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Hydrodynamic effects of the flow on the slab of the stand in the presence of cavitation

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Abstract. This (article) work is devoted to one, relatively unbalanced issue of the dynamics of hydraulic structures - the determination of hydrodynamic loads on the slabs of a high-pressure spillway in a cavitating flow in the presence of erosion-free energy absorbers.
Working on the implementation of these studies, the authors simultaneously studied in laboratory pulsation loads on a real structure - elements of the downstream spillway devices, below – the Kafirnigan hydroelectric complex.

1. Introduction

It should be noted that in cavitation studies carried out until recently, the effect of cavitation on energy absorbers was considered only from the point of view of the possibility of an erosion hazard and the effects of the flow on the absorbers themselves. There is no doubt, however, that the degree of development of cavitation affects the characteristics of pressure pulsation in the cavitating flow not only on the surface of the absorbers, but also not on the water column. In non-cavitation modes, the pulsation loads on the pond have been studied in some detail for some types of dampers. As for the loads on the stand at cavitation modes and erosion – free dampers, they have not been studied.

1.1. Force effects of the flow on the elements of hydraulic structures in the presence of cavitation.

As far as we know, the question of the effect of cavitation on the pulsation characteristics of the water flow acting on the slabs of the water face during the cavitation regime has not been practically studied. However, a qualitative understanding of pressure pulsations behind dampers can be obtained by the example of works studying the pulsation characteristics behind various kinds of obstacles (protrusions, gates, and so on), since both are essentially sources of cavitation, turbulence and pressure pulsations. In work [1], laboratory tests were carried out for a flat valve operating under high-speed flow conditions at a head of 200 m. One of the aspects of the work was studied the dynamic effect of the cavitating flow on the valve. According to the authors, the values of the standards for pressure pulsation on the valve in the presence of developed cavitation are two times higher than the values of the standards in its absence. In the supercavitation mode, such data are not presented because the author of the work failed to obtain supercavitation.

In the works of V. M. Lyatkher and L.V. Smirnov [2, 3], data were obtained on the characteristics of pressure pulsations in the flow separation zone at different absolute pressures, according to which there is an increase in dispersion and a significant deformation of the pulsation spectrum towards high frequencies as development of cavitation. In the separation zone, the spectrum changes during cavitation, naturally due to the fact that the most intense pulsations occur in the presence of cavitation.

A. Lokher and E. Naudasher carrying out systematic studies, obtained the intensity of pressure pulsation on the protruding walls, depending on the number of cavitation. In order to obtain information on flow-induced structural vibrations in common cases, pressure pulsations were measured on the protruding wall. It was found that the intensity of pressure fluctuations, linear correlation, and the spectra of wall pressure fluctuations strongly depend on the adhesion of the flowing stream to the wall; the cases of the absence of cavitation and without adhesion (d / b = 1) were initially investigated. At $d/b = 1$, there was no main frequency in the spectrum of pressure pulsations and the intensity of this load was comparatively low $(0.078\rho U_0^2/2)$. In the case of unstable adhesion of the flow to the wall (for $d/b = 3$), the force effects of the flow are distinguished by a high – frequency spectrum and pronounced peaks, while the pressure pulsations are much higher $(0.13\rho U_0^2/2)$. Cavitation at equal stages leads to an increase in flow pulsations, thus leading to more intense pressure pulsations in the low-frequency part of the spectrum, but only in those cases when the flow does not stick to the streamlined wall [4–9].

For a flow with unstable adhesion, cavitation works with it in antiphase, which leads to a decrease in the relative intensity of low-frequency oscillations. High-frequency oscillations, as the spectra of pressure pulsations show, increase in both cases, in connection with the ultrasonic spectrum of the cavitation phenomenon itself. With supercavitation $K = 1.8$, the pulsation standard decreases significantly. The authors of the reports explain the discovered phenomenon by the damping effect of air bubbles released from the water in the low pressure zone and accumulating in the displacement zone. Apparently, the cavitation steam-gas cavities (flares) themselves have a similar effect.

