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VORTICAL FLOW FEATURES IN A HEMISPHERICAL CAVITY ON A FLAT PLATE

Voropayev G.A., Voskoboinick V.A., Rozumnyuk N.V., Voskoboinick A.V.
Institute of Hydromechanics
National Academy of Sciences of Ukraine,
Kyiv 03680, Ukraine
vga@tbl.kiev.ua

ABSTRACT

This paper presents the results of numerical and experimental researches of generation of flow oscillations which are caused by interaction of the hydrodynamic and hydroacoustic phenomena inside a three-dimensional spherical cavity. The results of numerical and physical simulation of vortex movement features are shown inside a dimple and in its near wake. The symmetric and asymmetric large-scale vortical systems inside a cavity are find out depending on the flow regime, and location and periodicity of their break up are shown. The evolution of tornado-like vortices subjected to a switch mechanism that results in appearance of infra low-frequency modulating transversal oscillations of vortex motion inside the dimple. Discrete peaks are find out in spectral dependencies of pressure and velocity fluctuations. These local rises of the velocity and pressure fluctuation levels correspond to rotating frequency of the vortex systems inside the cavity, their breakup frequency, wake mode frequency of oscillations of cavity vortical movement, caused by a hydrodynamic resonance, and also self-sustained shear layer frequency of oscillations inside the dimple, which corresponded to a hydroacoustic resonance. The form and sizes of the quasi-stable large-scale vortex structures, the region of their origin and stages of development are submitted. Instantaneous and averaged characteristics of wall pressure fluctuations of vortical movement inside the cavity and in its near wake differ from each other, from nonlinear interaction of vortical structures with each other and streamlined surface

INTRODUCTION

Vortical flows in cavities on a streamlined surface considerably influence the hydrodynamic drag and heat transport. Introducing a regular arrangement of surface depressions called dimples is a well-known measure to increase heat transfer from a wall. Compared to a smooth wall, the Nusselt number can be significantly enhanced by dimples, whereas the increase of the pressure drop was found to be small (Isaev et al., 2005, Kiknadze et al., 2006). For that purpose, deep dimples with a ratio of depth to print diameter of h/D=(0.2…0.5) are typically applied to enhance the convective transport from the wall. A variety of shapes and sizes of cavities, and flow regimes lead to appearance and development of small- and large-scale vortices that essentially influences the boundary layer over the surface. Numerous numeral and experimental researches are conducted for finding an optimum shape and sizes of cavities, in order to increase the heat transfer, reduce drag and noise (Isaev et al., 2005, Khalatov et al., 2005, Ligrani et al., 2005, Rowley et al., 2002). The complexity of cavity flows, non-stationary and unsteady interaction with the boundary layer complicate the understanding of features of flows over surfaces with cavities, and also controlling such flows.

The paper presents the findings of the experimental research and numerical modeling of the vertical flow inside and past a hemispherical cavity in the surface of a plate.

PROGRAM AND METHOD OF INVESTIGATION

The numerical modeling utilizes the nonstationary 3D Navier-Stokes equations in the velocity-pressure variables. The calculation domain is a parallelepiped with a semispherical dimple at the bottom side. No-slip boundary conditions are specified on this solid surface. The fluid flows thorough the inlet plane at a specified velocity. On the lateral sides the periodic boundary conditions are specified, free-slip wall on the top boundary and zero-derivatives conditions on the outlet boundary.

Experimental researches of the incompressible fluid flow over a hemispheric dimple on a flat plate were conducted in the hydrodynamic tray 16 m long, 1 wide m and 0,8 m deep. With aim of visual researches, lateral walls of the hydrodynamic tray were made of glass. Water into the tray was supplied by pumps through a calming chamber, and water discharge was done through the window of discharge in the rear part the tray into a reservoir, installed under floor of the hydraulic laboratory. From the calming chamber, the water flow entered into a confusor and, after passing the system of turbulizing grids and honeycombs, reached the inlet of the hydrodynamic tray. At the distance of about 8 m from the inlet, a measuring area was equipped with control and measuring devices, lighting equipment and

