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Автоколивання потоку при обтіканні кругового циліндра зі сплітером

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Self-sustained oscillations in the flow past a circular cylinder with splitter plate

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Чисельно розв'язано задачу про генерацію автоколивань в потоці при обтіканні кругового циліндра з розділювальною пластиною (сплітером). Автоколивання полів швидкості і тиску викликано періодичним формуванням та відривом вихорів за циліндром. Показано еволюцію поля завихренності і сил, що діють на обтічне тіло, за різної довжини пластини сплітера.

Ключові слова: обтікання циліндра, сплітер, автоколивання, відрив вихорів, вихровий слід.

The problem of generation of self-sustained oscillations in the flow past a circular cylinder with a splitter plate is solved numerically. At the initial moment the fluid is at rest. We investigate both the transient process and the steady periodic vortex formation and shedding behind the cylinder. The evolution of the vorticity field is shown for various length of the splitter plate. It is demonstrated that the splitter oriented along the flow direction significantly reduces 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 nonmonotonically. In this paper we offer our explanation of this phenomenon. It is shown that when turning the splitter plate at some angle from the flow direction the process of vortex formation and shedding behind the cylinder is no longer strictly regular and periodic at the range of Reynolds number considered in the paper.

Key Words: flow past cylinder, vortex shedding, splitter plate, vortex wake, OpenFOAM.

Статтю представив д.ф.-м.н., проф. Жук Я.О.

Since vortex shedding in a flow behind a cylinder can lead to undesirable vibrations [1], it is necessary to be able to control this process. A simple way to decrease the drag and the oscillating lift force consists in positioning a splitter plate in the wake. The flow past a cylinder with a splitter plate has been the subject of many computational and experimental works [2-8]. In the experimental work [2] the models with 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 $10^4 < \mathrm{Re} < 5\times10^4$. It was concluded that splitter plates reduce the drag by stabilizing the separation points. They produce a wake narrower than that of a plain cylinder. Even a very short splitter plate markedly reduce the drag coefficient C_d. For example, h/d=1/16 effects the 9% reduction and h/d=1/8 effects the 16% reduction. C_d may be reduced by as much as 31% with a plate of h/d=1. The vortex shedding frequency varies by $\pm10\%$ within the range $h/d \le 2$. In [3] a discrete vortex model was developed to investigate the unsteady flow in the wake of a 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 [4] the control over the vortex shedding with splitter plates was numerically simulated at the Reynolds numbers of 80-160. Prediction of the vortex shedding was in close agreement with the experimental data by Williamson [5]. The experimental results in [6, 9, 10] were very similar to the numerical results in [4] at Re = 120-160. The net drag was significantly reduced by the splitter plate. There existed an optimum length of the plate for minimum drag at a given Reynolds number. In [7] an experimental study was carried out to investigate the effect of a splitter plate. The splitter plate length *h*/*d* varied from 0 to 1.5 and the Reynolds number was assumed to be 2400 and 3000. The experimental results showed that the splitter plate had an effect on stabilization of wake turbulences. For splitter plate length of *h*/*d*=0.5 and 0.75, the flow structure was significantly modified. The vortex shedding frequency decreased as compared to the bare cylinder case. For higher splitter plate length of *h*/*d*=1, 1.25 and 1.5, the generation of a secondary vortex was observed. It was determined that the splitter plate length of *h*/*d*=1 was optimal for suppression of the velocity fluctuations. The stabilizing effect of the splitter plate was more obvious at Re=3000. In [8] the flow around a cylinder with a splitter plate was numerically investigated using the finite volume method. The problem was considered in frames of Reynolds Averaged Navier-Stokes approximation. It was revealed that the vortex shedding behind a cylinder is completely suppressed when the splitter plate length is longer than some critical value which was proportional to the Reynolds number. When the splitter plate length was similar to the diameter of the cylinder, the vortex frequency, drag, and oscillation of the lift coefficient reached local minimum.

