Arch. Mech., 38, 4, pp. 431–438, Warszawa 1986

Acoustical activity of cavitation bubbles produced by ship propeller

E. KOZACZKA (GDYNIA)

THIS PAPER contains some experimental results of both a strong single bubble and a sequence of bubbles produced by a ship propeller. The acoustical method used for this purpose allows to obtain characteristics of the pressure generated by the growth and rapid collapse of the bubbles.

Praca zawiera rezultaty badań eksperymentalnych zarówno pojedynczych pęcherzy kawitacyjnych, jak również ich zbioru wytwarzanego przez śrubę okrętową. Zastosowana metoda akustyczna pozwala na otrzymanie charakterystyk ciśnieniowych związanych ze wzrostem i gwałtownym zapadaniem się pęcherzy.

Работа содержит результаты экспериментальных исследований так единичных кавитационных пузырьков, как тоже их совокупности, образованной гребным винтом. Примененный акустический метод позволяет получить характеристики давления с ростом и внезапным захлопыванием пузырьков.

1. Introduction

CAVITATION, the rupture of liquids, is one of the longstanding problems both in hydrodynamics and underwater acoustics. When the pressure of a liquid is reduced to a value slightly less than that of saturated vapour at the temperature of the liquid, then the liquid is in unstable state and normally tends to form vapour bubbles distributed throughout the liquid. The formation of those bubbles is so-called cavitation [1].

Currently the problem of bubble collapse has not been completely investigated. The phenomena of the growth and collapse of cavitation bubbles is very difficult to study since it is a very fast process [2].

One can observe large changes of acoustical pressure during bubble growth. In particular, strong acoustical effects take place during collapse of the bubbles. In the last years several researchers have investigated this problem both theoretically and experimentally. As concerns the formation of a single bubble by means of a laser, the works of LAUTERBORN [3, 4, 6] may be mentioned. The observation of cavitation bubble behaviour by means of holocinematographical methods has been studied by EBELING [5]| Next, the dynamics of bubbles has been theoretically investigated by PROSPERETTI [7].

The studies mentioned above constitute some elements of the general view on cavitation phenomena; however, they are mainly restricted to a single bubble.

In this paper the description of phenomena has been briefly presented and some experimental results have been shown as well. The investigations were carried out in an anechoic basin using the acoustical method.

2. Sound pressure produced by single bubble collapse

Single bubble formation can be carried out by means of a local deposit of energy. Usually it can be done using a laser that can induce cavities in liquids. For this purpose high light intensities are needed. One can use, for instance, a ruby laser or a neodymium one. Another source of energy which can be deposited in a very small area is a sparker. The discharge of electric energy that can be storaged, for example, in a battery makes it possible to generate a single cavitation bubble. This method of formation was used for generating bubbles and a time history of pressure has been presented here. The schematic view of the set-up for single bubble generation is shown in Fig. 1 [8].

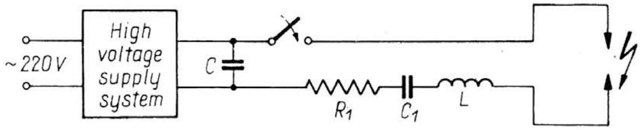

FIG. 1. Electrical system of the sparker and supply circuit.

For acoustical observation of pressure time history, a system was used that consisted of the following elements: a measuring hydrophone, a conditioning amplifier, a measuring amplifier, an analog to digital converter and a digital memory. This set-up is shown in Fig. 2. All of these elements were manufactured by Brüel and Kjaer Electronics Company from Denmark.

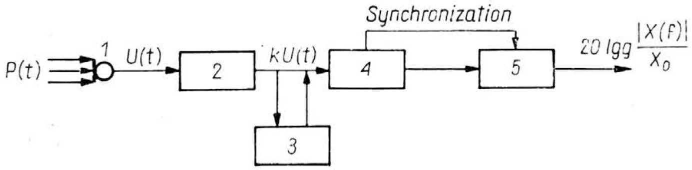

FIG. 2. Schematic view of the set-up used for spectral analysis *1* — the hydrophone with a conditioning amplifier, *2* — the measuring amplifier, *3* — the digital event recorder, *4* — the heterodyne analyser, *5* — the recorder.

The elements of the measuring chain are as follows:

the measuring hydrophone with receiving band ±2dB of 0.1 Hz – 140 kHz,

the 2635 type conditioning amplifier with transmission band ±0.5 dB of 2Hz – 200 kHz.

The signal from the hydrophone with a receiving characteristic that was flat to 100 kHz was supplied to an oscilloscope with memory after amplification. It was also transformed to a digital form and fed to the computer. The power spectrums were determined using the FFT algorithm [8].

