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Dimple Generators of Longitudinal Vortex Structures

*Volodymyr Voskoboinick, Andriy Voskoboinick,
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Abstract

Visual research of characteristic features and measurement of velocity and pressure fields of a vortex flow inside and nearby of a pair of the oval dimples on hydraulically smooth flat plate are conducted. It is established that depending on the flow regime inside the oval dimples, potential and vortex flows with ejection of vortex structures outside of dimples in the boundary layer are formed. In the conditions of a laminar flow, a vortex motion inside dimples is not observed. With an increase of flow velocity in dimples, boundary layer separation, shear layer, and potential and circulating flows are formed inside the oval dimples. In the conditions of the turbulent flow, the potential motion disappears, and intensive vortex motion is formed. The profiles of longitudinal velocity and the dynamic and wall-pressure fluctuations are studied inside and on the streamlined surface of the pair of oval dimples. The maximum wall-pressure fluctuation levels are pointed out on the aft walls of the dimples. The tonal components corresponding to oscillation frequencies of vortical flow inside the dimples and ejection frequencies of the large-scale vortical structures outside the dimples are observed in velocity and pressure fluctuation spectra.

Keywords: dimple generator, oval dimple, visualization, vortex structure, velocity profile, wall-pressure fluctuations

1. Introduction

Various inhomogeneities of the streamlined surface in the form of cavities or dimples are present in many hydraulic structures and constructions. Under appropriate conditions of the flow, large-scale coherent vortex systems and small-scale vortices are formed inside dimples that generate intense fluctuations of velocity, pressure, temperature, vorticity, and other turbulence parameters [1–3]. Boundary layer control uses these artificial vortex structures for drag reduction, increase of mixing, and noise minimization. Vortex structures of various scales, directions, rotational frequencies, and oscillations are generated in space and in time depending on the flow regime, the geometric parameters, and the shape of the cavities. Experimental and numerical results of aerodynamic and thermophysical studies showed a rather high efficiency of dimple reliefs, which allowed to increase heat and mass transfer for a slight increase in the level of hydrodynamic losses [4–6].

The boundary layer separation from the frontal edge of the cavity and the instability of the shear layer flow generate vortex structures inside the cavity. With the increase of flow velocity, one of the edges of vortex structures, circulating in

the cavity, is separated from the streamlined surface of the cavity and is extracted following the flow. These inclined structures have a longitudinal dimension that substantially exceeds their lateral scale. They intensively initiate the interaction of medium of the cavity and the surrounding area [2, 3, 7, 8].

The experience achieved by scientists and engineers when using dimple surfaces indicates that the creation of time and space stable vortex systems generated inside the cavities has a perspective value for boundary layer control. The creation of large-scale coherent vortex structures, with predefined qualities, allows you to change the structure of the boundary layer or the separation flow. It improves the heat and mass transfer, reduces the drag of streamlined structures, or changes the spectral composition of aerohydrodynamic noise, in order to reduce it [3, 9, 10].

In Refs. [11, 12], it was noted that spherical cavities for heat and hydraulic efficiency are not the best for turbulent regime of heat carrier flow and for laminar regime; their use is practically not justified. The presence of a switching mechanism of generation and ejection of vortex structures inside spherical cavities on a streamlined surface [13–15] does not allow to form longitudinal vortex structures that are stable in space and time, which are necessary for boundary layer control. This defect is absent in oval dimples, which are at an angle to the current direction. Asymmetry of the dimple shape due to its lateral deformation allows transforming the vortex structure and intensifying the transverse flow of liquid within its boundaries. Adding a shallow dimple of an asymmetric shape leads to a reorganization of its flow. A two-dimensional vortical structure in the dimple, generated in a symmetrical dimple during its laminar flow, is changed to an inclined monovortex. The high stability of the inclined structure should be noted, which ensures the stability of vortex intensification of heat transfer [16–18].

In this connection, the purpose of this experimental work is to study the characteristic features of the flow of a system of oval dimples on a flat plate and to study the fields of dynamic and wall-pressure fluctuations inside and on the streamlined surface of the inclined oval dimples and in their vicinity.

2. Experimental setup

Experimental research was carried out in a hydrodynamic flume with an open surface of water 16 m long, 1 m wide, and 0.4 m deep. The scheme of the experimental stand and the location of the measuring plate with dimples are given in works [19, 20]. At a distance of about 8 m from the input part of the flume, there were a measuring section equipped with control equipment and means of visual recording of the flow characteristics, coordinate devices, lighting equipment, and other auxiliary tools necessary for conducting experimental research. The design and equipment of the hydrodynamic flume allowed the flow velocity and water depth control in wide limits.