In works [10–17], the authors also note an increase in the standard of pressure pulsations in the flow separation zones and behind the protrusions of structures. So, in work [13], the research was carried out on the model of the construction spillway of the 2nd tier of the Sayano-Shushensko HPP. A two-dimensional protrusion was installed on the ceiling of the curved spillway and simulated the displacement of one of the elements of the precast concrete floor. The model of the spillway was made of plexiglass on a scale of 1:30 A.D. in. the protrusion height was 6 mm and the downstream length was 100 mm. The protrusion was the source of cavitation, the various stages of which were recorded visually.

The studies were carried out in a pressure mode of fluid flow. The flow velocity in the section of the ledge was 5 – 7 m/s. The pressure pulsations were recorded on the oscillogram both at atmospheric pressure inside the test bench and at different vacuum, providing a change in the cavitation process from the moment of its occurrence to the developed stages.

The authors note that the intensity of pressure pulsations in developed cavitation $(\beta = 0.3)$ is significantly higher than in the case of no cavitation regime, the flow around the rib (see Table 1).

Table 1.

Ridge Wrap Mode	$\sigma_p/V^2/2g$		
	1	2	3
Cavitation-free developed cavitation at $\beta=0.3$	0.019	0.088	0.025
	0.020	0.054	0.095

The above analysis of the oscillogram shows that the frequency and amplitude characteristics of pressure pulsations at various points of the cavitation zone depend on the location of these points within the indicated zone of the stage of cavitation development.

Computer processing of realizations of the cavitation-free process and with a developed stage of cavitation $(\beta = 0.3)$ made it possible to obtain the spectral density functions.

In the case of a cavitation-free flow around the rib, the bulk of the pressure pulsation energy falls on low frequencies (up to 3 Hz). During cavitation, the spectrum shape changes. The contribution of low-frequency components decreases, the maxima of the spectrum are shifted to a frequency of 20-30 Hz. The frequency range expands to high frequencies.

S. Wiegander and U. Chi [12, 13, 18–20], observing the transformation of the exposure spectrum in the region of reattachment of the flow, found an increase in pressure fluctuations by a factor of 6.

For the first time in hydraulic engineering, the force effects of a cavitating flow on erosion-free absorbers were studied by N.N. Rozanova [21–23]. On the basis of cavitation and pressures, the author of this work was able to obtain quantitative regularities of horizontal averaged and pulsating loads on absorbers, and the development of cavitation. During the experiments, a decrease in drag coefficients with the development of cavitation was recorded. The resulting graphical dependence $C_{\text{кав}}/C_0=f(\beta)$ for a jump in the limiting state indicates a change in the drag coefficients of erosion-free absorbers, and is approximated by the dependence $C_{\text{кав}}/C_0=\beta^{0.6}$.

The noted decrease in the drag coefficient during cavitation, especially under the conditions of the developed stage and supercavitation, the author explains there that with the development of cavitation the nature of this pressure distribution on the streamlined body changes.

As you know, from the literature, experimental studies of flow around various bodies (cylinder, plate, disk, others) show a change in the drag coefficient of a body, its reaction with the development of cavitation. Moreover, with a significant development of cavitation, the drag coefficient *"C"* is rather significantly reduced.

At the second stage, the author studies the ripple loads on the absorbers at their maximum swing. The analysis of the research results showed that when the absorbers operate in conditions of cavitation (initial and developed), an increase in the instantaneous pulsation component of the load occurs in comparison with the non-cavitation mode. For example, in the cavitation-free mode, the ripple coefficient δ_η is constant and equal to 0.14 while at the developed stage $(\beta=0.5)$ $\delta_\eta=0.65$, i.e. increased by 4.6 times, and at $\beta<0.5$ it is planned to decrease. In conclusion, we note that the hydrodynamic loads on the cavitation sources and behind them very strongly depend on the stage of cavitation. Therefore, it should be expected that a similar pattern can take place with cavitating erosion-free energy absorbers on the slabs of the water table in the downstream of the spillway hydraulic structures.

1.2. Discussion of the results based on the analysis of literature sources and setting the research objectives.

As the literature review shows, the operating conditions of the downstream damping devices of high-pressure structures are very difficult.

At flow velocities more than 12 - 15 m/s, downstream damping devices, as a rule, operate in a receipt mode. This mode of operation, first of all, gives rise to erosional destruction of the damper itself and the slabs located near it.

