SUPERCAVITATION – PROBLEMS AND PERSPECTIVES

Yuriy N. Savchenko

National Academy of Sciences – Institute of Hydromechanics, Kyiv, Ukraine

Abstract

A brief review of some investigations, which were initiated at the IHM, and new research of the hydrodynamic supercavitation are given in this paper. The main applications of the supercavitaion at underwater high-speed body motion with artificial supercavity, supercavitating water jets and noise suppression are presented. The main features of artificial supercavitation as gas leakage and supercavity closure are discussed. Further perspectives of supercavitation method development are analyzed.

1 Introduction

Cavitation is a fundamental property of liquids consisting in to not withstand the certain extending stresses. As is known, water is practically incompressible medium having properties weakly changing under pressure in hundreds and thousands atmospheres. However, when the pressure in liquid reduces lower than the saturated vapor pressure $p_{sv} = 0.021$ MPascal owing to action of extending stresses, discontinues of the continuity in form of bubbles, foils and cavities, which are filled by water vapor, are observed in water. For the first time Froude investigated this phenomenon and gave it name – cavitation originating from Greece word – cavity. The research cause is an abrupt loss of thrust on a propulsor of battle ship owing to arising cavitation on screws. It was established that the cavitation not only reduces effectiveness of screws, turbines and pumps and causes intensive destruction of them. Therefore, for a long time the cavitation was considered as an harm and undesirable phenomenon.

According to degree of development the three cavitation stages are defined.

Initial cavitation is always the bubble stage accompanied by strong characteristic noise of collapsing bubbles and having a property to destroy solid material, for example, blades of screws, pumps, turbines (Knapp et al 1970).

Partial cavitation is the stage when arising cavities cover a cavitating body part. The cavity pulses and is unstable.

Fully developed cavitation – supercavitation is the stage when the cavity dimensions considerably exceed the body dimensions.

The supercavitation also is the natural process inevitably arising at increase of motion velocity of a displacing body underwater at constant pressure P_0. Near the free surface the supercavitating range of velocities is reached already at velocities higher than 70 m/sec. For considerably small velocities, $V \geq 3$ m/s, supercavities are observed at penetration of bodies through the free water surface or at horizontal motion in the conditions of crossing the free boundary. In this case the supercavity is filled by atmospheric air and is related to artificial or ventilated supercavities forming at the lower speeds.

It is important to note that for the first time the supercavity investigation necessity arose in the process of preventing the cavitation inception where contours with constant pressure on the boundary were used. In Germany Prandtl and Reichardt have proposed to use the cavity sections obtained in the experiment for selection of the body sections with constant pressure for corresponding flow regimes. For long time this method was successfully used to design water inlet contours and struts.

In further, the supercavitating flow investigation was developed in Wagner (1932) work. He investigated the water entry of bodies. In that time the practical alication of the supercavitation consisted in solving problems of water entry without ricochets and planing (Reichardt 1946).

The considerable progress in the supercavitation investigation development was given in investigation of supercavitating foils for ship screws, pumps and hydrofoils (Posdunin 1944, Tulin 1955). This was stimulated by development of the theoretical methods of the cavity calculation past disks, wedges and cones (Knapp et al 1970, Logvinovich 1969, Epshtein 1970).

Appearance of the artificial cavitation method was very important, when Reichardt showed that it is possible to research experimentally the supercavitation phenomenon on an artificial cavity obtained by air blowing into the cavity at essentially lower speeds. In this case the cavitation number $\sigma = 2\frac{p - p_c}{\rho V^2}$ is a main parameter, where p is the hydrostatic pressure, p_c is the pressure in the cavity, ρ is water density , V is the mainstream velocity.

Application of the artificial cavitation method essentially simplified the researches of the cavitation phenomena and expanded application fields of the supercavitation (Knapp et al 1970, Logvinovich 1969, Epshtein 1970, Yegorov 1971).

2 Supercavitation as a perspective method of drag reduction

Nowadays, when the further increase of power of force installations using the atomic energy is not able to ensure the technically justified increase of vehicle motion speed, the problem on hydrodynamic drag reduction has got paramount importance.

It is necessary to note that the hydrodynamic drag reduction is important not only for vehicle speed increase, and for decrease of noises and perturbations in an environmental fluid and for ecological load reduction on a water medium as well.

The numerous and various ways of the drag reduction require realization of control actions, which may be conditionally divided into active and passive ones (Savchenko 1999):

– the passive control action ensures the drag reduction without energy consumption or due to the flow energy;

– the active control action ensures the hydrodynamic drag reduction of the friction or shape due to the energy rate or rate of special substances.

