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# ANALYZING THE FEATURES OF SELF-EXCITED OSCILLATIONS GENERATED BY THE FLOW PAST A CIRCULAR CYLINDER WITH A SPLITTER PLATE

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One method to control the flow past a solid body is the placement of a flat splitter plate behind the body. The splitter destroys the hydrodynamic feedback that initiates self-excited oscillations of the flow past the body. In such a manner, the splitter performs a stabilizing role, diminishing both the average drag force applied to the body and the oscillations in the trail behind the body. In the present paper, we numerically solve the problem of the generation of self-excited oscillations in the flow past a circular cylinder with a flat splitter plate connected at the rear. Both the transient process of vortex formation and separation from the cylinder's surface and the steady self-excited flow oscillations caused by the periodic vortex shedding behind the cylinder are investigated. The evolution of the vorticity field and the streamline pattern during both the transient and steady processes is described. It is shown that the hydrodynamic feedback channel is formed through the difference in pressure on the upper and lower surfaces of the solid body. The periodic change of its sign causes a periodic process of vortex formation and shedding. It is shown that the splitter oriented along the flow direction substantially reduces both the mean drag force and the amplitude of oscillation of the forces applied to the cylinder. With increasing splitter length, the average value of the drag force decreases monotonically, but the amplitudes of oscillation of the forces applied to the body change non-monotonically. In this paper, we give our explanation of this phenomenon. The calculated data for the main flow characteristics at various splitter lengths are represented. It is also demonstrated that when turning the splitter at a comparatively small angle, the process of vortex shedding from the body surface persists, but the process is no longer strictly regular and periodic.

*KEY WORDS: Aeolian tones, flow past a cylinder, splitter plate, OpenFOAM*

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## 1. INTRODUCTION

The flow of viscous fluid past a solid bluff body has been the subject of many computational and experimental studies. The reason for such popularity of these problems is that the flow around a solid bluff body occurs everywhere in nature and technology. The simplest example of such flows is the flow of viscous fluid past a circular cylinder. In the range of Reynolds number between 47 and $10^5$ the repetitive formation and shedding of vortices behind the cylinder is observed. This vortex shedding represents unsteady separation of flow past the cylinder. The eddies are shed continuously from each side of the circle boundary, forming rows of vortices behind the cylinder. This wake is called Kármán vortex street, named after Theodore von Kármán, who studied the vortex street in [1–4]. The first two pioneering papers were recently presented in the English translation [5,6]. T. Kármán's work on this problem intended to explain the mechanism of resistance of a solid body in motion and its relation to the vortex wake. Double series of vortices identical in modulus but opposite in sign of intensities arranged in a symmetrical or asymmetrical (staggered) order were established. He showed that the symmetric configuration of two vortex rows is always unstable. He also established that the spacing between successive vortices in either row and the distance between the rows has a definite ration. However the vortex street had been studied earlier by Mallock [7, 8], who concluded that the two rows of vortices behind the body can either be arranged in a symmetric or in a staggered configuration, and Bénard [9, 10], who observed the alternating formation of detached vortices on the two sides of a bluff obstacle. For more detailed survey of the early works on the vortex street behind a cylinder see [11].

Later, a large number of computational [12–32] and experimental [33–39] works on the flow behind a cylinder were published. The pattern of the flow around a cylinder significantly depends on the Reynolds number. It is known that the laminar flow behind the cylinder have three modes, depending on the value of the Reynolds number: continuous stationary flow, stationary separation and periodic separated flow. The non-separated flow occurs at the Reynolds number that does not exceed some relatively small threshold value. With increasing Reynolds number, under the action of the pressure gradient and the viscous forces, the laminar boundary layer separates from the surface of the cylinder. A pair of circulating vortices is formed behind the cylinder. Experimental works indicate the beginning of flow separation at $\mathrm{Re} \approx 4$ to 5 whereas most numerical calculations give $\mathrm{Re} \approx 5$ to 7 [40], [41]. With further increase of the Reynolds number, the size of the symmetrical vortex pair formed behind the cylinder increases and the vortices stretch along the flow direction. However the flow remains stationary until the Reynolds number reaches a certain critical value. This critical value is approximately 40. With further increase of the Reynolds number, the flow becomes unstable with respect to small perturbations, the symmetry of the flow behind the cylinder is broken and the flow becomes asymmetric. When the Reynolds number is about 50, the oscillations occur in the wake behind the cylinder, which enhance with increasing Reynolds number. When the Reynolds number reaches about 60, the flow is characterized by the periodic separation of vortices which are carried away by the flow. The vortices break away alternately from one or another side of the rear point of the cylinder, drift downstream and form the regular structure known as the Kármán vortex street. The dependence of the drag and lift coefficients, the vortex shedding frequency and the Strouhal number on the Reynolds number were established [12–31, 33–39]. It is well known that for certain Reynolds numbers flows past elongated bodies generate sounds called Aeolian tones in the literature. The history of study of the Aeolian tones is thoroughly expounded in [42, 43]. The physics of the process of vortex shedding and sound generation is described in detail in [43].

Since the formation and shedding of the vortices behind a cylinder or any other elongated body can lead to undesirable vibrations of the body and even to destruction of the structures, it is necessary to be able to control the process of vortex shedding and to reduce the resistance of the body and the amplitude of oscillation of the forces applied to it. A simple way to decrease the drag and oscillating lift forces in the flow around a circular cylinder consists in positioning a splitter plate in the wake parallel to the flow. Such a flow around a cylinder with splitter plate has been the subject of many computational and experimental works [44–51].

In the experimental work [44] the models having comparatively small splitters ($h/d \le 2$, where $h$ is a length of the splitter plate, $d$ is a diameter of the cylinder) were considered at the Reynolds number in the range $10^4 < \mathrm{Re} < 5 \cdot 10^4$. It was concluded that splitter plates markedly reduce the drag by stabilizing the separation points, produce a wake narrower than that for a plain cylinder and affect the Strouhal number to a lesser degree. Even a very short splitter plate markedly reduced the drag coefficient $C_d$ below the plain-cylinder value. For example, $h/d = 1/16$ effects a 9% reduction and $h/d = 1/8$ effects a 16% reduction. $C_d$ may be reduced by as much as 31% by an appropriate plate $h/d = 1$. The vortex shedding frequency varies with $h/d$ by ±10% over the range $h/d < 2$. In [45] a discrete vortex model was developed to investigate unsteady flow in a wake of a circular cylinder with a splitter plate. It was established that even the short splitter plate produces a significant change of the fluctuating lift: 80% reduction of the fluctuating lift for the plate of $h/d = 1/16$.

In [47] the vortex shedding behind a circular cylinder and its control using splitter plates was numerically simulated at the Reynolds numbers of 80 to 160. Prediction of the natural vortex shedding was in good agreement with the experimental data by Williamson [48]. The experimental results by [46, 52, 53] were very similar to the numerical results by [47] at Re=120 — 160. The vortex shedding behind a circular cylinder completely disappeared when the length of the splitter plate was bigger than a critical length, and this critical length was proportional to the Reynolds number. The Strouhal number rapidly decreased with the increased plate length until $h \approx d$ and showed two different behaviors at $1 < h/d < 2$ for the Reynolds numbers investigated. The net drag was significantly reduced by the splitter plate, and there existed an optimum length of the plate for minimum drag at a given Reynolds number. This optimum length of the plate was nearly the same as the size of the time-averaged deformed separation bubble due to the plate.

In [49] an experimental study was carried out to investigate the effect of a splitter plate on wake flows downstream of a circular cylinder. The splitter plate length $h/d$ was varied from 0 to 1.5 and the Reynolds number was considered at 2400 and 3000. The experimental results showed that the splitter plate had an influence on stabilization of wake turbulences. For shorter splitter plate length of $h/d = 0.5$ and 0.75, the flow structures were significantly modified and the vortex shedding frequency decreased as compared with bare cylinder cases. For longer splitter plate length of $h/d = 1$, 1.25 and 1.5, the generation of a secondary vortex was observed. There was an optimal value of the splitter plate length at $h/d = 1$ on suppression of velocity fluctuations. Moreover, the stabilizing effect of a splitter plate was more obvious at Re=3000 than that at Re=2400. In [50] the flow around a circular cylinder with a detached splitter plate was studied numerically in the Reynolds number range between 100 and 350 corresponding to the wake transition. The flow was analysed using DNS. It was shown that for small gaps the splitter plate causes a significant reduction in the vortex shedding frequency.

