

TRANSPORT. AVIATION TRANSPORT
TRANSPORTS. AVIĀCIJAS TRANSPORTS**ANALYSIS OF UNSTEADY FLOW PERIODIC PULSATIONS ACTION ON
AERODYNAMICS OF BODIES AT SUBCRITICAL REYNOLDS NUMBERS****NESTACIONĀRAS PLŪSMAS PERIODISKU PULSĀCIJU IETEKMES UZ
ĶERMENŪ AERODINAMIKU PIE ZEMKRITISKIEM REYNOLDSA SKAITĻIEM
ANALĪZE**

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Introduction

The study of the aerodynamic characteristics of bodies in the nonstationary hardly-compressible flow with the low-frequency periodic velocity pulsations represents theoretical and practical interest as well. At subcritical Reynolds numbers, if the flow's pulsations frequency is close to the frequency of separation frequency of makrovortexes, the flow pulsations can have a significant effect on the nature of the bodies streamlining with the flow separation zones [1, 2].

In this work by means of computer modelation were investigated aerodynamic parameters of the infinite cylinder, streamlined by the nonstationary gas flow with the periodic low-frequency pulsations relative to the average velocity at the Reynolds numbers $0.5 \cdot (10^3 \div 10^5)$. For the numerical calculations were used the Navier-Stokes equations and $(k - \epsilon)$ model of turbulence. Discretization of a computational domain of the flow was made by the method of finite volumes. For creation of a geometrical model and computation of the task, set of CAD/CAE software SolidWorks/CosmosFloWorks was used.

It was investigated the influence of flow pulsations in the range of the frequencies of $f = 0 \div 50$ Hz with the dimensionless amplitudes of pulsations $A = 0 \div 1$ relative to the average velocity of flow. Also was analyzed the influence of external flow with the periodic velocity pulsations of sinusoidal and rectangular type (the V , V_0 - velocity and the average velocity of flow, t – time)

$$V(t) = V_0 \cdot (1 + A \sin(2\pi ft)) \text{ m/s,}$$

$$V(t) = 1.45 \cdot (0.1 + A \cdot \text{sign}(\sin(2\pi ft))) \text{ m/s,}$$

$$\text{sign}(\varphi) = \begin{cases} 1; \varphi > 0 \\ 0; \varphi = 0 \\ -1; \varphi < 0 \end{cases}$$

Purpose of the work is to determine conditions and special features of the influence of periodic flow pulsations on the nature of flow, the frequency of vortex separation, form of Karman vortex trail and the aerodynamic coefficients of cylinder at subcritical flow's regime.

Results and discussion

The results of numerical calculations were processed in the dimensionless Reynolds numbers Re , Strouhal numbers Sh (dimensionless frequency of process), Mach numbers M (for the processes with different temperatures or pressures):

$$Re_0 = V_0 D / \nu, \quad Sh_0 = f_0 D / V_0, \quad Sh = f D / V_0, \quad M = V_0 / (\chi RT),$$

where D – diameter of cylinder, $\nu = 0,0000145 \text{ m}^2/\text{s}$ – kinematic viscosity modulus of air at normal conditions, f_0 – frequency of vortex separation, f – frequency of flow pulsations, χ – adiabatic index (for air $\chi = 1.4$), R – gas constant, T – fluid's temperature; Sh_0 , Sh – dimensionless frequencies of vortex separation and flow pulsations respectively. For the aerodynamically similar processes with different temperatures, diameters of cylinders, velocities of the flow, densities of medium and pulsations frequencies must be observed the equalities $Re_1 = Re_2$, $Sh_{01} = Sh_{02}$, $Sh_1 = Sh_2$, $M_1 = M_2$.

In the case of subcritical stationary flow ($5 \cdot 10^3 < Re_0 < 10^5$, $V = V_0 = \text{const}$) the dimensionless frequency of vortex separation Sh_{00} (hereafter we will call it eigenfrequency of the vortex separation") and the average Drag coefficient of the cylinder $\langle C_x \rangle$ barely depends on Reynolds number and, as shown in Figures 1 and 2, is respectively equal $Sh_{00} \approx 0.212$, $\langle C_x \rangle \approx 1.1$ [3]. On the graphs also are showed the results of the numerical calculations, executed by the authors and the confirming adequacy of used calculation methods. At the known value of Sh_{00} the dimensional frequency of the vortex separation can be determined according to the empirical equation [1].

$$f_{00} = (0.21 \dots 0.22) V_0 / D \approx 0.212 \nu Re / D^2 \text{ [1]}$$

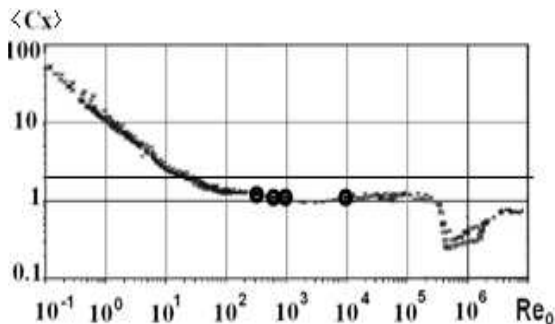


Fig. 1. The Drag coefficient of a circular cylinder as a function of flow regimes and Reynolds number with respect to cylinder's diameter