Transparent walls of a hydrodynamic flume, which were made of thick shock-proof glass, ensured high-quality visual research.

Hydraulically flat plate made of polished organic glass of 0.01 m thick, 0.5 m in width, and 2 m in length was sharpened from one (front) and from the other (aft) side. End washers are fixed to the lateral sides of the plate. At a distance of $X = 0.8$ m from the front edge of the plate, there was a hole, where the system of two oval dimples was installed, which was located at an angle of 30 degrees to the direction of flow (**Figure 1**). The diameter of a spherical part of the dimple (d) was 0.025 m. The width and length of the cylindrical part of the dimple were also 0.025 m. Thus, the oval dimples located at a distance of 0.005 m from each other had a width of 0.025 m, a length of 0.05 m, and a depth to width ratio of $h/d = 0.22$.

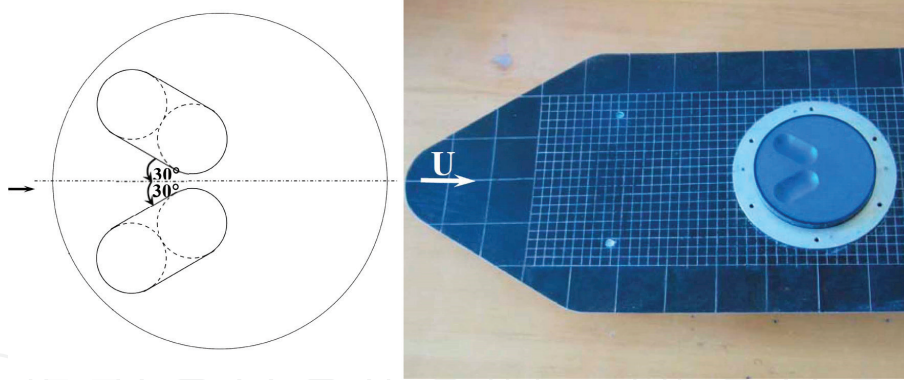


Figure 1.
Scheme and photography of the experimental plate with pair of the oval dimples.

According to the developed program and experimental research methodology, visual studies were initially carried out. Then, in the characteristic points of the vortex generation and the places of interaction of vortices with a streamlined surface, measurements of the fields of velocity and pressure were carried out. Visualization was carried out by drawing of contrasting coatings on the streamlined surface and coloring agents that were introduced into the stream. Paints and labeled particles through a small diameter tube were introduced into the boundary layer before the dimple and/or inside the dimple.

The study of the pressure fluctuation fields on the streamlined surface of the oval dimples and the plate, as well as the velocity fields of the vortex flow over the investigated surfaces, was carried out using miniature piezoceramic and piezoresistive sensors of pressure fluctuations and differential electronic manometers (**Figure 2a**). Specially designed and manufactured pressure sensors were installed in a level with a streamlined surface and measured the absolute pressure and the wall-pressure fluctuations [9, 21, 22]. Inside of the system of oval dimples and in their near wake, 12 sensors of pressure fluctuations were used (**Figure 2b**). The field of velocity fluctuations inside a pair of oval dimples and over a streamlined plate surface was measured by sensors of the dynamic pressure fluctuations or dynamic velocity pressure based on piezoceramic sensing elements.

The degree of the flow turbulence in the hydrodynamic flume did not exceed 10% for the velocity range from 0.03 to 0.5 m/s. The levels of acoustic radiation in the area of the dimples were no more than 90 dB relative to 2×10^{-5} Pa in the frequency range from 20 Hz to 20 kHz, and the vibration levels of the test plate with

