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Flow control by vortex cavity generator

The results of experimental studies of the features of the formation of vortex structures inside a semispherical cavity on a hydraulically smooth plane surface and the velocity and pressure fields that they generate are presented. Inside the cavity, a quasi-stable large-scale vortex structure and small-scale eddies are generated, which are ejected outward from the cavity.

Introduction

In aero hydrodynamics and thermophysics, the dimple surfaces that generate vortex structures are widely used. These vortices change the structure of the flow and intensify the processes of mixing and heat exchange, which is used in the creation of energy-saving structures and technologies. The generation of quasi-stable coherent vortex structures by cavities and trenches makes it possible to control the boundary layer, which is used to create devices that reduce aerodynamic drag, flow noise and vibration of a streamlined surface, which significantly improves the ecology of the environment [1-3]. The purpose of the study is to determine the features of the formation and evolution of coherent vortex structures inside and near the semispherical cavity on a flat surface and to study their influence on the space-time characteristics of the velocity and pressure fields.

Experimental stand and research technique.

Experimental investigations of semispherical cavity flow on the surface of a hydraulically smooth flat plate were carried out in a hydrodynamic flume. A measuring plate 2m long and 0.5m wide was installed above the bottom of the hydraulic flume 16m long, 1m wide and 0.8m deep at a distance of 8m from the entrance of the flume (Fig. 1a). A semispherical cavity of diameter d=0.1m was made in the center of the measuring plate. The flow velocity (U) over the plate with the cavity varied from 0.02m/s to 0.5m/s, the Reynolds numbers varied in the following ranges: $\mathrm{Re}_x = Ux/\nu = (0.2-5)\cdot 10^6$ and $\mathrm{Re}_d = Ud/\nu = (0.2-5)\cdot 10^4$, where x is the distance from a plate nose to a cavity center, ν is the kinematic coefficient of viscosity.

In the experiments we used flow visualization by contrasting water-soluble coatings and color inks. The velocity and pressure fields were measured by one and two-component hot-film anemometers and miniature wall-pressure fluctuation sensors. Anemometers were installed in the correlation blocks above the streamlined surface, and pressure fluctuation sensors were installed flush with the streamlined surface (Fig. 1b). Simultaneous registration of the velocity and pressure fields through a 16-channel analog-digital converter was carried out on a personal computer. Statistical processing and analysis of the research results was carried out using specially developed programs and algorithms. All the sensors were tested and verified by absolute and relative methods. The error in measuring the averaged or integral values

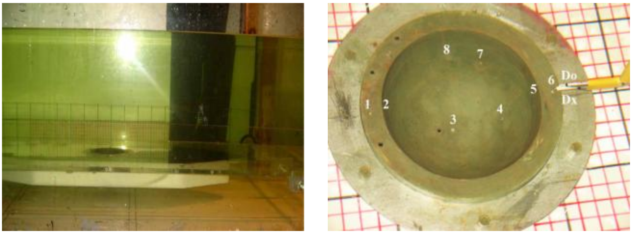

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Fig. 1 Experimental stend and sensors

was not more than 5%, the correlation dependences was not more than 10%, and the spectral characteristics was no more than 2dB in the frequency range from 0.02Hz to 1kHz with a confidence probability of 0.95 or 2σ .

Research results and data analysis.

Flow visualization showed that in condition of the laminar flow regime inside the semispherical cavity, a symmetrical vortex system is formed (Fig. 2a), the basis of which is a large-scale arcuate or horseshoe-shaped vortex. This vortex originates from the circulation flow, which is under a shear layer. The focus of the horseshoe vortex is located on the side walls of the cavity in its bottom part. The axis of the vortex has a curved shape, elongated upward in the median section of the cavity and pressed to the aft wall. The vortex oscillates in three mutually perpendicular planes with different frequencies and amplitudes. Periodically the vortex is ejected, mainly in its middle part, when critical dimensions are reached that exceed the dimensions of the cavity.

