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The effect of spoilers on flow around tandem circular cylinders

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ABSTRACT

Examining the flow characteristics around the cylindrical elements, such as offshore (submarine) pipelines which can be used in single or multiple arrangements, has a prominent place in fluid mechanics. The use of spoilers for self-embedding of these structures has been a subject that researchers have studied for many years. In this study, (a) the flow around a cylinder without and with a spoiler and (b) the effect of adding spoiler(s) to the tandem cylinders on the flow was experimentally investigated. In these experiments, where the ratio of the distance between the cylinders to the cylinder diameter is 2, the Reynolds number is 14000, which remains in the subcritical region. Four experiments were performed: the smoke-wire method was used for flow visualization, aerodynamic force measurement, velocity measurement by hot-wire anemometer, and pressure measurement to determine the pressure distribution on the cylinders. Pressure, velocity, and force results were recorded with the time histories in this study for the first time. Experimental studies show that when a spoiler is added to a single cylinder, an opposing lift force acts on that and the drag force increases due to the enlargement of the low-pressure region at the wake of the cylinder. In a tandem situation, when the upstream cylinder has a spoiler, no drag force acts on the downstream cylinder. The forces exerted on the upstream cylinder are not affected by whether the downstream cylinder has a spoiler. In the case of the downstream cylinder with the spoiler, the fluctuations in the aerodynamic forces of the upstream cylinder decrease owing to the downstream cylinder with the spoiler. The force fluctuations are more in the downstream cylinder, and unlike other tandem and single-cylinder cases, the vortex shedding becomes complex.

1. Introduction

Cylindrical elements have long been the focus of experimental and numerical investigation due to their extensive use in engineering applications. Subsea pipelines, bridge piers, factory chimneys, suspension bridges, heat exchangers, cooling towers, and oil exploration stations are engineering applications where the flow around the cylinder is crucial. Multi-cylindrical structures, have been widely adopted in offshore (submarine) engineering structures, in which cylinders are used in a row. In the literature, there are many experimental and numerical studies on the single cylinder (Bearman and Zdravkovich, 1978; Bloor, 1964; Kirkgoz et al., 2009; Nishimura and Taniike, 2001; Taneda, 1965; Wang et al., 2020; Zdravkovich, 1980). In these studies, they used various Reynolds numbers which are defined as:

$$\mathrm{Re} = \frac{u_\infty D}{\nu} \tag{1.1}$$

where u_∞ is the free stream velocity, D is the cylinder diameter and ν is the kinematic viscosity.

Taneda (1965) experimentally studied the vortex shedding behind the circular cylinder in a water tank at the Reynolds number of $Re = 170$ to investigate the wall proximity. The vortex shedding was observed for different gap ratios (G/D) which is the ratio of the gap between the cylinder and wall to the cylinder diameter, and it was found that walls increased the stability of the wake. In this study, the forces acting on the cylinder or the pressure area around the cylinder were not considered. Bearman and Zdravkovich (1978) experimentally investigated the flow around the cylinder on a flat plate in a wind tunnel for $Re = 25000$ and 45000. According to the pressure measurement results obtained in the experiments where they studied the wall proximity, they reported that the stagnation points at the cylinder upstream shifted towards the wall at small gap ratios. This was due to a lift force tending to move the cylinder away from the wall. However, they did not use any flow

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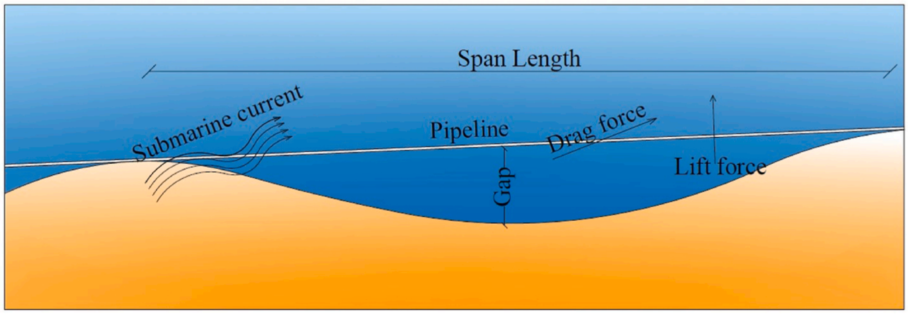


Fig. 1. Suspension of submarine pipelines.

visualization or force measurement method in their study. Nishimura and Taniike (2001) experimentally investigated the instantaneous pressure distributions around a circular cylinder for $Re = 61000$ in a wind tunnel. In this study, only pressure and force measurements were made. As a result of their measurements, they found that the Strouhal number (St = f D/u_∞ where *f* is the vortex shedding frequency, u_∞ is the free-stream velocity, and D is the cylinder diameter) obtained from the oscillation period of the drag force, lift force, stagnation point angle, and separation angle is $St = 0.202$. Kırkgoz et al. (2009) modeled the flow around the circular cylinder using the Ansys-FLOTRAN software in their study investigating the wall proximity at $Re = 9500$. Their study using three different turbulence models stated that the k-ω and SST k-ω models successfully estimated the velocity field for the flow around the cylinder.

To prevent the pipelines from environmental effects they are buried in the seabed by excavation. On the other hand, a self-embedding mechanism is desired to eliminate these excavation costs. In studies performed by placing a spoiler on the cylinder, it has been observed that the spoiler has an accelerating effect on the rate of self-embedding (Öner, 2008; Hulsbergen, 1986; Hulsbergen and Bijker, 1989; Zhu et al., 2013). The placement of the spoiler on the cylinders has been the subject of research, especially in the application of subsea pipelines (Bijker, 2000; Cheng and Chew, 2003).

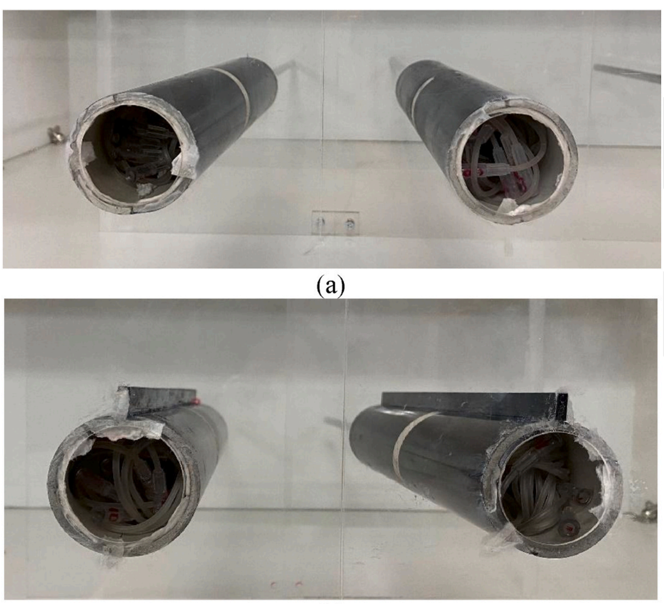
Local scouring may occur around the pipeline on the seabed or river bottom. As a result of such scouring, the suspension of the transmission line may cause damage to the pipeline. Hulsbergen and Bijker (1989) conducted experimental and numerical studies for a pipeline with a 0.25*D* height spoiler on a movable bed. As a result of their studies, they found that the spoiler caused significant changes in local flow characteristics, sediment transport, and pressure distribution. In addition, they reported that the spoiler accelerated the self-embedding process by 10 times compared to a cylinder without a spoiler. The spoiler increased the drag force while reducing the negative lift force. Bijker (2000) reported that the changes in the flow and pressure field surrounding the pipeline caused by the attachment of a spoiler accelerate the burial of the suspended pipeline. Cheng and Chew (2003) numerically investigated the flow around a circular cylinder with and without a spoiler for $Re = 1000$ and 2000. Their study reported that adding the spoiler increased the flow rate between the wall and the cylinder and the wall shear stresses. They concluded that when the spoiler was used the drag coefficient increased. While the pressure increased in the cylinder upstream, decreased downstream, and scour in the wake region increased due to increased vortex shedding. Öner (2008) examined the effect of the spoiler on the flow at G/D = 0.2 gap ratio in this numerical study on $Re = 840$ and 4150. In this study with a spoiler height of 0.2*D*, it was shown that the spoiler directed the flow to the sea bottom. In the study, they determined that while the pressure density increased in the upstream part of the cylinder, it decreased due to the change in the drag coefficient in the downstream part. Zhu et al. (2013) investigated the effects of utilizing the spoiler, the spoiler height, and the gap ratio on the scour and flow characteristics. They found that using the spoiler created a negative pressure area in the cylinder downstream and this negative pressure value increased as the spoiler height increased. In their examination, they found that an increase in spoiler height caused an increase in the absolute drag and lift coefficients.