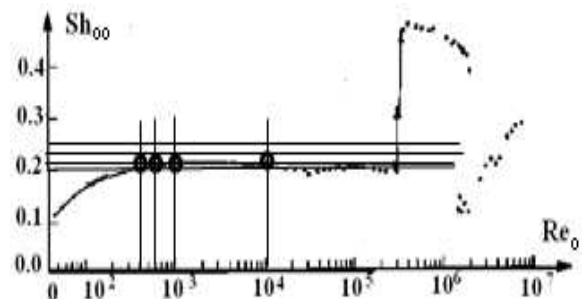


Fig. 2. The Strouhal number for a smooth circular cylinder as a function of the Reynolds number

For aerodynamically similar regimes according to equality conditions of Strouhal numbers Sh_0 follows that change of the cylinder's diameter or viscosity of flow initiate corresponding change of vortex separation frequency:

$$f_0 / f_{01} = \nu D_1^2 / \nu_1 D^2.$$

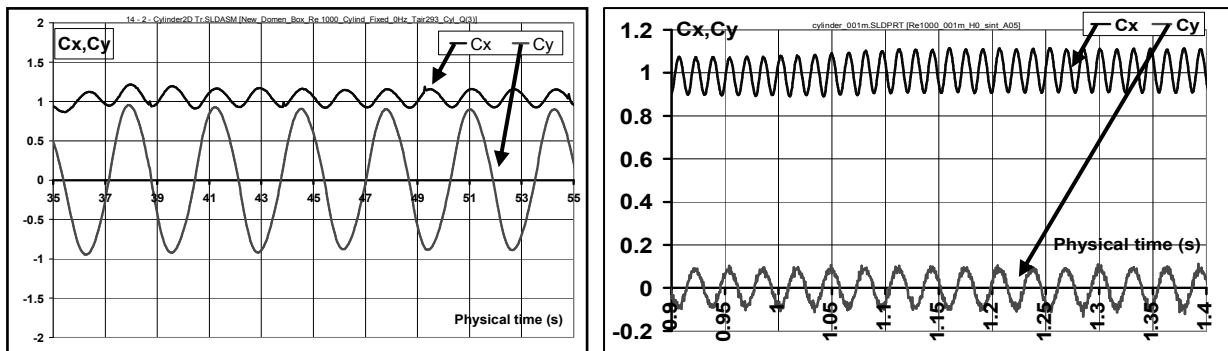
For instance, at $D = 10^{-1}$ [m] and $D_1 = 10^{-2}$ [m] and constant viscosities $\nu = \nu_1$ vortex separation frequency will differ 100 times. (see Figure 3).

As calculations showed, in the stationary flow a change of cylinder's diameter causes a proportional increase of the amplitude values of Lift coefficient A_{Cy} .

$$A_{Cy2} = A_{Cy1} * D_2 / D_1.$$

For instance, for cylinder at $Re_0 = 1000$ and $D = 0.1$ m and stationary flow the amplitude values of the Lift coefficient and Drag coefficient are values of the same order $A_{Cy} \sim A_{Cx} \sim 1$ (see Figure 3). With the decrease of diameter 10 times respectively decrease the values of Lift coefficient

($A_{Cy} \sim 0.1$). In the case of the pulsing flow the qualitative character of dependence remains, but accurately it is not observed. To the value A_{Cx} change of the diameter practically does not affect in entire investigated range of the numbers Re_0 and Sh_0 .

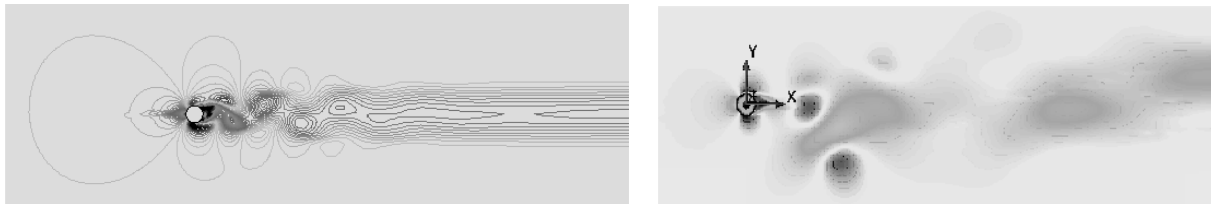


$Re = 1000, D = 0.1\text{m}, f = 0\text{Hz}, T_{\text{air}} = 293\text{K},$
 $T_{\text{cyl}} = Q$

$Re = 1000, D = 0.01\text{m}, f = 0\text{Hz}, T_{\text{air}} = 293\text{K}$
 $T_{\text{cyl}} = 293\text{K}$

Fig. 3. Influence of diameter cylinder D on frequency and amplitude of pulsations Cy, Cx for $f = 0, Re_0 = 1000$