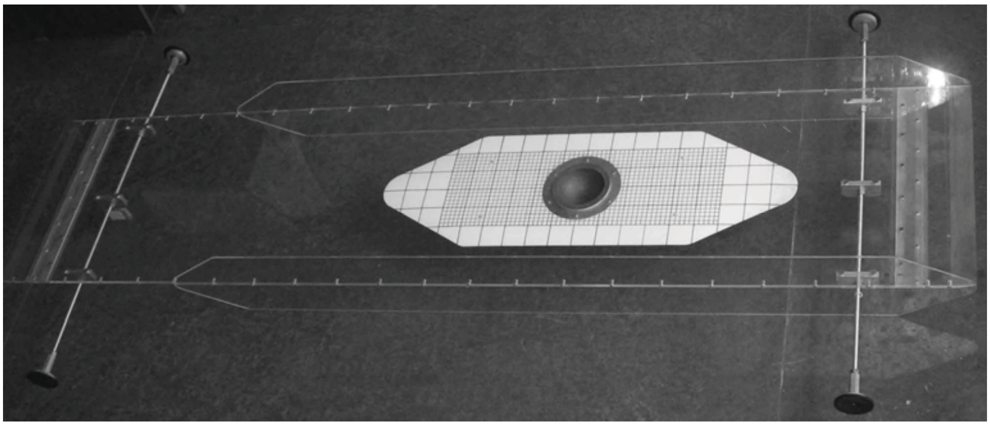


Fig. 1 Flat plate with the hemispherical cavity

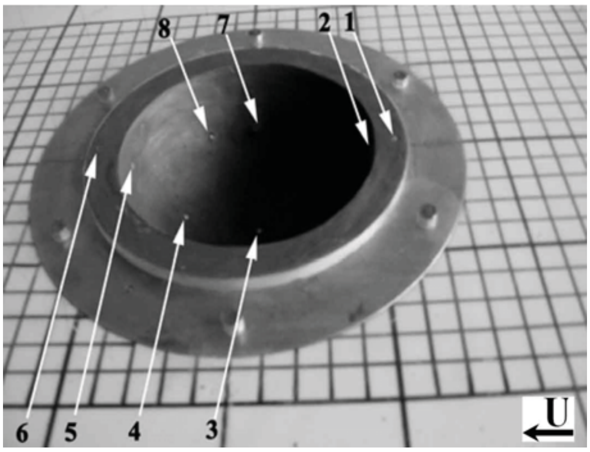


Fig. 2 Location wall pressure fluctuation sensors inside and near the hemispherical cavity

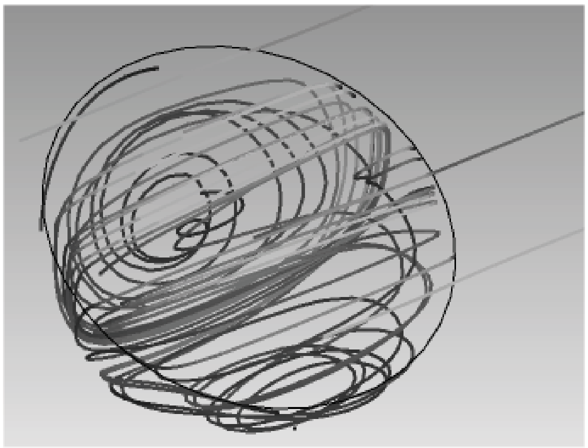


Fig. 3 Three-dimensional trajectories of marked particles inside the cavity for laminar flow

other auxiliary instruments, necessary for the experimental researches. The flow depth and velocity was regulated by means of the special equipment, allowing gradually changing these parameters. In the current research, the flow depth was maintained at about 0,4 m. The plate with hemispheric deepening was installed on the bottom of the measuring area of the hydrodynamic tray and located on the distance of 0,1 m from the tray bottom in parallel with its surface. Hydraulically smooth plate, made of polished organic glass, 0,01 m thick, 0,5 m wide and 2 m long, was sharpened on the leading and rear side, in order to provide an attached flow. End plates (organic glass, 0,005 m thick and 0,2 m wide) were fastened to lateral sides of the plate. At the distance of 1 m from the plate tip, an opening was made, into which a hemispheric dimple of 0,1 m diameter was installed (fig. 1).