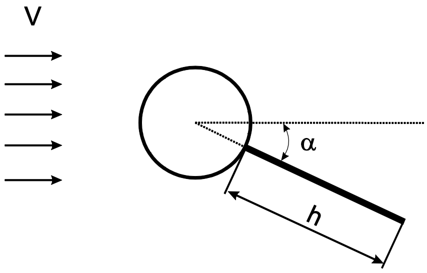

Fig. 1. Geometry of the problem

In this paper we described the hydrodynamic feedback channel which causes the periodic process of vortex shedding. The numerical simulation of the steady process of vortex shedding is performed for the splitter length in the range from *h*=*d*/2 to *h*=11*d*/2 but only for $\mathrm{Re}=200$. It is shown that a splitter plate oriented 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 decreases monotonically. The amplitudes of oscillation of the forces applied to the body change nonmonotonically. We give our explanation of this phenomenon. In the present paper the problem of viscous incompressible fluid flow past a cylinder with a splitter plate is solved numerically by using Direct Numerical Simulation (DNS) technique.

Statement of the problem. The algorithm for its numerical solution

Let us consider the problem of a flow of viscous incompressible fluid past a stationary circular cylinder with a flat splitter attached behind the cylinder. The splitter is an absolutely rigid thin plate. It can be oriented along the flow or 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 enters the domain through the left side ($x=0$) with the constant velocity V. Then the flow runs against a circular cylinder of diameter *d* with a thin splitter plate 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 model of viscous incompressible Newtonian fluid. Such flow 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 ρV^2. The key parameter of the problem which enters into the governing equations is the Reynolds number $\mathrm{Re}=Vd/\nu$, where ν is the kinematic viscosity of the medium.

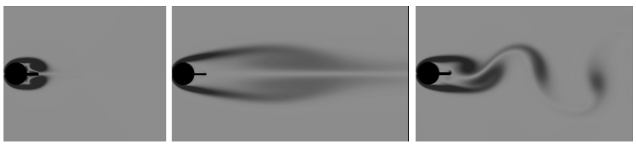

Fig. 2. Vorticity field during the transient process Re=200, $\alpha=0$, *h*=*d*/2: a) *t*=2.5, b) *t*=41, c) *t*=140

The boundary conditions for the velocity were specified as follows: the uniform flow at the inlet ($x=0$), the non-slip condition at the solid surface of the cylinder and the splitter, the zero normal gradient at the outlet ($x=L_1$). For pressure, the condition of zero normal gradient was formulated all over the boundary 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 h varied from $0.5d$ to $5.5d$.

The algorithm for numerical solution of the formulated problem is described in detail in [11]. It is based on the finite volume method, which is the most popular numerical approach in computational fluid mechanics. The toolbox with open code OpenFOAM was used for calculations. The spatial discretization was performed on a structured O-type grid with nodes concentrated near the solid surface of the cylinder and the splitter. The length of a control volume's side 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 [1]. 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.

Analysis of the numerical results

First we consider the transient process for the case that the splitter length is equal to the cylinder's radius $h=d/2$ and $\alpha = 0$. The flow develops in time from rest. Once the motion begins, a pair of vortices that have vorticity equal in absolute value but opposite in sign arises behind the cylinder. In other

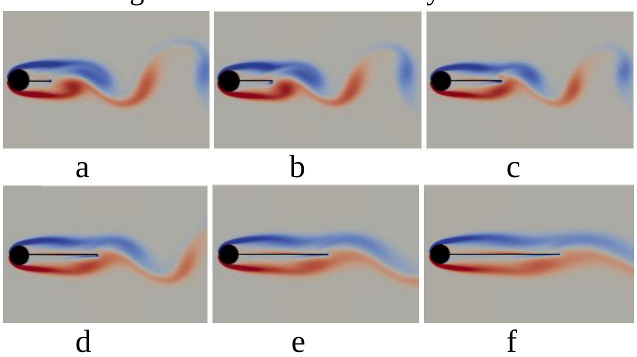

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Fig. 3. Vorticity field for the steady process of vortex shedding (Re=200, $\alpha = 0$): a) $h=d$, b) $h=3d/2$, c) $h=5d/2$, d) $h=7d/2$, e) $h=9d/2$, f) $h=11d/2$

words, two symmetric vortices that rotate in opposite directions appear at the rear. Figs. 2 demonstrate the vorticity field at three moments of time. In fig. 2a the vortex pair behind the cylinder has just arisen. The horizontal size of the vortices only slightly exceeds the diameter of the cylinder. As time goes on, the