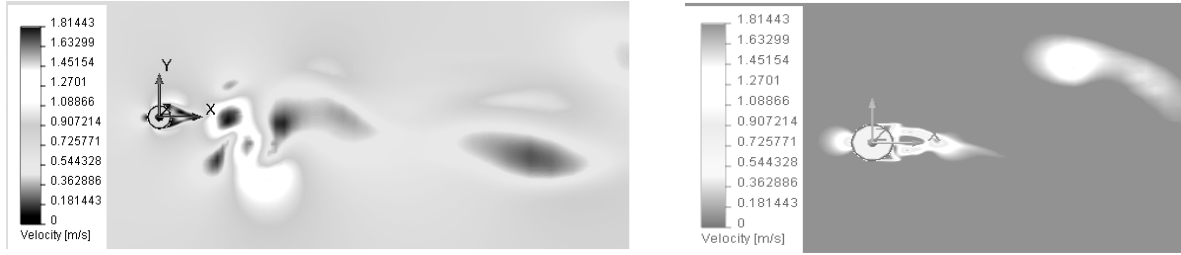
Analysis of numerous results of calculations showed that the flow's pulsations significantly influence the pictures of nonstationary velocity field near the cylinder, the frequency of vortex separation and the form of Karman's trail. In Figure 4 are showed the pictures of the velocity field in the stationary flow and the pulsing external flow with sinusoidal and rectangular impulses.



$D = 0.01\text{m}, Re_0 = 1000, T_{\text{air}} = T_{\text{cyl}}, f = 0\text{Hz}, t = 1.0\text{s};$
sine impulses

$D = 0.01\text{m}, Re_0 = 1000, T_{\text{air}} = T_{\text{cyl}}, f = 12\text{Hz},$
 $t = 1\text{s};$
sine impulses

Fig. 4a. Distribution of velocity fields in different time moments ($t = 1.0\text{s}$ and $t = 1.1\text{s}$, $D = 0.01\text{m}$, $Re_0 = 1000, T_{\text{air}} = T_{\text{cyl}}$, sine impulses, $f = 12\text{Hz}$)



$t = 1.0s$, $D = 0.01m$, $Re_0 = 1000$, $T_{air} = T_{cyl}$,
rectangular impulses, $H = 12Hz$.

$t = 1.1s$, $D = 0.01m$, $Re = 1000_0$, $T_{air} = T_{cyl}$,
rectangular impulses, $H = 12Hz$

Fig. 4b. Distribution of velocity fields in different time moments ($t = 1.0s$ and $t = 1.1s$, $D = 0.01m$, $Re_0 = 1000$, $T_{air} = T_{cyl}$, rectangular impulses, $f = 12Hz$)

In the stationary flow the frequency of vortex separation does not depend on time. Vortexes behind the cylinder are positioned in staggered order with a constant step. In the pulsating flow the intensity and the frequency of the of vortex separation depend on time, frequency, form and amplitude of flow pulsations. Karman vortex street behind the cylinder in this case is deformed both in the longitudinal and transverse directions and consists of the periodic system of free vortexes with the variable step and the variable intensity (see Figure 4).

Since the equation of relation between C_y and velocity of circulation for the closed circle around the body $\Gamma(t)$ is correct also in case of unsteady bodies streamlining $\Gamma(t) = 0.5 \cdot C_y(t) \cdot D \cdot V(t)$, intensity of vortexes at the separation moment can be approximately evaluated according to the values of the amplitudes of the pulsations $C_y(t)$. Change in the amplitude value of C_y testifies about a change of the intensity of the bound vortex (lifting vortex) of cylinder on the value of $\Delta\Gamma$ and to appearance of additional free separation vortexes with the total circulation $-\Delta\Gamma$. The frequency of the separation of additional free vortexes depends on the conditions of cylinder's streamlining.

In the stationary incident external flow there is one specific dimensionless frequency Sh_{00} – eigenfrequency of separation of the pairs of vortexes, which coincides with the frequency of the variations of the Lift coefficient C_y (see Figure 3). The dimensionless frequency of variations of the Drag coefficient C_x is two times higher than Sh_{00} and the frequency of the variations of the C_y (nature of its changes is determined by each of the alternately separating vortexes). Average value of periodic Lift force in this case is equal to zero, and the average value of Drag force $\langle C_x \rangle \approx 1.1$.

During the analysis of the influence of the pulsing flow on the aerodynamic coefficients it is necessary to determine the basic frequencies of the vortexes separation and pulsations of aerodynamic coefficients, and if subharmonics have a significant effect, consider them as well. Preliminary processing of the results of the calculations showed that for the analysis of the action of external flow's pulsations on aerodynamics of cylinder is enough to determine the first two characteristic frequencies:

- the basic dimensionless frequency of the vortex separation $Sh_0^{(1)}$ (the first harmonic), which in the stationary flow is equal to the eigenfrequency of vortex separation Sh_{00} ; in the general case the main frequency $Sh_0^{(1)}$ depends on flow's pulsations frequency Sh ;
- the characteristic dimensionless frequency of subharmonic $Sh_0^{(2)}$ (frequency of the separation of satellite vortexes), which also depends on flow's pulsations frequency Sh .