The number of numerical and experimental studies on using cylinders in tandem has increased in recent years (Hu et al., 2019; Schewe et al., 2021; Zhao et al., 2015). Kitagawa and Ohta (2008) numerically investigated the flow around two circular cylinders, far from wall effects. They found that the critical center-to-center pitch ratio is 3.25. For the pitch ratios lower than this critical value, vortices were shed only from the downstream cylinder. Sainte-Rose et al. (2014) investigated flow around tandem cylinders in highly turbulent conditions. In their study, which compared the classic Large Eddy Simulation (LES) and Large Eddy Simulation Variational Multi-Scale (VMS) simulation, they found that using the VMS formulation significantly improves the results compared to classic LES. Deng et al. (2020) experimentally investigated the drag forces on a rigid segment of a twin-tube submerged floating tunnel under various Re numbers and submergence ratios. They evaluated in their study the effects of the spacing distance between two cylinders and vortex-induced vibration (VIV) on the drag forces. They found that the VIV response amplitude and mean drag coefficient decrease with the decreasing submerge depth, especially when the depth ratio is below 3.7. Zhao et al. (2015) experimentally investigated the effect of the gap between the circular cylinders located next to each other. They found that the pitch ratio of $L/D = 1.5$, the ratio of the distance between cylinders to the cylinder diameter, was the critical limit for the vortex shedding from the downstream cylinder. Hu et al. (2019) considered the effect of the pitch ratio and the flow velocity on the scour. In their studies conducted in the range of $L/D = 1$–3, the upstream cylinder had more scour than the downstream cylinder in situations where $L/D \leq 2$. However, in the case of $L/D > 2$, they concluded that the scour under the upstream cylinder was smaller than the downstream cylinder. Schewe et al. (2021) investigated the flow around two adjacent cylinders at two different pitch ratios, $L/D = 2.8$ and 4, for high Reynolds numbers such as $Re = 1 \times 10^6$ and 1×10^7. In their study, they stated that the drag coefficient in the downstream cylinder gave comparable results concerning a single cylinder at both pitch ratios.

In all the studies on tandem cylinders in the literature, there is no spoiler on the cylinders. There is no study in which spoiler configurations on tandem cylinders are investigated.

All these studies have concentrated on the scenario in which the cylinder is laid at the bottom while undervaluing the scenario in which it is distant from the bottom. However, due to the level changes on the seafloor, the pipeline does not always lie on the bottom, as seen in Fig. 1. In places where these pipes with the spoiler have a free span, the hydrodynamic forces they are exposed to may be much higher because of its unfavorable aerodynamic shape and larger exposure area. This may cause unexpected damages (i.e. rupture, dislodgement); hence, this situation needs to be explicitly investigated. As a result, the case when the cylinder is far enough from the bottom so as not to be affected by the ground effect was examined experimentally in this study using different

Fig. 2. Wind tunnel.



(a)

(b)

Fig. 3. Cylinders (a) without (b) with spoiler used in the experiments.

methods.

The present study aims to experimentally investigate the flow characteristics around a single and tandem cylinder with and without a spoiler and to examine the effect of different spoiler configurations on the flow in tandem cylinders. Tandem cylinders with spoilers, which have never been studied in the literature, are presented in detail. Pressure, velocity, and forces were recorded with time histories for the first time in this study, and force fluctuations were considered. To see the different effects of the spoiler on different cylinders, the spoiler configuration has also been changed in tandem cylinders. In order to compare the results with those of a single cylinder, the pitch ratio has been used in the current investigation as L/D = 2, as it is known that two cylinders arranged in a tandem configuration react similarly to a single body at small pitch ratios (Xu and Zhou, 2004).

2. Experimental method

2.1. Wind tunnel and test cylinders

The experiments in this study were conducted in a suction-type wind tunnel at Erciyes University Wind Engineering and Aerodynamics Research Laboratory given in Fig. 2, which test section has a length of 2000 mm and a 500 mm × 500 mm cross-section. The wind tunnel operating speed limits are a maximum of 40 m/s, and a minimum of 3 m/s, and the turbulence intensity of the flow in the test section is below 1% (Genç et al., 2008, 2012, 2016a, 2016b, 2020; Açıkel and Genç 2016; Demir and Genç 2017; Koca et al. 2021, 2022a, 2022b, 2022c). For the velocity of 5 m/s used in this study, the Reynolds number for which the cylinder diameter is used as the characteristic length is $Re_D = 14000$.

The cylinders without and with spoilers used in this study are given in Fig. 3 (a) and Fig. 3. (b) respectively. All the cylinder diameters are $D = 50$ mm, and the height and thickness of the spoiler are $0.2D$ and $0.1D$ respectively. The cases tested in this study, created with different spoiler combinations, are given in Table 1. To prevent tip vortices formation, endplates made of plexiglass are attached to both ends of the cylinders as seen in Fig. 4.

Experimental setups can be affected by equipment characteristics such as probe placement, device accuracy, repeatability, ambient density, air temperature, and so on. Therefore, the uncertainty analysis for

Table 1
Experimentally tested cases.

Cylinder without the spoiler (N)	V=5m/s
Cylinder with the spoiler (S)	V=5m/s
Two cylinders with the spoiler (SS)	V =5m/s 2D
Two cylinders without the spoiler (NN)	V =5m/s 2D
The upstream cylinder with the spoiler and the downstream cylinder without the spoiler (SN)	V =5m/s 2D
The upstream cylinder without the spoiler and downstream cylinder with the spoiler (NS)	V =5m/s 2D

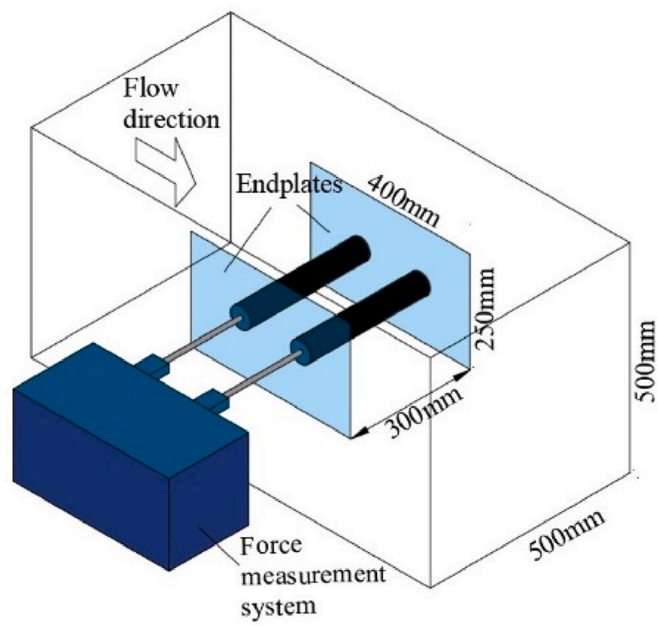


Fig. 4. Schematic view of experimental setup.

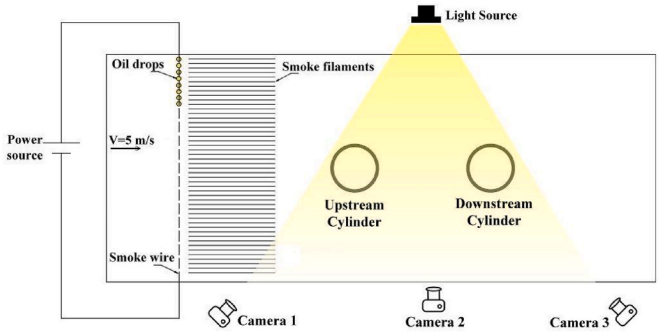


Fig. 5. Smoke wire experiment.