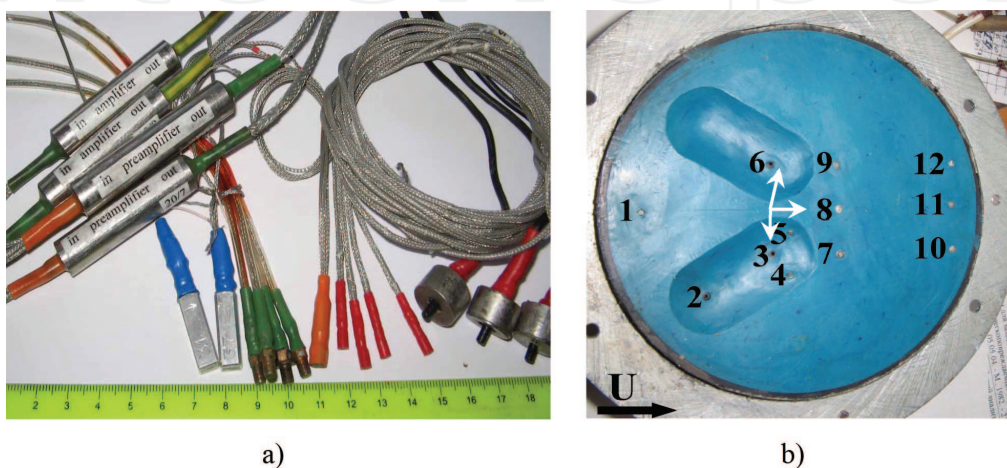


Figure 2.
Absolute pressure and pressure fluctuation sensors (a) and their disposition (b).

a pair of dimples and sensor holder did not exceed -55 dB relative to g (gravitation constant) in the frequency range from 2 Hz to 12.5 kHz. The measurement error of the averaged parameters of the fields of velocity and pressure did not exceed 10% (reliability 0.95). The measurement error of the spectral components of the velocity fluctuations did not exceed 1 dB, and the pressure and acceleration fluctuations—no more than 2 dB—in the frequency range from 2 Hz to 12.5 kHz.

3. Research results

The vortical motion in the middle of the dimples is not what was observed (**Figure 3a**) for a laminar flow regime over a pair of oval dimples ($U = (0.03...0.06)$ m/s, $Re_x = UX/\nu = (24,000...48,000)$, and $Re_d = Ud/\nu = (750...1500)$, where ν is the kinematic coefficient of water viscosity). The contrast dye was transferred inside the dimple along its front spherical and cylindrical parts and gradually filled the entire volume of the oval dimples. The separation flow was not observed inside the dimples, and colored dye, which was moved from the front of the dimple to its aft part, made non-intensive oscillatory motion.

When the flow velocity was increased to $(0.08...0.12)$ m/s, then a separation zone of the boundary layer appeared inside the front parts of the oval dimples. A shear layer began to form over the dimple opening, generating a circulating flow and a slow vortex motion inside the dimples (**Figure 3b**). This fluid motion had a kind of longitudinal spirals and was slow and almost symmetrical in each of the dimples. The liquid of the dimples fluctuated in three mutually perpendicular planes. The oscillation frequencies in each of the dimples were practically equal, but the destruction of the vortex sheet did not occur simultaneously. Contrast material went inside the dimples along their front semispherical and cylindrical parts. The separation and circulation areas behind the front edge of the dimple occupied almost half the volume of the dimple. There was a very slow rotation of the fluid inside the dimples, and its direction was coincided with the direction of the flow as well as its fluctuations along the longitudinal and transverse axes of the dimples. The disturbance package was transferred in the direction of the flow at a transfer velocity of approximately $(0.4...0.5) U$. In this case, the contrast material was ejected into the plate boundary layer over the region of the combination of the aft cylindrical and spherical parts of the dimple (**Figure 3b**). The ejection of a large-scale vortex or spiral-like vortices from the oval dimple was observed at a frequency close to $f = (0.16...0.2)$ Hz, which the Strouhal number corresponded to $St = fd/U = (0.04...0.05)$. A wake of the contrast material into the boundary layer outside the dimples was traced at a distance of about 8–10 in diameter of the dimple.

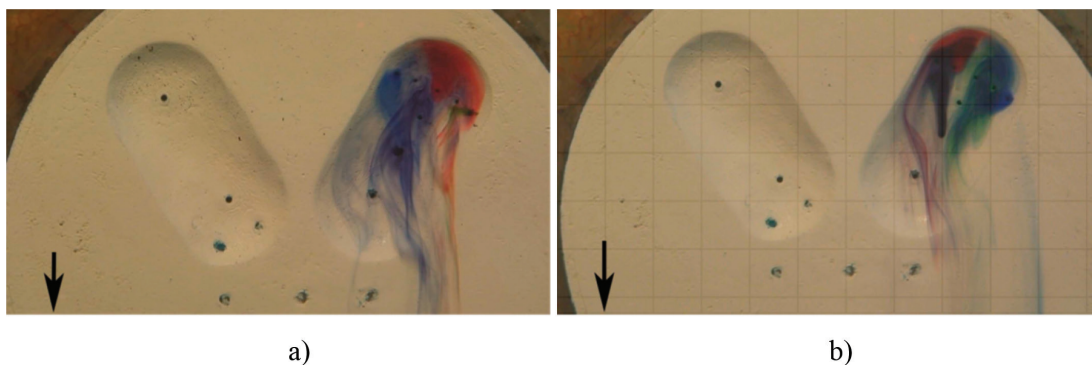


Figure 3. Flow visualization inside the oval dimple for $Re_x = 48,000$ (a) and $Re_x = 96,000$ (b).