The dimensional frequencies of the first harmonic and subharmonic were determined as a result of processing of calculation data about the Lift coefficient in the form of the graph of dependence $C_y(t)$. Transition to the dimensionless form is preceded according to the formulas, given above.

Main frequency of vortex separation $f_0^{(1)}$ was determined by the number of positive or negative half-periods on the graphs $C_y(t)$ in the defined time interval.

In the case of the small flow pulsations frequencies and weak action on the vortex separation ($Sh < 0.08$) subfrequency $f_0^{(2)}$ is determined by the frequency of modulation of curves $C_y(t)$ or $C_x(t)$ and practically is equal to the frequency of flow (Figure 5). For instance, for the sinusoidal pulsations (Figure 5a) the frequency of the first harmonic $f_0^{(1)} = 33$ Hz, and subfrequency $f_0^{(2)} = 1$ Hz.

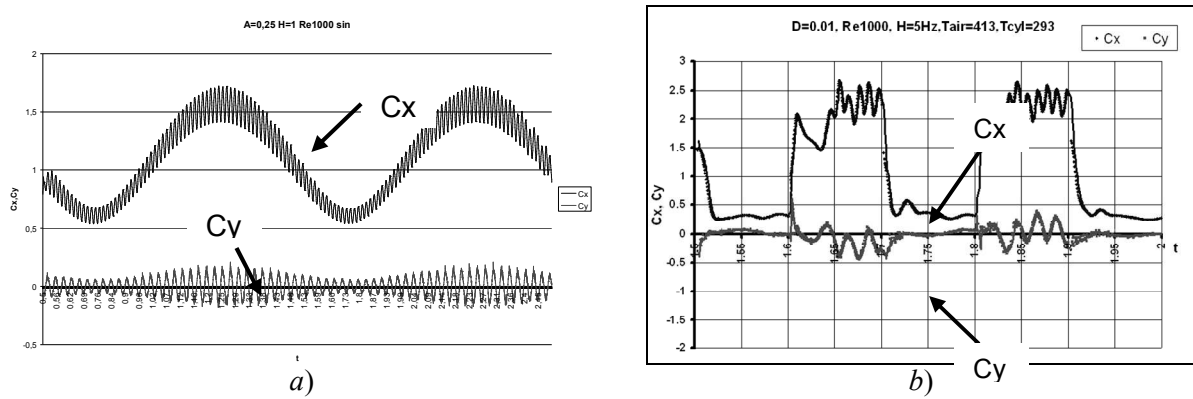


Fig. 5. Influence of form of impulse on frequency and form of pulsations of C_x , C_y
 a) $D = 0.01\text{m}$, $\text{Re}1000$, $f = 1\text{Hz}$, $A = 0.25$, $V \sim \sin(t)$; b) $D = 0.01\text{m}$, $\text{Re}1000$, $f = 5\text{Hz}$, $A = 0.5$,
 $V \sim \text{sign}(\sin(t))$

At $\text{Sh} > 0.08$ on the curves of $C_y(t)$ appear local weak extremums (see Figure 6) initiated by the pulsations of velocity, which testify about the separation of additional (satellite) vortexes with the frequency and the intensity, that differ from basic vortexes. In these cases the subfrequency $f_0^{(2)}$ is determined by the number of local extremums on the positive (negative) half-periods of curve $C_y(t)$ in the defined time interval. The dimensional frequencies of the variations of Drag coefficient (first harmonic and subharmonic) were determined as a result of processing of calculation dates for the dependence $C_x(t)$ given by means of above described method.

General concept about the influence of the dimensionless frequency of the flow in the range $0 \leq \text{Sh} < 1.0$ on form and amplitude of the pulsations of the aerodynamic coefficients C_x , C_y , and also form and the position of local extremums is possible to obtain on the basis of Figures 6a and 6b.

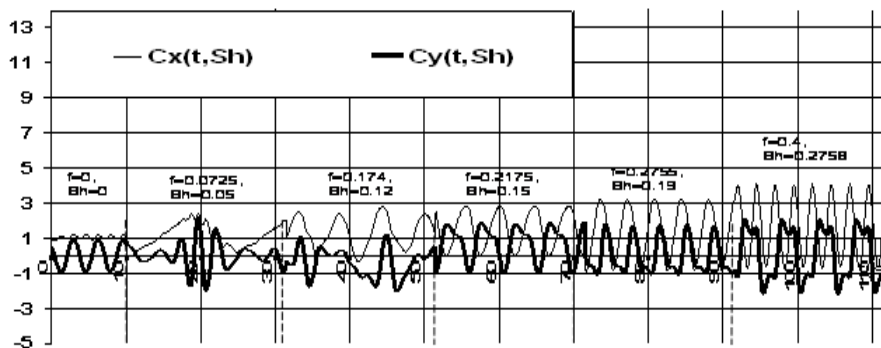


Fig. 6a. Influence of flow pulsations frequency on form and amplitude of pulsations of aerodynamic coefficients C_x , C_y in the range the flow pulsations frequencies $f = 0 - 0.4$; and Strouhal numbers $\text{Sh} = 0 - 0.2758$ for $\text{Re} = 1000$ and $D = 0.1$. By the dashed line separated zones within with $f = \text{const}$, $\text{Sh} = \text{const}$.

