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CAVITATION NUCLEI AND THRESHOLDS OF ACOUSTIC CAVITATION IN OCEAN WATER

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ABSTRACT

The paper is devoted to the results of experimental research on the measurements of acoustic cavitation thresholds of ocean water in different regions of the World Ocean. Different types of cavitation nuclei determing the tensile strength of ocean water are analyzed. Acoustic methods for measuring acoustic cavitation thresholds in ocean water are described. The results of acoustic cavitation threshold measurements are presented for the water of the Atlantic Ocean, the Pacific Ocean, the Indian Ocean, the Arctic Ocean and some other regions of the World Ocean, including the Arabian Sea, the Baltic Sea, the East Siberian Sea, the North Sea, the Philippine Sea, the Sea of Japan, the Sea of Okhotsk and the South China Sea. These measurements were carried out at many ocean expeditions. It should be noted that acoustic cavitation thresholds of ocean water have different values in different regions of the World Ocean.

INTRODUCTION

The tensile strength of ocean water determines the limiting values of acoustic power that can be radiated by powerful acoustic sources. Therefore, the knowledge of acoustic cavitation thresholds of ocean water at different depths in different regions of the World Ocean is of practical interest. Furthermore, the tensile strength of water determines the value of critical velocitie of the motion of different floating bodies in the ocean or sea water, which excess leads to the beginning of hydrodynamic cavitation.

Acoustic cavitation arises in the sea water or any other liquid under the action of a powerful acoustic field when the acoustic pressure amplitude P_m exceeds some threshold value P^*_m commonly called the tensile strength or acoustic cavitation thresholds. The P^*_m value in sea water depends on many hydrophysical and hydrochemical parameters of water. The influence of hydrostatic pressure P_o, linearly increasing with depth, is an important factor. The values P^*_m and P_o are bound up by the relationship $P^*_m = P_o - P_c$ where P_c is equal to the hydrodynamic cavitation threshold pressure value in liquid at which cavitation arises. The P_c value is equal to the saturated vapor pressure P_v for liquids with large sized cavitation nuclei. The P_c value can be negative for very pure liquids with small cavitation nuclei. The acoustic threshold pressure P^*_m values are always positive.

Hydrodynamic cavitation is induced by the influence of pressure pulsations arising in water due to rotation of screw propeller or to flow along the different bodies in the ocean water. In this case it is customary to call the pressure change $P_o - P_c$ as the tensile strength or cavitation threshold of water.

The acoustic cavitation threshold P^*_m for ocean water is also connected with the acoustic field frequency f which can vary over a wide range depending on the acoustic source. In the general case the value $P_o - P_c$ at hydrodynamic cavitation can differ from the value P^*_m at acoustic cavitation for the same conditions of sea water medium. However, on lowering of acoustic field frequency f to the value of a characteristic average frequency of hydrodynamic pulsations $< f >$ it is expected that the value P^*_m at acoustic cavitation will approach the value $P_o - P_c$ at hydrodynamic cavitation. This allows us to use the results of acoustic measurements to determine the thresholds of hydrodynamic cavitation in water.

CAVITATION NUCLEI

Usually, the tensile strength of sea water P*m increases with sea water depth. However, this increase can obey different laws that are determined, first of all, by the size and concentration of cavitation nuclei in the water.

In the upper sea water layer the most characteristic cavitation nuclei are gas bubbles, the size and concentration of which are determined by surface roughness and by hydrophysical parameters that determine gas solubility in the water. Usually in each specified water volume gas bubbles of different sizes R are presented, i.e. there is some statistical bubble size distribution density g(R). The concentration of bubbles with a radius between R and R+ ΔR is defined as $\Delta N(R) = g(R).\Delta R$ where ΔR is the incremental size range. For gas bubbles in sea water, a substantial increase of concentration N(R) with an increase of sea roughness and wind speed is characteristic. The problem of determining gas bubble sizes and bubble concentrations in ocean water can be solved by acoustic methods [1].

Cavitation in sea water can also arise on phase inclusions in the form of zooplankton or phytoplankton. The size of zooplankton range from 5 micrometre for nanoplankton to 1 mm for microplankton and about 5 cm for macroplankton. The sizes of phytoplankton are spread over an even wider range. At increasing depth in sea water, the population density of plankton decreases, although at some depth a local increase of density is observed in the form of extended layers known as sound scattering layers. Cavitation can also originate on solid nuclei which get into the sea water from the atmosphere, rivers and other sources. These solid nuclei can have different sizes, different forms and degree of wetting with water.