In [51] the flow around a single circular cylinder with splitter plate was numerically investigated using the finite volume method. The authors considered Reynolds Averaged Navier-Stokes approximation and closure schemes such as $k$-$\varepsilon$ or $k$-$\omega$ to create the turbulent energy field. They investigated the effects of varying splitter plate length and the Reynolds numbers on flow characteristic, such as vortex shedding, drag force, lift force, separation point, pressure, and friction coefficients of the cylinder. It was revealed that the vortex shedding behind a cylinder is completely suppressed when the splitter plate length is longer than the critical value, which is proportional to the Reynolds number. When the splitter plate length was similar to the diameter of the cylinder, the vortex frequency, drag, and lift coefficients reached local minimum depending on the Reynolds number.

The process of vorticity generation in a viscous fluid is described in detail in the monograph [54]. In particular, it is said: 'In the case of a viscous fluid B. de Saint-Venant showed that vorticity can not arise inside the fluid when conservative external forces applied, but necessarily diffuses inward from the boundaries'. In this paper we investigate not only the steady self-sustained oscillations of the flow caused by the periodic shedding of the vortices behind the cylinder, which generates the sound field, but also describe the transient process of birth, growth, and the beginning of vortex shedding in the wake of the body. We demonstrate how during the transient process the vorticity field is generated near the solid surface of cylinder, forming the boundary layer. Then later this boundary layer separates from the solid surface, forming a couple of eddies behind the cylinder. Later these eddies lose stability and the process of vortex shedding begins. We described the hydrodynamic feedback channel which causes a periodic process of vortex shedding. The numerical simulation of the steady process of vortex shedding is performed for the splitter length in the wide range form $h = d/2$ to $h = 11d/2$ but only for $\mathrm{Re} = 200$. It is shown that the presence of a splitter plate located along the flow significantly reduces the average drag force and the amplitude of oscillation of the forces applied to the body. With increasing splitter length the average value of the drag force decreases monotonically. At the same time the amplitudes of oscillation of the forces applied to the body change nonmonotonically. We give our explanation of this phenomenon.

By adding elongated elements, it is possible to effectively control the flow around bodies even at higher Reynolds numbers. Thus, in the works [55, 56] the characteristics of laminar and turbulent flow around cylinders with multiple elastic splitters in the function $10^4 < \mathrm{Re} < 10^5$ were investigated. It was shown that although the attached plates allow for a reduction in the total drag, increasing their flexibility finally leads to its increase.

In this paper, the problem of viscous incompressible fluid flow past a circular cylinder with a flat splitter plate attached to the rear is numerically solved using the Direct Numerical Simulation (DNS) technique. The authors have presented part of the obtained results in [57]. The new study offered to readers is a logical continuation of this discussion. It contains a more thorough analysis of the data in an expanded range of geometric and temporal parameters. Numerous illustrative materials accompany the text.

## 2. STATEMENT OF THE PROBLEM AND THE ALGORITHM FOR ITS NUMERICAL SOLUTION

Let us consider the problem of the flow of a viscous incompressible fluid past a stationary circular cylinder with a flat splitter attached behind the cylinder. The splitter is an absolutely rigid thin plate and can be located both along the flow and at some angle to the flow direction. The computational domain and the accepted designations are shown in Fig. 1. The computational domain occupies the rectangle $0 < x < L_1$, $0 < y < L_2$. The fluid come in through the left end ($x = 0$), where the constant velocity $V$ is designated. Then the flow runs against a circular cylinder of diameter $d$ with a thin splitter of length $h$ located behind it and leaves the computational domain through the right boundary ($x = L_1$).

The problem is formulated within the framework of the viscous incompressible Newtonian fluid model. Such a process is described by the nonstationary system of Navier–Stokes equations. To bring the governing equations to the dimensionless form, the cylinder diameter $d$ was taken as the length scale, the velocity of the uniform flow $V$ at a sufficiently large distance from the cylinder was taken as the velocity scale. Then the time scale is the magnitude $d/V$, the pressure scale is the double pressure head $\rho V^2$. The key parameter of the problem which enters the governing equations is the Reynolds number $\mathrm{Re} = Vd/\nu$, where $\nu$ is the kinematic viscosity of the medium.

The boundary conditions for the velocity were specified as follows: the uniform flow at the inlet of the computational domain, the non-slip condition at the solid surface of the cylinder and the splitter, the zero normal gradient at the outlet of the computational domain. For pressure, the condition of zero normal gradient was formulated all over the boundary of the computational domain except for the outlet. At the outlet a constant pressure was prescribed.

In this paper, we performed numerical calculations for $\mathrm{Re} = 200$ while the splitter length varied from $0.5d$ to $5.5d$. The splitter could be located not only along the stream, but also at some angle $\alpha$ to the flow direction.

The algorithm for the numerical solution of the formulated problem is described in detail in the work [58]. It is based on the finite volume method, which at the present time can be treated as the most popular numerical approach in fluid mechanics. The libraries of the toolbox with open code OpenFOAM were used for calculations. The spatial discretization was performed on a structured O-type grid with concentration of nodes near the solid sur-

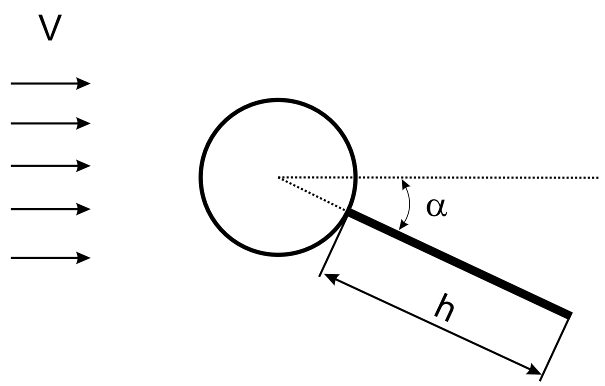



Fig. 1. Geometry of the problem

face of the cylinder and the splitter. The length of the side of the control volume did not exceed $10^{-4}$ in the immediate vicinity of the surface. The second-order schemes were used both for spatial and temporal discretization. In particular, the TVD scheme implemented in OpenFOAM was used to discretize the convective terms. For the discretization of the time derivative we used an implicit three-point asymmetric second-order scheme with backward steps (backward differencing scheme). In order to verify the constructed numerical algorithm, the classical problem of nonstationary flow separation behind a circular cylinder was solved numerically [30, 31]. The obtained results were compared with the numerical and experimental data of other authors. To parallelize the computations, we used MPI technology and the parallelization method known as the solution domain decomposition which is based on the geometric parallelism. The calculations were performed on the cluster supercomputer of the Institute of Cybernetics of NAS of Ukraine.

## 3. ANALYSIS OF THE NUMERICAL RESULTS

First we consider the transient process for the case that the splitter length is equal to the radius of the cylinder $h = d/2$ and $\alpha = 0$. The flow develops in time from rest. Once the motion began, a pair of vortices that have vorticity equal in absolute value but opposite in sign arises behind the cylinder. In other words, two symmetric vortices that rotate in opposite directions appear at the rear. In Fig. 2a and Fig. 3a the moment when the vortex pair behind the cylinder just has arisen is shown. The horizontal size of the vortices, that is the distance from the rear point of the cylinder to the point of intersection of the instantaneous streamlines, is only slightly larger than the diameter of the cylinder. Inside the formed vortices the local pressure minima are observed. Furthermore, as time goes on, the extent of the vortex pair behind the cylinder continues to grow and reaches a certain maximum value at the time approximately $t = 41$. The vorticity field and the streamlines pattern at this moment of time are shown in Fig. 2b and Fig. 3b. At the boundary of this stationary vortex pair the expanding mixing layer is formed, i.e. the shear flow layer that is characterized by significant transverse (in the direction of the $0y$ axis) vorticity gradients. Large transverse gradients are well known to contribute to flow instability. Because of this, on further increase of the vortex pair behind the cylinder, the symmetry of the flow is violated. In Fig. 2c and Fig. 3c the moment $t = 57$ is shown, when the flow symmetry just begins to collapse. Furthermore, as time goes on, the flow symmetry behind the cylinder completely collapses and the flow passes into the regime of steady periodic formation and shedding of vortices. The upper and lower vortices detach in turn. This can be seen in Fig. 2d and Fig. 3d, where the time $t = 140$ is shown. At that moment steady self-sustained oscillations of the flow behind the cylinder are already observed.