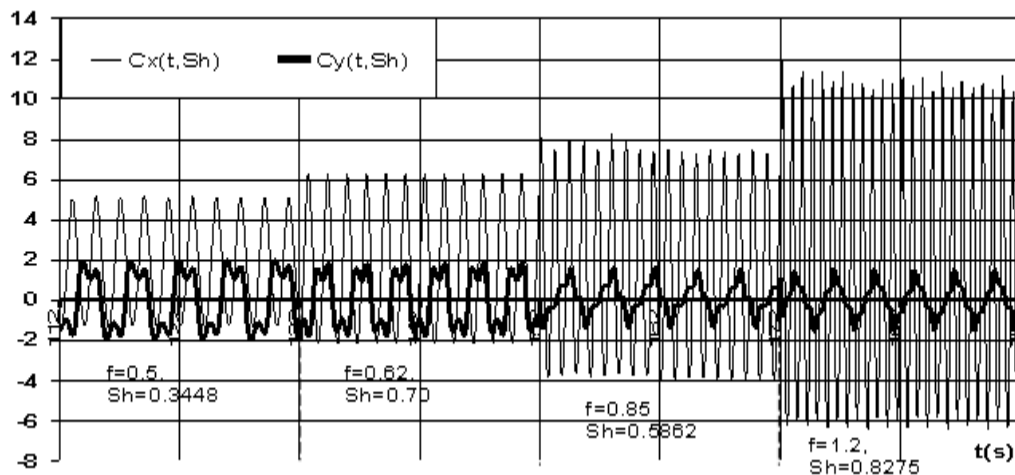


Fig. 6b. Influence of flow pulsations frequency on form and amplitude of pulsations of aerodynamic coefficients C_x , C_y in the range the flow pulsations frequencies $f = 0.5 - 1.2$; and Strouhal numbers $Sh = 0.3448 - 0.8275$ for $Re = 1000$ and $D = 0.1$. By the dashed line separated zones within with $f = \text{const}$, $Sh = \text{const}$.

Nature of the influence of the dimensionless flow's pulsation frequency on averaged Drag coefficient $\langle C_x \rangle$ is shown in Figure 7.

In the range of Strouhal numbers $Sh = 0.02 - 0.45$ (for the cylinder with the the diameter $D = 0.1\text{m}$ and at $Re = 1000$ in the range of dimensional frequencies $f = 0 - 0,66\text{ Hz}$) flow's pulsations cause an increase of the averaged coefficient $\langle C_x \rangle$ approximately in 40-50 % in comparison with the corresponding value in the stationary flow $\langle C_{x_0} \rangle = 1.1$.

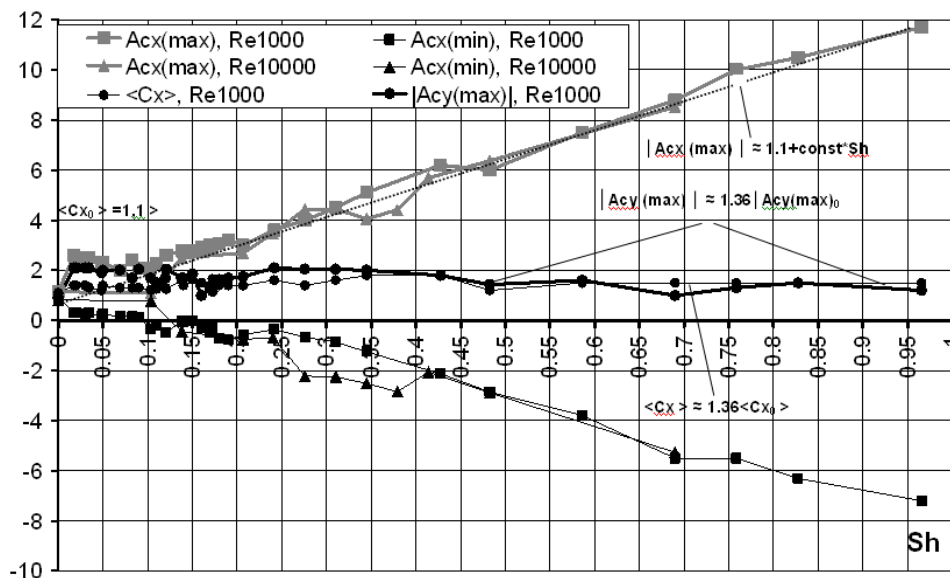


Fig.7. Influence of frequency of the flow Sh on variations of $A_{C_x(\max)}$, $A_{C_x(\min)}$, $\langle C_x \rangle$, $A_{C_y(\max)}$ for $Re = 1000$, $Re = 10000$, $D = 0.1\text{m}$.

In the range of relatively large Strouhal numbers at $Sh > 0.5$ flow's pulsations practically don't influence averaged Drag coefficient. Approximately it is possible to consider that $\langle C_x \rangle \approx \text{const}$ and it exceeds the corresponding value in the stationary flow in 20- 25%. Reynolds number at $Sh > 0.5$, as in the case of stationary flow, also practically does not influence the nature of change of $\langle C_x \rangle$. The weak influence of Reynolds number is observed and range $0.18 < Sh < 0.44$ see Figure 7), where the frequency of the first harmonic increases from the minimum value to the value of the eigenfrequency Sh_{00} (see Figure 8).