The choice of optimal control action on a fluid flow to stabilize the special flow scheme with small hydrodynamic drag also is great complexity. This scheme without this influence is not realized. Thus, the optimal control action means the minimum of the ratio of energy consumption on the control action, E_c, and advantage in total hydrodynamic drag of an object, ΔR (Gabrielli & Von Karman1950)

$$\overline{E}_{c\min} = \frac{E_c}{\Delta R V_\infty}.$$

The method of gas supply into the boundary layer and air lubrication creation were especially attractive to reduce the friction drag, as air density is less in 800 times than water density.

For the first time the hydrodynamic drag change at gas supply into the boundary layer was considered by Loytsyansky and Fedyaevsky (1942). In this paper, the assumptions about monotonous changing the parameters of the biphase mixture were stated.

The experimental researches by I. D. Zheltuhin (1965) have shown that the biphase medium properties may change spasmodically in the boundary layer. There are possible qualitatively different friction mechanisms than in a homogeneous fluid in this case.

The further researches on the drag reduction at saturating the boundary layer by air micro-bubbles have been carried out at the CSNII named for Krylov and shown a possibility of the friction drag reduction on 30 ÷50 % for range of numbers $\mathrm{Re} = 10^7$ at air rate $q \approx 2$ $\mathrm{dm^3/cm^2}$ ·hour through the porous covering with an orifice diameter $d \approx 2$ mm (see Figure 1, a) (Barbanel et al 1994).

As experiments have shown, the application of slot gas supply of the boundary layer is accompanied by increasing the air rate in 10 ÷20 times at the same drag reduction effect (see Figure 1, b).

The experiments on gas-saturating the boundary layer are continued in methods of the artificial cavitation. During air-supply the flow past the cavitating edge separates from a body and may form cavities of large aspect ratio. In this case the free water surface does not touch a body surface (see Figure 1, c) (Loytsyansky 1942).

It is interesting to note that this process may be realized due to the natural evaporation at speeds more than 70 m/s, when the gas phase will be supplied in the clearance not through a permeable surface and from the free cavity surface (see Figure 1, d) (Knapp et al 1970, Logvinovich 1969, Epshtein 1970).

Theoretically, such process may be realized with as much as small air clearance between the free boundary of water and a body.

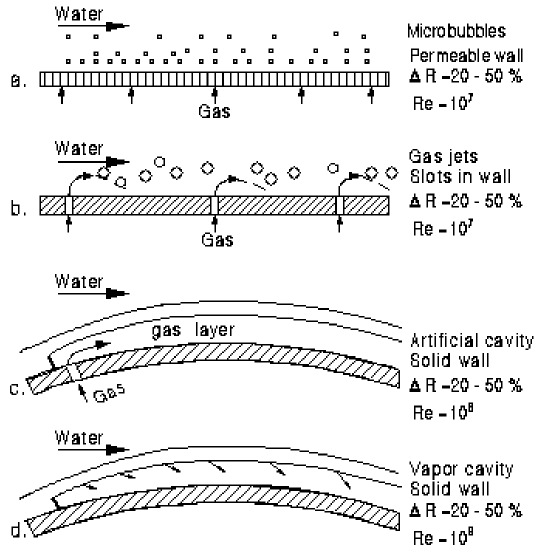


Figure 1: Possible flow schemes at gas blowing

However in practice, it is necessary to take into account the natural process of free cavity surface destruction and gas flow influence in the clearance.

In such flow scheme, it is necessary to consider the drop flow instead the bubble flow in the clearance where the impulse carry from the free fluid boundary to a solid surface through the drops may be realized.

The calculations and experiments on the drop flows in clearances have been carried out at the IHM UNAS.

In practice, the vehicle development is stipulated by that useful effect, which is reached at vehicle operation. The useful effect for transport ships consists in transportation of cargoes. Thus, the ship efficiency as vehicle efficiency will be determined by a commercial effectiveness (Gabrielli & Von Karman 1950)

$$K_p = \frac{PV}{N},$$

where P is the payload, V is the velocity, N is the power.

The velocity and distance are determining parameters for vehicles used for the military and rescue purposes. Thus, the hydrodynamic drag reduction positively influences on all the basic characteristics and increases the commercial efficiency factor due to the consumed power decrease or increase of velocity and distance.