The vortex motion became more intense when the flow velocity over the dimple system was increased up to (0.2...0.3) m/s ($Re_x = (160,000...240,000)$ and $Re_d = (5000...7500)$). The zone of potential flow near the separation wall of the oval dimple had almost vanished (**Figure 4a**). The entire fluid filling the front spherical part of the dimple is turned in a circulating flow and formed a coherent large-scale spindle-shaped vortex. This vortex had a source near the center of the spherical part of the dimple and made intensive oscillations. During the ejection, the spindle-shaped vortex structures began to lift above the front hemispheres of oval dimples and to stretch along the axis of the dimples. Then they were ejected outside the dimples over their aft parts. These large-scale vortex structures were rotated in the XOZ plane in each of the dimples in opposite directions. For example, in the left dimple in **Figure 4a**, the vortex rotated against the clockwise arrow, and in the right—clockwise. Ejection of vortex structures from the dimples was sometimes observed at the same time, but in most cases, ejections occurred at different time intervals. At the same time, there was no interaction of these vortex structures in the near wake of the dimples. The frequency of ejections of large-scale vortex structures from each of the dimples was estimated as (0.4...0.6) Hz or $St = (0.04...0.06)$. In addition, ejections of the small-scale eddy structures were also observed. These vortices were broken off from the upper part of a large-scale spindle-shaped vortex during its formation, when its transverse scale exceeded the depth of the dimple. Vortex structures retained their identity at a distance (7...9) of the diameter of the dimple.

The contrast dye inside the dimple was concentrated inside the front spherical parts of the dimple (**Figure 4b**) for developed turbulent flow and flow velocity (0.4...0.5) m/s ($Re_x = (320,000...400,000)$ and $Re_d = (10,000...12,500)$). Here, spindle-shaped vortex structures were generated, and they were ejected from the dimples at a frequency close to 1 Hz ($St \sim 0.05$). Color dyes, swirling in a spindle-shaped vortex, were intensively oscillated in three mutually perpendicular planes. When the transverse scale of the spindle-shaped vortex exceeded the depth of the dimple, an intensive ejection of small-scale structures was observed from its upper part. These vortices were flushed over the region of the conjugation of the front spherical part of the dimple and its aft cylindrical part. The ejection frequency of small-scale vortices was estimated as (4...5) Hz or $St = (0.2...0.25)$. As shown by the dye visualization (see **Figure 4b**), in the gap between the dimples, the flow did not undergo significant perturbations, as can be seen on the dye on the axis of the plate, which was not washed.

The intensity of the fluctuations of the longitudinal velocity over the streamlined surface of the oval dimple (u'/U), which was calculated from the fluctuations of the dynamic pressure ($u'_{rms} = \sqrt{2(p'_{rms})_{dyn}/\rho}$) measured by the piezoceramic

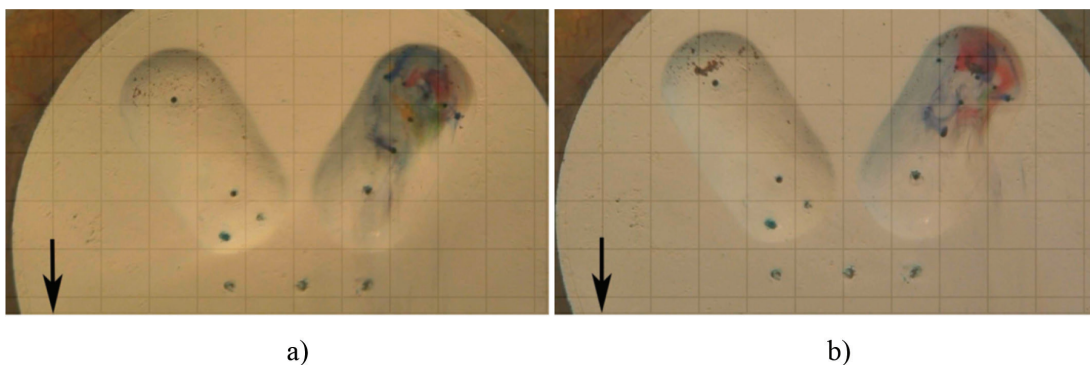


Figure 4.
Flow visualization inside the dimple for $Re_x = 240,000$ (a) and $Re_x = 400,000$ (b).