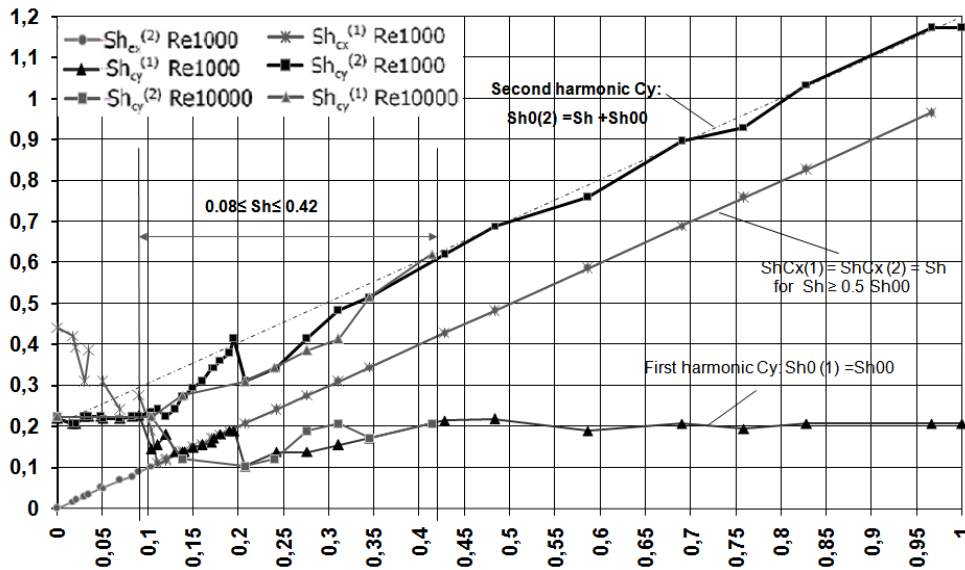


Fig. 8. Dependence of dimensionless frequencies of vortex separation $Sh_0^{(1)}$, $Sh_0^{(2)}$ and $Sh_{Cx}^{(1)}$, $Sh_{Cx}^{(2)}$ from flow pulsation frequency Sh for $Re1000$, $Re10000$

Unlike the average value $\langle C_x \rangle$, the amplitude values of the Drag coefficient A_{Cx} in the range $Sh > 0.5$ increases approximately linearly with an increase of Sh and at $Sh \approx 1$ (for $D = 0.1m$, $Re = 1000$ dimensional frequency $f \approx 0.75 - 1.4$ Hz). This increase is more than 10 – 12 times higher than the corresponding value in the stationary flow (see Figure 7). Moreover, in the entire range of $Sh > 0.15$ minimum amplitude values of Drag coefficient become negative (Figure 7). It means that instead of the Resisting force, along the flow, on the cylinder periodically will act the Propelling force directed against the flow.

The amplitude values of alternating Lift coefficient A_{Cx} in the zone of large Strouhal numbers $Sh > 0.5$ unlike to the value A_{Cy} are approximately constant $A_{Cy(max)} \approx 1.36 |A_{Cy(max)}|_0$ (here $|A_{Cy(max)}|_0 = 0.95$ absolute value of amplitude value A_{Cy} in steady flow, see Figure 7).

At Strouhal numbers $Sh < 0.5$, excluding range $0 < Sh < 0.02$ and $0.08 < Sh < 0.18$, value of A_{Cy} is approximately constant and in is 2 – 2.5 times higher than A_{Cy} in the stationary flow. In range $0 < Sh < 0.02$ value A_{Cy} sharply increase, which indicates the growth of the intensity of separation vortices. In range $0.08 < Sh < 0.18$, on the contrary, vortices partially are suppressed and value A_{Cy} decreases till the value corresponding to stationary flow (Figure 7).

Thus, in the pulsing flow on the cylinder acts the periodic longitudinal force, whose amplitude is proportional to the flow's pulsation frequency and which several times, exceeds the amplitude of periodic transverse force. The dominant role in the creation of longitudinal force plays the vortices separation with the frequency, equal to the flow's pulsation frequency.

Analysis of dependence of the basic dimensionless vortex separation frequency $Sh_0^{(1)}$ (the first harmonic) on the frequency of flow Sh in the narrow range $0 \leq Sh < 0.42$ was executed by the authors earlier in the work [4]. Processing the results of calculations in the wider range $0 \leq Sh < 1.0$ taking into account the first two harmonics for the frequency of vortex separation and frequency of Drag coefficient's variation made it possible to obtain the following regularities. There are three consecutive zones of flow's Strouhal numbers, inside which the dimensionless frequency of the vortex separation $Sh_0^{(1)}$ (the first harmonic) changes or remains constant.