For surface vehicles, the tendency of decreasing the waterline area and wetted surface of the hull by dynamic means of the hull maintenance above the water is precisely observed. There are ships with the small waterline area twin hull ships (SWATHS), hydrofoil ships, hovercraft, ekranoplanes and hydroplanes.

Thus, the energy consumption to realize the dynamic ways of the hull maintenance above the water may be related to the control action of the drag reduction (Savchenko 1999).

For underwater motion, the same way of the wetted hull surface reduction may be applied due to fully developed artificial or vapor cavitation (supercavitation) (Logvinovich 1969, Epshtein 1970, Savchenko 1996).

Calculations have shown that 20-multiple advantage in hydrodynamic drag may be at velocity 100 m/s and cavitation number $\sigma = 0.01$, and 1000-multiple advantage in drag may be obtained at $\sigma = 10^{-4}$ (Savchenko 1996)

Comparing the efficiency of the different ways of the hydrodynamic drag reduction with the efficiency of the artificial and vapor cavitation, it is possible to see its preference and hence, application perspective. Besides, the vapor layer between the water and hull unites many methods of the drag reduction such as:

- Adhesion reduction of water to a surface or slippage;
- Mobile surface effect (the gas stream velocity in the clearance may be equal to water stream velocity);
- Modification of the physical constants of the boundary layer (here, medium density reduction);
- Gas-supply into the boundary layer. (Here: - the gas is blown through the solid body surface in the case of artificial supercavitation; - the gas is supplied from the supercavity surface in the case of vapor cavitation).

However, the application of the supercavitating flow schemes requires respectively high specific power of a vehicle. So, for velocity 100 m/s at cavitation numbers $\sigma = 0.05 \div 0.01$ the limiting specific power will be about $\frac{N}{D} = 1500 \div 2000$ H.p./t, that is compared to the specific power of planing ships in the universal Gabrielly-Karman (1950) diagram.

3 Supercavitating flow schemes for underwater motion of bodies

Main difficulties of using the supercavitating flow scheme for underwater objects are connected with necessity of ensuring the object motion stability in conditions of loss of Archimedes buoyancy force and location of a point of the drag force application in front of the object mass center.

Possible schemes of supercavitating flow around bodies of revolution with hydrodynamic unloading the object weight *G* in the cavity are shown in Figure 2 (Savchenko et al 1998, Savchenko et al 1999).

In the fours possible motion schemes the object weight *G* is compensated by two hydrodynamic forces

$$G = Y_1 + Y_2 \,,$$

where Y_1 is the lift on the cavitator; Y_2 is the lift on the planing part of the hull.

Two-cavity flow scheme (Figure 2, a) has considerable washed area of the stern hull part. It permits to use traditional means of object motion stabilization. Besides the increased stability, this scheme gives a possibility to use the pressure difference in the nose P_{CN} and tail P_{CR} cavities for creation of additional propulsion or drag reduction

$$\pi D_b^2 / 4(P_{CR} - P_{CN}) = \Delta \mathrm{X} \,.$$

To realize the flow schemes (Figure 2,a and b) it is necessary to maintain constant place of the cavity closure. It will save invariable value of forces and moments during change of motion depth and velocity.

Preservation of constancy of the cavity closure conditions also is important for preservation of constancy of gas leakage Q_L and balance of gas mass in the artificial cavity.

3.1 Supercavity closure on the body

A description of processes occurring in the cavity closure zone is the most difficult problem of the hydrodynamics of fully developed cavitating flows.

According to the known theoretical closure schemes the cavity may be closed on the solid body by following ways (see Figure 3):

- Ryabushinsky scheme. A cavity is closed on the solid surface analogous to the cavitator (Figure 3, a).
- Zhukovsky-Roshko scheme. A cavity is closed on the cylinder with diameter D_c equal to the diameter of the biggest cavity section (Figure 3, b).
- Brilluene scheme. A cavity is closed on the solid body with a base cavity formation, where $p_{c2} > p_0$ and $\sigma < 0$. In this case the base cavity is closed without a critical point formation (Figure 3, c).
- Efros scheme. A cavity is closed with formation of a reentrant jet which may have effect on the body (Figure 3, d).

The theoretical schemes of closure a, b, c provide a closure of the free surface with a solid body surface at zero angle of attack. This is very difficult for practical realization. Therefore, to realize the steady closure it is necessary to apply the blowing or suction of fluid in the closure place. In paper (Maltsev et al 1976) , the scheme of steady cavity closure on the jet of the liquid flowing from the aperture in the closurer having an elliptical shape was proposed.