The vortical flow was visualized by means of the wash-off contrast coatings and colored inks or paints injected into the boundary layer in front and inside the cavity. The velocity field was measured with hot-film probes. The wall-pressure fluctuations and total pressure fluctuations were measured with the small-scale piezoceramic pressure fluctuation sensors flush-mounted in the surfaces and placed in the boundary layer, correspondingly. Fig. 2 shows the arrangement of sensors inside the cavity. Up to 16 sensors were simultaneously engaged in the measurements. The electric signals from sensors were passed to the PC by means of the analog-to-digital converter. The experiments were performed at the flow velocity from 0.03m/s to 0.5 m/s, the corresponding Reynolds numbers ranged $Re_x=(2…40)\cdot 10^4$ and $Re_D=(3…50)\cdot 10^3$, the ratio of the cavity diameter to the momentum thickness was $D/\theta=(30…50)$.

A three-dimensional unsteady vortical flow appeared in the cavity subjected to resonance oscillations. The motion of vortical structures and pressure waves in the cavity lead to formation of deterministic and random velocity and pressure fluctuations inside the cavity and above the plate. The correlations between the unsteady fields of velocity and pressure generated inside the hemispheric cavity were studied by means of spectrum and cross-correlation analyses. The statistical processing of data allowed to define the space-time dependencies between velocity and pressure fluctuations, reveal their sources and places of generation,

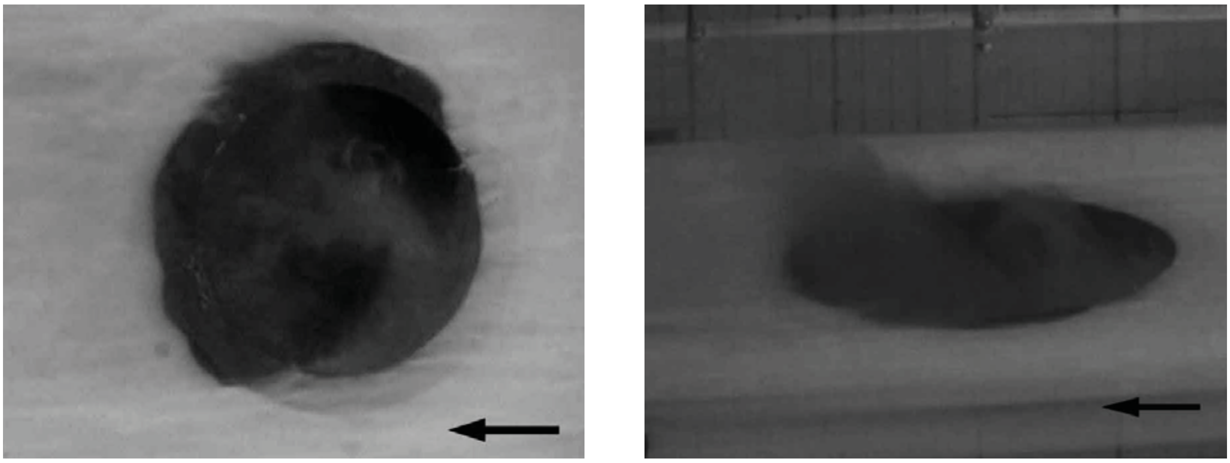


Fig. 4 Visualization of coherent asymmetrical tornado-like vortical structures inside and near the hemispherical cavity

scales, direction of motion and transport velocity of the coherent vortical structures which form the cavity.