This occurs where the cavitation torch closes on the structure. An attempt to avoid these undesirable phenomena by lining erosion sites with steel sheets does not always lead to the desired result, since often the steel lining is torn off by hydrodynamic forces.

Tearing off of the cladding occurs in two cases: firstly, when the cladding is loosely in contact with the concrete to be protected, and, secondly, when there are not enough anchors. In both cases, fractures occur from fatigue phenomena in the metal due to multiple oscillatory cycles from hydrodynamic loads. It is difficult to avoid this in cavitation modes, since the spectrum of pressure pulsations in this case is very wide, which leads to oscillations of the linings at resonance frequencies. Apparently, the issue of the strength of the linings is an object of special research and should be dealt with both theoretically and experimentally in the future.

In [15], it is indicated that a comparison of the pressure pulsation standards obtained in nature under conditions of developed cavitation and on a model tested on a vacuum bench with simulated external pressure showed that when recalculating data from model to field according to Froude, the relative value of the discrepancy between the compared standards ripple does not exceed 9%.

Investigations of pressure pulsations on the model at an unmoded external pressure showed that the standards of these pulsations, recalculated for natural Froude, are underestimated (by about 2.5 times) in comparison with the full-scale values obtained during cavitation. The largest relative discrepancy between these data was 63% [2].

In addition, it can be noted that under cavitation modes, other important flow characteristics also change, such as the weir discharge coefficient, the drag coefficients of the absorbers and the pattern of the body flow with the water flow.

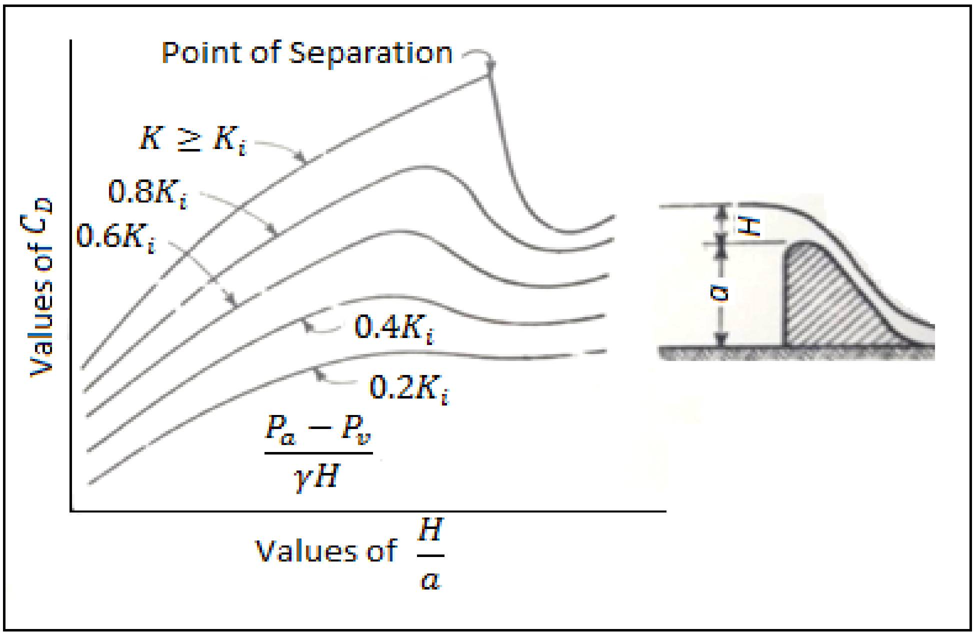

Figure 1. Shows a graph illustrating the change in the weir discharge coefficient from the cavitation rice K and H/a [1].

The given factual material makes it possible to assert that for the correct accounting of hydrodynamic loads during cavitation, the models of the investigated structures should also be tested in the cavitation mode. Such a way of achieving the indicated modes, such as increasing the flow rate on the model, does not solve the problem, since the linear and speed scales of modeling the structure are not observed (the main thing is that the hydraulic stuck is not modeled).