The mechanism of the gas leakage from the cavity closing on the body is very complex and depends on many factors. There are:

a) cavity perturbations: its floating-up, wave deformations, natural break down of the free boundary, radial velocity in the closure place;

b) parameters of the body: shape in the closure place, surface roughness, vibrations;

c) closure conditions: an angle of the free boundary in flow, value of perimeter of the washed line; presence of liquid and gas jets, presence of special additions changing the surface tension and fluid viscosity.

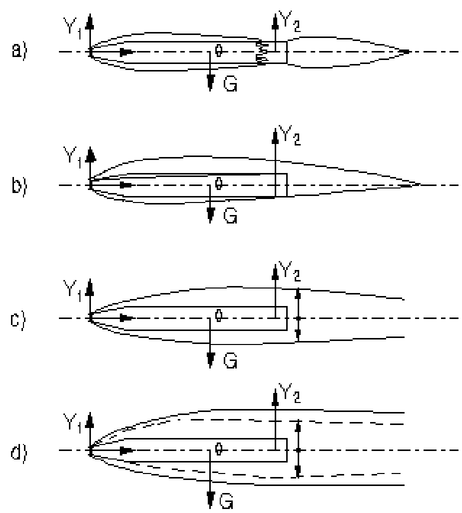


Figure 2: Schemes of body stabilization in supercavity

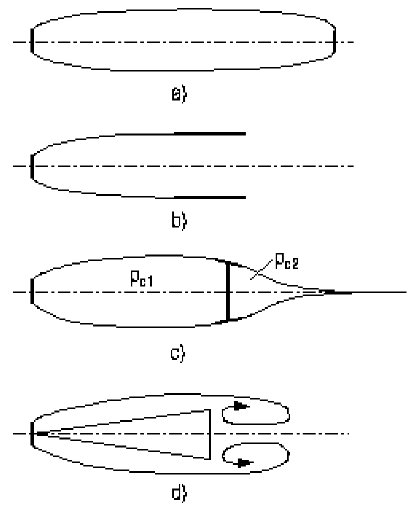


Figure 3: Theoretical schemes of cavity closure by: *a* - Ryabushinsky; *b* - Zhukovsky-Roshko; *c* - Brilluene; *d* - Efros.

An experience of work with artificial cavities shows that the value of the gas leakage from the cavity may be compared with rate of liquid being supplied to the cavity from the reentrant jets. It is possible to explain physically that the liquid supplying to the cavity foams, mixes up with gas and is carried-over from the cavity as a mixture of gas and water.

Starting from equations of impulse preservation, the area of cross section of the reentrant jet flowing to the cavity at its free closure is equal (Logvinovich 1969)

$$S_j = \frac{c_x}{4}\frac{\pi D_n^2}{4}.$$

At condition of closure of the cavity on the circular cylinder with diameter D_b, the reentrant jet intensity will depend on ratio of areas of sections of the cavity middle part, $\pi D_c^2/4$, and area of cross section of the cylinder, $\pi D_b^2/4$, and $D_b \le D_c$

$$Q_j = kV \cdot S_j\left(1-\frac{D_b^2}{D_c^2}\right),$$

where k is a some coefficient taking the cavity closure conditions into account.

At $D_b = D_c$ we obtain a condition of the cavity closure by Zhukovsky-Roshko scheme with zero gas leakage.

Theoretically, the zero gas-leakage may be ensured at the cavity closure on the body having the diameter smaller than the maximal diameter of the cavity $D_b < D_c$ owing to the agreement of the cavity curvature with the body curvature in the closure place.

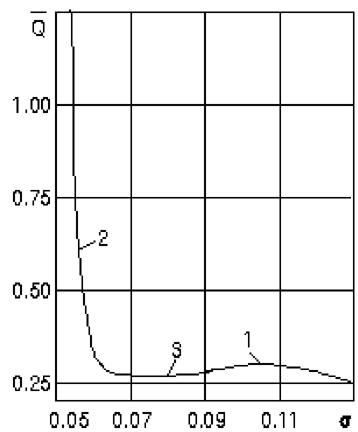
Here, the tangential to the body and the tangential to the cavity boundary should have the same angles of inclination $\alpha < \alpha_B$ to the horizontal axis in the closure point.

To ensure the zero gas-leakage is practically impossible. However, a possibility of it reduction to the minimal value, which are stipulated by presence of micro-scale perturbations, remains. These perturbations are stipulated by natural collapse of the free cavity boundary, the flow turbulence and the body vibrations.

