated at different arrangements of the SPs. The St  
355 represents VS phenomenon and is calculated from FFT (Fast Fourier Transform) algorithm  
356 over the time history of the lift force. The variation of St against  $S/D$  for the cases of flexible  
357 SPs is demonstrated in Fig. 6(a). The corresponding results for the cases of rigid SPs are  
358 presented in Fig. 6(b). In addition, the result of the bare cylinder case is included in both plots.  
359 Using the rigid and flexible SPs as a passive control method reduces the St compared to the  
360 bare cylinder except some specific arrangements of flexible SPs (one SP at  $S/D \leq 0.5$  as well  
361 as two SPs at  $S/D = 0$  and  $2 \leq P/D \leq 3$ ) in which a slight enhancement in St is observed.  
362 Maximum enhancement of St among these cases occurs in one attached SP case ( $S/D = 0$ )  
363 with 8.0% increase compared to bare cylinder. It is in agreement with the numerical study of  
364 Abdi et al. [8]. The increase in St is due to the formation of a “tip vortex” in the first SP. It

365 interacts with the main vortices shedding from the cylinder and causes an increase in instability  
 366 in the shear layers of the cylinder. As shown in Fig. 6(a), the Strouhal number of two flexible  
 367 cases monotonically decreases for  $P/D \geq 0.5$  as  $S/D$  increases (except the case with  $S/D =$   
 368  $0.5, P/D = 3$ ). There are three local minimum in the  $St$  graphs: In one SP at  $S/D = 1$  and in  
 369 two SPs when  $S/D = 0.5$  and  $P/D = 3$  as well as at  $S/D = 1.5$  and  $S/D = 2$  in  $P/D = 0$ . The  
 370 reason for these sudden drop will be discussed later in below Fig. 7. As shown in Fig. 6(b), the  
 371  $St$  in all cases with rigid SPs decreases compared to bare cylinder. The VS from the cylinder is  
 372 very sensitive to arrangements of the SPs. Similar to flexible cases, there are some sudden  
 373 reductions at  $S/D = 1.5$  and  $S/D = 2$ . These sudden reductions are due to significant  
 374 modifications in the flow patterns in which the VS is suppressed perfectly. As the distance  
 375 between the rigid SPs increase to  $P/D \geq 2$ , the effect of SPs on wake structure becomes less  
 376 and the  $St$  number increases. The rigid SPs at a close distance to each other act like a long SP  
 377 and interrupt the contact between the shear layers of the cylinder. The most noticeable  $St$   
 378 reduction in both cases of rigid and flexible SPs occurs in the case of two SPs with the gap  
 379 ratio of  $S/D = 1.5$  and  $P/D = 0$ . This configuration results in a dramatic reduction of 97.8%  
 380 and 76.35% in  $St$  compared to the bare cylinder in the case of rigid and flexible SPs,  
 381 respectively. In addition, compared to the attached cases ( $S/D = 0$  and  $P/D = 0$ ), the  
 382 corresponding configuration of  $S/D = 1.5$  and  $P/D = 0$  reduce the  $St$  by 97.2% and 71.2% in  
 383 the case of rigid and flexible SPs, respectively. It indicates that the wake control can enhance  
 384 effectively using detached SPs instead of attached ones.

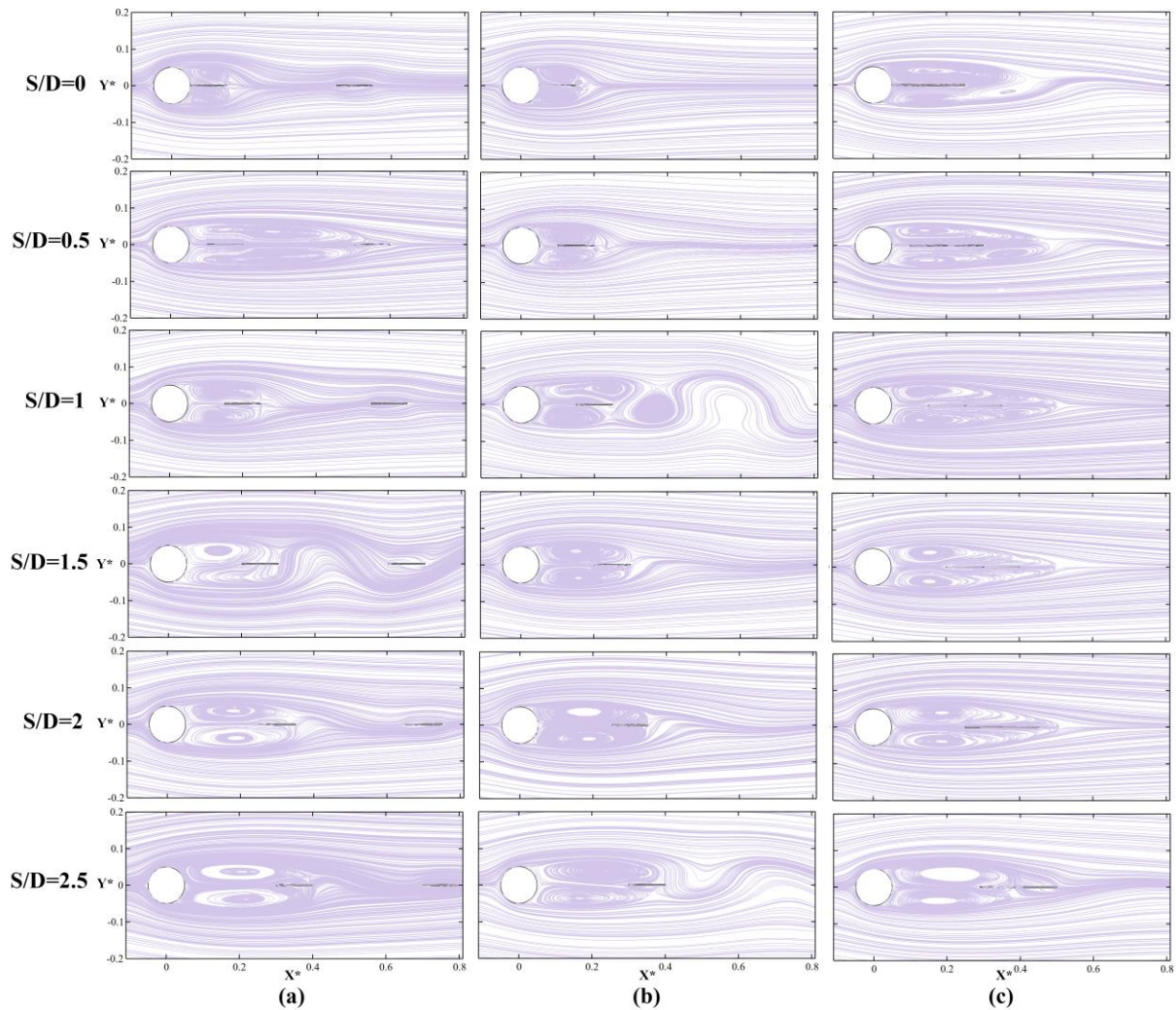
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388 **FIG. 6.** Strouhal number at various  $P/D$  and  $S/D$ : (a) flexible SPs, (b) rigid SPs.