sensors, depending on the distance from the streamlined surface (y/δ , where δ is the boundary layer thickness in front of the oval dimple), is presented in **Figure 5a**. These results were obtained for two flow velocities, namely, $U = 0.25$ m/s ($Re_x = 200,000$) and $U = 0.45$ m/s ($Re_x = 360,000$). The results were measured over the streamlined surface of one of the oval dimples above the wall-pressure fluctuation sensor of No. 2 (see **Figure 1b**). The longitudinal velocity fluctuations are increased with approach to the streamlined plate surface. They have a maximum and then are decreased at the level of the plate surface above the opening of the oval dimple. When the dynamic pressure fluctuation sensors are deepened in the opening of the oval dimple, the velocity fluctuations again increased (the boundary of the shear layer) and then decreased (the core of the circulating flow inside the dimple).

The change of the rms values of the wall-pressure fluctuations measured on the streamlined surface of the oval dimple and in its vicinity is presented in **Figure 5b** depending on the Reynolds number. The normalization of the root mean square values of the wall-pressure fluctuations was carried out by the dynamic pressure ($q = \rho U^2/2$). In this figure, the curve numbers correspond to the numbers of the wall-pressure fluctuation sensors, which are set to the level with the streamlined surface in accordance with **Figure 1b**.

Thus, the wall-pressure fluctuations on a flat surface before the dimples are subjected to a quadratic dependence on the flow velocity. It should be noted that the wall-pressure fluctuations normalized by the dynamic pressure in the undisturbed boundary layer before the oval dimples are approximately 0.01, practically, in the entire range of studied Reynolds numbers.

Consequently, the smallest levels of the wall-pressure fluctuations are observed at the bottom of the oval dimples, in their front parts, especially for low flow velocities and Reynolds numbers (curve 2, **Figure 5b**). Inside the oval dimples, the levels of the wall-pressure fluctuations are greatest in the aft spherical parts of the dimples and in the near wake immediately after the dimples (see curves 4, 7, and 9 in **Figure 5b**).

A spectral analysis of the wall-pressure fluctuations on the streamlined surfaces of the oval dimples and plate was performed. To do this, we used the fast Fourier transform algorithm and the Hanning weighting function, as recommended in [23–25]. Power spectral densities of the wall-pressure fluctuations on a streamlined surface of oval dimples and on a flat plate near the system of these dimples have clearly visible discrete peaks which correspond to the nature of the vortex and jet motion over the investigated surfaces.

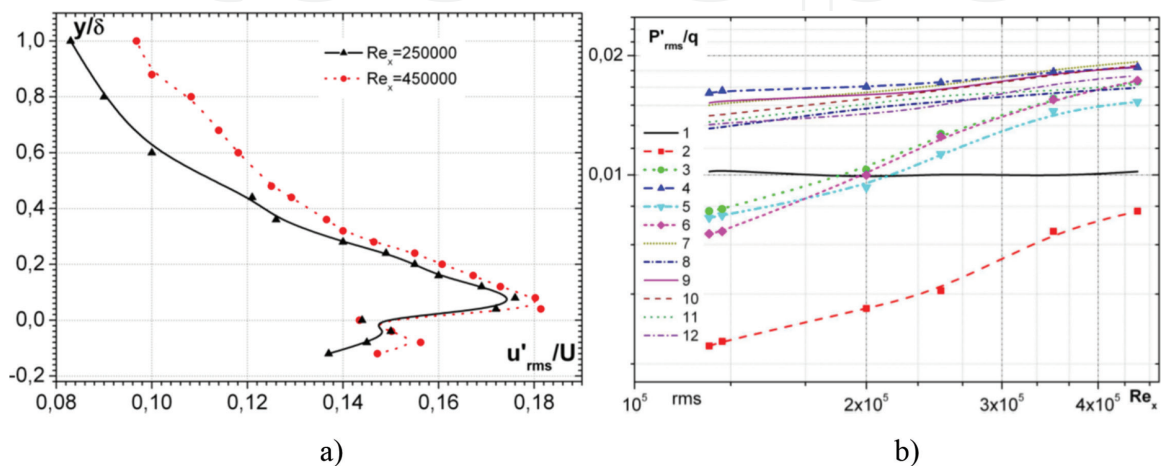


Figure 5. Velocity profile (a) and root mean square value of wall-pressure fluctuations (b).