To study the hydrodynamic characteristics of cavitating flows, it is most expedient to carry out research in vacuum cavitation stands. They make it possible to study the quantitative characteristics of a structure at various degrees of development of cavitation processes on it. As the experience of operating real structures with a head of 20 – 30 m and more shows, it is either impossible to exclude the phenomenon of cavitation on damping devices, or rather complex engineering measures are required. Therefore, there is a desire to go on the assumption of the degree of development of cavitation with the use of without erosion structures. This assumption can be found in the works of N.P. Rozanov [24]. The principle without erosion absorbers is that at various stages of cavitation, the zones of formation and decay of cavitation flares do not have direct contact with solid boundaries of the flow.

2. Methods

2.1. The experimental technique and processing of experimental data are given in. Results of experimental studies of pulsation pressures at individual points of the water basin.

The question of the pulsation of hydrodynamic pressures and loads on the slabs of the water face both with and without dampers in cavitation-free modes have been studied rather well. It has been proven that the presence of absorbers leads to a redistribution of pulsation loads over the area of the water face. In other words, in some areas of the water circulation, the pulsation loads can significantly exceed their average value, which must be taken into account when designing.

The question of the influence of cavitation on the redistribution of pulsation loads over the area of the water basin is currently practically not studied. Although many researchers have noted that the pressure pulsation during cavitation changes.

In this regard, during the experiments, the standards of pressure fluctuations along the longitudinal and transverse sections of the water section were studied, depending on the stage of cavitation, the degree of flooding of the jump and the type without erosion absorbers. A preliminary amplitude analysis of the process realizations showed that the intensity of pressure pulsations depends on a number of factors: the parameters β and n (where n is the jump flooding coefficient), the location of the point under study, and the presence of various designs of energy absorbers in the water cut.

3. Results and Discussion

The nature of the dependence $P_i' = f(q)$ where q is the specific water consumption is close to linear. In figures 2...4 show the graphs of the pressure fluctuation standard P_i' normalized by the velocity head in the compressed section $\gamma V_1^2/2g$ along the length of the water stand without cavitation and in the presence of cavitation is different. For example, without cavitation, the maximum and minimum standards of pulsations differ by about 4 times, and in the developed stage of cavitation $\beta = \beta_0 \approx 0.5$ – more than 6 times, where β_0 – is the stage of cavitation, at which the greatest hydrodynamic effects of the flow are observed for cavitating erosional structures, as well as the maximum intensity of cavitation erosion. In our experiments $\beta_0 \approx 0.5$. The second case is less favorable for the operation of the slabs of the slab, since the increased pulsation loads with large irregularities in length can lead to an increase in the moment forces on the slabs of the slab. In addition, the normal vertical loads on the plate also increase, since the absolute value of the pressure pulsation standard at the advanced stage of cavitation increases by more than 2 times.

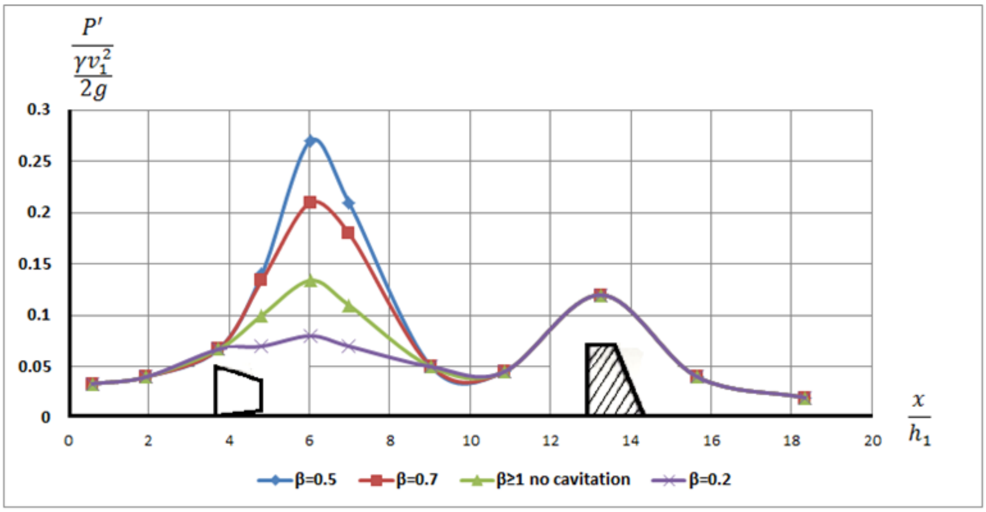

Figure 2. Distribution of the intensity of pressure pulsations along the length of the water wall at different stages of cavitation ($\beta = K/K_{cr}$) for the damper №1 ($n=1$)