3. Results of experimental investigation of a single bubble

We study some experimental results that consist of the shapes of the pressure pulses and their power spectrums of the single cavitation bubble produced by the local deposite of electric energy. In Fig. 3a we can see the time pressure history of the single bubble that is formed by the set-up shown in Fig. 1. One can notice that a spike of pressure is of very short duration and its peak value is large. The power spectrum of the pressure signal generated by the single bubble has a nearly flat characteristic and wide band character.

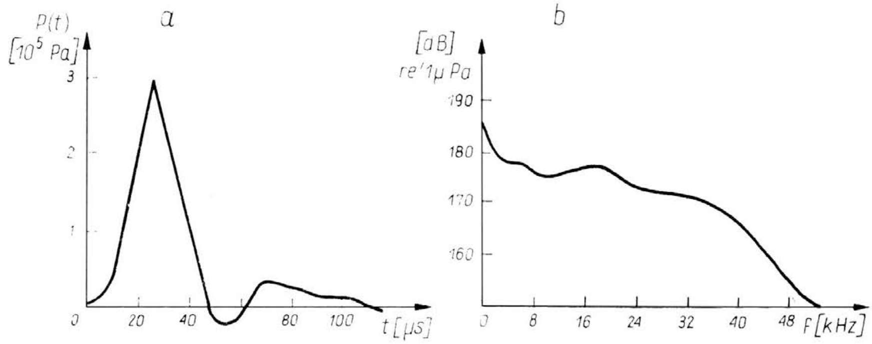

FIG. 3. Characteristics of a single cavitation bubble. *a* — the shape of the pressure spike of a single cavitation bubble collapse, *b* — its power spectrum.

The volume changes that generate an acoustic pressure field by the cavitation phenomenon are the so-called zero-poles or monopoles. The single bubble radiates essentially an omnidirectional acoustic wave although directional radiation patterns can be generated by forming at some time arrays of single bubbles.

The omnidirectional character of the acoustic field allows to measure the sound pressure radiated by collapse of a single cavitating bubble in an arbitrary point of observed space. The positive peak of sound pressure generated by the collapse of a single bubble can be calculated by means of the following formula [11]:

$$p^{+}_{\max} = \frac{P}{27}\,\frac{a_0}{r}\left(\frac{P}{Q}\right)^2\left[1+6\left(\frac{Q}{P}\right)+9\left(\frac{Q}{P}\right)^2-100\left(\frac{Q}{P}\right)^3\right], \tag{3.1}$$

where $P = p(a)-p(\infty)$ — collapse pressure, $p(a)$ — pressure in the liquid just outside the surface of a bubble, $p(\infty)$ — pressure in a steady state, a_0 — maximum radius of the bubble, Q — permanent pressure of gas dissolved in the liquid, r — distance between the center of a bubble and the observation point.

It is very difficult to obtain good measuring accuracy of bubble diameter because of the very short time of growth and collapse. The very high speed camera used here does not give good results. The diameter of a bubble can currently be estimated by means of the following formula [7], [11]:

$$a_0 = \frac{1.093 T_c \sqrt{\frac{P}{\varrho}}}{1+\frac{Q}{P}}, \tag{3.2}$$

where T_c — time of collapse, ϱ — density. The time of collapse can be determined from pressure time history (see Fig. 3). As can be seen from the formula [2], the maximum diameter of a bubble depends weakly on the amount of gas in the liquid. The maximum diameter of a bubble a_0, for the case shown in Fig. 3a calculated by means of the formula (3.1) is equal to $a_0 = 1.33 \cdot 10^{-3}$ m. The measured pressure $P = 2 \cdot 10^5$ Pa, $Q/P = 0.006$, $\varrho = 998$ kg/m^3, $T_c = 8.66 \cdot 10^{-5}$ s. The positive peak of pressure is equal to $p^+_{\max} = 2.84 \cdot$ $\cdot 10^{-5}$ Pa. This result was obtained from calculation. The experimental one is equal to $p^+_{\max} = 2.98 \cdot 10^5$ Pa.