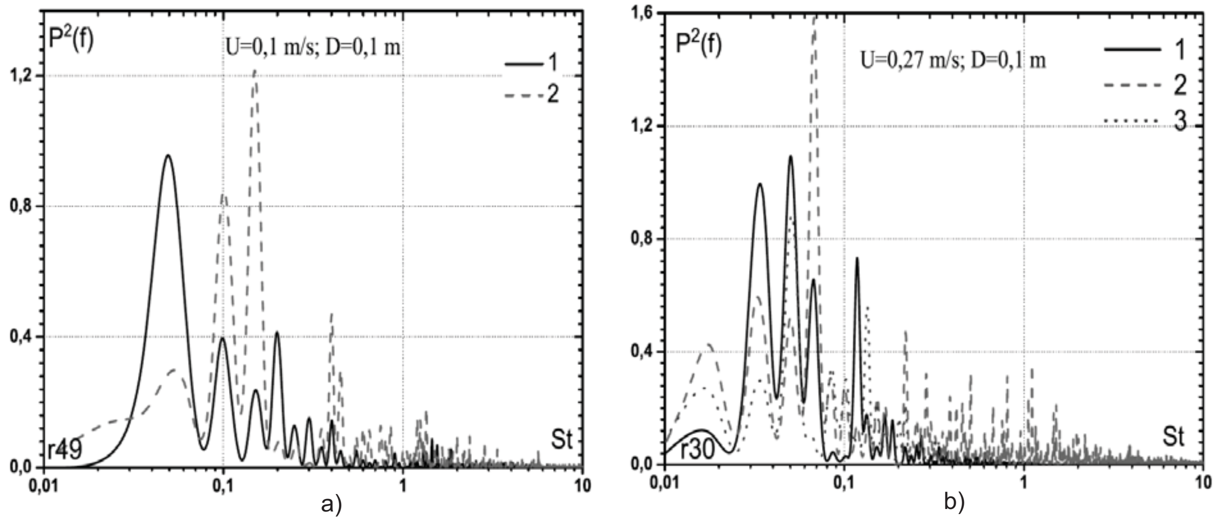
RESULTS AND DATA ANALYSIS

The numeral modeling and experimental results have revealed the characteristic features of the vortical flow inside the cavity in dependence on the flow regime. Separation zones are formed in a hemispheric small dimple, where circulation motion of fluid appear. Shear layers are generated above a dimple which at moving along the cavity mouth convolve into vortical systems. Near the rear wall of the cavity, these vortices generate higher levels of fluctuations and vorticity, and also cause instability of the vortical motion inside and in the neighborhood of the cavity. Also revealed are resonance oscillations inside the cavity, ejections of vortex systems from the cavity and their functional dependencies on the flow conditions. Kinematical and dynamical characteristics of the vortical flow in the cavity and boundary layer over the plane surface about the cavity are determined.

At the laminar flow mode, a recirculation flow appears inside the cavity which does not break up into the boundary layer above the plate, but behaves like an autonomous internal vortex flow. The laminar flow patterns obtained from numerical modeling in a semispherical dimple at the Reynolds number based on the dimple diameter up to 30000 are qualitatively similar to those in a semi-cylindrical cavity only in the symmetry plane. In the rest of the dimple volume, the influence of three-dimensionality changes all the flow parameters. The flow velocity is much slower than the mean flow velocity. Mainly the flow velocity in the mean flow over the dimple increases and pressure reduces; the boundary layer on the surface behind the dimple thickens similar to that about a semi-cylindrical cavity (Turnow et al., 2008, Voropaev et al., 2008a). Inside the dimple two circulating zones appear on each side from the longitudinal symmetry planes. There is no exchange of fluid between the zones (fig. 3). Normal vorticity has opposite sign in the zones. Three-dimensional trajectories of marked particles reveal vortical flow in the dimple than qualitatively resembles vortical braid with strongly skewed axis of rotation along the dimple span. In the center the axis bulges up, creating a loop, and reaches the dimple mouth. On the sides it embeds symmetrically. Thus in the center two segments of the vortical braid (the loop sides) are almost perpendicular to the plate surface. It can lead to appearance of instability (break) of the braid-like vortex in the dimple. Moreover at higher velocity of the mean flow and/or presence of perturbations in the flow, the flow instability can result in domination of one side of the vortical braid and regular (nonsymmetrical) bursts of fluid from the dimple that was observed in experiments. It should be noted that the internal flow interacts with the boundary layer in the form of very rare and irregular wash-off of small parts of liquid (small-scale vortex) from the cavity in its rear part.