389 To further explore the underlying mechanisms of the sudden  $St$  reductions in the cases of two  
 390 flexible SPs at  $P/D = 0$  & 3 and one flexible SP at  $S/D = 1$ , the streamlines at different  $S/D$  are  
 391 presented in Fig. 7. As shown in Fig. 7(a), as  $S/D$  increases in the case of two flexible SPs at  
 392  $P/D = 3$ , two strong cylinder vortices expand further from the cylinder, and consequently the  
 393  $St$  number decreases. In contrast to other cases, at  $S/D = 0.5$  in Fig. 7(a), it is observed that  
 394 the expanded cylinder vortices divided into four vortices in the wake region. The two stronger  
 395 ones are transferred downstream with the fluid flow and two smaller vortices near the cylinder

395 grow and expand to repeat the same cycle. Similar to Fig.7(a), vortices elongate by increasing  
 396 the  $S/D$  in Fig. 7(b). There is a distinct flow pattern for one SP case at  $S/D = 1$  in which the  
 397 shear layers cannot interact with each other properly. As can be seen in Fig. 7(c), the vortices  
 398 are elongated more compared to Fig. 7(a) and Fig. 7(b) and they reach to their maximum length  
 399 at  $S/D = 1.5$  and 2 corresponding to their lowest  $St$  number. From these observations, it is  
 400 expected that significant reduction occurs in drag and lift forces in the unsteady flow (as can  
 401 be seen in Fig. 10(a) and Fig. 13). These effective control performances are achieved using  
 402 detached SPs, which has a noticeable effect on the wake stabilization. It is interesting to note  
 403 that these two flexible SPs cases, do not have any oscillations in the mentioned arrangements  
 404 and only low amplitude oscillation exist in the one SP case at  $S/D = 1$  (Fig. 16).



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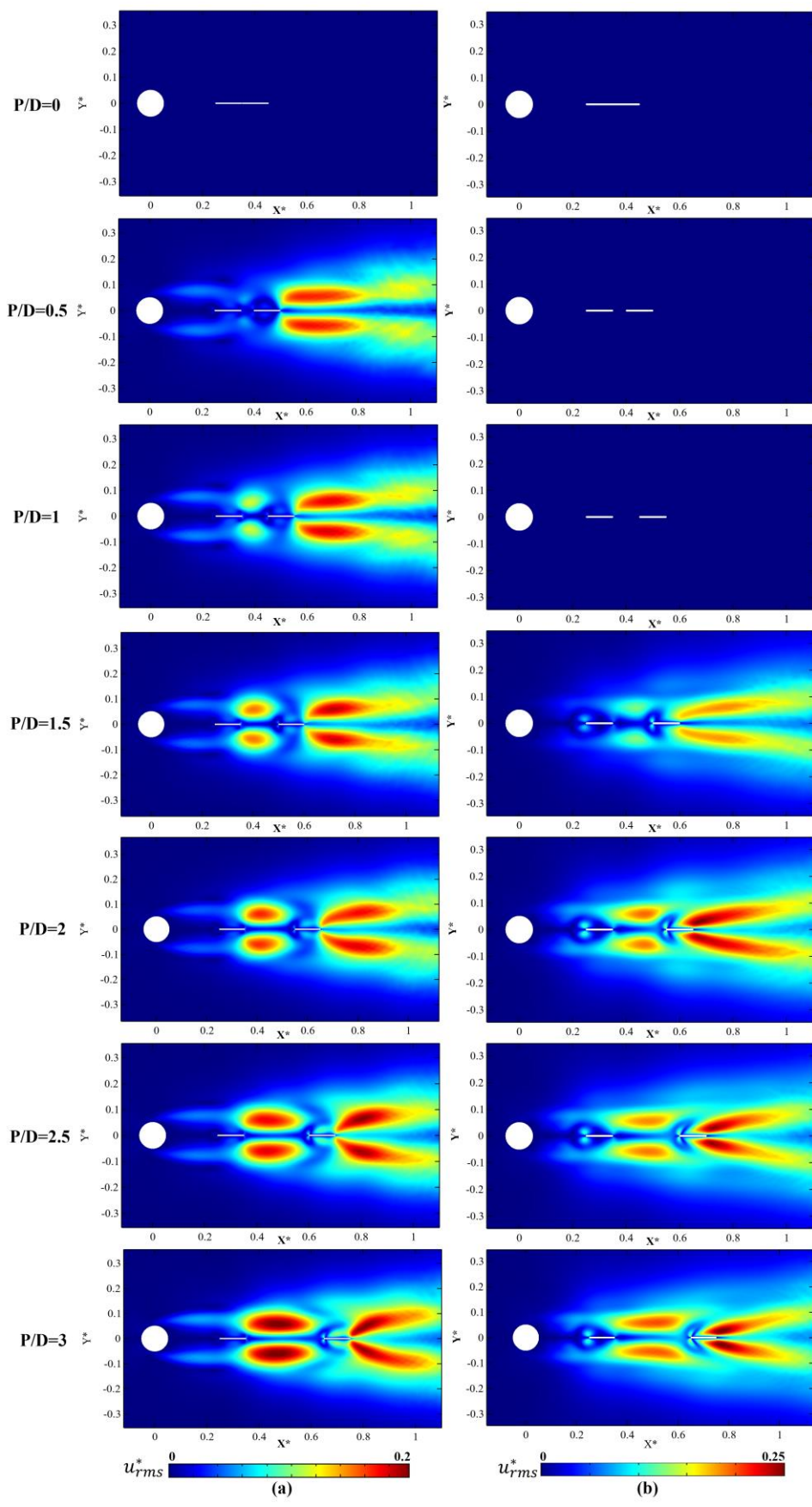
406 **FIG. 7.** Time-averaged streamlines for flexible SPs at different  $S/D$ : (a) two SPs case ( $P/D = 3$ ), (b) one SP  
 407 case, (c) two SPs case ( $P/D = 0$ ).