5 m/s velocities was conducted for the pressure coefficient (C_P), lift coefficient (C_L), and drag coefficient (C_D), and their values are found 6.9%, 8.7%, and 7.2% respectively. The blockage ratio of a cylinder without a spoiler is $(0.05 \times 0.3)/(0.5 \times 0.5) = 0.06$ (6%). The blockage ratio of the cylinder with the spoiler is $(0.06 \times 0.3)/(0.5 \times 0.5) = 0.072$ (7.2%). The blockage corrections are not made on the experimental results, because the blockage effects on the experimental results are negligible when the blockage ratio is less than 10% (Schreck et al., 2007).

2.2. Flow visualization by smoke-wire experiment

The smoke-wire experiment, one of the flow visualization methods, was used in this study due to its practical application in wind tunnels. In these experiments, a copper resistance wire with a thickness of 0.3 mm was placed in the upstream region, and an electrical current of 90 V was applied to the wire. The smoke filaments, formed by the combustion of paraffin-based oil dripped on the wire, were recorded by three video cameras placed from different perspectives (Fig. 5). Videos recorded at a 60-fps capture rate were examined in detail. The frame that best represented the flow was selected (Fig. 6).

2.3. Velocity measurement by hotwire anemometer

A hot-wire anemometer was utilized with a traverse system to obtain the velocity changes caused by the effect of the spoiler on the flow around the cylinder. Two uniaxial velocity probes are placed at 0.5*D* downstream of the cylinders in the flow direction. In the vertical axis, measurements were collected through a line at the range of 1 mm, starting from 1*D* above the cylinders and up to 1*D* below (Fig. 7). As seen in Fig. 7, the velocity data at the wake of the cylinders were collected simultaneously. Each location was measured for 5 s at a frequency of 1000 Hz, yielding 5000 velocity data.

The hot-wire test, one of the most detailed and precise methods for velocity measurements, is also a unique method for obtaining vortex-shedding frequencies. The spectral analysis of the velocity data was performed by the Fast Fourier Transform (FFT) algorithm and the vortex shedding frequency was obtained from this analysis results.

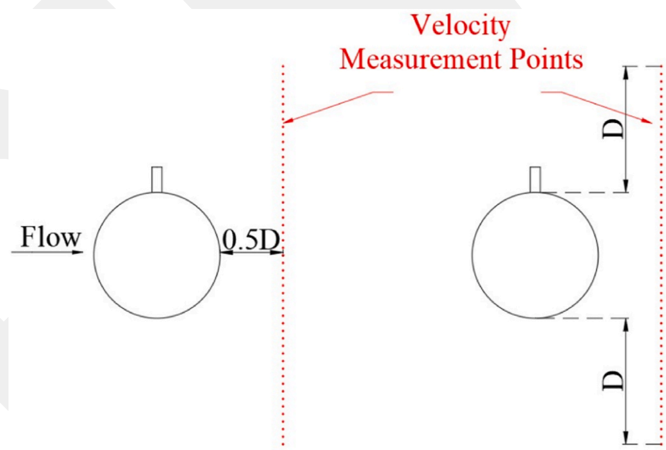


Fig. 7. Velocity measurement points.

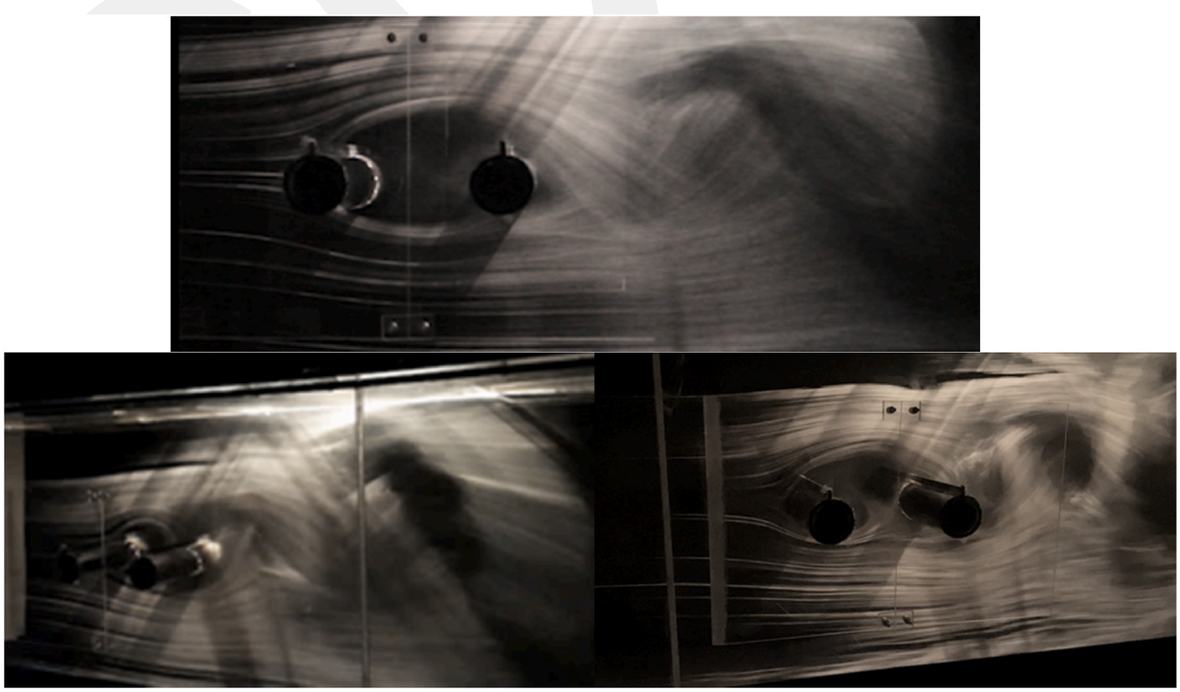


Fig. 6. Photos taken from three different perspectives.

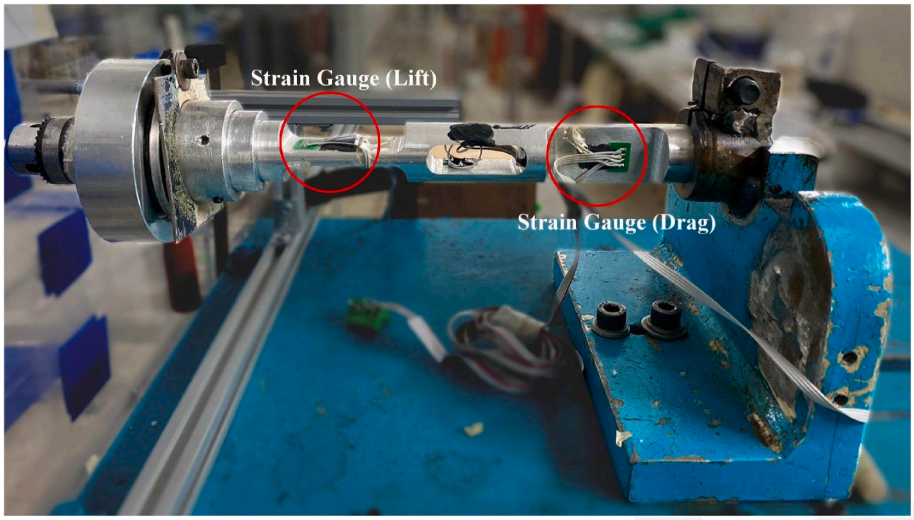


Fig. 8. Force measurement system.

Fig. 9. Pressure measurement test setup.

2.4. Aerodynamic force measurement

Force measurements were taken separately for both cylinders using a three-component force balance system that could measure lift, drag, and moment forces (Fig. 8). By measuring aerodynamic forces for 60 s at a frequency of 1000 Hz, 60000 force data were collected from each cylinder. By taking the average of these data, mean lift and drag forces were determined and these were converted into dimensionless aerodynamic coefficients by using the following equations:

$$C_L = \frac{F_L}{\frac{1}{2}\rho U_\infty{}^2 A} \tag{2.1}$$

$$C_D = \frac{F_D}{\frac{1}{2}\rho U_\infty{}^2 A} \tag{2.2}$$

where ρ is the air density, U_∞ is the free stream velocity, A is the relevant surface area and F_L and F_D are the lift and drag forces respectively.