Let us consider the steady process of self-sustained oscillations of the flow behind the cylinder. The vorticity fields and the pressure distribution over the splitter and cylinder surface are represented in Fig. 4 for one period of oscillation with a step of quarter-period ($T/4$). When constructing the pressure distribution over the solid surface of the splitter and the cylinder, the surface is went around clockwise starting from the splitter end. In other words the point $l = 0$ corresponds to the splitter's rear point. The center vertical dotted line in the figure corresponds to the front point of the cylinder. The left and right dotted lines cut off the surface of the splitter from the surface of the cylinder. For the initial time

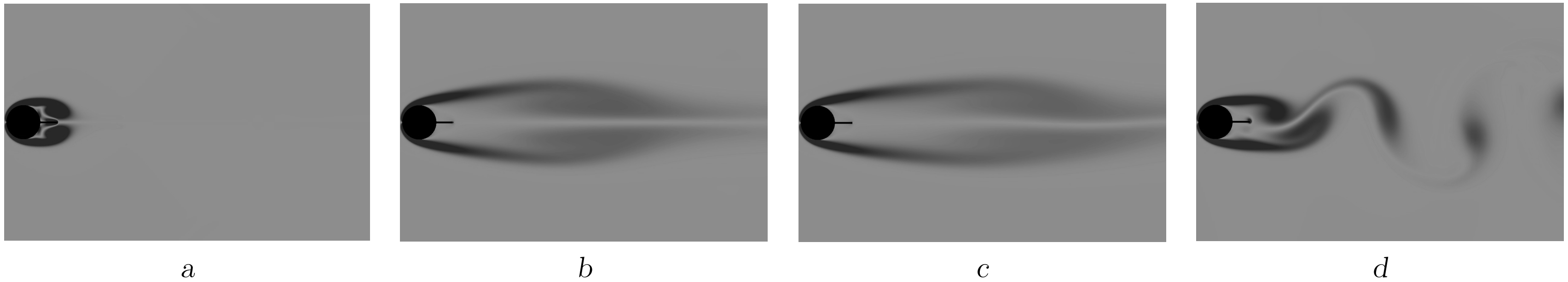



Fig. 2. Vorticity field during the transient process for $\mathrm{Re} = 200$, $h = d/2$, $\alpha = 0$:
$a$ — $t = 2.5$, $b$ — $t = 41$, $c$ — $t = 57$, $d$ — $t = 140$

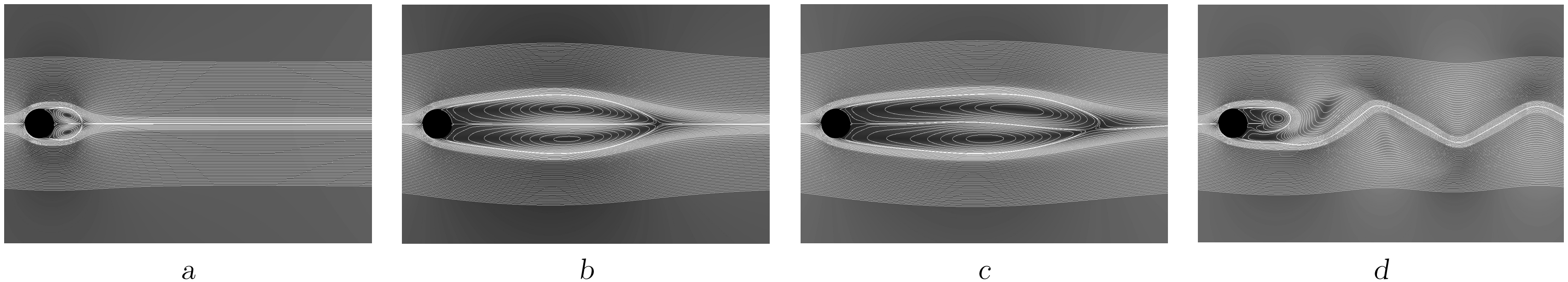
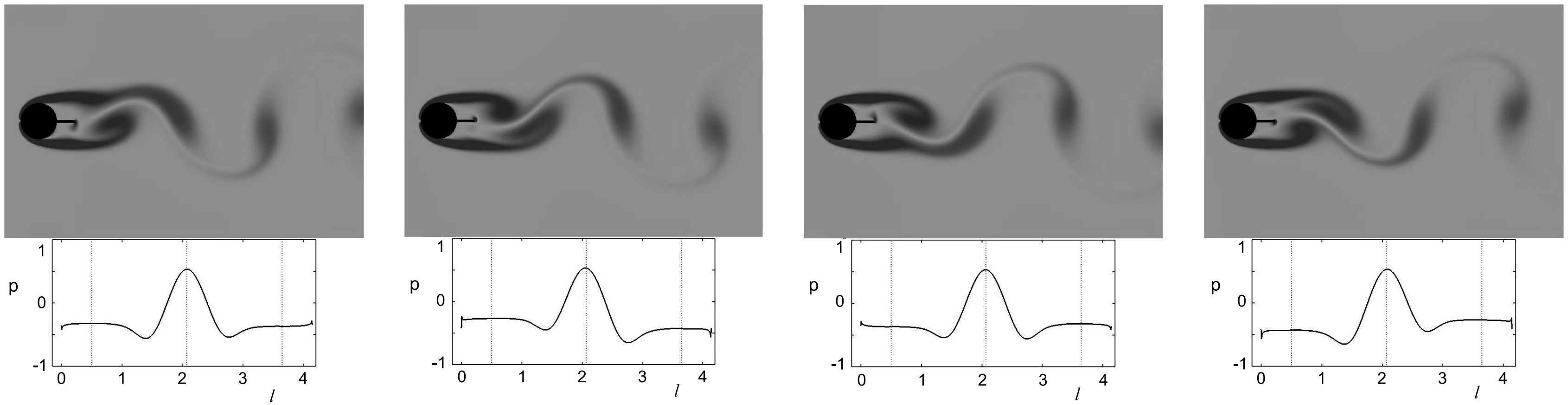



Fig. 3. Instantaneous streamlines during the transient process for $\mathrm{Re} = 200$, $h = d/2$, $\alpha = 0$:
$a$ — $t = 2.5$, $b$ — $t = 41$, $c$ — $t = 57$, $d$ — $t = 140$

moment ($t = 0$) we take the moment when the lift coefficient, which as shown below oscillates periodically around zero, becomes zero ($C_y = 0$).