408 To investigate the dynamics of the mean wake flow for the case of flexible and rigid SPs,  
 409 contours of dimensionless RMS of streamwise velocity ( $u_{rms}^*$ ) and transverse velocity ( $v_{rms}^*$ )  
 410 at different  $P/D$  and fixed  $S/D = 2$  are displayed in Fig. 8 and Fig. 9, respectively. In von-  
 411 Karman Street, the vorticity diffusion mechanism is affected by the fluctuations in velocity.  
 412 Hence, the reduction of velocity fluctuations can be a representative of elimination of the VS.  
 413 Using the SPs in this study leads to a reduction in velocity fluctuations and consequently  
 414 suppression of the VS. Depending on the position of the SPs, there are two or four peaks in the



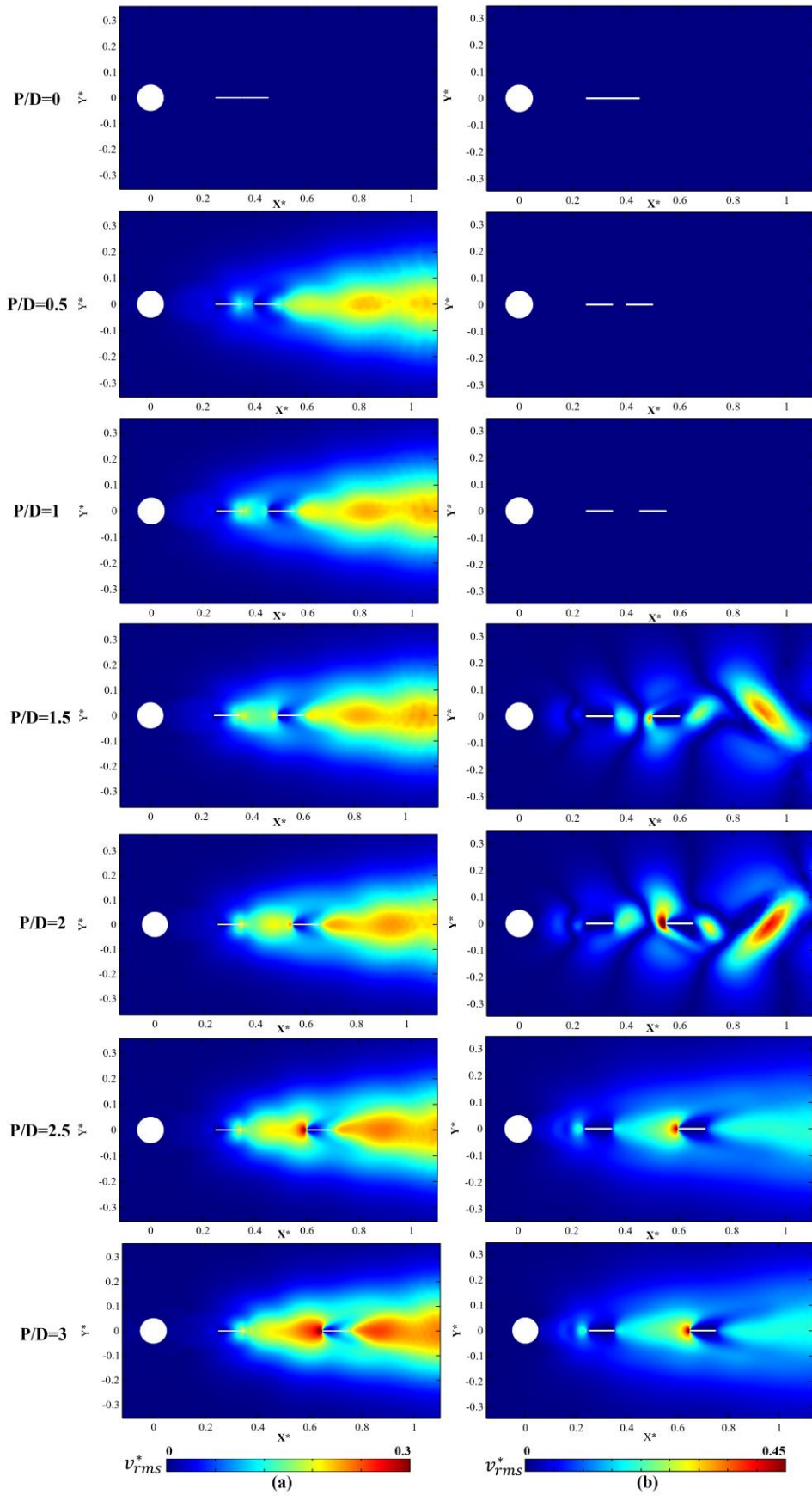
415 profile of  $u_{rms}^*$  (Fig. 8). The peaks coincide with the roll-up locations of the shear layers and  
416 are distributed symmetrically with respect to the centerline of the cylinder [55]. For flexible  
417 SPs at  $P/D = 0.5$ , the velocity fluctuations between the two SPs are very small, so only two  
418 peaks can be observed after the second SP. By increasing the distance between SPs ( $P/D \geq$   
419  $1$ ), more space is available for rolling up the shear layers in the wake structure. As can be seen  
420 in Fig. 8 for  $P/D \geq 1$ , two peaks are generated between the SPs and gradually becomes  
421 stronger. A similar trend can be seen for the rigid cases. However, the peaks between the SPs  
422 as well as after the second SP are generated at  $P/D \geq 1.5$ . The distribution of  $v_{rms}$  can be  
423 attributed to the variation of the lift force [61]. So, it can be utilized as a representative of the  
424 lift variation to evaluate the effectiveness of the proposed control method. Moreover,  $v_{rms}$   
425 indicates the interaction between the wake vortices. The value of  $v_{rms}^*$  for all cases decreases  
426 significantly compared to the bare cylinder. As can be seen in Fig. 9 (a), the peak location  
427 alters by changing  $P/D$ . For the flexible cases, it forms between the two SPs at  $P/D = 0.5$ ,  
428 and it increases gradually in both size and value of the  $v_{rms}^*$ . the second plate moves further  
429 away, there is more free space for the interaction of the shear layers and consequently, the  
430 velocity fluctuation increases. There are two main regions for formation of the large peaks: the  
431 frontal edge of the second SP, where the sharp edges facilitate growth of the shear layers, and  
432 downstream area of the second SP, where the vortices can form freely. For the rigid cases (Fig.  
433 9 (b)), there is no peak at  $P/D \leq 1$ . By increasing  $P/D$ , in contrast to other cases, four peaks  
434 are captured in the wake region at  $P/D = 1.5$  and  $P/D = 2$ . Two peaks are formed between  
435 the SPs in the vicinity of the SPs edges. Also, two peaks are apparent after the second SP,  
436 which tend to be asymmetric relative to the wake centerline. By further increase of  
437  $P/D$  ( $P/D \geq 2.5$ ), the distribution of  $v_{rms}^*$  becomes symmetric with respect to the wake  
438 centerline. Moreover, one strong peak is formed on the front edge of the second SP. For the  
439 rigid SPs, the maximum value of  $v_{rms}^*$  occurs on the front edge of the second SP at  $P/D = 2$   
440 due to strong curling of the shear layers besides the constructive mechanism of interactions of  
441 shear layers of the cylinder and SP. As can be seen in Fig. 8 and Fig. 9, the velocity fluctuations  
442 for specific arrangement of the flexible case ( $P/D = 0$ ) and the rigid case ( $0 \leq P/D \leq 1$ ), are  
443 almost zero and no peak is captured. The reason is that the short distance between the two SPs  
444 ( $P/D$ ), causes the SPs to behave like a continuous long SP. Hence, the SPs prevent the contact  
445 between shear layers and the symmetric vortices form along the SPs. Consequently, the  
446 velocity fluctuations are negligible.