Cavitation nuclei in sea water can originate from small vapour bubbles generated by high energy particles caused by cosmic rays or radioactivity. Primary cosmic rays, composed mainly of protons and α-particles, get transformed into secondary particles consisting of electrons and μ-mesons at the sea level. Electrons are rapidly absorbed in water while μ-mesons possess great penetration power and are poorly absorbed in water. Electrons and μ-mesons interact with the electrons of sea water atoms engendering δ-electrons. Local heat released by δ-electrons when they lose energy leads to the formation of vapour bubbles which are smaller than 10^{-6}cm in diameter.

In contrast with charged particles causing ionization, neutrons interact only with atomic nuclei as they pass through sea water. As a result, concentrations of free radicals and atoms of oxygen and hydrogen can arise in the water. Due to their structure they act as molecules of dissolved oxygen and hydrogen, and can form bubbles owing to coagulation of gas molecules. A great number of both experimental and theoretical works [2] are devoted to the influence of neutrons and ionizing particles upon the tensile strength of water. Similar effects may be caused by such primary cosmic particles as neutrinos.

All the enumerated cavitation nuclei appear in the sea water medium owing to the action of outside forces and disturbances. However, even in case of complete isolation from external influences, the formation of vapour bubbles is possible due to the manifestation of thermodynamic heterophase fluctuations. The sizes of such cavitation nuclei do not exceed 10^{-7}cm. Under normal conditions in sea water these cavitation nuclei are negligibly small compared to gas bubbles, plankton and solid particles.

MEASUREMENT TECHNIQUE

The determination of the tensile strength of sea water by acoustic methods amounts to the measurement of the acoustic field threshold amplitude P^*_m which, if exceeded, causes cavitation to develop. Characteristic changes of acoustic signals allowing the determination of the acoustic cavitation threshold are presented in Figure1.

Cavitation was excited by the initial tonal acoustic signal with a basic frequency f and amplitude P_m. The frequency of exciting initial signal was 10 kHz. The onset of cavitation corresponds to the rise of an acoustic cavitation noise signal with the pressure P_n that contains the discrete harmonic spectral components with the frequencies of nf, where $n=2,3,\ldots$, and also the continuous spectrum component of the received signal. Figure 1 and Figure 2 show examples of experimental measurements of the initial acoustic signal P_m and the cavitation noise signal P_n in sea water as the electrical voltage V of a high power acoustical source increased. These experimental results were carried out in September 1982 in the Sea of Japan at a latitude about 42°*N* and longitude about 132°*E*.

The relation of the acoustic cavitation noise signal P_n to the amplitude of the main basic tonal signal P_m determines the coefficient K of nonlinear distortions of the acoustic signal at the beginning of acoustic cavitation, where $K = P_n / P_m$. Experimental investigations into the onset of acoustic cavitation in sea water with different physical and chemical characteristics (temperature, salinity, gas content and others) at different depths showed that the value $K = 0.1$ corresponds to the onset of cavitation at some threshold amplitude $P_m = P^*_m$. In Figure 1 the cavitation threshold value P^*_m and appropriate noise value P_n are marked with light circles. The idea of a spectral criterion for the onset of acoustic cavitation was first used by us in 1963 [3], and later a similar measurement technique was employed by others authors [4].

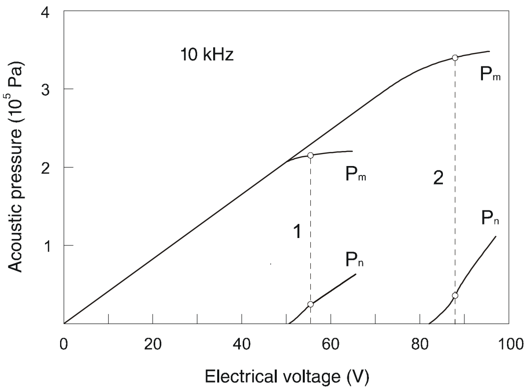

Figure 1. Initial acoustic signal and cavitation noise signal at different depths. 1-depth of 5 m, 2-10 m.

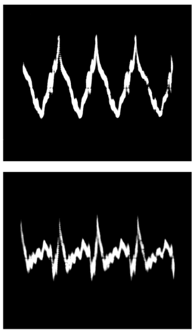

Figure 2. Total signal (on top) and cavitation noise (below).