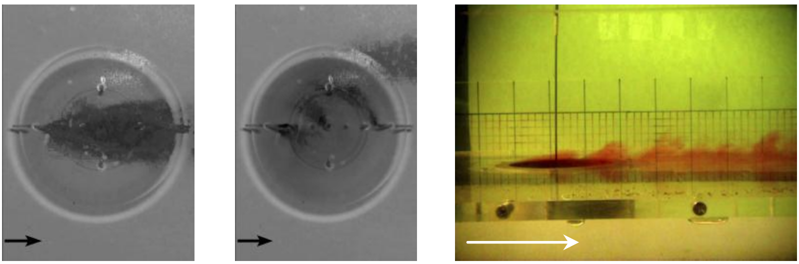

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Fig. 2. Visualization of vortex flow inside and about cavity

When critical Reynolds numbers $\mathrm{Re}_d \approx (1-3)\cdot 10^4$ are reached, a transitional flow regime sets in and the formation of the symmetric vortex structures is violated within the semispherical cavity. As a result, an asymmetric vortex system is generated (Fig. 2b) in the form of a large-scale inclined vortex. This vortex is located inside the cavity at an angle of about (30-60)° with respect to the direction of

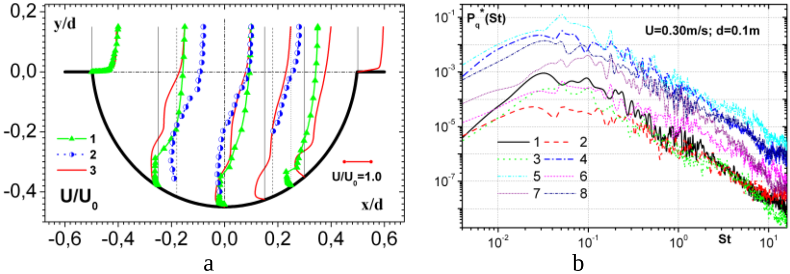

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Fig. 3. Velocity profile and spectra of the wall pressure fluctuations

the oncoming stream [4]. Its source or focus is in the near-bottom region closer to the front wall of the semispherical cavity, and the vortex sink is located on the opposite side part of the aft wall relative to the median section of the cavity. An asymmetrical inclined vortex is ejected outward from the cavity above its aft wall with a dimensionless frequency $St = fd/U \approx 0.05$. During the evolution of asymmetric inclined vortices, a low-frequency switching of the vortex flow from one side part of the cavity to the opposite part is observed [5]. After several ejections of the inclined vortex, a new asymmetric vortex generates inside the cavity, but on the opposite side of the cavity. The ejection of vortex systems from the cavity is observed at a considerable distance from the cavity, and these vortices reach the outer boundary of the boundary layer (Fig. 2c).

When there is a developed turbulent flow regime, the asymmetry of the vortex structures is preserved, but randomness in the process of the vortex generation is appeared. Inside the cavity auto-oscillations and vortex flow fluctuations with low and high frequency are generated, which modulate each other. The frequency of low-frequency transverse oscillations inside the cavity corresponds to the Strouhal number $St \approx 0.02$, the ejection of asymmetric inclined vortices over the aft wall of the semispherical cavity occurs at a frequency for which the Strouhal number is (0.04-0.06). In this case, the ejections of the small-scale eddies of the shear layer over the opposite side of the aft wall of the cavity are observed with frequency $St \approx 0.4$ (first mode) and/or $St \approx 0.8$ (second mode).

It is found that the general laws of variation of the integral characteristics of the velocity field are: firstly, the presence of alternating regions of increase and decrease in the average values of the longitudinal velocity over the cavity, which is due to the influence of the cavity on the boundary layer; secondly, the increase in the average and fluctuation velocity as the shear layer approaches the aft wall of the cavity; thirdly, the appearance in the near-bottom region of the cavity of the return flow, arising in the interaction zone of the vortex structures of the shear layer and the aft wall of the cavity (Fig. 3a). Research results [6] (curve 1), [7] (curve 2) and our experiments (curve 3) are shown in Fig. 3a.