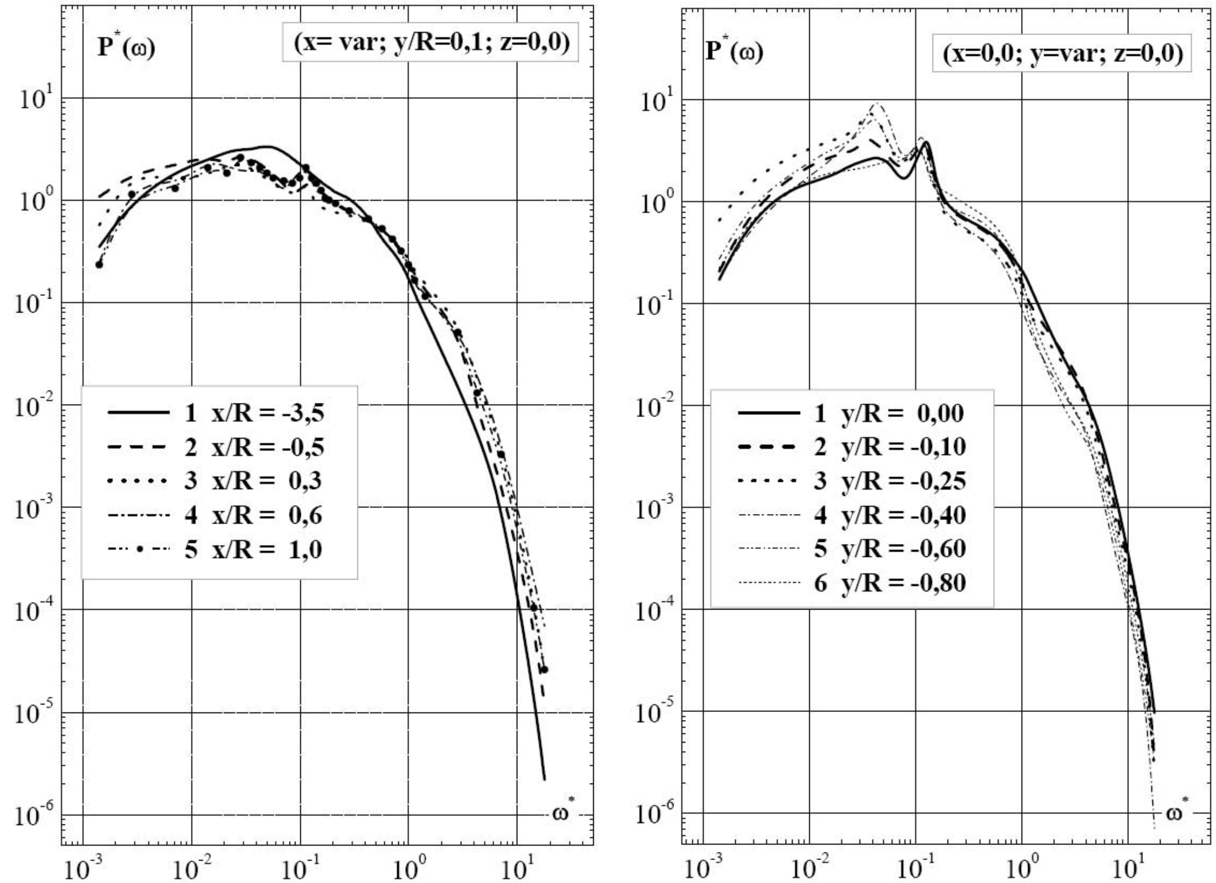
Experimental results shown, that at $Re_x=(2\ldots8)\cdot10^4$ or $Re_D=(3\ldots10)\cdot10^3$ a hair-pin or horseshoe vortical structure is formed in the hemispheric dimple, with its legs reaching the bottom part of the dimple closer to the rear and almost symmetrically. Head of the hair-pin structure lifts up to the shear layer boundary and turns to the rear wall, and it is regularly broke up from the dimple. Approaching the transition regime, the large-scale vortical system begins to break up from the cavity alternatively at different sides of the cavity (fig. 4). In the transition regime, an asymmetric vortical structure is formed inside the cavity and periodically broke up above the rear wall of the cavity under at the angle of (40…50)° to the flow direction. The direction of rotation of the vortical system and, consequently, alternation of the cavity sides where the system if formed and broke up, happens extremely rarely and not regularly. At approaching to the turbulent mode at $Re_x=(3.4)\cdot10^5$ ($Re_D=(3.4)\cdot10^4$) the bursts of the asymmetric structure happens at higher frequency and is observed above the rear wall at angle not exceeding 10° relative the flow direction. Intensity of the breaking structures increases and they reach the external border of the boundary layer above the plate almost above the rear edge of the hemispheric dimple.