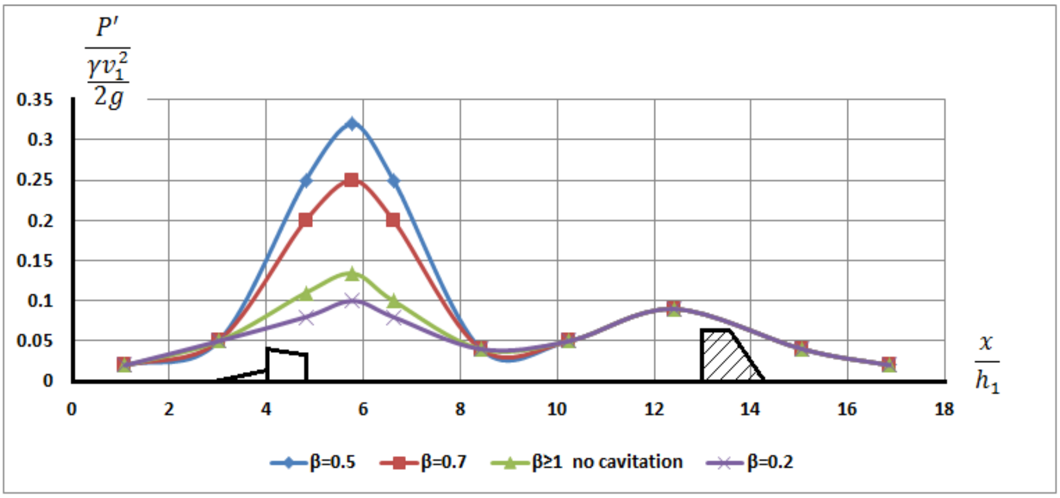

Figure 3. Distribution of the intensity of pressure pulsations along the length of the water wall at different stages of cavitation ($\beta = K/K_{cr}$) for the damper №2 (*n=1*)

As a result, the study of the distribution of pulsation pressure in the water basin by “point” sensors revealed that the standards of pressure pulsation recorded by the sensor located in front of the first row of absorbers are practically the same in all stages of cavitation (figure 4, a). The result obtained indicates that the pressure pulsations in front of the dampers are practically independent of the cavitation stage. This was to be expected, since a violent flow was observed in front of the damper at the sensor installation site. Apparently this is mainly due to the fact that the cavitation torch was not above the sensor.

