Unsteady cavities near the hydrofoil with a small aspect ratio

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Abstract. Using digital processing of high-speed visualization data on a cavitation flow near NACA hydrofoil with critically low aspect ratio, the frequencies of the formation and separation of cavities in the flow are identified. It is shown that in the case of development of cloud cavitation the main dimensionless frequency varies within 0.4, which corresponds to the type of internal instability. The Strouhal number corresponds to the frequency of attached cavity occurrence and varies in range from 0.6 to 0.8. The Strouhal numbers calculated in third mode exceed 1. This mode corresponds to the forming of very small cavities near the leading edge of hydrofoil.

1. Introduction
It is very important to investigate fluid flows in various complex hydrodynamic systems, for example, pumping equipment, high-pressure hydroelectric power stations, associated with the occurrence of pulsations in the flow and, as a consequence, large vibration loads on the entire complex. The resulting pulsations are determined by the internal structure of the flow. The main contribution is made by the formed cavities, whose behavior entails flow separation accompanied by flow pulsations and dynamic loads on the entire system. The unsteady and vibrational behavior of cavitation structures is still a problem for many researchers, and obtaining information about cavitation phenomena in various hydrodynamic systems is important.

The flow near a hydrofoil NACA series is actively investigated by various authors both in the case of cavitation [1–4] and non-cavitating conditions [5, 6] since it has wide technical application.

It is known that cavities with the length below the dimensions of the chord are nonstationary [7–9]. The main cause of the cavitation flow unsteadiness is the reentrant jets. They are formed in the trailing part of the cavity due to a large pressure gradient. As it is shown in the work by Callenaere et al. [10], the two different types of unsteady cavitation flow can be determined. The authors study an attached cavity with the reentrant jet under the cavity. If the reentrant jet breaks the cavity near the leading edge of the foil, the single cavitation cloud moves downstream, and this regime is the classical type of cloud cavitation near the hydrofoil. In work [10] the velocity of the reentrant jet is measured using data of visualization images. Good correlation between the cloud cavitation flow regime and the area of high-pressure gradient is shown. However, there is a different way for the reentrant jet. It reaches the leading edge of the attached cavity and separates it into some small cavitation clouds along its entire length. The small clouds disappear very quickly. The authors propose to call this type of the cavity instability “the wave”. As it is shown experimentally, this type of cavitation flow is associated with the influence of external factors on the cavity, for example, the influence of other cavities, the features of
the stand, etc. Also, in the work of Callenaere et al. [10], it is noted that the first described type of the flow occurs in the case of a rather thick cavity, and the second takes place in a rather thin one. Thus, it is concluded that in the case of a cloud type flow the main role belongs to internal instabilities of the cavity, and for the second type, it is played by external instabilities.

A bifurcation between two zones of oscillations of an attached cavity for all hydrofoils is shown by Kawakami et al. [3] and Watanabe et al. [11]. Each of the zones is described in different frequency ranges. For thin hydrofoil a typical bifurcation exists at the parameter $\sigma / 2\alpha = 4$, where $\sigma$ is the cavitation number, and $\alpha$ is the angle of attack. When the oscillatory system enters one of these zones, the system turns out to be stable. Namely, a small perturbation of the local pressure or local flow velocity near the cavity does not cause any significant changes in the oscillation frequency or amplitude of the cavity and does not entail a transition to another cavitation flow regime.

Callenaere et al. [10] calculated the Strouhal numbers for two instabilities. For regimes with internal instability, the values of the Strouhal numbers usually change in the range of 0.30–0.45. In cases where systemic instability or external instability prevails, the Strouhal numbers are distributed between 0.05–0.20. If Strouhal numbers are over 0.5, the main oscillation frequency of the cavity is due to structural excitations [12].

Moreover, the aspect ratio of hydrofoil is a key parameter affecting the cavitation flow as a result of the main oscillation frequency of the cavity [3]. In the work authors compare the cavitation flows occurring near the NACA profiles in the range of aspect ratios from 1.43 to 2.35. Authors suggest that the Strouhal number decreases with a decrease in the size of the vapor-gas regions. A similar result was obtained by Luo et al. [13] in the range of $2.5 < \sigma / 2\alpha < 4$. However, in the range of $\sigma / 2\alpha < 2.5$, the values of the Strouhal numbers for hydrofoils with low aspect ratios are larger.

A significant part of the work is devoted to the study of cavitation flow instabilities. It should be noted that in this work, we study the frequency characteristics of the formation and separation of cavities near the NACA profile with a critically low aspect ratio equal to 0.02; various modes of cavitation flow near the hydrofoil are investigated and analyzed; and the results obtained are compared with the results of other authors in a wide range of aspect ratios from 0.2 to 4.