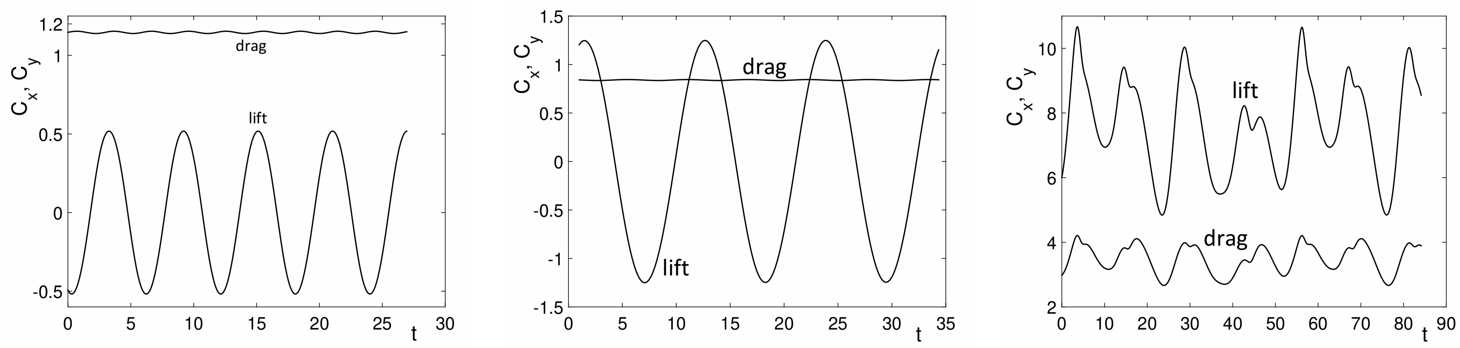
It can be seen that the vortices are already formed not immediately behind the cylinder surface, as it was in the flow past a circular cylinder without a splitter [30, 31], but behind a splitter. That is the vortices interact not so much with the cylinder, but rather with the splitter tip. It is worth noting that, just in the same manner as in the case of flow past a cylinder where aeolian tones occur, in this flow we also see the periodic change of the pressure distribution over the surface, which can also serve as a source of sound oscillations. Thus, at the instant $t = T/4$ the pressure minimum is located at the upper part of the surface but at the instant $t = 3T/4$ the pressure minimum is already located at the lower part of the surface.

The periodic nature of the flow in the cylinder's wake leads to the fact that the forces applied to the cylinder change periodically in time as well. The interaction of the vortices has practically no effect on the front critical point, because of its remoteness from the vortex separation region. Fig. 5a shows the time evolution of both the drag coefficient $C_x$ and the lift coefficient $C_y$ for $h = d/2$, $\alpha = 0$. Obviously, the forces change periodically. Moreover, the period of drag variation is half the period of lift force variation. In other words, the oscillation frequency of the force acting on the cylinder and the splitter in the horizontal direction is twice as large as the oscillation frequency of the force in the vertical direction. The same effect occurs in the flow past a circular cylinder without a splitter [30,31]. The other two Fig. 5 show the time variation of the force coefficients for the splitter length $h = 11d/2$. Fig. 5b corresponds to the case when the splitter is positioned along the flow direction. In this case, due to the symmetric geometry of the problem, the lift force oscillates around zero, and the frequency of the drag force oscillation is twice higher than the frequency of the lift force oscillation. It worth noting that with elongation of the splitter the amplitude of the lifting force variation grows so much that its peak values exceed the drag force. At the same time, the drag force decreases slightly. Thus, comparing Fig. 5a and Fig. 5b we can see that as the splitter length increases the drag force slightly decreases, whereas the amplitude of the lift force variation increases more than twice. Fig. 5c corresponds to the case when the splitter is turned at the angle $\alpha = 20°$ to the flow direction. In this case, the average value of the lift force becomes nonzero due to the deviation of the splitter. Moreover, the curve corresponding to the lifting force lies higher than the curve corresponding to the drag force. That is even a relatively small deviation of the splitter by the angle $\alpha = 20°$ results in the fact that the lift force exceeds the drag force. It should also be noted that the time variation of the forces applied to the solid body is no longer obviously periodic. That means that even a slight deviation of the splitter with its length $h = 11d/2$ leads to the violation of strict regularity of the process. Fig. 6 show the vorticity field of the flow at four time instants with the interval $T/4$. It can be seen that the boundary layer formed at the upper part of the cylinder separates from the cylinder surface and becomes a free shear layer before reaching the splitter surface. The large vortices and reverse flow zones may appear between the upper separated free shear layer and the splitter surface. In the lower part of the cylinder, on the contrary, the shear layer is located near the solid surface up to the splitter tip. The separation of the shear layer and the formation of a large vortex occur behind the rear point of the splitter. Thus, the oscillations of the upper and lower shear layers are of different nature and differ in frequency. This explains the violation of strict regularity and




*a* *b* *c* *d*

Fig. 4. The vorticity field during a period of the steady process of vortex shedding for Re = 200, $h = d/2$, $\alpha = 0$ (the lower figures show the pressure distribution over the surface of the body):
$a$ — $t = 0$, $b$ — $t = T/$, $c$ — $t = T/2$, $d$ — $t = 3T/4$




*a* *b* *c*

Fig. 5. The periodic oscillations of the coefficients of forces applied to the solid body for Re = 200:
$a$ — $h = d/2$, $\alpha = 0$, $b$ — $h = 11d/2$, $\alpha = 0$, $c$ — $h = d/2$, $\alpha = 20°$

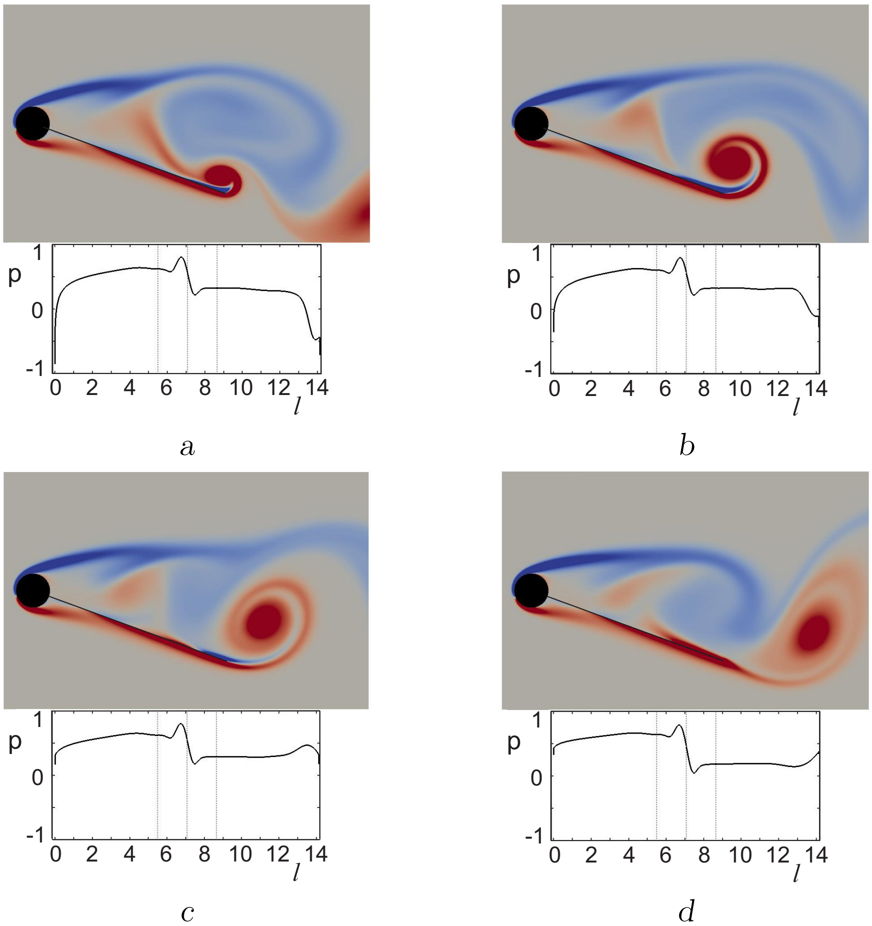



Fig. 6. The vorticity field during a period of the steady process of vortex shedding for Re = 200, $h = 11d/2$, $\alpha = 20°$ (the lower figures show the pressure distribution over the surface of the body): a — $t = 0$, b — $t = T/$, c — $t = T/2$, d — $t = 3T/4$

periodicity of the oscillation process of the forces applied to the cylinder and the splitter. In other words, the process of vortex formation and shedding from the body surface continues but the strict regularity and periodicity of this process is no longer observed.