3.2 Hysteresis effect of cavity dimensions at cavity closure on the body

Experiments on control of dimensions of the artificial cavity closing on the bodies have found the hysteresis effect. This effect appears the stronger the more the body surface curvature where the cavity closes.

A control of the artificial cavity is realized due to presence of dependence of cavitation number on the gas-supply intensity (rate) into the cavity $\sigma = f(Q)$ (Figure 4).



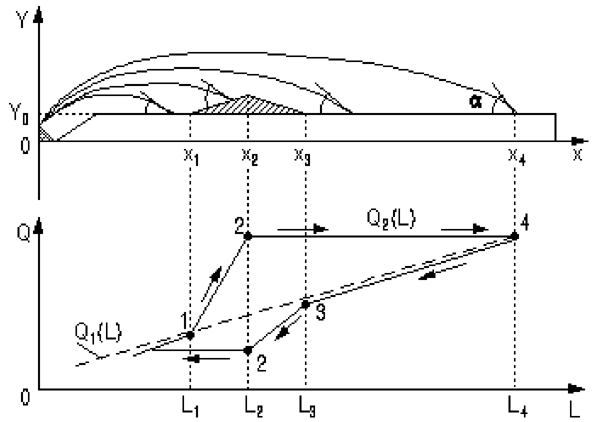


Figure 4: Typical dependence of the gas leakage rate $\overline{Q}$ on the cavitation number σ.

Figure 5: Hysteresis effect at the supercavity closure on the body. Hystresis loop of $Q(L)$

If we consider the two-dimensional cavity closure zone on the plane $Y = y_0$ (Figure 5), it is possible to note that the closure angle α will be increased with the cavity dimension growth in the closure zone

$$\alpha(x_1) < \alpha(x_3) < \alpha(x_4),$$

because of the increase of the ratio D_c / y_0 and relative cavity dimensions. Thus, the velocity on the cavity boundary will be changed insignificantly due to smallness of cavitation number variation

$$V_c = V\sqrt{1+\sigma}.$$

In this case the specific value of the gas leakage from the cavity will depend only on a local angle of the cavity closure on the vehicle hull

$$Q_L = Q(\alpha).$$

This dependence existence is explained physically by existence of dependence of the reentrant jet rate (section) on angle α, $q_{RS} = q(\alpha)$. The reentrant jet arrives to the cavity, mixes with gas and carries over the gas in form of bubbles and foam. This mixture forms a two-phase wake behind the cavity. Dependence of the gas leakage at the cavity shape changing on the plane $y = y_0$ is shown in Figure 5 by dotted line $Q_1(L)$.

We note this hystreresis property for function of the artificial cavity supply is very important, since it may be used for stabilization of the cavity closure on the body at corresponding design of the body surface shape.

Several new and projected underwater vehicles exploit supercavitation as a means to achieve extremely high submerged speeds and low drag. The dimensions of existing or notional supercavitating high–speed bodies range from that of bullets as Adaptable High-Speed Undersea Munitions (AHSUM) having supersonic speeds (Kirschner 1998) or the projectiles of the Rapid Airborne Mine Clearance System (RAMICS) (Rapid Airborne Mine Clearance System 1996) to that o full scale heavy weight torpedoes (Litovkin 1996).

4 Supercavitating water jets

For enough high initial velocities of the jet outflow under continuous air-supply supercavities may develop, when the jet is extended in the liquid within the gas supercavity in gas medium on distance up to 1.5 of the supercavity length from the nozzle exit section.

Under usual conditions the jet is extended in the rest liquid with half velocity $V_0/2$. The cavity dimensions are determined by the relations

$$D_c = D_n \sqrt{\frac{c_x}{\sigma}}; \qquad L_c = \frac{D_n}{\sigma}\sqrt{c_x \ln\frac{1}{\sigma}},$$

where D_n is an equivalent disk diameter connected with the jet diameter d_j by relation $d_j = 0.205 D_n$; c_x is the hydrodynamic drag coefficient for the disk $c_x = 0.82$ (Logvinovich 1969, Yegorov et al 1971, Gurevich 1979).

In the experiments the water jets with diameter 5mm and outflow velocity up to 200 m/s reach length 3.5 m under supercavitating vapour regime, when the cavity is filled by saturated water vapour.

Stationary supercavitating jets may be formed at the jet ejection towards the stream. At velocities up to 70 m/s the continuous gas supply into the jet boundary layer is necessary to form the supercavity in water. For velocities higher than 100 m/s the special supply is not necessary, because the cavities are filled by saturated water vapour. The supercavitating jets formed by water jet in the water tunnel at velocity 9 m/s due to artificial air-supply into the supercavity are shown in photo (Figure 6). An experimental dependence of the jet length L_j to the frontal point of the cavity on the velocity in the jet $\overline{V}_j = V_j / V_\infty$ is shown in Fig 7.