2.5. Pressure measurement

The pressure measurement test was carried out by the pressure taps placed on the cylinder to determine the pressure distribution around the cylinder. There are 12 measuring points on a cylinder yielding a total of 24 points in a tandem arrangement. In the pressure measurement system given in Fig. 9, 24 pressure gauges were used together with a pitot-static tube. Pressure measurements were conducted from these points simultaneously. This way, the pressure effects that would occur when the cylinders were in tandem were obtained for both cylinders simultaneously. The data were collected at a frequency of 1000 Hz, and the measurement was carried out for 150 s to reflect the average correctly. Thereby, 150000 pressure data were recorded for each point in each test

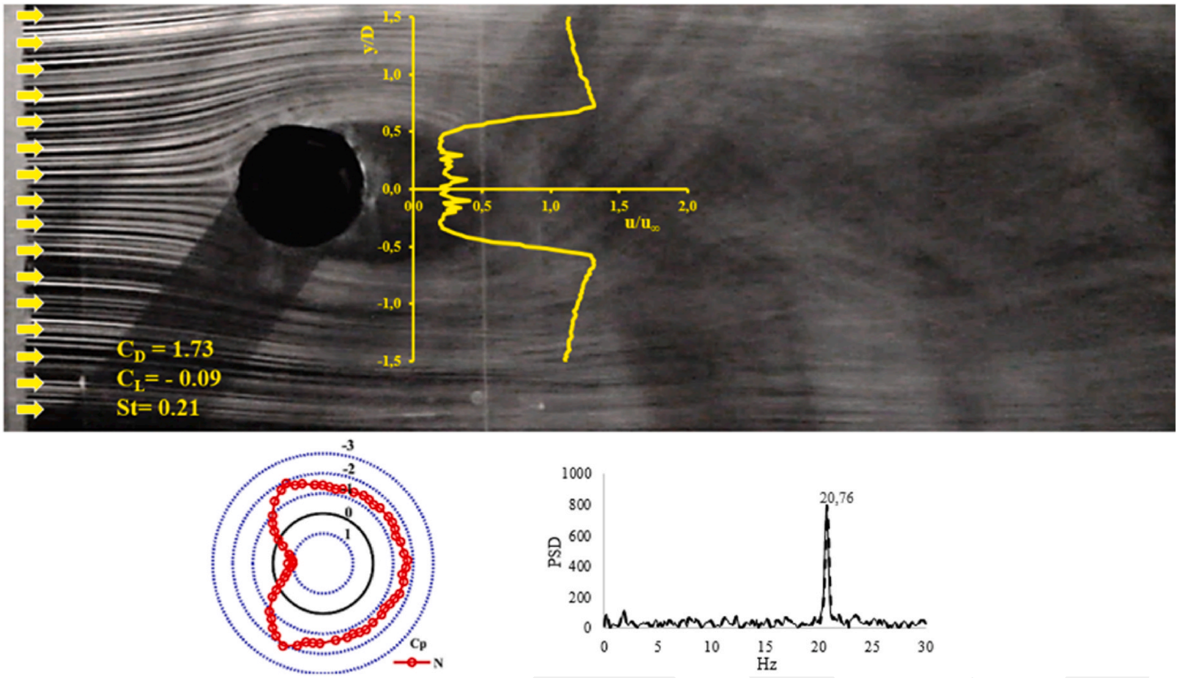


Fig. 10. Experimental findings for single cylinder without the spoiler (N).

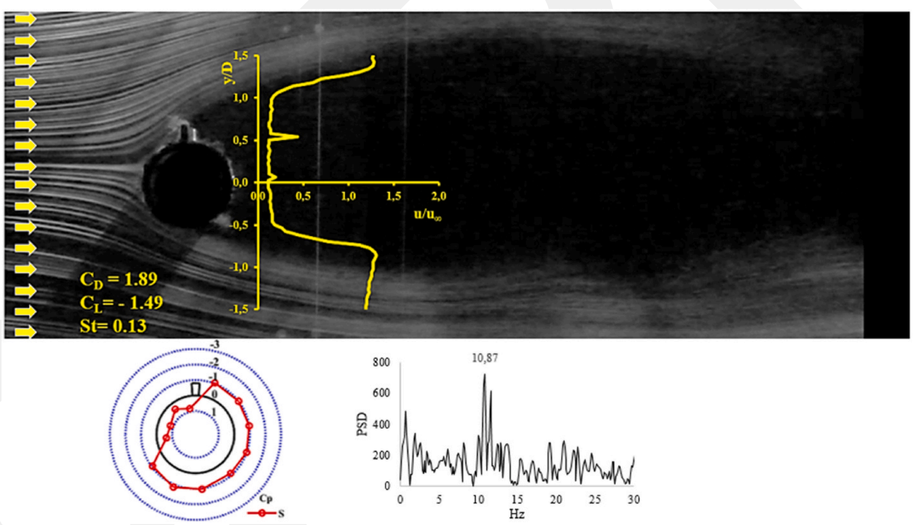


Fig. 11. Experimental findings for the single cylinder with the spoiler (S).

case. By taking the average of these values obtained, the dimensionless pressure coefficient was calculated by using the following equation:

$$C_P = \frac{P - P_\infty}{\frac{1}{2}\rho U_\infty^2} \tag{2.3}$$

where ρ is the air density, U_∞ is the free stream velocity, and P and P_∞ are static pressures on the cylinder, and free stream static pressure respectively.

3. Results

The velocity data obtained with the hotwire system were rendered dimensionless by dividing them by free-stream velocity (u/u_∞) and the velocity distribution graph was created. The frequency values calculated via FFT analysis using the hot wire data, which were taken separately for the upstream and downstream cylinders, were converted into the dimensionless Strouhal numbers.

Thus, the shedding frequencies of the Von Karman vortices and the variation of the Strouhal number due to these frequencies could be analyzed.

The mean pressure values obtained from the pressure measurement experiments were rendered into dimensionless pressure coefficients using equation (2.3) and plotted in polar coordinates. The resulting force values were transformed into dimensionless drag and lift coefficients using equations (2.2) and (2.1). All these experimental data and phenomena related to flow physics were visualized by the smoke wire test result photographs together.

3.1. *Experimental findings for single cylinder*

Examining the smoke wire experiment frames and the pressure graphs reveals that adding a spoiler to the cylinder increases the size of

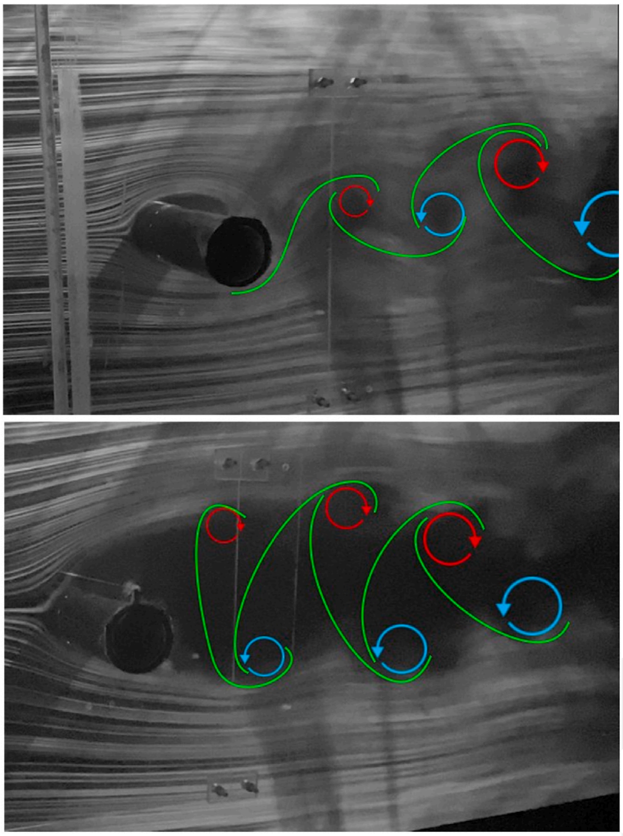


Fig. 12. Vortex shedding patterns behind a cylinder without the spoiler (a) and with the spoiler (b).

the cylinder wake zone and the low-pressure area. The data obtained from the experiments carried out for a single cylinder without the spoiler (N) are given in Fig. 10, and for a single cylinder with the spoiler (S) are given in Fig. 11. Since the low-pressure area increased, the drag force on the cylinder with the spoiler ($C_D = 1.89$) is 17% greater than the cylinder without the spoiler ($C_D = 1.73$) which is consistent with the literature (Bianchi et al., 2020; Damroudi et al., 2020, oner, 2016; Zhao and Wang, 2008). Shear layers (green lines in Fig. 12) vortices formed in clockwise (red arrows in Fig. 12) and counterclockwise (blue arrows in Fig. 12) directions by shedding from the top and bottom of the cylinder without the spoiler to meet each other at the wake zone (Fig. 12a). On the contrary, the vortex formations cannot meet each other for the cylinder with the spoiler due to the low-pressure region having a wide area both horizontally and vertically. As a result, this leads to an increase in drag force (Fig. 12b).