The drag and lift coefficients can be formally represented as a sum of constant and oscillating parts

$$C_x = \bar{C}_x + \tilde{C}_x, \qquad C_y = \bar{C}_y + \tilde{C}_y, \tag{1}$$

where $\bar{C}_x$, $\bar{C}_y$ are the constant components of the forces applied to the cylinder and the splitter (it is obvious that if the splitter is positioned along the incoming flow direction, $\bar{C}_y = 0$, if the splitter deviates by some angle $\alpha$, a nonzero mean value of the lift force arises), $\tilde{C}_x$, $\tilde{C}_y$ are the oscillating components of the forces.

Tab. 1 shows the values of the constant component $\bar{C}_x$, the amplitudes of the oscillating components $\tilde{C}_x$, $\tilde{C}_y$, and the ratio of these amplitudes for various splitter lengths. The following denotations are used: $T$ is the oscillation period, St is the Strouhal number, $\bar{C}_x$ is the average value of the drag coefficient, $A_x = \max|\tilde{C}_x|$ is the amplitude of the drag coefficient oscillations, $A_y = \max|\tilde{C}_y|$ is the amplitude of the lift coefficient oscillations,

Tab. 1. The calculated characteristics of the periodic flow vs. splitter length $h$ (Re = 200, $\alpha = 0$)

| $2h/d$ | 1 | 2 | 3 | 5 | 7 | 9 | 11 | 0 |
|---|---|---|---|---|---|---|---|---|
| $T$ | 5.89 | 6.30 | 5.72 | 5.78 | 7.22 | 9.11 | 11.2 | 5.082 |
| St | 0.170 | 0.159 | 0.175 | 0.173 | 0.139 | 0.110 | 0.089 | 0.197 |
| $\bar{C}_x$ | 1.146 | 1.044 | 1.039 | 0.997 | 0.927 | 0.875 | 0.840 | 1.343 |
| $A_x \times 10^3$ | 7.2 | 2.4 | 6.2 | 11.0 | 5.2 | 4.4 | 4.9 | 50.0 |
| $A_y$ | 0.518 | 0.333 | 0.416 | 0.949 | 1.150 | 1.241 | 1.249 | 0.686 |
| $N \times 10^2$ | 1.39 | 0.72 | 1.49 | 1.16 | 0.45 | 0.35 | 0.39 | 7.3 |

$N = A_x/A_y$ is the ratio of the oscillation amplitudes of the coefficients $C_x$ and $C_y$. In addition, the table shows the values of the oscillation period and the Strouhal number. In all the cases under consideration the splitter plate was located along the flow direction ($\alpha = 0$), and the Reynolds number was assumed to be Re = 200.

It is evident that the presence of the splitter plate behind the cylinder substantially reduces the average value of the drag coefficient. Moreover, the drag coefficient continues to decrease as the splitter length increases. This happens apparently due to the fact that vortices are formed behind the cylinder and near the splitter, which leads to the appearance of reverse motion zones near the surface of the body. The reverse flow near the body reduces the drag. It should also be noted that in the presence of a splitter the amplitude of the drag coefficient oscillation decreases substantially. Thus, in the flow around a cylinder without a splitter ($h = 0$) the amplitude of the drag coefficient oscillation is $5 \cdot 10^{-2}$. In the presence of even a small splitter, whose length is equal to the radius of the cylinder, the amplitude of the drag coefficient oscillation decreases to $0.72 \cdot 10^{-2}$. With further elongation of the splitter, the oscillation amplitude of $\tilde{C}_x$ behaves nonmonotonically. First it decreases up to $h = d$, then grows up to $h = 5d/2$, then decreases again up to $h = 9d/2$ and then grows again. This apparently depends on how many vortices detached from the cylinder surface can be located along the splitter. It should also be noted that in the presence of a splitter, the period of oscillations, that is the time between formation and shedding of two adjacent vortices, increases substantially. On further increase in the splitter length the period of vortex formation increases as well. However, this process is nonmonotonic. Thus, if the splitter length changes from $h = d$ to $h = 3d/2$, the period sharply reduces.

Fig. 7–12 represents the vorticity field of the flow at various splitter lengths. The splitter is positioned along the flow. At the bottom part of the figures the pressure distribution over the surface of the body is presented. The vertical dotted lines cut off the surface of the cylinder from the surface of the splitter. It is seen that for $h = d$, the shear layers formed on the cylinder surface separate from the cylinder and move along the splitter. The formation of large eddies in the wake occurs behind the rear point of the splitter. Consequently, the large vortices formed in the flow interact with the rear part of the splitter rather than with the cylinder surface. The interaction of the formed vortices with the rear part of the splitter must apparently make a significant contribution to the generated sound field and can not be neglected. As the splitter length increases, the interaction of the rear part of the splitter with the large vortices formed in the shear layers behind the cylinder increases. So, even at

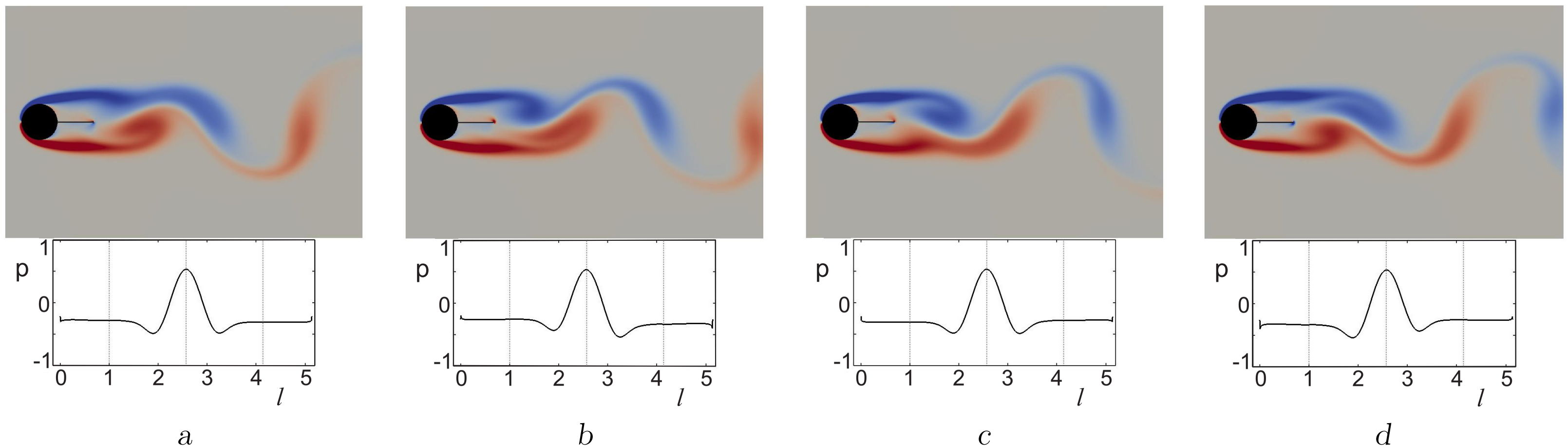



Fig. 7. The vorticity field during a period of the steady process of vortex shedding for Re = 200, $h = d$, $\alpha = 0$ (the lower figures show the pressure distribution over the surface of the body):