The method of calculation of cavities past a jet cavitator has been developed at the IHM of NAS of Ukraine (software CAVAR). For given channel parameters and cavity length the supercavity shapes and cavitation number are calculated in dependence on the value of liquid rate W through the channel (Deynekin 1994).
Supercavitating water jet was considered as method of underwater cutting solid materials as steel, concrete, bottom deposits.

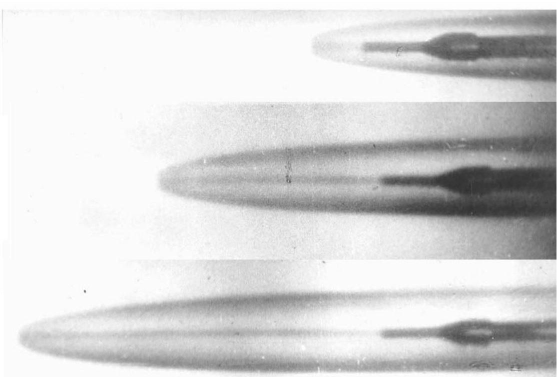


Figure 6: Supercavities formed by water jet in water tunnel at $V = 9$ m/s

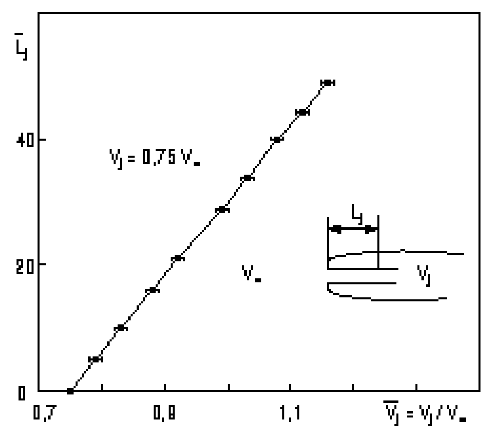


Figure 7: Experimental dependence of water jet length $\overline{L}_j$ on jet velocity $\overline{V}_j$

5 Supercavitation as method of noise suppression

At the IHM UNAS the supercavity near a body was considered as the element of mechanism to control sound radiation (Grinchenko 1998). In Figure 8, a test equipment is presented. At the top of part 1 a hydrophone is situated. There is a sound radiator in region 4. The signals from hydrophone were considered for two cases. First the equipment was put in flow without cavity. The flow velocity was small to produce natural vapor cavity. In the later case the artificial cavity – 2 was created near the head part of equipment. In both the cases the same value of electric voltage was used as an exciting force of the sound radiator in region 4.

The results of sound measurement are given in Figure 8. The line crossing squares corresponds to the first case. The crosses identified the line corresponding to the second one. It is natural that the presence of cavity sufficiently changes the conditions of work for hydrophone. The nearby sources of sound are working similar to acoustically soft surface. One can see that the cavity plays a role of such surface in very wide frequency band. In Figure 8, we can see the same difference in 20 dB between sound levels of source.

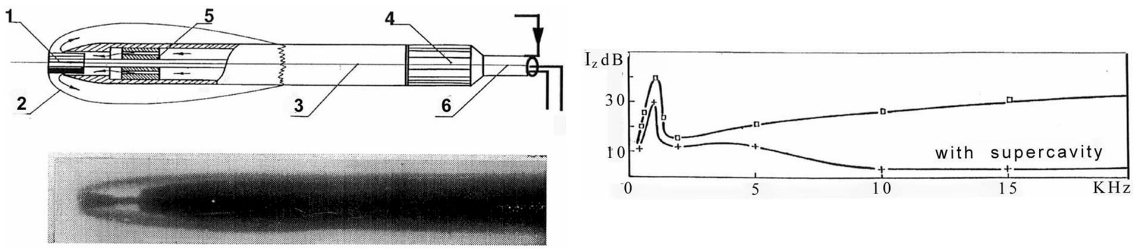


Figure 8: Experimental supercavity model with hydrophone, photo of supercavitating flow and result of sound magnitude (voltage I_{Σ} ,dB) measurement: 1 - hydrophone-cavitator; 2 - supercavity; 3 - supercavitating body of revolution; 4 - sound radiator; 5 - permeable spacer.

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