Now the second example of single bubble collapse will be presented. The study was carried out in the following conditions $P = 2 \cdot 10^5$ Pa, $Q/P = 0.02$, $r = 10$ m. On this basis, some results describing the dynamics of collapse were obtained. They are as follows: $a_0 = 1.73 \cdot 10^{-3}$ m, $p^+_{\max} = 3.6 \cdot 10^3$ Pa. The measured values are the following: $p^+_{\max} = 3.54 \cdot 10^3$ Pa, $T_c = 1.11 \cdot 10^{-4}$ s. The above information is connected with the first spike of sound pressure. The second spike (see Fig. 4) is connected with the rebound of a cavitation bubble. The third spike is an acoustic impulse reflected from the hard wall of the measuring basin. The previously mentioned permanent, dissolved gas can play an important role in the collapse phenomenon. In the first place it is responsible for cushioning the final collapse process and storing some of the kinetic energy connected with rapidly collapsing bubbles as potential energy. The stored potential energy does not allow a bubble to collapse to a zero radius. As a result of this, one can observe rebound of bubbles. The collapse process can repeat itself three or four times. As can be seen in Fig. 4, the dynamics of the rebound is smaller than the first collapse. The main purpose of these investigations was to explain the nature of cavitation bubble collapse pressure that was carried out to make easier the interpretation of the problem of sound generation by a single bubble.

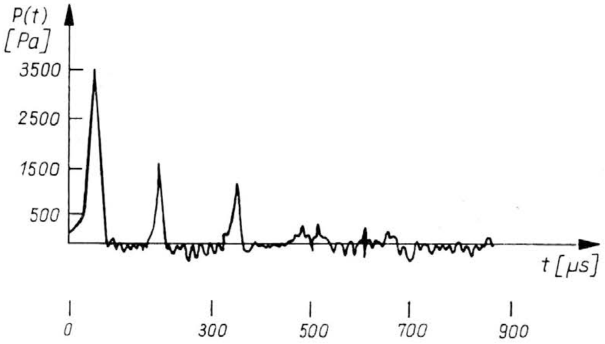

FIG. Time history of bubble multiple collapses.

The explanation of the mutual interaction between cavitation bubbles is very difficult up to now and from this point of view we should first study the phenomena of the single cavitation bubble.

4. Investigation of the sound generation by a cavitating ship propeller

The sound generated by a cavitating ship propeller is in its nature more complicated than sound radiated by single bubble collapse. The pressure consists of two parts [9]. The first one, connected with hydrodynamic interaction between the propeller's blades and the surrounding medium, is called rotating noise. The second part is strictly connected with cavitation bubble activity.

The radiation in the sub-cavitation range has almost a purely dipole distribution [10]. Cavitation on the propeller constitutes an additional source of underwater acoustic disturbances which are, by their nature, different from those which exist in the sub-cavitation range. The growth and collapse of vapour or air bubbles produce strong acoustic effects. The bubbles, when distributed within the area of propeller operation, can be considered as point sources of weak shock waves. Furthermore, the formation of the vapour bubbles brings about rapid growth of nonuniformity in the velocity field and also in the medium (two-phase).

Here the results of investigations carried out in an anechoic basin by means of the measuring set-up shown in Fig. 5 have been presented. The first characteristic, i.e. the time history of the sound pressure, is shown in Fig. 6. One can easily notice the pressure spikes formed by cavitation bubble collapse. They are very strong in comparison with the "rotating noise". The single spike of pressure is similar to the one shown in Fig. 3a or Fig. 4.

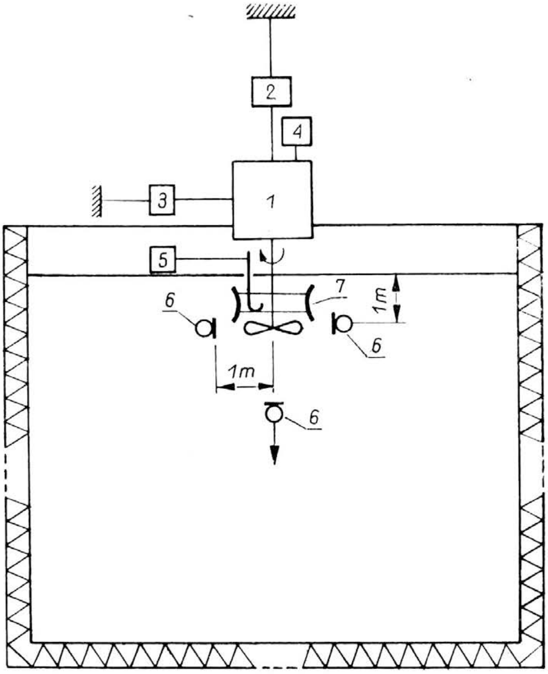

FIG. 5. Diagram of a set-up for measuring underwater acoustic disturbances produced by a ship propeller in an anechoic basin. *1* — the electric motor, *2* — the dynamometer for measuring the thrust force, *3* — the dynamometr for measuring the torque, *4* — the set-up for measuring the propeller speed, *5* — the set-up for measuring the flow speed, *6* — the system of hydrophones, *7* — the acoustically transparent nozzle.