$a$ — $t = 0$, $b$ — $t = T/$, $c$ — $t = T/2$, $d$ — $t = 3T/4$

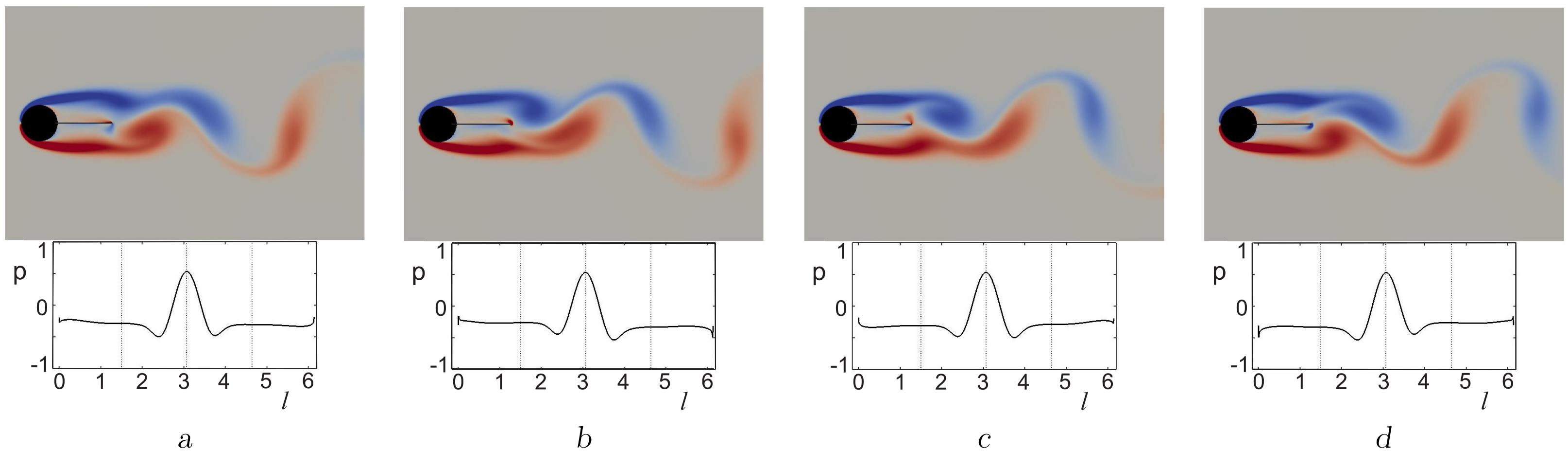



Fig. 8. The vorticity field during a period of the steady process of vortex shedding for Re = 200, $h = 3d/2$, $\alpha = 0$ (the lower figures show the pressure distribution over the surface of the body):

$a$ — $t = 0$, $b$ — $t = T/$, $c$ — $t = T/2$, $d$ — $t = 3T/4$

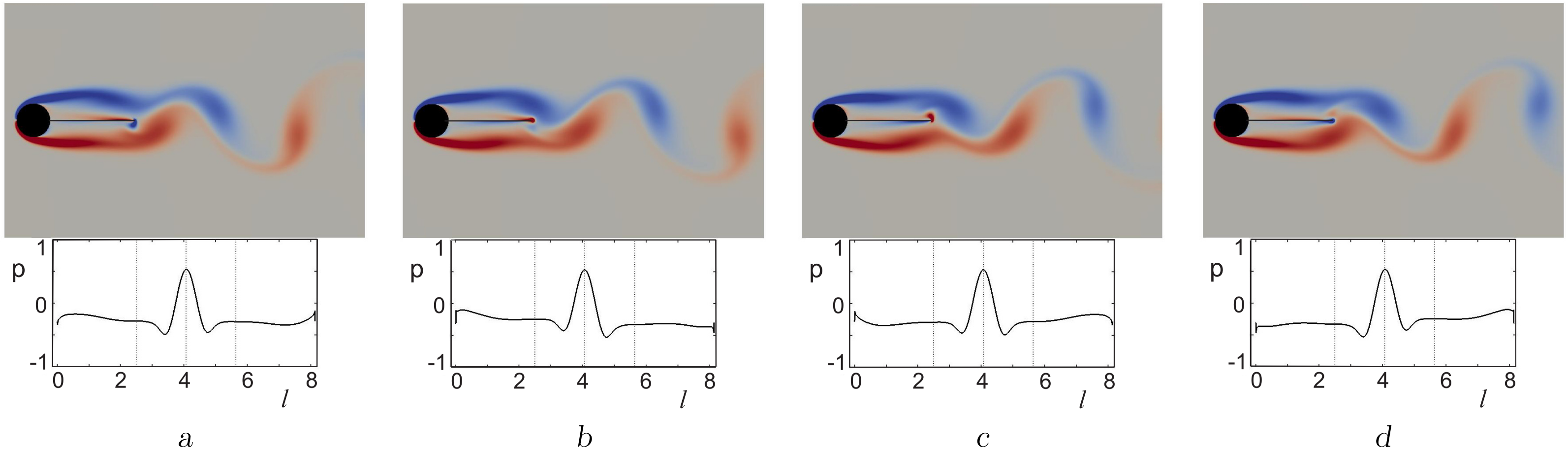



Fig. 9. The vorticity field during a period of the steady process of vortex shedding for Re $= 200$, $h = 5d/2$, $\alpha = 0$ (the lower figures show the pressure distribution over the surface of the body):
a — $t = 0$, b — $t = T/$, c — $t = T/2$, d — $t = 3T/4$

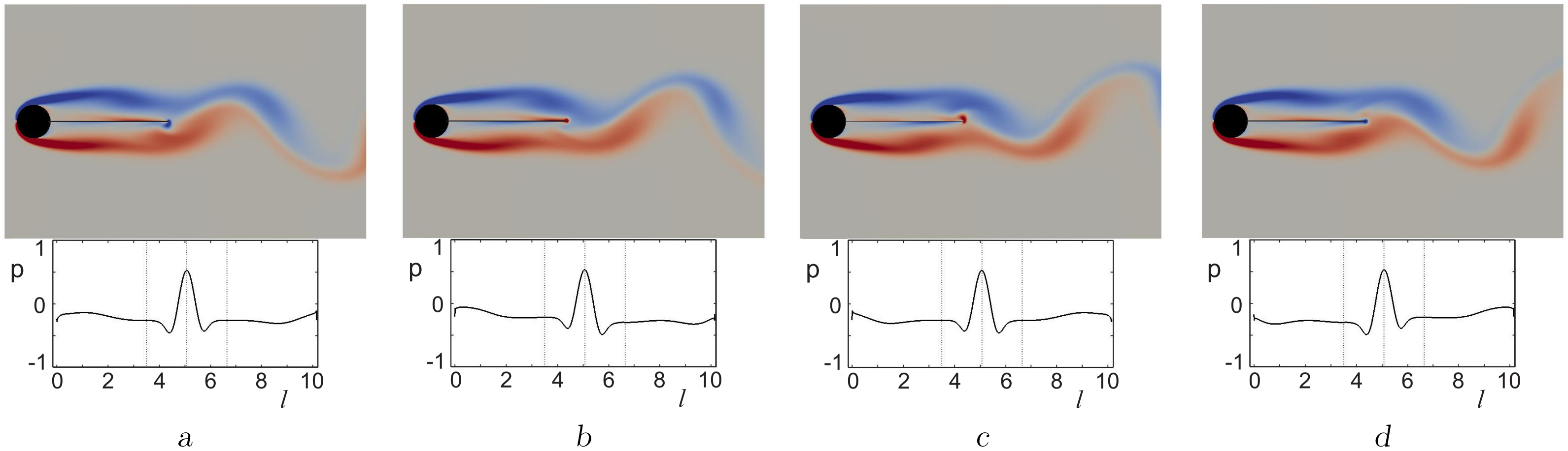



Fig. 10. The vorticity field during a period of the steady process of vortex shedding for Re $= 200$, $h = 7d/2$, $\alpha = 0$ (the lower figures show the pressure distribution over the surface of the body):
a — $t = 0$, b — $t = T/$, c — $t = T/2$, d — $t = 3T/4$