In our work [3] we suggested to use a water-filled cylindrical acoustic source to stimulate cavitation in the water but not on the radiating surface of the source. Figure 3 and Figure 4 show two schemes for measuring the acoustic cavitation thresholds P^*_m in sea water. The techniques of the measuring the tensile strength of the sea water, presented in Figure 3, are based on the use of cylindrical acoustic sources which are usually manufactured from piezoceramic active materials. The resonance frequencies f of such acoustic sources are connected with the diameter of the sources d by the formula $f = c_p/\pi d$, where c_p is the sound speed in the piezoceramic material. Such sources are suited to use at frequencies greater than 1 kHz. To use them for measurements at lower frequencies requires an excessive increase in the value d, which leads to construction difficulties.

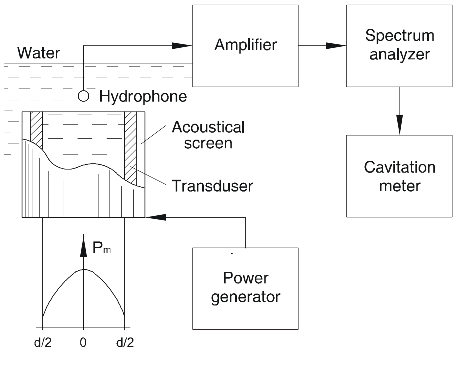

Figure 3. Scheme with water-filled cylindrical piezoceramic acoustic source.

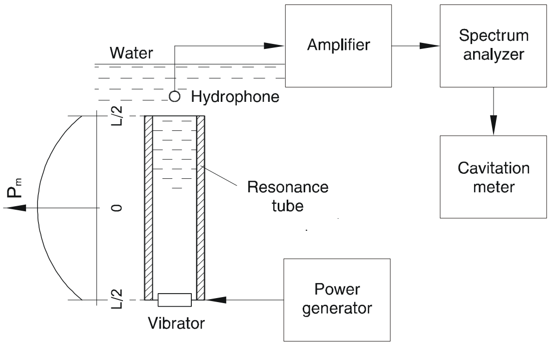

Figure 4. Scheme with the resonance metal tube excited at one end by the acoustic vibrator.

To excite cavitation in sea water at low frequencies, in the order of hundreds of Hertz, it is more convenient to use sound sources which are resonant metal tubes, open at one end and excited at the other by an acoustic vibrator [5]. Figure 4 shows this system, where sea water fills the tube and the onset of cavitation may be observed approximately in the middle section of the tube, where the amplitude of the acoustic standing wave is a maximum. The resonant frequency of such acoustic sources f is connected with the tube length L by the formula $f = c_o/2L$, where c_o is the sound speed in the sea water.

CAVITATION THRESHOLDS IN DIFFERENT REGIONS OF THE WORLD OCEAN

The results of experimental measurements of acoustic cavitation thresholds in different regions of the World Ocean are presented below.

The Arctic Ocean

Particular results were obtained in the East Siberian Sea at the site with the coordinates 76°N and 164°E, where the measurements of acoustic cavitation thresholds were carried out in May 1969. The measurements were conducted from a drifting block of ice with a thickness about 3 m. The air temperature was minus 12°C. The water temperature varied from minus 1.68°C near the water surface to minus 1.55°C at a depth of 50 m.

Table 1. Acoustic cavitation thresholds at
different frequencies in the Arctic Ocean.

Frequency *(kHz)*	2.0	4.0	6.0	8.0	10.0	15.0
Threshold $(10^5\,Pa)$	1.9	2.9	3.8	4.7	5.6	6.9

Table 1 presents threshold data at a depth of 10 m, and indicates that in the arctic water the values were too high. This result was because the ice cover prevented any surface roughness of the sea water which caused small sizes and concentration of gas cavitation nuclei. It is seen that the acoustic cavitation thresholds of ocean water can differ by several times with frequency f. When the frequency f increases the value of the acoustic cavitation threshold P^*_m also increases.

The Atlantic Ocean

These measurements were carried out in the northern part of the Atlantic Ocean during two different seasons: the spring season, March-April 1968, and the summer season, June-July 1968. Figure 5 presents the experimental results for P^*_m as a function of latitude in the Atlantic Ocean, from the equator to the North Sea and the Baltic Sea. In Figure 5 the solid circles correspond to the measurements in the spring season while the open circles correspond to the summer measurements. The cavitation was excited at depths of 10 m and 20 m by a continuous tonal signal at a frequency of 10 kHz.