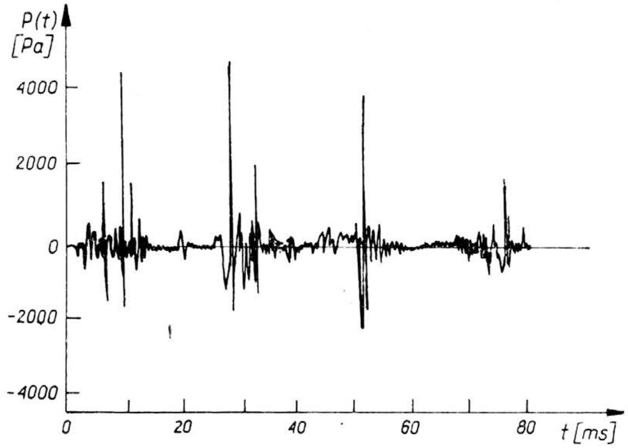

FIG. 6. Time history of the sound pressure produced by a cavitating ship propeller, the beginning of cavitation.

The investigation of the first stage of cavitation development, that is the formation of a single bubble on a blade of the ship propeller or close to it, was carried out in experimental conditions similar to those during the study of a single collapse. The basic parameters were as follows: $P = 1.1 \cdot 10^5$ Pa, $Q/P = 0.04$, $r = 1$ m. The diameter of the bubble was estimated as $a_0 = 1.47 \cdot 10^{-3}$ m for sound pressure $p^+_{\max} = 4.5 \cdot 10^3$ Pa. It is worth mentioning that to obtain knowledge about the time history of a single collapse during ship propeller work is a very difficult task. In addition, both growth and collapse processes are random. One can notice nearly the same dynamics of bubbles produced by the ship propeller as that created by electric discharge. For a variety of reasons it is better to examine single bubble forms both in determined points of a frame of reference and in time. Concerning the cavitation noise produced by a ship propeller as a result of the se-

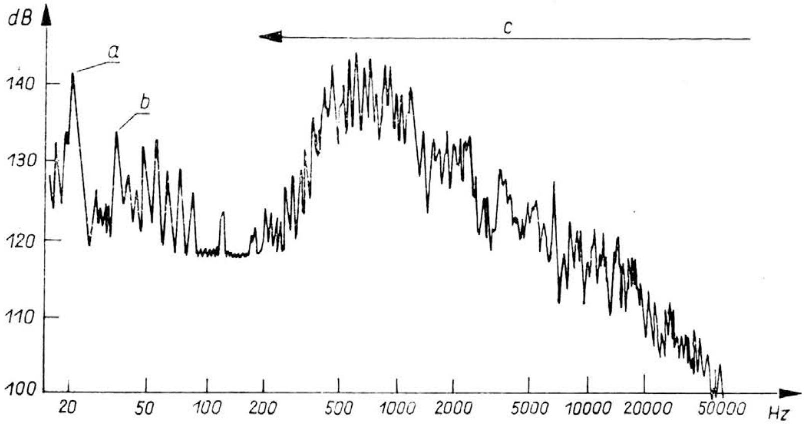

FIG. 7. Power spectrum of the pressure produced by a ship propeller. a — the frequency spike connected with blade rotation (the first harmonic frequency being equal to the product of the blade number and the rotating speed [r.p.s.]), b — the frequency spike of the second harmonic, c — the spectrum's range connected with the cavitation process.

quence of random collapsing bubbles, it should be mentioned that this process strongly depends on the development of the cavitation.

The decrease of a cavitation number causes the growth of numerous large bubbles as a result of increasing rotation speed. The large number of collapses involves cushioning of the final collapse process and for this reason a feature of the power spectrum is changed.

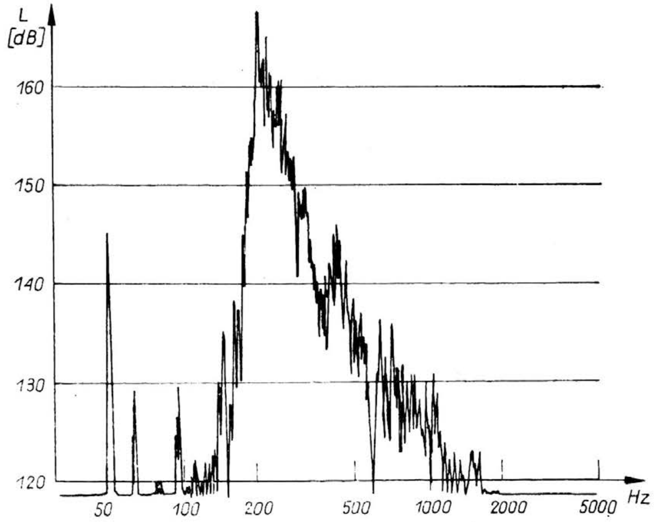

FIG. 8. Power spectrum of the developed stage of cavitation.