While the cylinder does not have a spoiler, the lift coefficient is relatively insignificant as $C_L = -0.09$ but rises to $C_L = -1.49$ when the spoiler is attached. The addition of the spoiler causes the vortices to enlarge top-downstream of the cylinder (Fig. 12b), creating a low differential pressure. This issue can also be seen from the pressure coefficient graph in Fig. 11. At the bottom of the cylinder with the spoiler, the pressure difference increases due to the velocity, causing a negative lift force on the cylinder. In the case of a cylinder with the spoiler, the low-velocity zone measured by the hotwire system at the wake region is broader than that of the cylinder without the spoiler (Fig. 12). Since the separated flow area is narrower in the case of the cylinder without the spoiler, it can be said that the inertial forces are higher, and these forces suppress the flow.

The Strouhal number obtained from the spectral analysis of the velocity for the cylinder without the spoiler (N) was determined as $St = 0.21$ and it was found to be compatible with the literature. In the single cylinder with the spoiler (S), the Strouhal number was calculated as 0.13, indicating that adding a spoiler reduces the vortex shedding frequency, which means bigger vortices at the wake (Fig. 12).

3.2. Experimental findings for tandem cylinders

In the tandem cases, the pitch ratio between the cylinders is determined as $L/D = 2$. The results obtained for two cylinders without the spoiler (NN) and two cylinders with the spoiler (SS) placed in the tandem case are given in Fig. 13 and Fig. 14, respectively. To see the effects of the spoiler on both cylinders separately, experiments were conducted by placing the spoiler on the upstream and downstream cylinders one by one. *There is no case in the literature where neither two cylinders with*

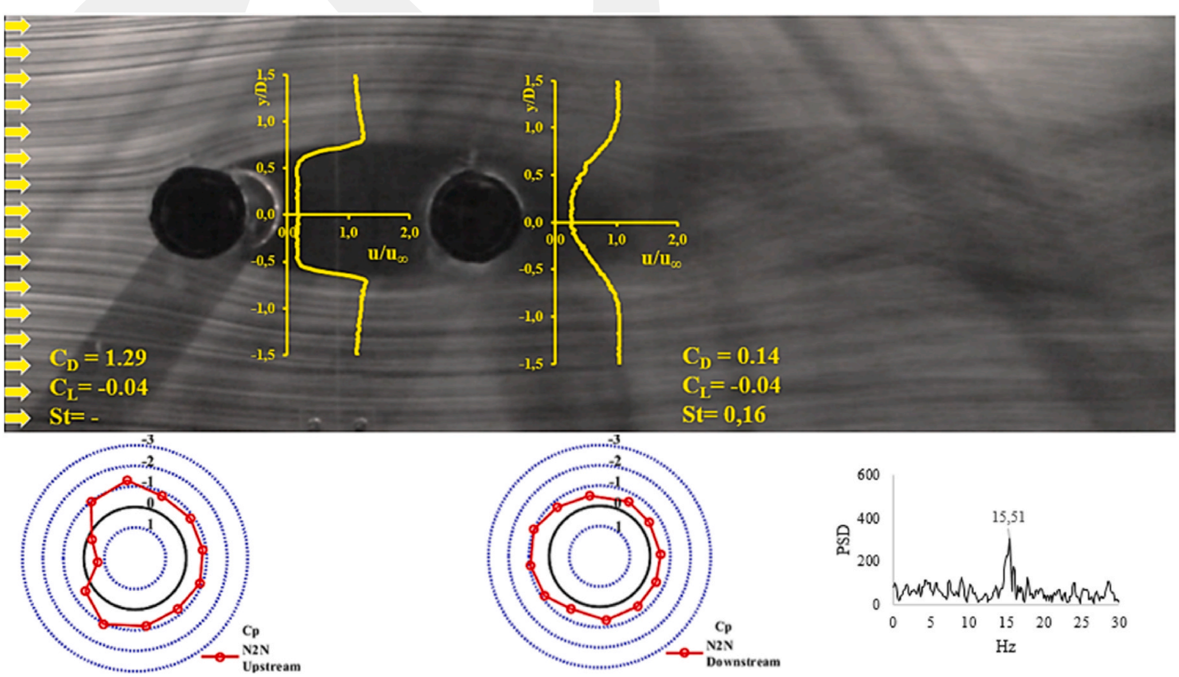


Fig. 13. Experimental results for two cylinders without the spoiler (NN) arranged in tandem.

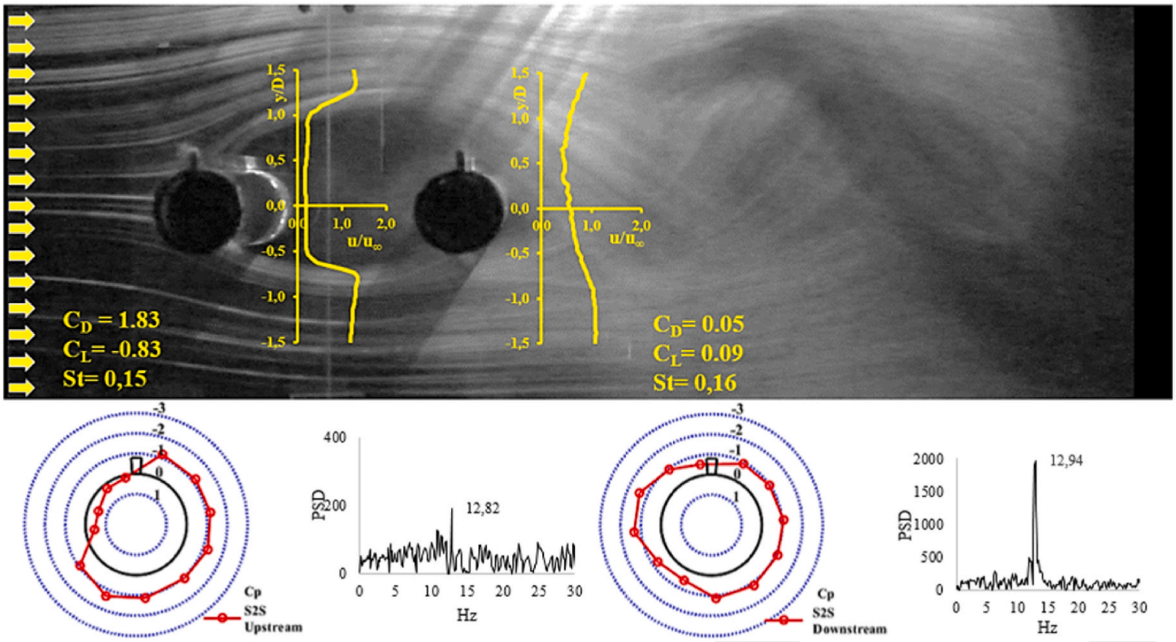


Fig. 14. Experimental results for two cylinders with the spoiler (SS) arranged in tandem.