In the first zone (range of flow's Strouhal numbers $0 < Sh < 0.09$) the vortex separation occurs with a constant dimensionless frequency of the first harmonic $Sh_0^{(1)}$, equal to the frequency of separation in the stationary flow ($Sh_0^{(1)} \approx Sh_{00} \approx 0.21$, see Figure 8). The influence of flow's pulsations reveals in the appearance of modulation of the dependence of $C_y(t)$ (see Figure 6) and the subharmonics with the dimensionless frequency $Sh_0^{(2)}$, is equal to the flow's frequency $Sh_0^{(2)} = Sh$ (Figure 8, the bisector of right angle), which in range $0 < Sh < 0.09$ practically do not influence the main frequency of vortex separation.

In the second zone ($0.09 < Sh < 0.42$) appears the special features of the nonlinear action of flow pulsations on the vortex separation and the Karman trail. With an increase of dimensionless external flow's pulsations frequency, in this zone several times occurs the partial suppression of the main frequency of vortex separation by flow's pulsations.

In the range $0.08 < Sh < 0.42$ frequency of the first harmonic $Sh_0^{(1)}$ three times reaches the minimum $Sh_0^{(1)} \approx 0.5 Sh_{00} \approx 0.11$ (at $Sh = 0.5 Sh_{00} = 0.11$, $Sh = 0.14$ и $Sh = Sh_{00} = 0.21$) and the three times maximum $Sh_0^{(1)} \approx Sh_{00} \approx 0.21$ (at $Sh = 0.125$, $Sh 0.9Sh_{00} = 0.19$ и $Sh = 2Sh_{00} = 0.42$). Especially in this zone in the range $0.21 \leq Sh < 0.36$ amplitude value of coefficient $Cy(t)$ (respectively and the intensity of separation vortex) reaches extreme value – 2 to 2.5 times exceeding that corresponding value of Cy in the stationary flow.

In the third zone ($Sh > 0.42$) an increase of frequency of flow pulsations does not affect the frequency of the first harmonic $Sh_0^{(1)}$, which is approximately to 5% lower than its eigenfrequency of vortex separation Sh_{00} . The value $Sh_0^{(1)}$ in this zone does not depend on the Reynolds number. Separation of intensive additional vortexes in the considered zone significantly changes the form of curve $Cy(t)$, on which appear the clearly expressed symmetrical extremums see Figure 6, $f \geq 0.4\text{Hz}$, $Sh \geq 0.2758$). The dimensionless frequency of subharmonics $Sh_0^{(2)}$ (second harmonic), which determines the frequency of the separation of additional vortexes in the range $Sh > 0.42$, linearly depends on the flow's pulsation frequency (Figure 8) and approximately can be determined according to the equation $Sh_0^{(2)} = Sh + C * Sh_{00}$, where $C \approx 0.95 \div 1$.

Thus, in the third zone flow pulsations do not influence the frequency of separation of main vortexes $Sh_0^{(1)} \approx Sh_{00}$, which determines the main frequency of the of Lift coefficient $Cy(t)$ variations and its amplitude value A_{Cy} (see Figure 7). At the same time flow pulsations completely determine the frequency of separation of the additional vortexes, which deform the originally sinusoidal profile of dependence $Cy(t)$.

The special interest rise the frequency characteristics of the Drag coefficient $Cx(t)$. In the first zone and at the beginning of the second zone ($0 < Sh < 0.5 Sh_{00}$) the main frequency of its variations $Sh_{Cx}^{(1)}$ with an increase of the number Sh is partially suppressed by flow pulsations and decrease approximately linearly from the value $Sh_{Cx}^{(1)} = 2 * Sh_{00}$ at $Sh = 0$ till value $Sh_{Cx}^{(1)} = 0.5 * Sh_{00}$ at $Sh = 0.11 = 0.5 * Sh_{00}$. The second harmonic $Sh_{Cx}^{(2)}$ is completely determined by flow pulsations in entire range $0 < Sh < 1.0$, i.e., is fulfilled the equality $Sh_{Cx}^{(2)} = Sh$. In the case $Sh = 0.11 = 0.5 * Sh_{00}$ both frequencies coincide: $Sh_{Cx}^{(1)} = Sh_{Cx}^{(2)} = Sh$. From this point occurs “the seizure” of the frequencies of the variations of the coefficient $Cx(t)$ by the flow pulsations frequency and for the dimensionless frequencies $Sh \geq 0.5 Sh_{00}$ is fulfils the equality $Sh_{Cx}^{(1)} = Sh_{Cx}^{(2)} = Sh$. Further increase of the flow's pulsation frequency $Sh > 0.5 Sh_{00}$ leads to above described linear increase of the pulsations amplitude $Cx(t)$ and periodic appearance of longitudinal force, directed against flow (Figures 6 and 7). Let's note that the nature of the action of the longitudinal pulsations of velocity on the aerodynamic coefficients of immovable cylinder differs from the action of the stationary flow on the oscillatory cylinder, investigated in a number of works, for instance.

Conclusions

The results of numerical calculations showed that at subcritical regime of bodies streamlining with the flow separation the periodic velocity pulsations of incident flow significantly influence the frequency of the vortex separation and pulsations of aerodynamic coefficients, and also their average and amplitude values.