Figure 6a shows the power spectral densities of the wall-pressure fluctuations, which were measured inside one of the oval dimples for a flow velocity of 0.25 m/s ($Re_d = 6250$ and $Re_x = 200,000$). The spectra were normalized by the dynamic pressure and external variables, namely, the diameter of the oval dimple and the flow velocity ($p_q^*(St) = (p')^2(St)U/q^2d$). Frequency (f) was normalized and presented as the number of Strouhal St . The numbers of curves correspond to the numbers of pressure fluctuation sensors, which are shown in **Figure 1b**. The maximum levels of the wall-pressure fluctuations occur at the aft wall of the dimple, where there are the intense interactions of the vortex flow ejected from the dimple and the shear layer formed above the streamlined surface of the plate. The smallest spectral levels of wall-pressure fluctuations occur at the bottom of the front spherical part of the oval dimple (curve 2). The ejections of the large-scale vortex structures observed during visual investigations occur at a frequency of (0.37...0.45) Hz or $St = (0.04...0.05)$.

Oscillations of the vortex flow inside the oval dimple are observed at frequencies (0.035...0.037) Hz or $St = (0.003...0.004)$ and (0.13...0.15) Hz or $St = (0.013...0.015)$ in the longitudinal and transverse directions relative to the axes of the oval dimple, respectively. In this case, the oscillations of the vortex motion and, respectively, the field of the wall-pressure fluctuations inside the dimple correspond to the subharmonics and harmonics of higher orders of these frequencies, as it is clearly illustrated in **Figure 6a**.

The results of the measurements of the power spectral densities of the wall-pressure fluctuations along the middle section of the oval dimple system, as well as inside the dimples, are shown in **Figure 6b**. It should be noted that under the boundary layer on a flat surface of a hydraulically smooth plate, the spectral levels of the wall-pressure fluctuations (curve 1) are minimal and do not have the tonal or discrete peaks observed inside and near the dimples. Behind the oval dimples, these discrete peaks are clearly visible on the spectra, but the tone frequencies near the system of oval dimples and at a distance of $2d$ differ from them (see curves 8 and

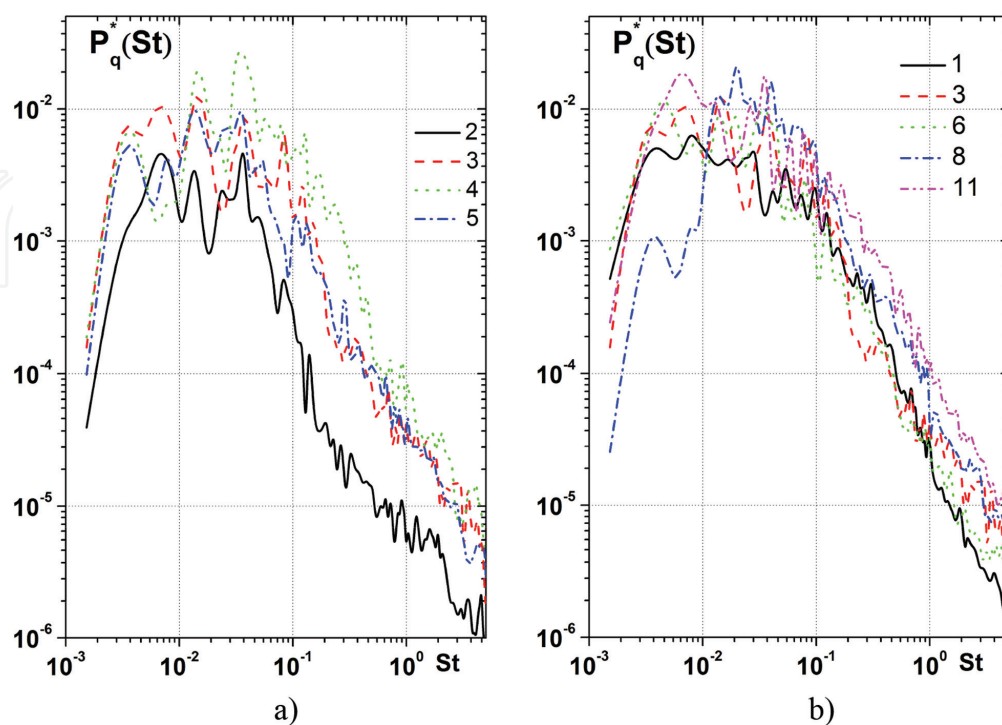


Figure 6.
 Power spectral densities of the wall-pressure fluctuations inside (a) and near (b) the oval dimple for the Reynolds number $Re_x = 200,000$.