It is seen from Figure 5 that in the North Atlantic Ocean some variability in the thresholds was observed depending on the latitude. The thresholds had higher values near the equator and decreased with increasing latitude. This effect was more manifest at a depth of 20 m than at the 10 m depth. The sites with latitude 54°30'N (longitude 4°52'E) indicate measurements in the North Sea while the two sites at latitude 55°33'N (longitude 15°55'E) and latitude 57°46'N (longitude 20°09'E) were in the Baltic Sea. They are shown in Figure 5 as separate points with the different values of cavitation thresholds corresponding to measurements in March and July 1968.

Simultaneous measurements of hydrological and hydrochemical parameters were carried out at the same points in the Atlantic Ocean. It was discovered that the tendency for P^*_m to decrease with distance from the equator was related to an increase in the dissolved gas and oxygen content in the water at higher latitudes in the North Atlantic Ocean. The same tendency was observed in the Indian Ocean and the Pacific Ocean.

The Indian Ocean

The measurements of the acoustic cavitation thresholds in the Indian Ocean were carried out during March-April 1987, the autumn season of the Southern Hemisphere. The measurements were made at a site with latitude about 20°N in the Arabian Sea to one about latitude 45°S in the southern part of the Indian Ocean. The cavitation was excited at the depths of 10 m and 20 m by using continuous tonal signals at frequencies of 750 Hz, 2.3 kHz, 5.4 kHz and 10 kHz. In the Indian Ocean some variability in P^*_m, depending on the latitude, was also observed. This variability increased with increasing frequency. The highest variability was at 10 kHz. Higher threshold values occurred near the equator and decreased with distance away in either the northern or southern directions. This effect was more manifest at a depth of 20 m than at 10 m. The tendency for P^*_m to decrease with distance from the equatorial region is associated with an increase of dissolved gas, that is inversely proportional to the sea temperature, and with an increase of gas bubble concentration, which varies directly with sea roughness.

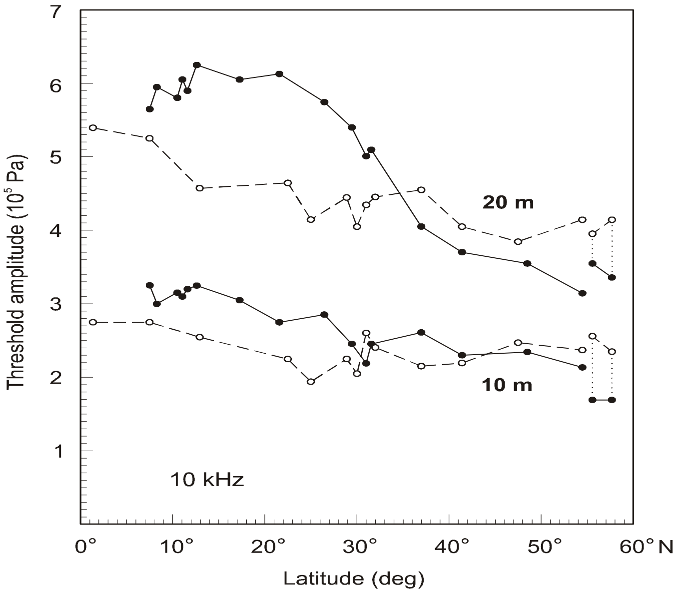

Figure 5. Acoustic cavitation thresholds in the Atlantic Ocean as a function of the latitude at different seasons of 1968. The marks ● correspond to spring, the marks ○ – to summer.

The Pacific Ocean

The measurements of acoustic cavitation thresholds in the Pacific Ocean were carried out in different years from 1964 through 1985. The most extensive measurements were undertaken from September to November 1982 and from October to November 1983. In both cases, it was the autumn season in the northern part and spring season in the southern part of the Pacific Ocean. The measurements in different years were carried out at the high latitude and longitude ranges. Figure 6 presents the experimental values of P^*_m as a function of the latitude obtained during September-November 1982 in the Pacific Ocean, from a latitude about 49°N, near the Kamchatka Peninsula, to the latitude 15°30′S in the Coral Sea. Again, cavitation was excited at depths of 10 m and 20 m by a continuous 10 kHz signal. As Figure 6 shows, cavitation thresholds in the Pacific Ocean also depended on latitude, with higher thresholds near the equator and decreasing with distance from it in either the northern or southern parts of the Pacific Ocean.