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**FIG. 8.** Contours of dimensionless RMS of the streamwise velocities ( $u^*$ ) against  $P/D$  at  $S/D = 2$ : (a) flexible cases, (b) rigid cases.

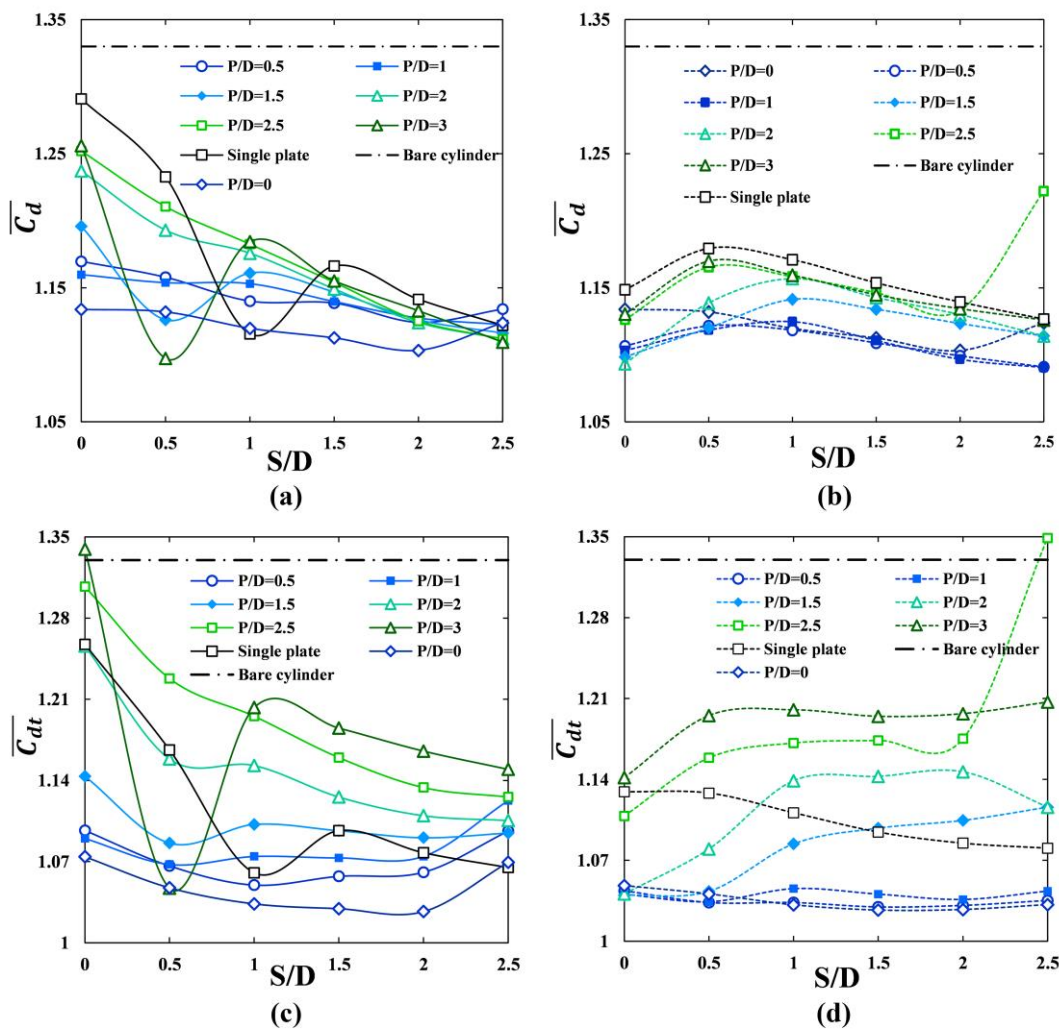


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**FIG. 9.** Contours of dimensionless RMS of the transverse velocities ( $v^*$ ) at different P/D and fixed S/D =2: (a) flexible cases, (b) rigid cases.

### 3.3. Hydrodynamic coefficients

455 Hydrodynamic forces are evaluated in this section to assess the effect of the SPs in the  
 456 suppression of VS. Oscillations in drag and lift forces resulted in vibration of the structure,  
 457 which has a destructive impact on lifetime. The drag coefficient is calculated in two ways in  
 458 this study; forces are integrated over the cylinder surface ( $\overline{C_d}$ ), or they are integrated over the  
 459 cylinder and SPs surfaces ( $\overline{C_{dt}}$ ). Fig. 10(a)-(b) display the  $\overline{C_d}$  versus  $S/D$  for flexible and rigid  
 460 SPs and the corresponding results of  $\overline{C_{dt}}$  are depicted in Fig. 10(c)-(d), respectively. Fig. 10(a)-  
 461 (b) clearly shows significant reductions in the mean drag coefficients compared to the bare  
 462 cylinder. For the flexible case (Fig. 10(a)), the overall trend of  $\overline{C_d}$  is descending as  $S/D$   
 463 increases with a sudden reduction in one SP case at  $S/D = 1$  and in two SPs at  $S/D = 0.5$  with  
 464  $P/D = 1.5$  and 3. The sudden reduction can be attributed to the base pressure coefficient which  
 465 will be discussed at the end of this section.



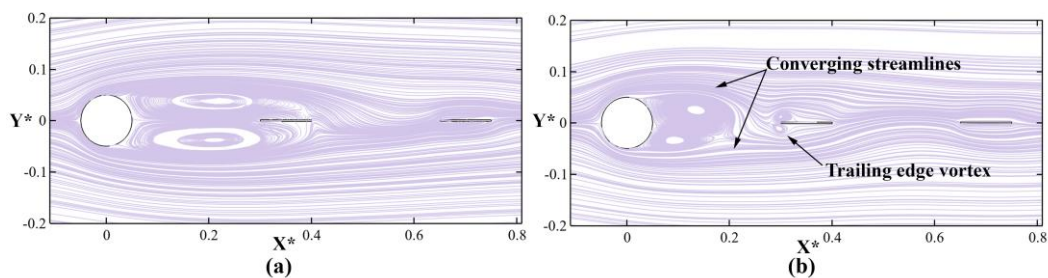
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467 **FIG. 10.** Variation of the time-averaged drag coefficients against  $S/D$  at various  $P/D$ : (a)  $\overline{C_d}$  in flexible SPs, (b)  
 468  $\overline{C_d}$  in rigid SPs, (c)  $\overline{C_{dt}}$  in flexible SPs, (d)  $\overline{C_{dt}}$  in rigid SPs.