At the turbulent mode, a symmetric vortical system is generated with two sources at the side walls, which is



a) b)

Fig. 5 Power density spectra of the wall pressure fluctuations inside the cavity for flow velocity: a) – 0.1 m/s; b) – 0.27 m/s



a) b)

Fig. 6 Power density spectra of the longitudinal velocity fluctuations inside the cavity

periodically, and frequently chaotically, broke up in the boundary layer along the longitudinal axis of the cavity in the shape of unfolding helix at relatively high frequency.

Spectral dependencies of the velocity and pressure fluctuations versus frequency and wave representations have shown the presence of discrete peaks which corresponded to the characteristic features of the vortical motion inside the cavity and the vortex breakdown in the boundary layer outside the cavity (fig. 5 and fig. 6).

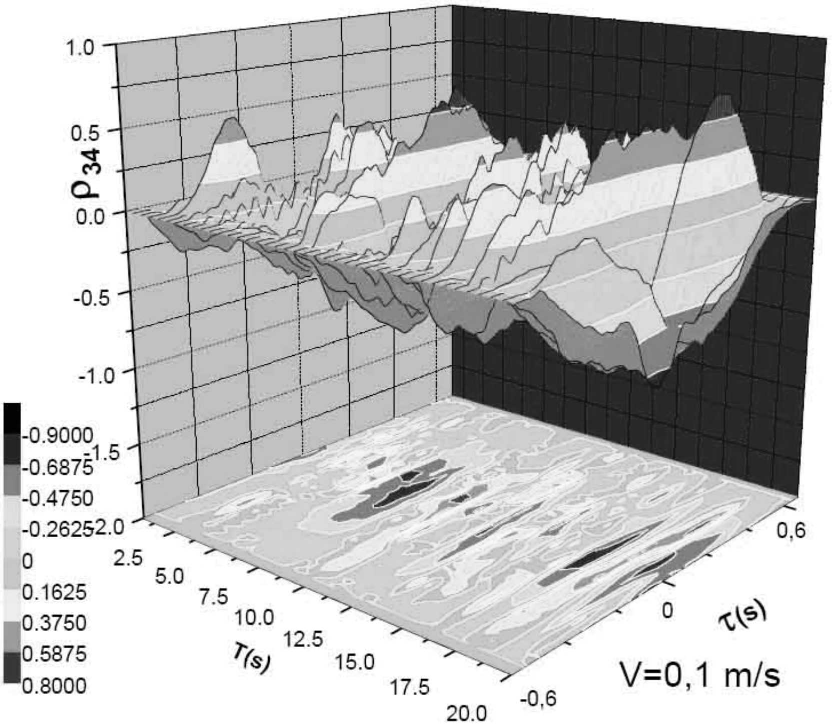


Fig. 7 Three-dimensional shot-time cross correlations of the wall pressure fluctuations

Fig. 5a shows the power density spectra of wall pressure fluctuations at the flow velocity of 0.1m/s. Curve 1 corresponds to the data from the sensor of wall pressure fluctuations sensor N 3 mounted in the center of the dimple bottom (see fig. 2). Curve 2 is the dependence of the power density spectra of wall pressure fluctuations are measured on the cavity rear wall by sensor N 4. On the bottom of the hemispheric dimple for this flow regime ($Re_x=8\cdot10^4$ and $Re_D=1\cdot10^4$) there is a maximum value of spectral levels of the wall pressure fluctuations on frequency about 0.05 Hz ($St=fd/U\approx0.05$) and its high harmonics. On the rear wall of the cavity where the shear layer impinges, a maximum of the wall pressure fluctuations was registered on frequencies about 0.16 Hz and 0.4 Hz or St=0.16 and St=0.4.