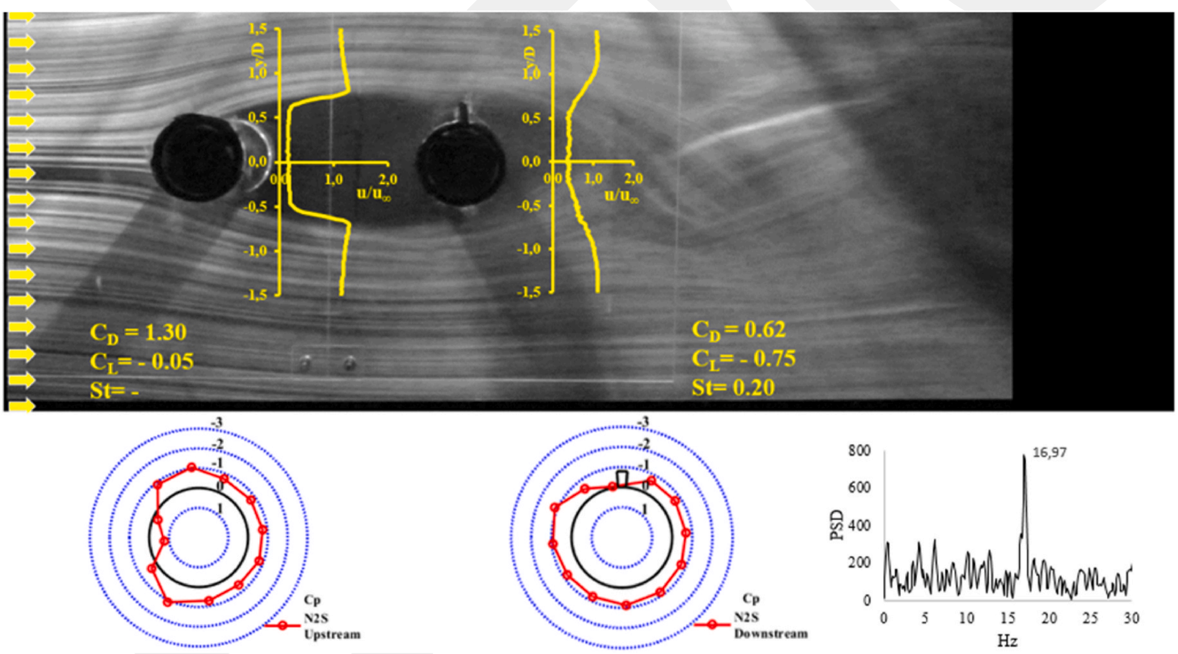


Fig. 15. Experimental results for upstream cylinder without the spoiler and downstream cylinder with the spoiler (NS).

spoilers are used together, nor a combination of cylinders with and without the spoiler. The results for NS-case, where the upstream cylinder is without the spoiler and the downstream cylinder is with the spoiler, are given in Fig. 15, and the data obtained for the case SN where the upstream cylinder is with the spoiler and the downstream cylinder is without the spoiler are given in Fig. 16.

When the NN and NS cases given in Figs. 13 and 15 are examined together, it is seen that the vortex shedding from the upstream cylinder interacts with the downstream cylinder's spoiler, causing the flow to disperse, eddies to shrink, and thus the vortices to accelerate (Fig. 17). As a result, the Strouhal number increased from 0.16 to 0.20 with vortex shedding frequency. Furthermore, the wake region of the downstream cylinder enlarged due to this fragmentation and the drag coefficient increased ($C_D = 0.62$). In the case of the upstream cylinder without the spoiler and downstream cylinder with the spoiler (NS), the eddies dominated the downstream cylinder, resulting in a negative lift coefficient ($C_L = -0.75$). In NN and NS cases where the upstream cylinder is without the spoiler, the drag and lift coefficients obtained in the upstream cylinders have remarkably close values ($C_D = 1.29$ and 1.30, $C_L = -0.04$ and -0.05 respectively). The same thing is observed in SS and SN cases where the upstream cylinder with the spoiler ($C_D = 1.83$ and 1.87, $C_L = -0.83$ and -0.85 respectively). Therefore, it can be said that in the case of $L/D = 2$, the upstream cylinder is not affected by another cylinder placed downstream.

In cases where the upstream cylinder is without the spoiler (NN and NS), a periodic vortex shedding does not occur in the upstream

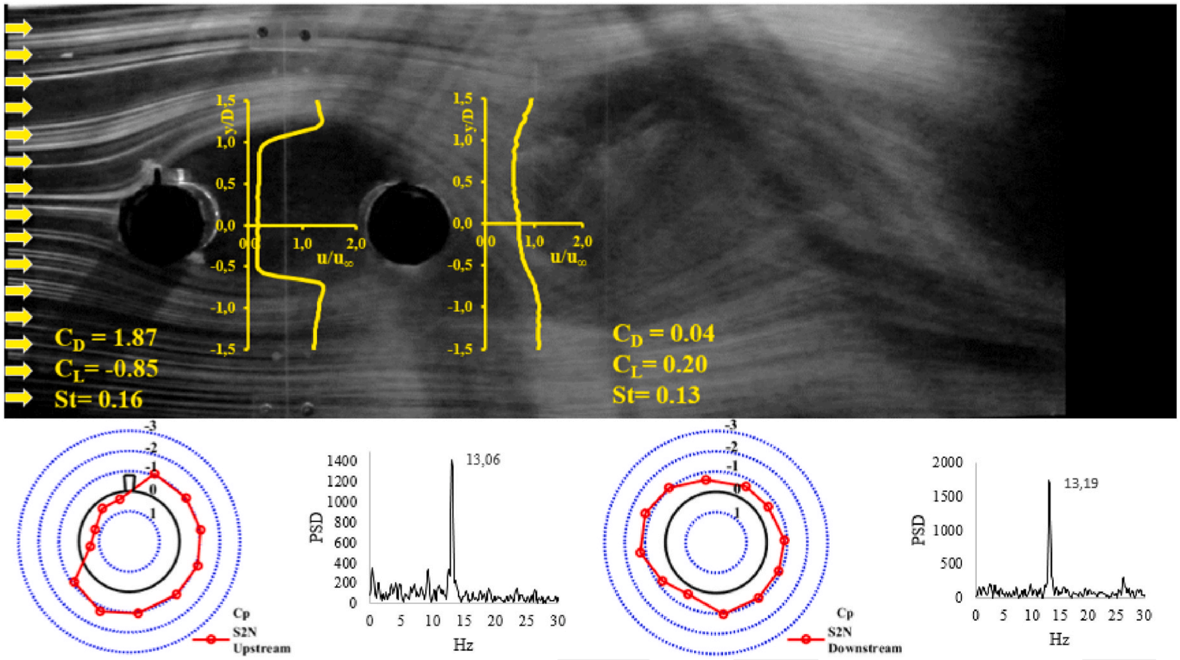


Fig. 16. Experimental results for the upstream cylinder with the spoiler and the downstream cylinder without the spoiler (SN).

cylinder's wake region (Fig. 17), so a peak could not be obtained in the spectral analysis graph and thus the Strouhal number could not be calculated. This phenomenon can be explained by the fact that vortex shedding could not occur during the vortex formation from the upstream cylinder due to the nearby downstream cylinder (Fig. 17). On the contrary, this fact is not seen in cases where the upstream cylinder with the spoiler (SS and SN). In these cases, the Strouhal numbers are calculated at the wake of both the upstream and downstream cylinders.

When comparing the downstream cylinders in the NN and SN cases, adding a spoiler to the upstream cylinder has a positive effect on the downstream cylinder by enabling the flow separated from the upstream cylinder to attach to the downstream cylinder and reducing the drag coefficient from 0.14 to 0.04. When the NN and SN cases given in Figs. 13 and 16 are compared, it is seen that the flow separations on the cylinder increase, and the wake region enlarge when a spoiler is added to the upstream cylinder (Fig. 17). While the drag coefficient is C_D = 1.29 for the upstream cylinder without the spoiler, C_D = 1.87 for the cylinder with the spoiler. $C_L = -0.84$ for the upstream cylinder in the case of SN due to the negative lift effect of the vortices shed from the cylinder with the spoiler (Fig. 17).

When the cases NN and SS given in Figs. 13 and 14 are compared if both cylinders have a spoiler, the drag force acting on the upstream cylinder increases while the drag force acting on the downstream cylinder decreases. This is caused by the broad wake region of the upstream cylinder with the spoiler (Fig. 17).

In the case of SS, the lift coefficient at the upstream cylinder was $C_L = -0.83$, while the lift coefficient in the downstream cylinder was relatively small, $C_L = 0.09$. The same thing was observed in the SN configuration as well. Therefore, when the upstream cylinder has a spoiler, the aerodynamic forces on the downstream cylinder are insignificant.

When the downstream cylinder velocity distributions are examined, it is seen that the flow has low fluctuation in all test cases. In this case, it can be concluded that the fluctuation due to the flow separations is low at the measurement points, and this is caused by the downstream cylinder being in the upstream cylinder's wake region. Downstream cylinders are always under negative pressure in all test cases. The negative pressure area is enlarged in cases where the downstream cylinder is with the spoiler. Considering the upstream cylinders, NN and NS cases showed a similar distribution trend with the N case; SN and SS cases, on the other hand, showed a similar distribution trend with the S case. The negative pressure area of the downstream cylinder was greater in the SS case than in the NS case.