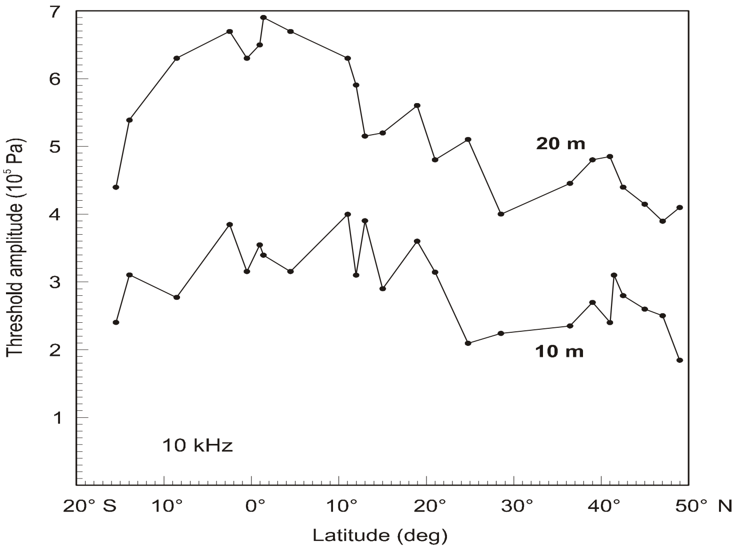

Figure 6. Acoustic cavitation thresholds in the Pacific Ocean as a function of the latitude during September-November 1982.

CONCLUSIONS

It should be noted that acoustic cavitation thresholds have different values in the different regions of the World Ocean. Table 2 presents a comparison of P^*_m values obtained in the different Oceans and Seas at different time from 1968 to 1987. The results in Table 2 correspond to measurements at a standard depth of 10 m and a frequency of 10 kHz.

The results of the measurements presented in Table 2 were carried out in the open areas of water of the Atlantic, Indian and Pacific Oceans. The values at the Arctic Ocean correspond to the measurements in an area of water in the East Siberian Sea. It is seen that the acoustic cavitation threshold was lowest in the Indian Ocean and highest in the Arctic Ocean. A big difference was seen between the thresholds for the enclosed water of the seas shown in the lower part of the table. The lowest values were observed in the Black Sea, the Sea of Okhotsk and the Baltic Sea. The highest value was observed in the East Siberian Sea and the Arctic Ocean.

Table 2. Acoustic cavitation thresholds at different regions
at a depth of 10 m and at a frequency of 10 kHz.

Region	Time	P^*_m (10^5 Pa)
The Arctic Ocean	May 1969	5.6
The Atlantic Ocean	April 1968	3.2
The Indian Ocean	March 1087	2.8
The Pacific Ocean	October 1982	3.6
The Arabian Sea	March 1987	2.8
The Baltic Sea	June 1968	2.3
The Black Sea	September 1964	1.8
The East Siberian Sea	May 1969	5.6
The North Sea	June 1968	2.4
The Philippine Sea	September 1982	2.5
The Sea of Japan	September 1982	2.6
The Sea of Okhotsk	September 1964	2.2
The South China Sea	September 1985	2.4

The knowledge of the cavitation thresholds P_m^* of sea water at different regions of the World Ocean is of practical interest. First of all, the value of cavitation threshold P_m^* determines the limited levels of the acoustic intensity J_c that could be radiated by powerful acoustic sources at cavitation by the formula:

$$J_c = K_a \left(P_m^*\right)^2 \qquad \textbf{(Eq. 1)}$$

where K_a is the coefficient that determines type of the acoustic field, for the plane acoustic wave $K_a = (1/2\rho c)$, where ρ is a density and *c* is sound velocity of sea water.

Moreover, the value of cavitation threshold P_m^* permits to determine the value of the critical speed V_c of the motion of some floating bodies in the ocean water. For the motion of the solid body in the sea water we could use the formula:

$$V_c \simeq K_h \left(P_m^*\right)^{1/2} \qquad \textbf{(Eq. 2)}$$

where we introduce the coefficient $K_h \simeq \left(2/\rho K_f K_p\right)^{1/2}$, where the coefficient K_f is defined by the form of floating body, the coefficient K_p is caused by the regime of hydrodynamic pulsations at the floating body.

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