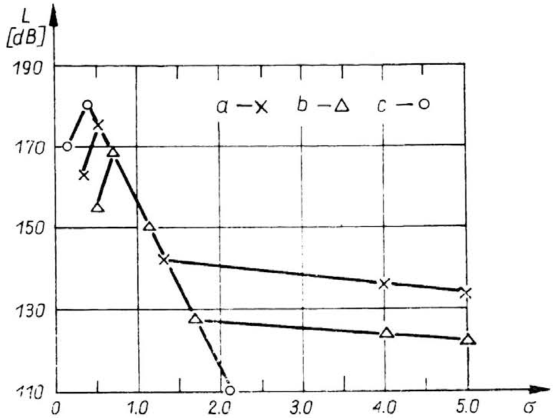

FIG. 9. Sound pressure level dependence on cavitation number. *a*, *b*, *c* — the ship propellers with different hydrodynamic characteristics.

This can be easily noticed by comparing Fig. 7 with Fig. 8. The power spectrum of sound pressure connected with the developed stage of cavitation is a narrow band as distinguished in Fig. 7. The largest value of the power spectrum at frequency equal to 208 Hz is connected with random pulsation of the cavitation bubbles. Rarefaction of water density as a result of the developed stage of cavitation causes the cushioning of the dynamic process of collapsing and also decreases the thrust of the ship propeller. The latter is related to results shown in Fig. 9. It presents the graphical relation between the sound pressure level and the cavitation number. It is of interest to note that the sound pressure level rapidly decreases just when the cavitation numbers are less than a — $\sigma < 0.7$, b — $\sigma < 0.5$ and c — $\sigma < 0.4$, respectively, for the examined ship propellers. This phenomenon, as it has been underlined previously, is strictly correlated with a fall of the thrust. Some of these results have already been reported [9, 10]

5. Conclussions

The investigations of the dynamics of the growth and collapse of a bubble using the acoustic method allow us to determine the peak pressure and the time history of this pressure. For this purpose a measuring system with a wide band transmission characteristic is required. Power spectrums can give us information about the stage of cavitation development.

References

1. G. K. BATCHELOR, *An introduction to fluid dynamics*, Cambridge University Press, 474–493, 1970.
2. R. T. KNAPP, J. W. DAILY, F. G. HAMMIT, *Cavitation*, Mc Graw-Hill, New York, 1970.
3. W. LAUTERBORN, *Kavitation durch Laserlicht*, Acoustica, **31**, 51, 1974.
4. W. LAUTERBORN, *Cavitation and coherent optics*, Cavitation and Inhomogeneities in Underwater Acoustics, [Ed.] W. LAUTERBORN, Springer-Verlag, Berlin 1980.
5. K. J. EBELING, *Application of high speed holocinematographical methods in cavitation research*, Cavitation and Inhomogeneities in Underwater Acoustics, [Ed.] W. LAUTERBORN, Springer-Verlag, 35–41, Berlin 1980.
6. W. LAUTERBORN, R. TIMM, *Bubble collapse studies at a million frames per second*, Cavitation and Inhomogeneities in Underwater Acoustics, [Ed.] W. LAUTERBORN, Springer-Verlag, 42–46, Berlin 1980.
7. A. PROSPERETTI, *On dynamics of non-spherical bubbles*, Cavitation and Inhomogeneities in Underwater Acoustics, [Ed.] W. LAUTERBORN, Springer-Verlag, 13–22, Berlin 1980.
8. E. KOZACZKA, *An impulsive source of strong underwater acoustic disturbances*, Arch. Acous., **5**, 4, 305–314, 1980.
9. E. KOZACZKA, *The acoustical effects produced by a cavitating ship propeller*, Arch. Mech. Eng., **29**, 2, 167–186, 1982 [in Polish].
10. E. KOZACZKA, *Sound radiation produced by a ship propeller*, Arch. Acoust., **4**, 3, 221–243, 1979.
11. D. R. ROSS, *Mechanics of underwater noise*, Pergamon Press, 202–222, New York 1976.

Received November 5, 1985.