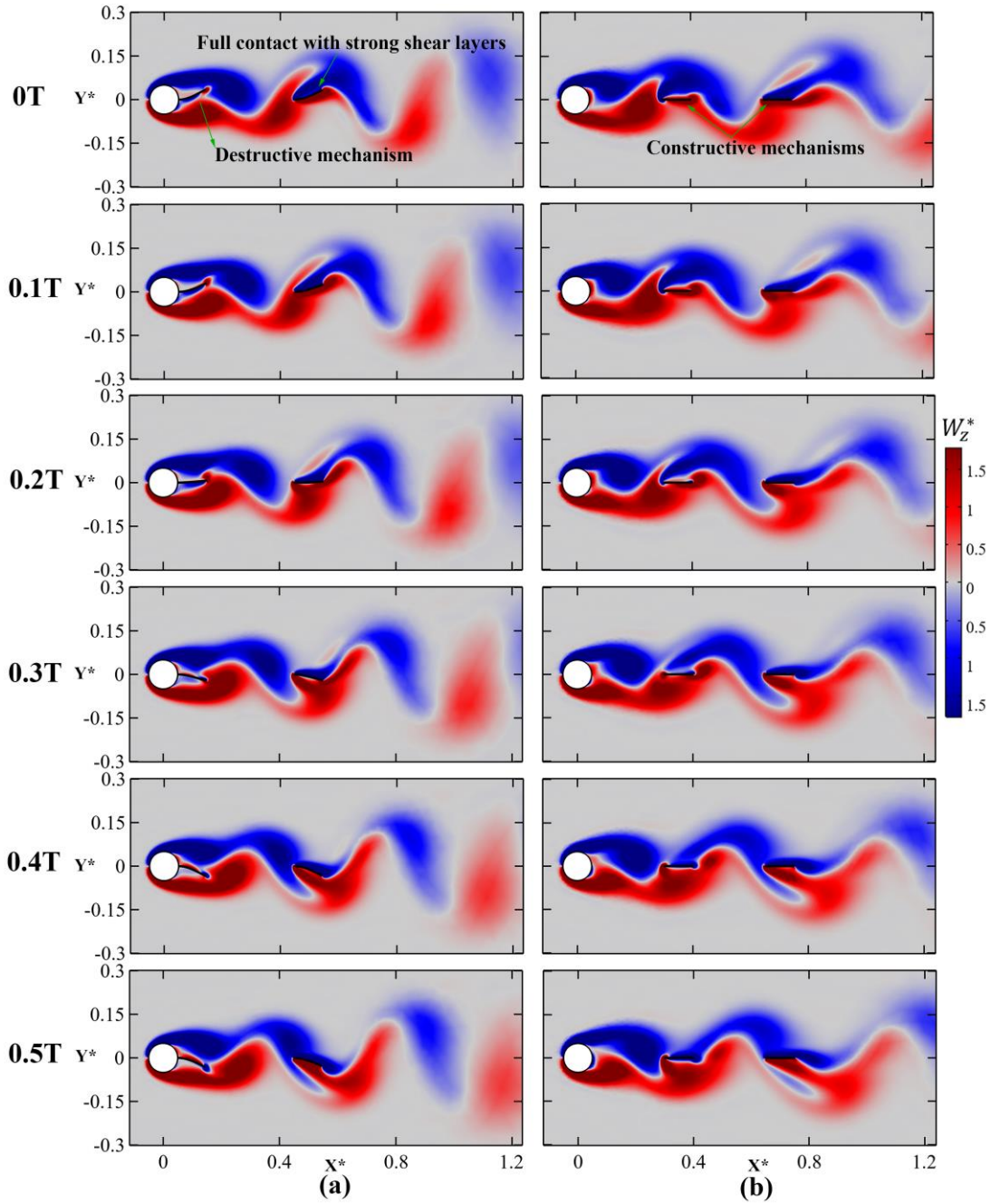
469 For the case of one SP, the rigid SP is more efficient in drag reduction compared to the flexible  
 470 one except for  $S/D = 1$  (Fig. 10 (a)-(b)). That is because in flexible case, two main strong  
 471 vortices turn into four weaker ones and only two small vortices remain to interact with the

472 cylinder (Fig. 7(b)). Moreover, in some configurations of two SPs, the flexible SPs are more  
 473 efficient in the  $\overline{C_d}$  reduction than the rigid one ( $2 \leq P/D \leq 2.5$  and  $S/D \geq 2$  and also  $P/D =$   
 474  $3$  and  $S/D = 0.5$  and  $2.5$ ). To clarify the reason for the higher reduction in the flexible SPs  
 475 cases, the case with  $P/D = S/D = 2.5$  is selected for further discussion in which a sudden  
 476 jump occurs in  $\overline{C_d}$  (Fig.10(b)). Streamlines of this case are shown in Fig.11 for both flexible  
 477 and rigid SPs. The first rigid SP which is close to the cylinder, modifies the wake structure in  
 478 such a way that two small vortices are generated at the trailing edge of the first SP and the  
 479 cylinder vortices cannot significantly grow (Fig.11(b)). However, the cylinder vortices in the  
 480 flexible cases can grow freely because the first SP moves with the cylinder shear layers. The  
 481 wake region in the rigid cases has lower pressure and consequently a higher  $\overline{C_d}$  is observed in  
 482 the Fig. 10. For the rigid cases, the minimum of  $\overline{C_d}$  occurs in the case with two SPs when  
 483  $S/D = 2.5$  and  $P/D = 0.5$  and  $1$ . In these arrangements, 18% reduction is obtained compared  
 484 to the bare cylinder. For the flexible cases, the maximum reduction in  $\overline{C_d}$  is achieved for the  
 485 case of two SPs ( $S/D = 0.5$  and  $P/D = 3$ ) with 17.48% reductions compared to the bare  
 486 cylinder-

487 The main differences between the  $\overline{C_{dt}}$  and  $\overline{C_d}$  graphs originated from the viscous drag of the  
 488 SPs because their pressure drag is not significant. As can be seen in Fig. 10, the trends of  $\overline{C_{dt}}$   
 489 graph is similar to  $\overline{C_d}$  with slightly bigger values which is due to the viscous drag over the SPs.  
 490 In all cases of flexible and rigid SPs, the value of  $\overline{C_{dt}}$  is lower than the bare cylinder except at  
 491  $S/D = 0$  and  $P/D = 3$  in the flexible SPs and  $P/D = S/D = 2.5$  in the rigid SPs. The  
 492 instantaneous dimensionless spanwise vorticity contours ( $W_z^*$ ) for a half cycle of oscillation in  
 493 the two cases with higher  $\overline{C_{dt}}$  are provided in Fig. 12. For the flexible ones, it can be seen that  
 494 the main shear layers are under the destructive mechanism with the tip vortex of the first SP.  
 495 This effect does not let the main vortices of the cylinder to grow significantly and force them  
 496 to separate faster. In the rigid case (Fig12 (b)), this effect is not existed. However, the first SP,  
 497 do not let the main cylinder vortices to grow further.