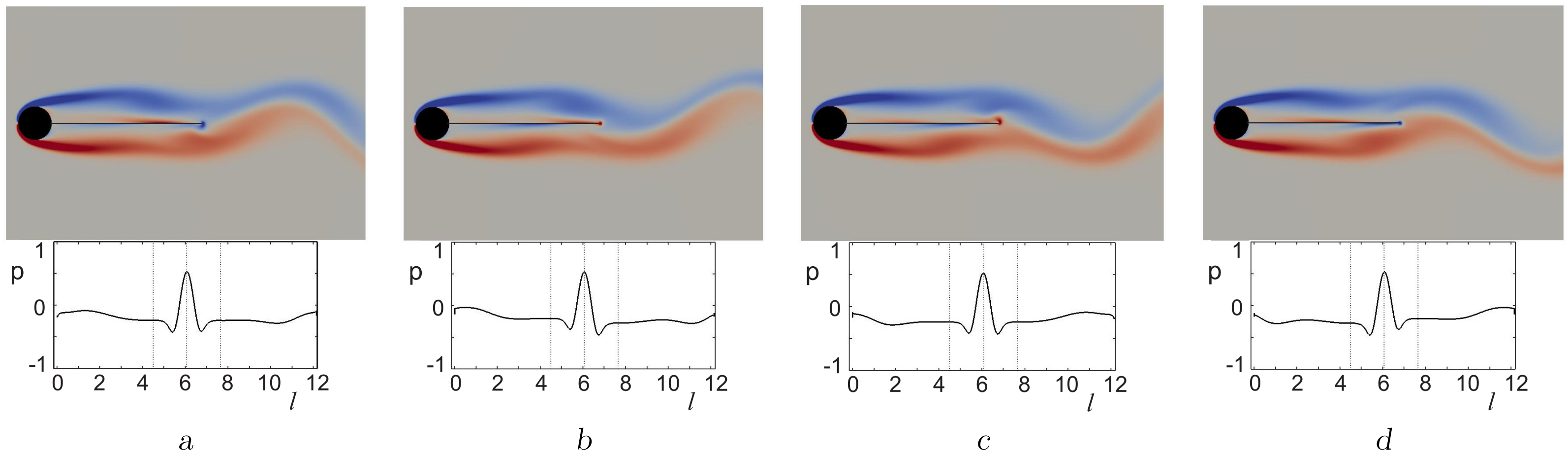



Fig. 11. The vorticity field during a period of the steady process of vortex shedding for Re $= 200$, $h = 9d/2$, $\alpha = 0$ (the lower figures show the pressure distribution over the surface of the body):
$a$ — $t = 0$, $b$ — $t = T/$, $c$ — $t = T/2$, $d$ — $t = 3T/4$

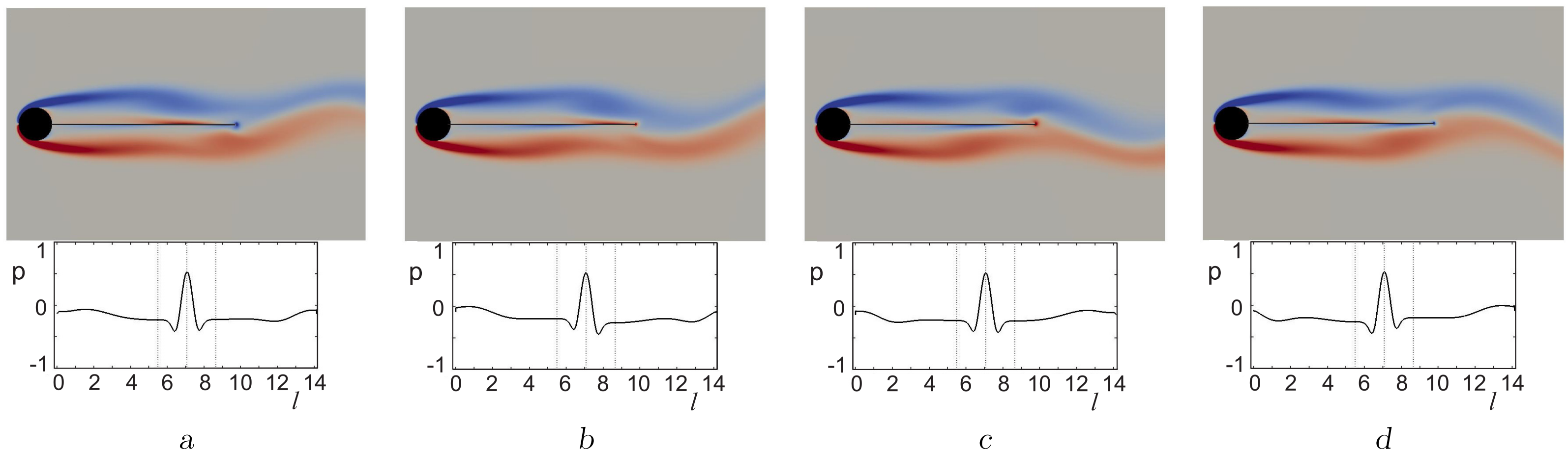


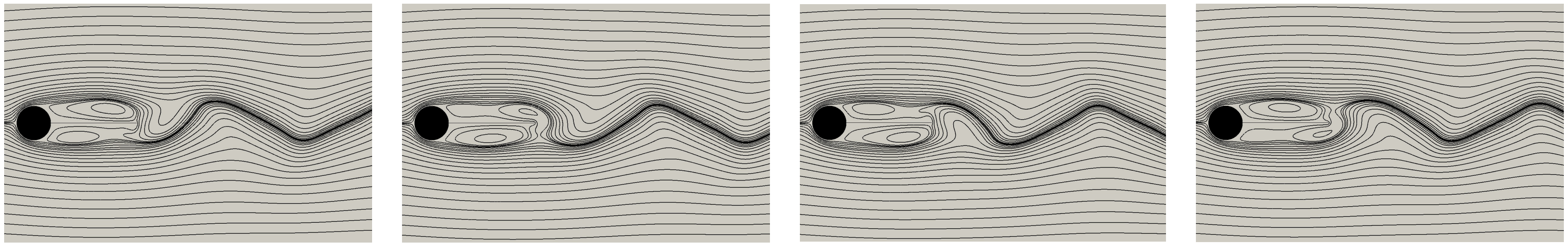

Fig. 12. The vorticity field during a period of the steady process of vortex shedding for Re $= 200$, $h = 11d/2$, $\alpha = 0$ (the lower figures show the pressure distribution over the surface of the body):
$a$ — $t = 0$, $b$ — $t = T/$, $c$ — $t = T/2$, $d$ — $t = 3T/4$

splitter length equal to five radii of the cylinder $h = 5d/2$ it is clear that the large eddies are formed before the rear part of the splitter rather than behind the splitter. With further splitter elongation (see, for example, $h = 9d/2$ and $h = 11d/2$), the large eddies in the wake, similar to the Karman vortex street, is no longer observed. The separated shear layers simply take a wavy form. Thus, the elongation of the splitter has a generally stabilizing effect on the flow.

Figs. 13–16 show instantaneous streamlines of the flow at time instants with the interval $T/4$ at various splitter lengths. It is easy to see that there are large vortex structures on both sides of the splitter in the region between the splitter and the detached shear layers. As a consequence, some zones of reverse flow occur at the surface of the splitter. As already noted above, this leads to the fact that the average drag force and the oscillation amplitude of the drag coefficient decrease sharply in the presence of a splitter. With a further increase in the splitter length, not one but several large vortices can be located at each splitter side (see, for example, Figs. 15 and 16). The different number of the vortices located along the splitters of different length, apparently, is the reason that the oscillation amplitude of the drag coefficient behaves nonmonotonically with an increase in the splitter length. First, it decreases up to $h = d$. With such values of the splitter length there is one vortex near each side. The vortices lead to the decrease in both the average value of the drag coefficient and the amplitude of drag oscillations. Then, as the splitter length increases to $h = 5d/2$, the size of these vortices increases, which leads to a decrease in the stability of such a system. As a consequence, the oscillation amplitude of the drag force increases with the splitter extension to $h = 5d/2$. It is seen in Fig. 13 that even at $h = 5d/2$ two large vortices arise alternately in the vicinity of the splitter sides. As a result, as the splitter length increases from $h = 5d/2$ to $h = 9d/2$, the oscillation amplitude of the drag coefficient decreases. With a further increase in the splitter length the size of the vortices near the splitter sides increases. And this again leads to the increase in instability of such a system. Therefore, as the splitter length increases above $h = 9d/2$, the amplitude of oscillation of the drag force increases again. Although the average value of the drag coefficient decreases monotonically with increasing splitter length in the entire range of values of $h$.