The sample time histories of force measurements for cylinders without and with the spoiler are given in Fig. 18. Each cylinder in each case has been tested for 60 s. While calculating the averages of these forces, the unsteady parts are eliminated. When examining these force measurements closer, the dimensionless time range tU_∞/D = 2300–2400 is used which is proper for all cases to reach the quasi-steady state.

Fig. 19 shows the time histories of C_D and C_L of upstream and downstream cylinders for the dimensionless time range tU_∞/D = 2300–2400 after reaching a quasi-steady state for all cases. The forces acting on the downstream cylinder always encounter fluctuation amplitudes that are noticeably greater than those felt by the upstream cylinder. This is because the downstream cylinder experiences wake interference from the upstream cylinder. The fluctuations of the lift and the drag force coefficients which are given in Fig. 19a and b respectively point out the periodic oscillations of these forces. Besides, adding a spoiler to a single cylinder creates a negative lift force that periodically oscillates. The graphs show that the spoiler increases the mean drag force while its fluctuation amplitude decreases owing to the more prominent vortices (Fig. 12).

Fig. 20–23 indicate the time histories of C_D and C_L for tandem cylinders without/with the spoiler. In the case of tandem, when there are two cylinders in a row, the oscillation amplitude of the force coefficients is reduced because the downstream cylinder affects the vortex shedding of the upstream cylinder (Fig. 17). Moreover, as seen from Fig. 17 the downstream cylinder is under the influence of both the vortex shedding of the upstream cylinder and the vortices formed in its wake region, so the force fluctuations are higher than the upstream cylinder. When we examine the case of spoilers added to the tandem cylinders when the spoiler is added to the downstream cylinder, the force fluctuations of the upstream cylinder decrease due to the increase in flow separation, and the fluctuation is more in the downstream cylinder. Unlike other tandem and single cylinder cases, the vortex shedding mingles (Fig. 17).

(a)
(b)
(c)
(d)

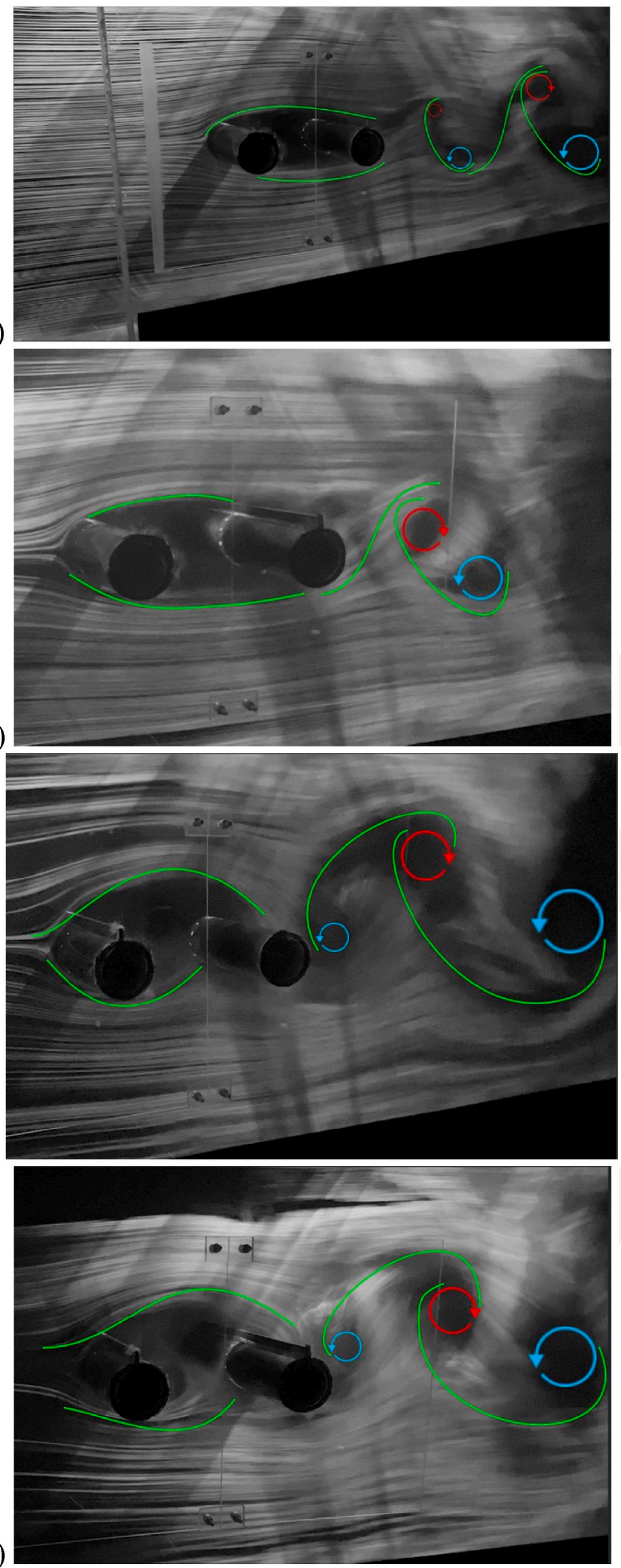


Fig. 17. Vortex shedding patterns behind two cylinders (a) without the spoiler (NN), (b) upstream cylinder without the spoiler and downstream cylinder with the spoiler (NS), (c) upstream cylinder with the spoiler and the downstream cylinder without the spoiler (SN), (d) two cylinders with the spoiler (SS).

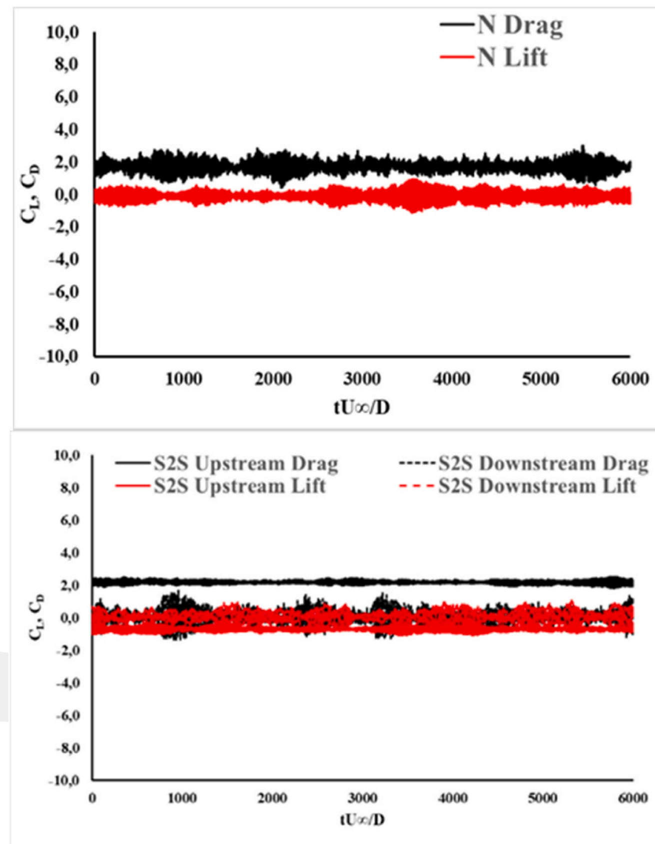


Fig. 18. Time histories of force coefficients.

4. Conclusion

In this study, besides the single cylinder cases with and without a spoiler, the tandem cases where both cylinders without the spoiler (NN), both with the spoiler (SS), the upstream cylinder with the spoiler and the downstream one without the spoiler (SN), the upstream cylinder without and downstream one with the spoiler (NS) was studied experimentally in detail.

In cases where the cylinders are single, the use of the spoiler increases the drag coefficient and creates a negative lift effect. Using the spoiler caused the formation of a low-pressure area around the cylinder.

In SN and SS cases where the upstream cylinder with the spoiler, the lift coefficients of the upstream cylinder are remarkably close, $C_L = -0.83$ and $C_L = -0.84$, respectively. From this, it is understood that the lift coefficient acting on the upstream cylinder with the spoiler is independent of a spoiler on the downstream cylinder. When these lift coefficients are compared with the case of the single cylinder with the spoiler (S), it is seen that if another cylinder is added to $2D$ downstream of a cylinder with the spoiler, its lift coefficient reduces by 44%.