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 499 **FIG. 11.** Time-averaged streamlines for two SPs case at  $P/D = S/D = 2.5$ : (a) flexible SPs, (b) rigid SPs.  
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**FIG. 12.** Instantaneous dimensionless spanwise vorticity contours ( $W_z^*$ ) for two SPs case (a) flexible SPs at  $S/D = 0$  and  $P/D = 3.5$ , (b) rigid SPs  $P/D = S/D = 2.5$ .

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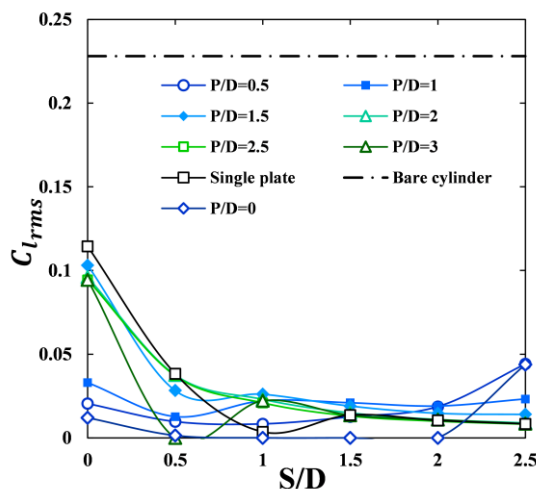
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Fig. 13 presents the variation of RMS of the lift coefficient ( $C_{l_{rms}}$ ) against  $S/D$  for the case of flexible SPs. When flow past over a bluff body, vortices which have a low pressure region on their center are shed alternately relative to the wake centerline [62]. Therefore, there is a low-pressure region on one side of the cylinder (vortices side) and a high-pressure region on the other side. By shedding vortices, fluctuations in the lift force occur. Hence, the reduction of  $C_{l_{rms}}$  is a representative of the wake oscillation. As can be seen, using flexible SPs reduces  $C_{l_{rms}}$  dramatically compared to the bare cylinder. There is a noticeable reduction in all cases for  $S/D \geq 0.5$  which shows detached SPs have a better performance in terms of  $C_{l_{rms}}$  reduction compared to the attached ones. Also, it can be seen that  $C_{l_{rms}}$  is completely suppressed in one SP at  $S/D = 1$  and in two SPs at  $0.5 \leq S/D \leq 2$  and  $P/D = 0$  as well as  $S/D = 0.5$  and

514  $P/D = 3$ . It should be noticed that the variation in  $\overline{C_d}$  and  $C_{l_{rms}}$  is directly related to the time-  
 515 averaged pressure coefficient ( $\overline{C_p}$ ), which will be discussed in the next section.



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FIG. 13. RMS of the lift coefficient ( $C_{l_{rms}}$ ) at different arrangement of the flexible SPs.

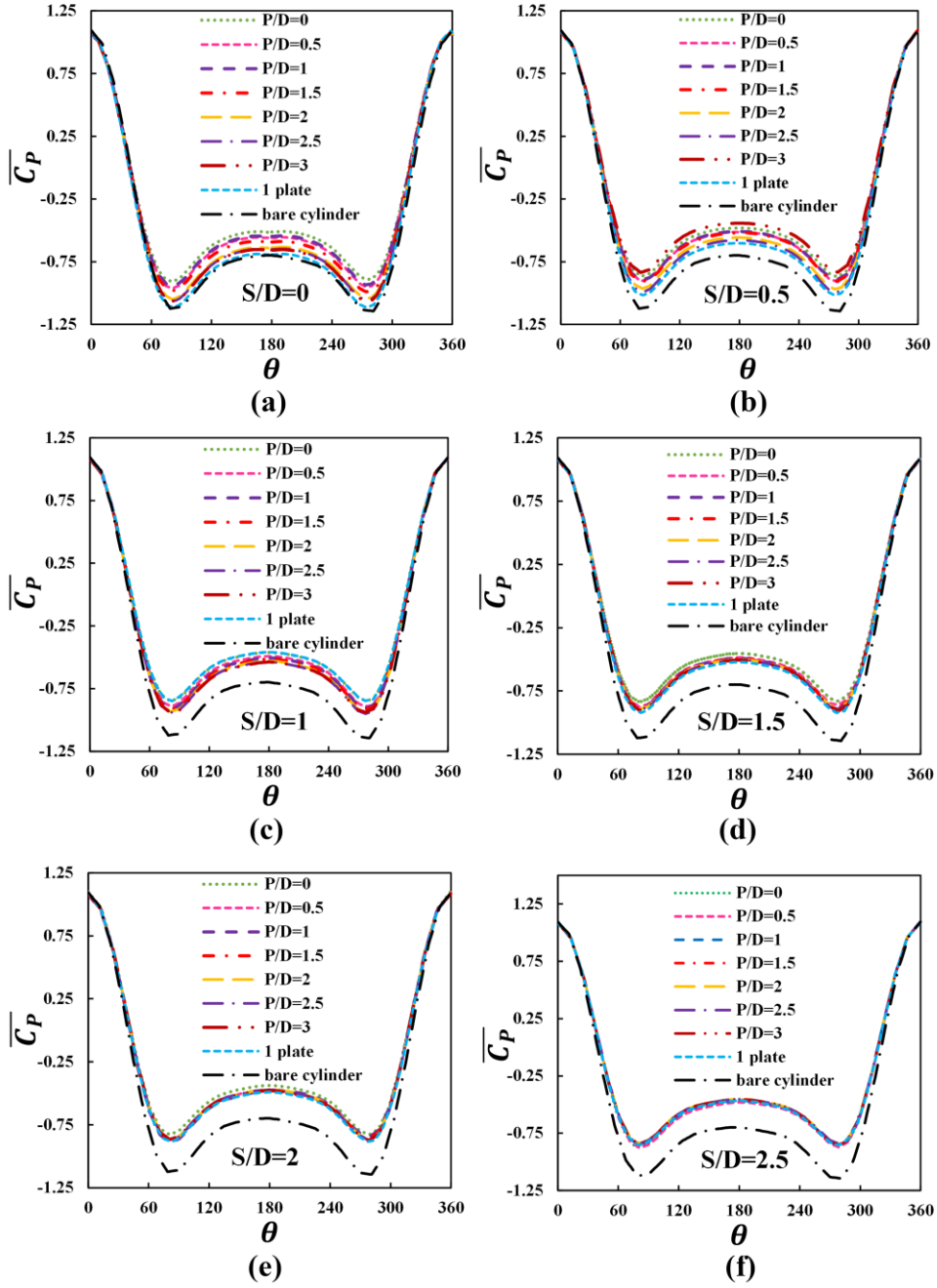
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### 3.4. Pressure coefficient