The intensity of the field of the wall pressure fluctuations on the aft wall of the cavity is almost an order of magnitude higher than on the front wall and the difference is increased with increasing velocity. The lowest levels of fluctuations

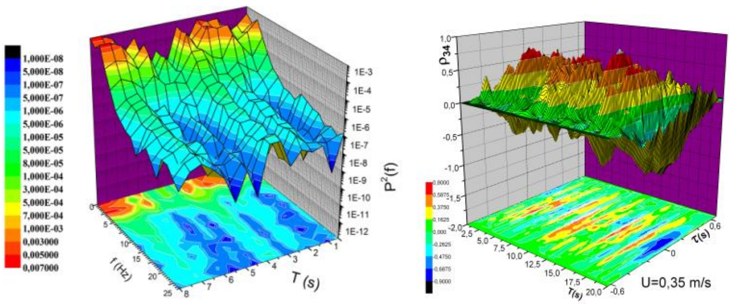

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Fig. 4. Spectrogram (a) and correlogram (b) of the pressure fluctuations

of dynamic pressure take place in the region where the core of a large-scale vortex is located, and they are almost an order of magnitude lower than in the bottom region of the cavity.

It was found that the statistical moments of the higher orders of the field of velocity and wall pressure fluctuations undergo significant changes inside the cavity and in its near wake with respect to the parameters that are measured for boundary layers on a smooth flat surface (Fig. 3b). In the frequency and wave spectra, discrete components are appeared that correspond to low-frequency oscillations of the vortex flow inside the cavity, whose frequencies correspond to the Strouhal number 0.003. Tone modes are also observed at the ejection frequencies of vortex structures outside the cavitiy St =(0.04-0.06), at the frequencies of rotation of the circulation flow inside the cavity St =(0.08-0.1) and at the frequencies of auto-oscillations of vortex structures of the shear layer St =(0.4-0.5) (first mode) and St =(0.7-1.0) (second mode). With flow velocity increase, the frequency range of energy-carrying vortex structures inside the semispherical cavity is widened both in the low and high frequencies [8]. With flow velocity increase, large-scale low-frequency vortex systems make the greatest contribution to the total energy of the velocity fluctuation field. In the wave spectra of the velocity fluctuation field, the discrete rise rates are observed at longitudinal wavenumbers [9] $k_x \approx 0.015/\delta$, $k_x \approx 0.05/\delta$ and $k_x\delta \approx 0.15$, where δ is the boundary layer thickness.

Spectrograms and correlograms of the fields of pressure and velocity fluctuations are obtained on the basis of short-term spectral and correlation analyzes (Fig. 4). The nonstationary in time and inhomogeneous in space characteristics of coherent vortex systems that are formed by vortex motion inside and near the semispherical cavity are determined. Tonal increases in spectral dependences, the presence of intense correlations and anticorrelations are caused by the low-frequency or low-wave motion of the vortex flow inside the semispherical cavity, the rotational frequencies and the ejections of coherent large-scale vortex structures, and relatively high-frequency ejections of small-scale vortices of the shear layer outside from the cavity in the boundary layer.

Conclutions

It is found that inside the semispherical cavity a quasistable symmetric or asymmetric large-scale vortex structure and small-scale vortices which are ejected outside from the cavity are generated. These vortex structures are originated from a circulation flow inside the cavity and shear layer which is boundary layer separation from a front wall of the cavity. A vortex flow inside the cavity stimulates an appearance of discrete peaks in the frequency and wave velocity and pressure spectra on frequencies of low-frequency oscillations of vortex flow, on frequencies of rotation and ejection of large-scale vortex structure and on frequencies of auto-oscillations of vortices of shear layer. In the wave spectra of the velocity fluctuation field, the discrete rise rates are observed at longitudinal wavenumbers $k_x \approx 0.015/\delta$, $k_x \approx 0.05/\delta$ and $k_x\delta \approx 0.15$.

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