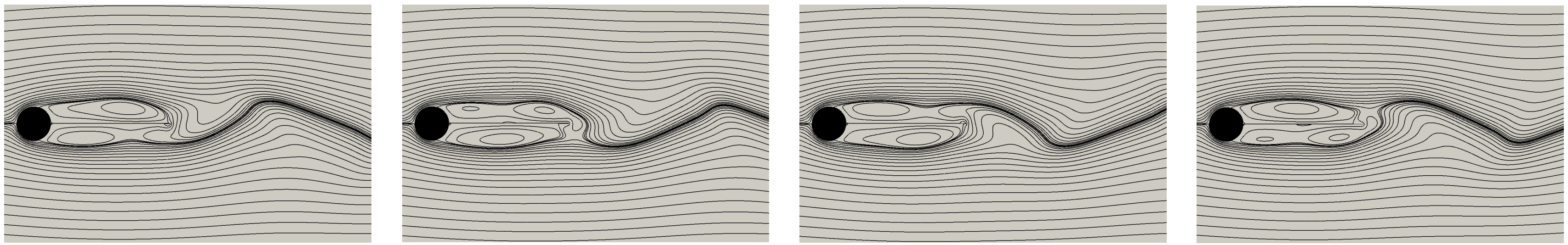
## 4. CONCLUSION

The problem about the flow past a circular cylinder with a flat splitter plate attached at the rear of the cylinder is solved numerically. The evolution of the vorticity fields and the streamline pattern during the transient process of vortex formation and initiation of the vortex shedding behind the cylinder is described. The process of steady self-sustained oscillations of the flow caused by the periodic vortex shedding is also described. The hydrodynamic feedback channel is formed through the difference in pressure on the upper and lower surfaces of the cylinder and the splitter plate. The periodic change of its sign causes the periodic process of vortex formation and shedding. The calculated data for the main flow characteristics at various splitter lengths are represented. The case when the splitter is turned at some angle to the flow direction is also considered. It is shown that the presence of a splitter located along the flow significantly reduces the average drag force and the amplitude of oscillation of the forces applied to the body. With increasing splitter length the average value of the drag force decreases monotonically. At the same time the amplitudes



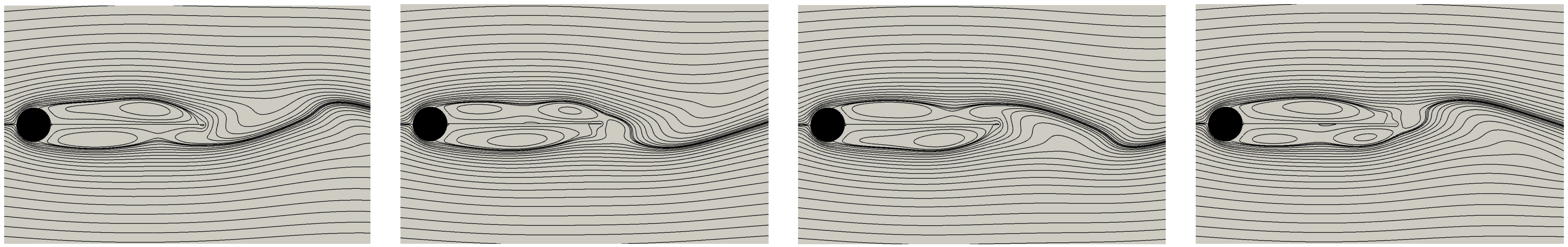
*a* *b* *c* *d*

Fig. 13. Instantaneous streamlines during the period of the steady process of vortex formation and shedding for Re = 200, $h = 5d/2, \alpha = 0$:
$a$ — $t = 0$, $b$ — $t = T/4$, $c$ — $t = T/2$, $d$ — $t = 3T/4$



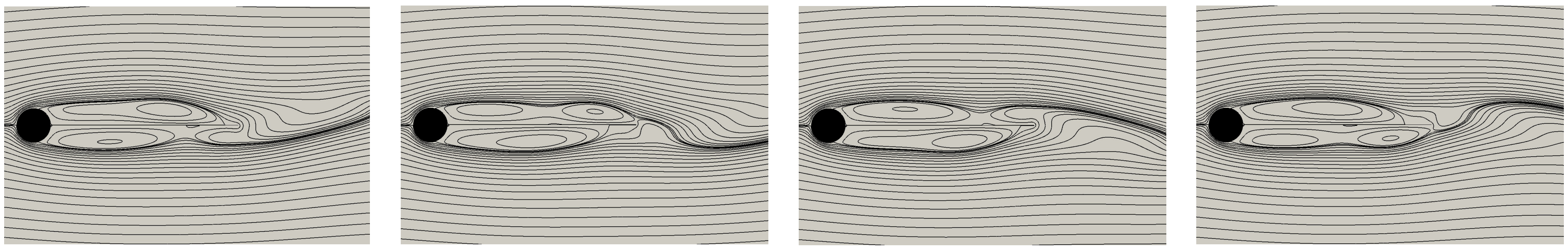
*a* *b* *c* *d*

Fig. 14. Instantaneous streamlines during the period of the steady process of vortex formation and shedding for Re = 200, $h = 7d/2, \alpha = 0$:
$a$ — $t = 0$, $b$ — $t = T/4$, $c$ — $t = T/2$, $d$ — $t = 3T/4$



a b c d

Fig. 15. Instantaneous streamlines during the period of the steady process of vortex formation and shedding for Re = 200, $h = 9d/2, \alpha = 0$:
$a$ — $t = 0$, $b$ — $t = T/4$, $c$ — $t = T/2$, $d$ — $t = 3T/4$



a b c d

Fig. 16. Instantaneous streamlines during the period of the steady process of vortex formation and shedding for Re = 200, $h = 11d/2, \alpha = 0$:
$a$ — $t = 0$, $b$ — $t = T/4$, $c$ — $t = T/2$, $d$ — $t = 3T/4$

of oscillation of the forces applied to the body change nonmonotonically. It is also shown that when the splitter is turned at the relatively small angle $\alpha = 20°$, the process of vortex shedding from the body surface is also observed, but such a process is no longer strictly regular and periodic. In conclusion it should be said that the periodic change in pressure on the sides of the cylinder and the splitter plate is a source of sound oscillations of the dipole type, which has been observed experimentally by many researchers.

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***І. В. Вовк, В. С. Малюга***

**Аналіз особливостей автоколивань, генерованих при обтіканні кругового циліндра з пластиною-сплітером**

Один зі способів контролю потоку повз тверде тіло полягає у розміщенні плоского розділювача (сплітера) позаду тіла. Розгалужувач фактично руйнує гідродинамічний зворотній зв'язок, який ініціює автоколивання потоку, що обтікає тіло. Таким чином сплітер виконує стабілізуючу роль, зменшуючи як середню силу опору, що прикладена до тіла, так і коливання в сліді за тілом. У даній роботі ми чисельно розв'язуємо задачу генерації автоколивань, що збуджуються у потоці при обтіканні кругового циліндра з плоским розгалужувачем, приєднаним ззаду. Досліджено як перехідний процес утворення і відокремлення вихорів від поверхні циліндра, так і усталені автоколивання потоку, викликані періодичним скиданням вихорів за циліндром. Описано еволюцію вихрового поля та картину ліній течії під час як перехідних, так і усталених процесів. Показано, що гідродинамічний канал зворотного зв'язку утворюється через різницю тиску на верхній і нижній поверхнях твердого тіла. Періодична зміна знаку цієї різниці спричинює періодичний процес утворення та скидання вихрів. Показано, що розгалужувач, орієнтований вздовж напрямку потоку, істотно зменшує як середню силу опору, так і амплітуду коливань сил, прикладених до циліндра. Зі збільшенням довжини розгалужувача середнє значення сили опору монотонно зменшується, але амплітуди коливань сил, прикладених до тіла, змінюються немонотонно. У цій роботі ми даємо наше пояснення цього явища. Представлено розрахункові дані для основних характеристик потоку при різних довжинах розгалужувача. Також показано, що при повороті розгалужувача на порівняно невеликий кут процес скидання вихорів з поверхні тіла все ще зберігається, але процес вже не є строго регулярним та періодичним.

*КЛЮЧОВІ СЛОВА: еолові тони, обтікання циліндра, пластина-сплітер, OpenFOAM*