519 The variation of  $\overline{C_d}$  and  $C_{l_{rms}}$  can be justified by the pressure distribution over the cylinder  
 520 surface. Fig. 14 depicts the symmetric curve of  $\overline{C_p}$  in the case of flexible SPs versus angle ( $\theta$ ).  
 521 The  $\theta$  is the angle between the centerline of the cylinder and an arbitrary point on the surface  
 522 of the cylinder. It is defined from the front stagnation point. The  $\overline{C_p}$  of the bare cylinder is also  
 523 plotted in Fig. 14. The trend of  $\overline{C_p}$  curve is similar for both cases of flexible SPs and the bare  
 524 cylinder. In addition, the  $\overline{C_p}$  curve shares the same profile at all ratios of S/D and P/D.

525 The maximum  $\overline{C_p}$  occurs at  $\theta = 0^\circ$  (or  $360^\circ$ ), where the flow slows down towards the frontal  
 526 stagnation point. By increasing  $\theta$ , the flow accelerates at the upper and lower sides of the  
 527 cylinder, which causes drop in pressure until reach to the minimum at almost  $\theta = 83^\circ$ . where  
 528 the time averaged separation is occurred [63]. After flow separation,  $\overline{C_p}$  increases until it  
 529 reaches the rear stagnation point at  $\theta = 180^\circ$ . Using SPs slightly increases the pressure in the  
 530 rear surface of the cylinder. The reason is that the presence of SPs downstream of the cylinder  
 531 modifies the flow wake and makes appropriate pressure balance on the cylinder surface. So,  
 532 there would be a significant reduction of the pressure component of the drag and lift coefficient,  
 533 which leads to lower values of  $C_{l_{rms}}$  and  $\overline{C_d}$ .



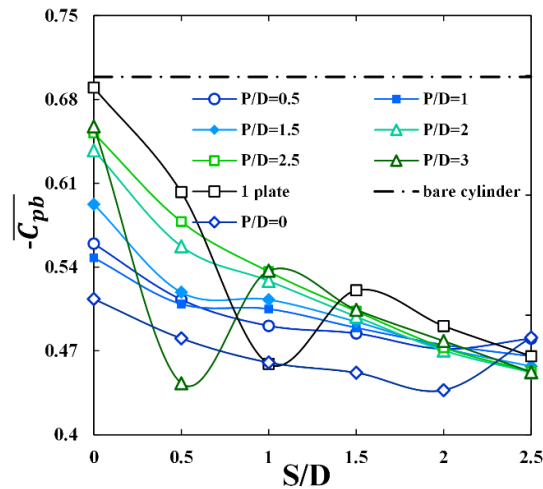


534  
535 **FIG. 14.** The  $\overline{C_p}$  distribution for the case of flexible SPs at various  $S/D$  and  $P/D$ : (a)  $S/D=0$ , (b)  $S/D=0.5$ , (c)  
536  $S/D=1$ , (d)  $S/D=1.5$ , (e)  $S/D=2$ , (f)  $S/D=2.5$ .

537 If the  $\overline{C_p}$  is calculated at  $\theta = 180^\circ$ , the base pressure coefficient would be obtained (equation  
538 (18)). Figure 15 indicates the graph of time-averaged base pressure coefficient, which  
539 multiplied by (-1) for convenience of analysis ( $-\overline{C_{pb}}$ ). The value of  $-\overline{C_{pb}}$  for all arrangements  
540 of SPs is smaller than the value of the bare cylinder. Since the SPs modifies the flow wake and  
541 increase the pressure at the rear stagnation point. Furthermore, it shares almost similar trends  
542 with  $C_{l_{rms}}$  (Fig. 13) and exactly the same trend with  $\overline{C_d}$  (Fig. 10(a)). It proves that the main  
543 reason of the lift and drag fluctuations is pressure variation over the cylinder. The sudden drops  
544 in  $\overline{C_d}$  in Fig. 10(a) can be justified by Fig. 15 where a lower  $-\overline{C_{pb}}$  can be observed in the



545 mentioned points (in one SP case at  $S/D = 1$  and in two SPs at  $S/D = 0.5$  with  $P/D = 1.5$   
 546 and 3).



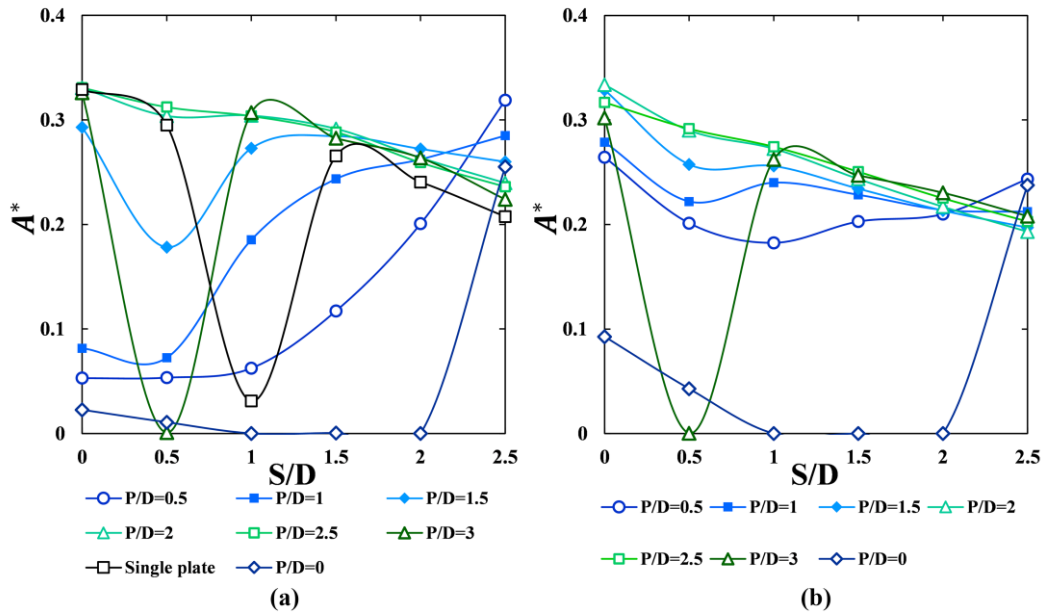
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548 **FIG. 15.** Time-averaged base pressure coefficient ( $-\overline{C_{pb}}$ ) at different arrangement of flexible  
 549 SPs.