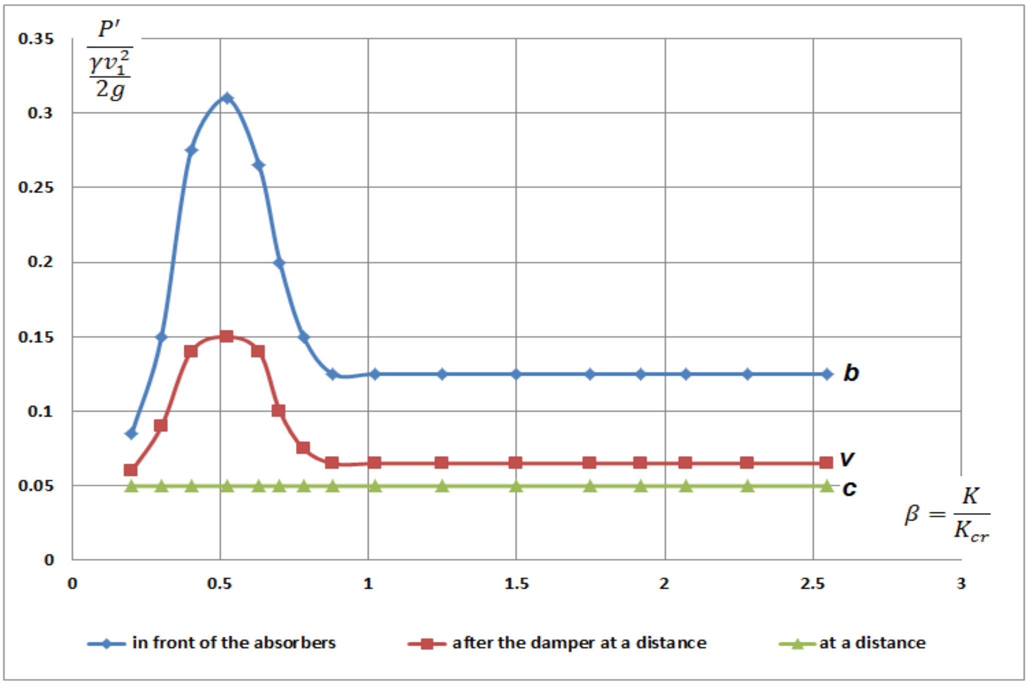

Figure 4. Standard of pressure pulsation at the bottom of the pond, depending on the stage of cavitation β, for the damper № 2; c) – before extinguishers; v) after the damper at a distance x $= 3h_1$; b) on distance x $= 3h_1$.

The greatest hydrodynamic loads are experienced by the slabs of the pond located behind the first row of absorbers at a distance of $(0.5 – 1.5)\ h_1$ from the latter (fig. 4, b). The fact that the greatest pressure pulsations are observed is the greatest dissipation of the flow energy due to the formation of turbulent vortices and cavitation flows. In this case, the largest value $P_i^{\prime}/\gamma\ V_1^2/2g$ occurs at the developed stage of cavitation $\beta=0.5$ and as cavitation develops, the pressure pulsation standards sharply decrease and become smaller during supercavitation than in the non-cavitation mode (that is, at $\beta\geq 1$). A sharp decrease in hydrodynamic pressures during super cavitation can be explained by the fact that during super cavitation a long cavity is formed behind the damper and the transfer of forces to the slab occurs through the water - air environment, that is, the loads decrease. Comparison of the obtained values of the pressure pulsation standards at individual points of the slabs of the water table in no cavitation mode without erosion absorbers № 2, with the data of O.N. Chernykh on the study of pressure pulsations on the slabs of the Shamkhor water system [22], showed good agreement of the results.

It is of some interest to compare the pulsation characteristics without erosion and erosion energy absorbers. For erosion-free damper type № 2, cavitation begins in the zone where the damper meets the inclined threshold. As cavitation develops, the size of the flame increases and it has a decisive effect on the pulsation characteristics of the pressure at the water side (the standard of pulsation increases by 2, 3 times). The plume breaking out from the damper is closed in the flow.

4. Conclusions

1. Under cavitation conditions, the extinguishing ability of the absorbers deteriorates (the drag coefficient decreases), but this does not mean that the use without erosion absorbers in these cases is impractical, since a slight increase in the size of the absorbers can preserve their energy extinguishing properties.
2. A model study of the downstream of spillway hydraulic structures should be carried out on vacuum cavitation stands, which allow regulating cavitation modes (simulating a hydraulic jump and maintaining the Froude similarity criterion). As a result, it seems possible to trace the influence of the degree of development of cavitation on the hydrodynamic loads in the downstream.
3. As a result of the experiments, the areas of the greatest influence of cavitation on the pulsations of hydrodynamic pressures were revealed, and graphical dependencies were also proposed for determining the standards of pressure pulsations at individual points of the water stand at different stages of cavitation. The highest intensity of pressure fluctuations is observed behind the absorbers at a distance of $(0.5 – 1.5)\ h_2$. The effect of cavitation on pressure pulsations is practically transformed at a distance of four compressed depths.
4. Under cavitation conditions, the hydrodynamic pressures on the slab of the water face increase and reach their maximum value in the developed stage of cavitation $(\beta = 0.5)$. In this case, the standard of pressure pulsation at the “points” in the zone of the developed stage of cavitation can increase by a factor of 2 – 2.4 in comparison with the non-cavitation regime.

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