2. Experimental conditions

The experimental investigations of the cavitation flow near NACA0012 hydrofoil in a vertical hydrodynamic loop of the Institute of Thermophysics SB RAS were carried out. The hydrofoil in a 1 mm gap between two parallel transparent plates was studied. The angle of attack of the hydrofoil was $20^\circ$ relative to the incoming flow. The hydrofoil chord length, $C$, was 60 mm. The radius of curvature of the trailing edge was 5 mm. The working channel was 200 mm long and 120 mm high. The length of the inlet section of the pipe was more than 50C, so that a fully developed turbulent flow entered the test section [14]. The flow rate was varied inside the loop by the pump. The hydrofoil was made by machining one of the walls of the working channel from transparent plexiglass which provided a surface roughness of about $Ra = 2.5 \mu m$. Bulk velocities calculated from the flow rate varied in the range from 8 to 16 m/s, but cavitation conditions arose from 9.8 m/s. To minimize the amount of dissolved gas, we used an iterative degassing method for several hours, including turblization of the flow at high Re values, followed by evacuation of the evolved air bubbles with a vacuum pump from a reservoir located in the upper part of the experimental setup. The Reynolds number was calculated as $Re = U_0 \cdot C / \nu$, where $\nu$ was the kinematic viscosity, $U_0 = Q / S$ was the bulk velocity, $Q$ was the flow rate, where $S$ was the cross-sectional area of the rectangular working section minus the midsection of the foil, and $C$ was the chord length. The number of cavitation $\sigma = 2 (P_0 - P_{vap}) / \rho U_0^2$, where $P_0$ was the pressure inside the input test section, $P_{vap}$ was vapor pressure, and $\rho$ was the density of water. The Strouhal number was calculated as $St = fC / U_0$, where $f$ is the main shedding frequency of cavities, $C$ is the chord length, and $U_0$ is the bulk flow velocity [3, 13]. Experimental investigations were carried out by the method of high-speed visualization using a Photron fastcam nova s12 camera with a sampling rate of more 100 kHz in order to identify the main features of the cavitation flow.
3. Results

For a detailed study of the spatial structure and dynamics of the vapor-gas cavities, a high-speed visualization was carried out. The areas with the nucleation cavities were fixed with a sampling rate of up to 200 kHz and higher. A homogeneous light source was located behind the measuring area towards the camera. Such configuration of the experimental equipment provides high contrast images on the recording device with clear boundaries of cavitation clouds. Digital image processing was used to identify and analyze the cavitation clouds based on the obtained high speed visualization data. The first step was edge detection via binarization method to extract the contour of the cavities. It included conversion to grayscale, contrast optimization, noise removal and the multi-stage edge detection algorithm based on the Otsu double thresholding method. The next step was to fill the holes inside the transparent regions of the cavity. Further main geometrical and regime parameters were obtained and analyzed. These were characteristic sizes of the clouds, area and shape. Areas of the cavitation clouds was calculated using the sum of image pixels classified as "cloud" and the position of the cavity was determined by analogy with the center of mass of the geometric figure.

The volume of the vapor-gas cavity for each image could be calculated by multiplying the sum of pixels by the channel height and the pixel-to-millimeter conversion factor. Figure 1 shows an example of the change in pixel sum for each image in a single imaging set. Given this signal and knowing the time delay between frames, we use the FFT to calculate the occurrence and separation frequencies of the cavitation clouds.

![Figure 1](image)

**Figure 1.** An example of cavitation area (in pixels) variation calculated for 5000 images.

On the data of high-speed visualization of cavitation flow near a NACA0012 hydrofoil with a rounded trailing edge for a very low aspect ratio $s/C = 0.02$ various flow regimes were investigated. Some interesting features of the development of cavities were examined.

The regime of cloud cavitation is shown in Figure 2. Reynolds number $Re = 8 \cdot 10^6$, and cavitation number, $\sigma$, is 1.73. The cavitation clouds forming in the area of about $0.6C$ of the hydrofoil are a conglomerate of flat vapor-gas bubbles. The vapor-gas bubbles are prolated along the chord foil, assumingly, due to the influence of the liquid flow direction. The size of the vapor-gas flat bubbles changes with the time of the cloud cavitation downstream. Moreover, there is a fusion of flat cavities. During fusion, the ring-shaped waves arise on the surface between the cavity and the wall of the working channel. The wave structures quickly disappear (the lifetime is less than 0.25 $\mu$s). This conglomerate of gas-vapor bubbles rotates and collapses as a whole.

Another cavitation cloud forms behind the rounded trailing edge of the hydrofoil. The process of the arising and development of this cloud completely correlates with the process of the development of the attached cavity. Thus, with the development of a re-entrant jet along the hydrofoil surface, a cloud appears behind the trailing edge. After the detachment of the attached cavity and the next change in the direction of the flow above the foil to the direction "downstream", the cloud detached from the trailing edge of the hydrofoil and its further collapse.
The small attached cavity is shown near the leading edge of the hydrofoil. The length of the attached cavity changes with time. On the surface of the attached cavity the wave structure appears as a result of the development of the Kelvin-Helmholtz instability [15]. A spiral vortex wake appears above the attached cavity in narrow slotted channels which is, assumingly, part of the horseshoe vortex, forming in front of the leading edge of the hydrofoil [16]. A horseshoe vortex forms as a boundary layer, approaches and interacts with an obstacle. The higher velocity flow from the top of the boundary layer moves down the obstacle surface and then upstream, forming a vortex that streamlines the obstacle in the form of a necklace or a horseshoe (the phenomenon has the same name). The horseshoe vortex being linked to the mean flow skew is categorized as a secondary flow of the first kind according to Prandtl [17]. Various authors [18, 19] have found that the strength and location of horseshoe vortices are linked to the leading-edge geometry.

![Figure 2. Regime of cloud cavitation](image)

Using digital image processing of visualization data, the main frequencies of the formation of cavities in the flow near the wake of the hydrofoil have been obtained. The dimensionless frequency parameter, the Strouhal number has been calculated using parameters: $C$ - hydrofoil chord length and $U_0$ - bulk velocity. The obtained Strouhal numbers for the NACA hydrofoil with a very low aspect ratio $s/C = 0.02$ are in the range from 0.3 to 0.45, which according to Callenaere et al. [10], Kravtsova et al. [1] corresponds to the type of intrinsic instabilities of the cavity, a typical example of which is cloud cavitation, observed for all investigated regimes of the cavitation flow in this work.

The second mode varies in range from 0.6 to 0.8, corresponding to the frequency of the attached cavity occurrence. The Strouhal numbers calculated in third mode are more than 1. This mode corresponds to the form of very small cavities near the leading edge of the hydrofoil.

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