Based on the example of cylinder's streamlining by the pulsing flow with a dimensionless frequency of variations $Sh > 0.42$ are shown that unlike to the bodies, oscillating in the stationary flow, the amplitude values of Drag coefficient increases proportional to value Sh and can 5 to 10 times exceed it's corresponding amplitude in the stationary flow. The frequency of the variations of Drag coefficient also increases proportional to the flow's pulsation frequency.

In the defined range of Strouhal numbers ($Sh > 0.42$) the main frequency of the vortex separation (the first harmonic) practically does not depend on the flow's pulsation frequency and it is approximately equal to the frequency of the vortex separation in the stationary flow. Flow's pulsations do not influence the amplitude value and the main frequency of the Lift coefficient's variations. It is

shown that in the range the small numbers $Sh < 0.42$ there are ranges, in which the frequency of the vortex separation is partially suppressed, and the amplitude values of Lift coefficient increase 2 to 2.5 times in comparison with the stationary flow.

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Ušakovs V., Filipsons G., Sidenko N. Nestacionāras plūsmas periodisku pulsāciju ietekmes uz ķermeņu aerodinamiku pie zemkritiskiem Reynolds skaitļiem analīze

*Darbā prezentēti datoranalīzes rezultāti, analizējot applūstoša cilindra aerodinamiskos raksturlielumus nestacionārā gāzes plūsmā ar attiecībā pret vidējo ātrumu mainīgas zīmes pulsācijām pie Reynolds skaitļiem, zemākiem par kritisko. Parādīts, ka uzplūstošās plūsmas periodiskās pulsācijas ievērojami ietekmē virpuļu atrašanās frekvenci un aerodinamisko koeficientu pulsācijas, kā arī to vidējās un amplitūdas vērtības. Ir izdalīti trīs plūsmas pulsāciju frekvenču diapazoni, kuros virpuļu atrašanās frekvences, kā arī aerodinamisko parametru un to amplitūdas vērtību izmaiņas raksturs ievērojami atšķiras. Tā, piemēram, trešajā diapazonā ar bezdimensionālu pulsāciju frekvenci $Sh \geq 2Sh_{00} \geq 0.42$, vidējais cilindra frontālās pretestības koeficients $\langle Cx \rangle \approx 1.36 * \langle Cx_{00} \rangle$ ($\langle Cx_{00} \rangle$ – attiecīgais koeficients stacionārā plūsmā), pulsāciju frekvence un Cy amplitūdas vērtības pieaug proporcionāli Sh . Koeficienta Cy pulsāciju frekvence un amplitūdas vērtības ir līdzvērtīgas to vērtībām stacionārājā plūsmā.*

Ushakov V., G.Filipsons, Sidenko N. Analysis of unsteady flow periodic pulsations action on aerodynamics of bodies at subcritical Reynolds numbers

*In the work are presented the results of the computer analysis of the aerodynamic characteristics of the cylinder, streamlined with nonstationary gas flow by the alternating pulsations relative to the average velocity at the subcritical Reynolds numbers. It is shown that the periodic pulsations of velocity of incident external flow significantly influence the frequency of the vortex separation and variations of aerodynamic coefficients, and also their average and amplitude values. There are allocated three ranges of flow pulsations frequency, inside which character of changes of vortex separation frequency, aerodynamic parameters and their amplitude values significantly differs. Particularly, in the third range at the dimensionless frequency of pulsations $Sh \geq 2Sh_{00} \geq 0.42$: the average Drag coefficient of cylinder $\langle Cx \rangle \approx 1.36 * \langle Cx_{00} \rangle$ ($\langle Cx_{00} \rangle$ corresponding coefficient in the stationary flow), frequency of pulsations and amplitude values of Cx increases proportionally to Sh . Pulsations frequency and amplitude values of Cy are constant and are approximately equal to their values in the stationary flow.*

Ушаков В., Филиппсонс Г., Сиденко Н. Анализ воздействия периодических пульсаций нестационарного потока на аэродинамику тел при докритических числах Рейнольдса

*Представлены результаты компьютерного анализа аэродинамических характеристик цилиндра, обтекаемого нестационарным газовым потоком со знакопеременными пульсациями относительно средней скорости при докритических числах Рейнольдса. Показано, что периодические пульсации скорости набегающего потока значительно влияют на частоту отрыва вихрей и пульсаций аэродинамических коэффициентов, а также на их средние и амплитудные значения. Выделены три диапазона частот пульсаций потока, внутри которых характер изменения частоты отрыва вихрей, аэродинамических параметров и их амплитудных значений существенно различаются. В частности, в третьем диапазоне с безразмерной частотой пульсаций $Sh \geq 2Sh_{00} \geq 0.42$: средний коэффициент лобового сопротивления цилиндра $\langle Cx \rangle \approx 1.36 * \langle Cx_{00} \rangle$ ($\langle Cx_{00} \rangle$ соответствующий коэффициент в стационарном потоке), частота пульсаций и амплитудные значения Cx возрастают пропорционально Sh , частота пульсаций и амплитудные значения Cy постоянны и примерно равны их значениям в стационарном потоке.*