The increase of the flow velocity does not essentially change the behavior of spectral dependences but increases the number of discrete peaks, changes their amplitude and ranges of frequencies where they were registered. Fig. 5b shows the power density spectra of wall pressure fluctuations at the flow velocity of 0.27m/s. Curve 1 represents the data from the sensor of wall pressure fluctuations N 3 in the center of the hemispherical cavity bottom. Curves 2 and 3 are dependences of the power density spectra of wall pressure fluctuations measured on the cavity rear wall by sensors N 4 and N 5. Discrete pikes of power density spectra of wall pressure fluctuations are observed on frequencies about 0.09 Hz, 0.14 Hz, 0.19 Hz and 0.32 Hz, depending on the position of pressure fluctuations sensor on the streamlined surface (see fig. 5b). Strouhal numbers of St=0.033; 0.052; 0.07 and 0.118 correspond to those frequencies. It should be noted that on the bottom of the hemispheric dimple predominate the wall pressure fluctuations with frequencies corresponding to Strouhal numbers of about 0.05 and 0.03 and to their subharmonics, and also to higher-orders harmonics. The wall pressure fluctuations in this frequency range are caused by the low-frequency burst of the intensive asymmetric tornado-like vortex, which was observed visually in the hemispheric cavity (Voropaev et al., 2008b). Alternate breakup of this intensive tornado-like vortex near the lateral cavity walls (at an angle of about 45 degree relative the streamline) correlates with the wake mode of oscillations discribed in papers by Rowley et al. (2002), Gharib and Roshko (1987) and Bres and Colonius (2008). In the bottom of the rear wall, where the pressure fluctuations sensor N 4 was mounted, there are the most intensive wall pressure fluctuations which have higher frequency of oscillations in comparison to the bottom area of the cavity (fig. 5a and fig. 5b).

Presence of the semispherical dimple on the plate surface results in substantial changes in spectra of the velocity fluctuations. The monotonous mode is disrupted by discrete peaks (see fig. 6a). The power spectral density of velocity fluctuations in the dimple increase over the low-frequency range and decrease over the high-frequency range. When approaching the location of the core of quasistable large-scale vortex in the dimple, the spectral energy grows at the frequency of the vortex rotation, and decrease over the high-frequency and low-frequency ranges. It is revealed that three-dimensional wake and shear-layer modes of the vortical flow oscillations are generated in the cavity. Experimental results have shown rather intensive correlations between the wall pressure fluctuations at various locations inside the cavity and on the plate. The correlation level between the velocity and pressure fields have determined both close to the streamlined surface and directly on walls of the cavity and plate. The group convection velocity of the vortical structures forming the shear layer makes up to 50 % the flow velocity, and the recirculation flow velocity at the bottom of the hemispherical cavity does not exceed 15 % the flow velocity.

On the basis of short-time spectrum and correlation analyses, the non-stationary and non-uniform in space characteristics of the coherent vortical systems inside and past the open cavity have been found (fig. 7). Temporal periodicity of mutual cross-correlation characteristics of the wall pressure fluctuations between two sensors, located on the fixed distance corresponds to frequencies of the shear and wake modes of resonance oscillations in the dimple. Registration of the time lag, at which the cross-correlation or anticorrelation has maximum, enables to determine the group convective velocity of the coherent vortical structures during their formation and development, as well as the phase of development and direction of motion inside the dimple.

CONCLUSIONS

The results of numerical and physical simulation of vortex movement features are shown inside a dimple and in its near wake. The symmetric and asymmetric large-scale vortical systems inside a cavity are find out depending on the flow regime, and location and periodicity of their break up are shown. The evolution of tornado-like vortices subjected to a switch mechanism that results in appearance of infra low-frequency modulating transversal oscillations of vortex motion inside the dimple.

Discrete peaks are find out in spectral dependencies of pressure and velocity fluctuations. These local rises of the velocity and pressure fluctuation levels correspond to rotating frequency of the vortex systems inside the cavity, their breakup frequency, wake mode frequency of oscillations of cavity vortical movement, caused by a hydrodynamic resonance, and also self-sustained shear layer frequency of oscillations inside the dimple, which corresponded to a hydroacoustic resonance.

The form and sizes of the quasi-stable large-scale vortex structures, the region of their origin and stages of development are submitted. Instability of the vortical flow in a dimple and breakup into the boundary layer substantially influences the instantaneous and mean characteristics of the pressure and velocity fields inside the semispherical dimple and in its neighborhood. As a result, the instantaneous and mean characteristics of pressure fluctuations in the vortical flow inside the dimple and in its near wake are different, that was demonstrated in the research.

The spectrum dependencies, which have discrete pikes related with formation and development of coherent vortical structures in a 3D dimple and breakup from the dimple, gradually smooth at moving away from the dimple, and finally, become monotonically varying that is typical for unbroken turbulent boundary layer over a smooth plane. Thus the boundary layer gradually restores away from the dimple.

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