### 550 3.5. Amplitude of the SPs' fluctuation

551 The flexible SPs have a periodic deformation due to the continuous local pressure difference  
 552 across them. The maximum deformation is observed at the tip of the SPs. Fig. 16 illustrates the  
 553 dimensionless SPs tip amplitude ( $A^* = A/D$ ) for the first and second flexible SPs. Both  
 554 diagrams share the same trends except for  $0.5 \leq P/D \leq 1$ . That is because increasing the gap  
 555 between the SPs ( $P/D$ ) changes the wake region. In several cases, measurement of the  
 556 normalized tip amplitude indicates a higher amplitude of the two SP cases compared to the one  
 557 SP cases in the corresponding arrangements. Comparison of the total normalized tip amplitude  
 558 shows that the amplitude of the two SPs increases with the ratio of 18.29 compared to the one  
 559 SP at  $S/D = 1$ . The maximum value of  $A^*$  is observed at the second SP with  $S/D = 0$  and  
 560  $P/D = 2$  due to the appropriate arrangement of the SPs for contacting with shear layers. The  
 561 same  $A^*$  in one SP cases is obtained when the SP is attached to the cylinder ( $S/D = 0$ ).  
 562 Moreover, the amplitude of the two SPs cases at  $1 \leq S/D \leq 2$  and  $P/D = 0$  and at  $S/D = 0.5$   
 563 and  $P/D = 3$  are zero, which is inconsistent with  $C_{l,rms}$  results in Fig. 13. This is related to  
 564 wake stabilization effect of the SPs which causes vortices became symmetric with respect to  
 565 the wake centerline. As a result, the SPs are not subject to any resultant force in the  
 566 perpendicular direction to main flow stream. It should be noted that for a case of one SP, the  
 567 trends of the  $St$  graph (Fig. 6(a)) and  $A^*$  graph (Fig. 16(a)) are the same. It can be concluded  
 568 that higher displacement of the SPs tip leads to increase of the wake instability and results in a  
 569 higher Strouhal number. However, for the case of two SPs, the behavior of  $St$  and SPs  
 570 amplitudes are different because of the complicated mechanism of VS and the negligible effect  
 571 of the SPs on cylinder oscillation at further distances.

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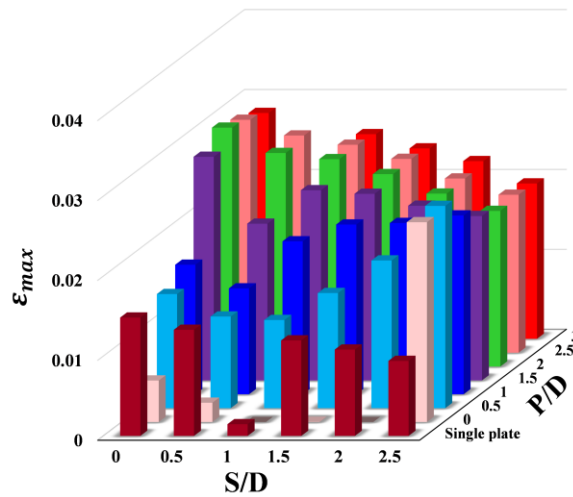
574 **FIG. 16.** The non-dimensional tip amplitude ( $A^*$ ) against  $S/D$  at various  $P/D$  for the case of flexible SPs: (a)  
 575 first SP, (b) second SP.

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### 577 3.6. Strain

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579 The strain is an essential parameter for generating electricity from a piezoelectric polymer.  
 580 Hence, to harvest more electricity from the flow, the strain ( $\epsilon$ ) of the SPs should be investigated  
 581 in detail. In our study, the VS induces strain in the SPs. The maximum strain of flexible SPs  
 582 ( $\epsilon_{max}$ ) at various arrangements of SPs is shown in Fig. 17. The corresponding results of one  
 583 SP case are added to the figure. For the cases of two SPs, the presented strain is the sum of the  
 584 first SP strain and the second SP strain. By performing a parametric study based on gap-ratios  
 585 ( $S/D$  and  $P/D$ ), the effect of SPs arrangement on strain can be analyzed. As can be seen, in  
 586 the one SP case, the highest strain occurs at  $S/D = 0$ . The strain in the case of two SPs is larger  
 587 than the one SP in several arrangements of SPs. Hence, adding the second SP has a significant  
 588 effect on increasing the strain and higher energy can be harvested from the flow in the case of  
 589 two SPs compared to one SP. The highest value of  $\epsilon_{max}$  in two SPs case occurs at  $1.5 \leq P/D \leq$   
 590  $3$  and  $S/D = 0$  which is the best arrangement for locating a piezoelectric polymer. In this  
 591 range,  $P/D = 1.5$  is recommended due to less value of the  $\overline{C_d}$ .



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FIG. 17. Variation of maximum strain ( $\epsilon_{max}$ ) of the flexible SPs against  $S/D$  and  $P/D$ .

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#### 4. Summary and conclusion

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In this study, fluid flow over a stationary cylinder at  $Re = 100$  is investigated in the presence of rigid and flexible SPs. The novelty of this work is the use of one and two detached SPs downstream of a cylinder, in which the non-dimensional gap distance between the first SP and cylinder as well as the distance between the SPs are varied. The results of this study can be used energy harvesting by the piezoelectric polymer. A comprehensive parametric study is performed to consider the effect of SPs-cylinder distance as well as the SPs' distance to find the optimal design for energy harvesting. To the best of authors' knowledge, there is no inclusive study in literature that aims at minimizing the unwanted wake effects, while maximizing the harvested energy simultaneously. To make such an assessment, the drag and pressure coefficients as well as the Strouhal number are evaluated. The tip amplitude and strain of the flexible SP are calculated and the optimal arrangement of SPs for installing a piezoelectric polymer are obtained ( $S/D = 0$  and  $P/D = 1.5$ ). It is found that the maximum decrease in the  $St$  occurs at  $S/D = 1.5$  and  $P/D = 0$  for both cases of rigid and flexible SPs. The arrangement of SPs results in a reduction of 97.8% and 76.35% for rigid and flexible cases compared to the bare cylinder, respectively. The results also reveal that the rigid and flexible SPs can successfully suppress the VS. However, the performance of rigid SPs is more effective than the flexible SPs for eliminating the VS. Results indicate that the  $St$ ,  $\overline{C_d}$ ,  $\overline{C_p}$  can be controlled significantly by using detached SPs in certain arrangements. In addition, changing the location of the SPs varies the strain in the SPs and can lead to different amounts of electricity generation with piezoelectric polymer. With regards to the current worldwide energy demands, and transition into clean energy, the use of such flexible SPs provides considerable benefits over the typical cylindrical structure for energy harvesting. An efficient design of a cylindrical structure for energy harvesting with significant applications in industry can be a potential topic of future research in this area.

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## 625 **Conflict of interest**

626 The authors declare that they have no conflict of interest.

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## 632 **Data availability**

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

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