In both cases NN and NS, where the upstream cylinder is without the spoiler, the upstream cylinder's drag coefficient is $C_D = 1.29$. When these drag coefficients are compared with the case of the single cylinder without the spoiler ($C_D = 1.73$), it is seen that another cylinder added to $2D$ downstream reduces the upstream cylinder's drag coefficient by 25%.

In cases where the upstream and downstream cylinders are without the spoiler (NN), the drag and the lift forces acting on the downstream cylinder are quite small. However, when the upstream cylinder does not have the spoiler, but the downstream cylinder has the spoiler (NS), the drag and lift coefficients are $C_D = 0.62$ and $C_L = -0.75$.

In the case of $L/D = 2$, the downstream cylinders remain in the wake region of the upstream cylinder. In the tandem cases of different spoiler

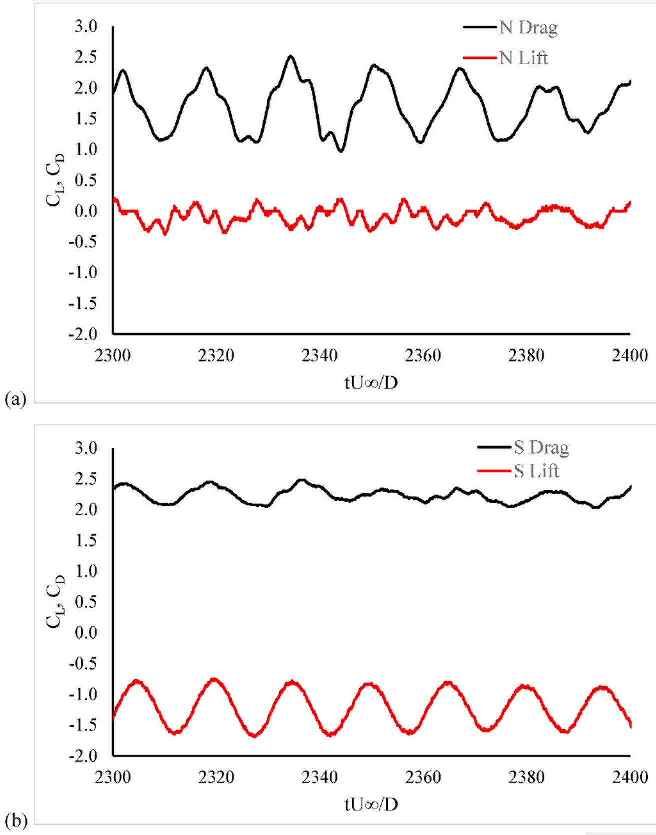


Fig. 19. Time-dependent force coefficients for a cylinder without (a) and with (b) the spoiler.

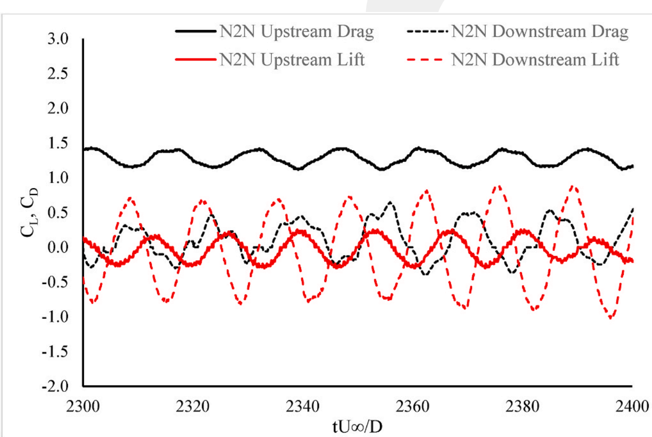


Fig. 20. Time-dependent force coefficients for tandem cylinders without the spoilers (NN).

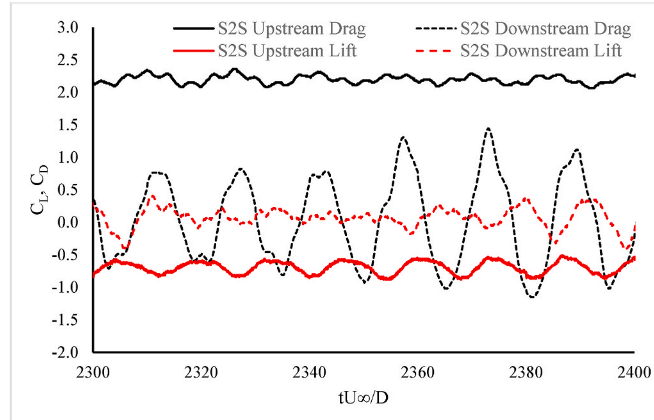


Fig. 21. Time-dependent force coefficients for tandem cylinders with the spoilers (SS).

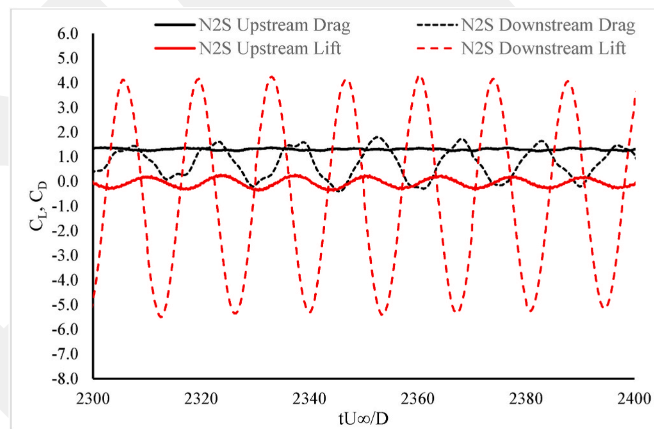


Fig. 22. Time-dependent force coefficients for the case upstream cylinder without the spoiler and downstream cylinder with the spoiler (NS).

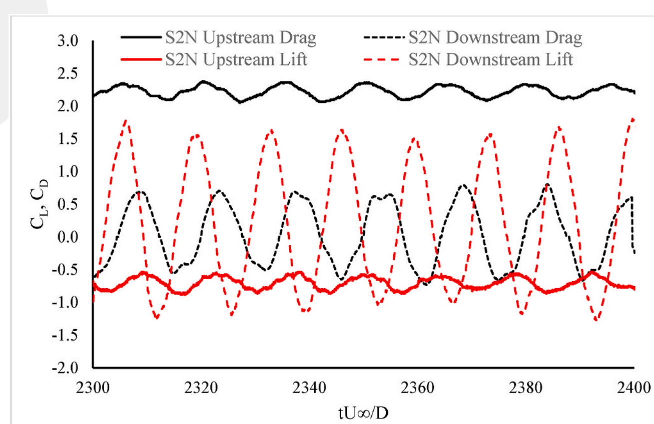


Fig. 23. Time-dependent force results for the case upstream cylinder with the spoiler and downstream cylinder without the spoiler (SN).

combinations, the downstream cylinder is exposed to minimal lift and drag forces, except in the case of NS.

In the tandem cases, the oscillation of the forces in the upstream cylinder is reduced, because the downstream cylinder affects the vortex shedding of the upstream cylinder. Moreover, the downstream cylinder is influenced by both the vortex shedding of the upstream cylinder and the vortices formed in its wake region. Hence its force oscillation amplitudes are higher than the upstream cylinder. In the cases of tandem with spoiler, due to the flow of the downstream cylinder with the spoiler, the force oscillation amplitudes of the upstream cylinder decreases because of the increase in flow separation, and the oscillation is more in the downstream cylinder, unlike other tandem and single cylinder cases, the vortex shedding becomes complex.

The use of spoilers in the use of pipelines is an important topic that is currently used for self-embedding of the pipe. This study is pioneering in determining the forces acting on the pipelines with their oscillations and the pressure distribution in the case of tandem spoilers.

CRediT authorship contribution statement

Mücella İlkentapar: Formal analysis, Investigation, Validation, Conceptualization, Data curation, Methodology, Visualization, Writing - original draft. **Serhat Akşit:** Formal analysis, Validation, Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing - original draft. **Halil Hakan Açıkel:** Formal analysis, Conceptualization, Data curation, Methodology, Visualization, Writing - review & editing. **Ahmet Alper Öner:** Project administration, Conceptualization, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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