11 in **Figure 6b**). In the middle section of the oval dimple system, where the sensor number 8 is located, the character of the pressure fluctuation spectrum differs from that which occurs on the aft wall of the dimple. Here, the maximum of spectral levels is observed at a frequency of 0.2 Hz ($St = 0.02$), and in the frequency range of the order of 0.03 Hz ($St = 0.003$), the intensity of the wall-pressure fluctuations is negligible. At a distance of $2d$ from the dimples, the tonal peaks appear in the spectra corresponding to the ejection frequencies of large-scale vortex structures outside of the dimples. Thus, the traces of the vortex flows ejected from the oval dimples are intersected at the location of the sensor No. 11.

Experiments have shown that all sensors located at a distance of $2d$ from the system of oval dimples record the field of the wall-pressure fluctuations with tonal peaks in the spectra corresponding to the ejection frequencies of large-scale vortex structures from the dimples, the frequencies of oscillatory motion inside the dimples, and their subharmonics and harmonics of higher orders. In this case, the spectral levels at such a distance from the dimples are of lesser value than in the near wake of the dimples. Thus, with the distance from the system of oval dimples, the boundary layer is gradually restored, which was observed during the visualization of the flow.

In the conditions of developed turbulent flow ($Re_d > 11,000$ and $Re_x > 350,000$), the spectral characteristics of the wall-pressure fluctuation field are similar to those observed for Reynolds numbers $Re_x = 200,000$ and $Re_d = 6250$. But the spectral levels become higher (**Figure 7a**). The highest spectral levels of wall-pressure fluctuations, as well as tonal peaks, are observed on the aft spherical part of the oval dimple as for the lower flow velocity. The smallest spectral levels are generated in the forward spherical part of the dimple (curve 2). Discrete peaks are observed at frequencies (0.05...0.06) Hz or $St = (0.003...0.004)$, (0.11 ...0.13) Hz or $St = (0.006...0.007)$, and (0.8...0.9) Hz or $St = (0.04...0.05)$. The first two low-frequency ranges correspond to the oscillation frequency in the oval dimple, and the frequency range $St = (0.04...0.05)$ is due to the ejection of large-scale vortex structures from the dimple. Also in the spectral characteristics of the field of the