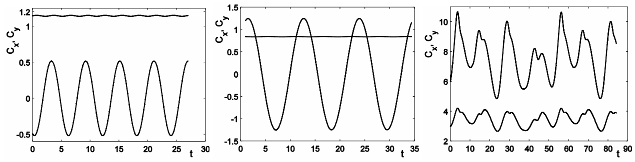

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Fig. 4. Periodic oscillations of the force coefficients acting on the solid body: a) for $h=d/2$, $\alpha = 0$, the upper curve is the drag coefficient C_x, the lower curve is the lift coefficient C_y, b) for $h=11d/2$, $\alpha = 0$, the curve with a small amplitude of oscillations is C_x, the curve with the high amplitude is C_y, c) for $h=11d/2$, $\alpha = 20^{\circ}$, the upper curve is C_y, the lower curve is C_x

extent of the vortex pair grows and reaches a certain maximum value at the time approximately t=41. The vorticity field at that moment of time is shown in fig. 2b. 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 velocity gradients. High transverse gradients lead to flow instability. On further increase of the vortex pair, the symmetry of the flow is violated. At the moment t = 57 the flow symmetry begins to collapse. As time goes on, the flow symmetry behind the cylinder completely collapses and the flow passes into the regime of periodic vortex shedding. The upper and lower vortices detach in turn. This regime is demonstrated in fig. 2c for the time t = 140.

Now let us consider the steady process of self-sustained oscillations of the flow behind the cylinder. The vorticity fields are represented in fig. 3 for various lengths of the splitter plate. The splitter is positioned along the flow. It can be seen that the vortices are formed not immediately behind the cylinder surface, as it was in the flow past a circular cylinder without a splitter [1], but at some distance from the rear of the cylinder. It means that the vortices interact not so much with the cylinder, but rather with the splitter plate. 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. As the splitter length increases, the interaction of the rear part of the splitter with the large vortices formed in the shear layers increases. At splitter length *h*=5*d*/2 the large eddies are formed before the rear part of the splitter. With further splitter elongation (*h*=9*d*/2 and *h*=11*d*/2), the large eddies in the wake are 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.

Таблиця 1

The periodic flow characteristics for various values of the splitter length *h* (Re=200, α=0). The following denotations are used: *T* is the oscillation period, St is the Strouhal number, C_x^c is the average value of the drag coefficient, A_x is the amplitude of the drag coefficient oscillation, A_y is the amplitude of the lift coefficient oscillation, $N = A_x / A_y$ is the ratio of the oscillation amplitudes of the coefficients C_x^0, C_y^0

h	0	r	$2r$	$3r$	$5r$	$7r$	$9r$	$11r$
T	5.082	5.89	6.30	5.72	5.78	7.22	9.11	11.2
St	0.197	0.170	0.159	0.175	0.173	0.139	0.110	0.089
C_x^c	1.343	1.146	1.044	1.039	0.997	0.927	0.875	0.840
A_x	$5\cdot10^{-2}$	$7.2\cdot10^{-3}$	$2.4\cdot10^{-3}$	$6.2\cdot10^{-3}$	$1.1\cdot10^{-2}$	$5.2\cdot10^{-3}$	$4.4\cdot10^{-3}$	$4.9\cdot10^{-3}$
A_y	0.686	0.518	0.333	0.416	0.949	1.150	1.241	1.249
N	$7.3\cdot10^{-2}$	$1.39\cdot10^{-2}$	$0.72\cdot10^{-2}$	$1.49\cdot10^{-2}$	$1.16\cdot10^{-2}$	$0.45\cdot10^{-2}$	$0.35\cdot10^{-2}$	$0.39\cdot10^{-2}$

The periodic nature of the flow in the cylinder's wake leads to the fact that the forces applied to the cylinder change periodically 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. 4a 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. 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 [1]. The other two fig. 4 show the time variation of the force coefficients for the splitter length $h = 11d/2$. Fig. 4b 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 plate the amplitude of 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. 4a and 4b 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. 4c corresponds to the case when the splitter is turned at the angle $\alpha = 20^\circ$ 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 of the lifting force lies higher than the curve of the drag force. So, even a relatively small deviation of the splitter by the angle $\alpha = 20^\circ$ 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. Even a slight deviation of the splitter plate of the length $h = 11d/2$ leads to violation of strict regularity of the vortex shedding process. Figs 5 show the vorticity field for $\alpha = 20^\circ$. 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. The large vortices and reverse flow zones may appear between the upper separated free shear layer and the splitter surface. On the contrary, in the lower part of the cylinder the shear layer is located near the solid surface up to the splitter tip. The separation of the lower shear layer and the formation of a large vortex occur behind the splitter. Thus, the oscillations of the upper and lower shear layers are of different nature and differ in frequency.