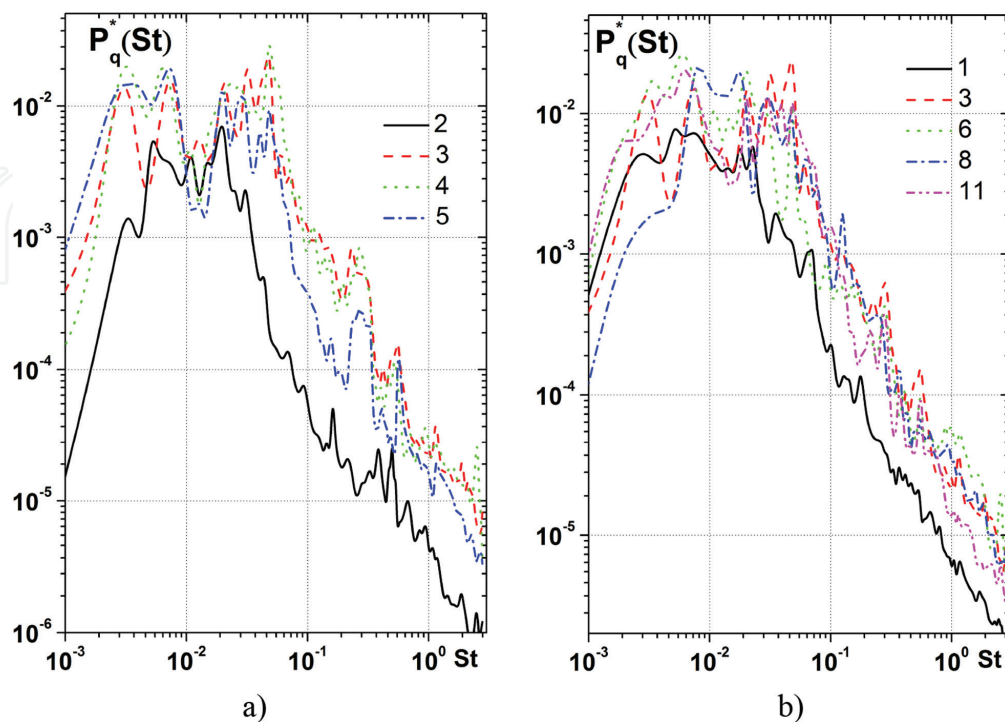


Figure 7. Power spectral densities of the wall-pressure fluctuations inside (a) and near (b) the oval dimple for the Reynolds number $Re_x = 400,000$.

wall-pressure fluctuations inside the oval dimple, there are discrete peaks that correspond to subharmonics and harmonics of higher orders of dominant frequencies of the vortex motion.

The features of the vortex motion, as well as wall-pressure fluctuation field, which it generates, in the near wake of the oval dimple system, in its middle section and at a distance of $2d$ from the system of oval dimples, are shown in **Figure 7b**. The spectral levels of the wall-pressure fluctuations in the wake behind the aft spherical part of the dimple are similar to those obtained inside the oval dimple as for a lower flow velocity. At the same time, the spectra in the middle section of the system of oval dimples (in their near wake) have a specific character with a maximum at 0.13 Hz (curve 8 in **Figure 7b**). Behind the aft spherical part of the oval dimple in the spectral dependences of the field of the wall-pressure fluctuations, there are tone peaks which are characteristic of the vortical motion inside the oval dimples. In the middle section of the oval dimple system at a distance $2d$ from the dimples, discrete peaks appear in the spectral levels of wall-pressure fluctuations. They are characteristic for the low-frequency oscillations of the vortex motion inside the dimples, as well as for the ejection of large-scale vortex structures from the dimples. The intensity, for example, of the wall-pressure fluctuations at the ejection frequency, is much lower for this flow regime than that observed for the velocity flow 0.25 m/s (**Figures 6b** and **7b**). This is due to the fact that for a large flow velocity, the interaction between the vortices of each of the dimples takes place more distant from the dimples, and the distance $2d$ from the pair of oval dimples for this regime is in the initial stage of this interaction.

4. Conclusions

1. The visual images of the vortex flow formed inside the oval dimple system are obtained, and the characteristic features of vortex formation for different flow regimes are determined. It has been experimentally established that the separation flow was not observed inside the dimples for laminar regime. For transient flow regime and small flow velocities within the oval dimples, the formation of very intense longitudinal spirals is observed, which are rotated and slowly fluctuated along the longitudinal and transverse axes of the dimples. For a turbulent flow regime inside the oval dimples, the spindle-shaped vortices are formed, which, with increasing velocity, are pressed against the front spherical parts of the dimples. These spindle-shaped vortices, reaching the scales of the dimples, are ejected from the oval dimples, disturbing the structure of the boundary layer. Inside the oval dimples, there is a low-frequency oscillatory motion in mutually perpendicular planes relative to the axes of the dimples, whose frequency is increased with increasing flow velocity.
2. It is shown that the intensity of the field of the velocity fluctuations has maximum values near the streamlined surface and also on the boundary of the shear layer in the opening of the oval dimple. The intensity of the wall-pressure fluctuation field is greatest in the interaction region between vortex structures of the shear layer and large-scale vortex systems ejected from the dimples with the aft wall of the oval dimple. The smallest intensity of the wall-pressure fluctuations occurred at the bottom of the oval dimple in its forward spherical part.
3. It has been established that depending on the flow regimes in the spectral characteristics of the field of the wall-pressure fluctuations measured on the

streamlined surface, characteristic features appear in the form of discrete peaks corresponding to the frequencies of low-frequency oscillations of the vortex flow inside the oval dimples and the ejection frequencies of large-scale vortex systems from the dimples. In the middle section of the system of oval dimples (in their near wake), there is no interaction of vortex structures that are ejected from the dimples. With a distance of more than two diameters of the dimple, intensive tone peaks are observed in the spectral dependences. They correspond to the ejection frequencies of large-scale vortices and the frequency of oscillations of the vortex motion inside the dimples, both in the middle section of the system of the dimples and behind their aft spherical parts. With the distance from the system of oval dimples, the intensity of the tonal oscillations, which are characteristic for the vortical motion inside the dimples, is decreased, and the boundary layer is restored.

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