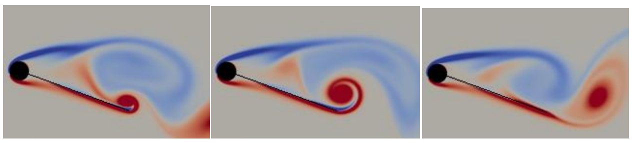

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Fig. 5. The vorticity field during the vortex shedding period *T* (Re=200, $\alpha = 20^\circ$, *h*=11*d*/2): a) at some time $t = t_0$, b) at $t = t_0 + T/4$, c) at $t = t_0 + 3T/4$

This reasoning explains the violation of strict regularity and 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 forces applied to the cylinder and the splitter can be represented as a sum of constant and oscillating parts $\mathbf{F} = \mathbf{F}^c + \mathbf{F}^o$. It is obvious that if the splitter plate is positioned along the incoming flow direction, $C_y^c = 0$, if the splitter deviates by some angle α, a nonzero mean value of the lift force arises $C_y^c \neq 0$. Table 1 shows the values of the constant component C_x^c, the amplitudes of the oscillating components C_x^0, C_y^0 and the ratio of these amplitudes for various splitter lengths. In addition, the table shows the period of the oscillation and the corresponding Strouhal number. It is evident that 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 because the vortex formation behind the cylinder leads to appearance of some reverse motion zones near the surface of the splitter plate. The reverse flow near the body reduces the drag. It should also be noted that the splitter plate substantially decreases the amplitude of the drag coefficient oscillation. 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 plate, 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 plate, the oscillation amplitude of C_x^0 behaves nonmonotonically. First, it decreases as *h* grows up to *h=d*, then it increases for *h* up to *h*=5*d*/2, then it decreases again for *h* up to *h*=9*d*/2 and then increases 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 plate the oscillation period, that is the time between shedding two adjacent vortices, increases substantially. On further elongation the splitter plate the period of vortex formation increases as well. However, this process is nonmonotonic. Thus, if the splitter plate length changes from *h=d* to *h*=3*d*/2, the period sharply decreases. Figs. 6 show instantaneous streamline patterns at various splitter plate lengths. It is easy to see that there are large vortex structures on both sides of the splitter. 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. The fact that a different number of

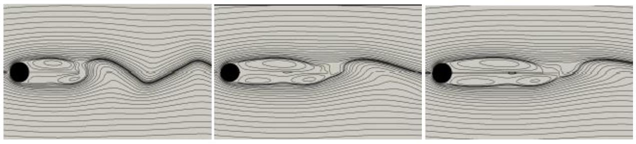

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Fig. 6. Instantaneous streamlines (Re=200, *α*=0): a) *h*=5*d*/2, b) *h*=9*d*/2, c) *h*=11*d*/2

the vortices are observed along the splitters of different length explains why the amplitude of the drag coefficient oscillation behaves nonmonotonically with increase in the splitter length. First, it decreases as *h* increases 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*=5*d*/2, these vortices grow, which leads to reduction in the flow stability. As a consequence, the amplitude of the drag force oscillation increases with the splitter extension to *h*=5*d*/2. At *h*=5*d*/2 two large vortices arise alternately near the splitter sides. As the splitter length increases from *h*=5*d*/2 to *h*=9*d*/2, the amplitude of oscillation of the drag coefficient decreases. With a further elongation the splitter plate the size of the vortices near the splitter sides increases. This again leads to the instability of such a system. Therefore, as the splitter length increases above *h*=9*d*/2, the amplitude of oscillation of the drag force increases again. However the average value of the drag coefficient decreases monotonically with increasing splitter length *h*.

Conclusion

The flow past a circular cylinder with a flat splitter plate is numerically simulated. The self-sustained oscillations of the flow caused by the periodic vortex shedding are studied. 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 a splitter plate oriented along the flow direction reduces significantly the average drag and the amplitude of oscillation of the forces. With increasing splitter length the average drag decreases monotonically.

The amplitudes of oscillation of the forces change nonmonotonically. If the splitter plate is turned at the angle $\alpha = 20^{\circ}$, the process of vortex shedding is also observed, but such a process is no longer regular and periodic. In conclusion it should be said that the periodic change in pressure on the side of the body is a source of sound oscillations of the dipole type.

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