Acoustic measurements of bubbles in the wake of ship model in tank

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The interest in bubble generation by moving ships is due to the fact that the large bubble wake areas, which can reach several kilometers, can be used for ship detection. The laboratory towing tank experiments with self-propelled model ship models enabled the collection of a large data set in controlled conditions, which can be used for development and validation of the theory of bubbles and turbulent ship wakes. Bubble concentrations in various spatial points was measured by using the attenuation of the ultrasonic sweep signal in the frequency band from 100 to 800 kHz between two acoustic sensors placed at a distance 20cm. The attenuation of sound produced by bubbles was observed for several minutes after model of ship passed the point of measurement. The attenuation was recalculated to the bubble size distribution for bubbles from 4 to 32 microns using the theory of resonance bubble attenuation. The dependencies of bubble concentration of model ship speed and type of propeller were investigated. A theory describing the dynamics of wake turbulence based on the shear-free turbulent wake was developed. The measured reduction of bubble concentration as a function of time was in good agreement with the developed theory.

1 Introduction

Moving ships can generate bubbles by propeller cavitation, by the breaking of ship generated waves, and by air entrapment in the turbulent boundary layer under the ship hull. Interest in bubbles produced by moving ships is often connected with the bubble influence on sound propagation near the ship. The bubble layer can affect the parameters of sound propagation through the layer [1-6] and ship noise radiation [7]. The interest in bubble generation by moving ships is also connected with the opportunity of ship detection, since bubble wakes can reach lengths of several kilometres.

The first detailed tests of bubble measurements in wakes of ships and submarines were conducted during WWII [1] using measurements of sonar signal scattering and attenuation. These methods are still are widely used for bubble measurements. High frequency multibeam sonars were used for measurements of spatial bubble distributions in wakes of ships [8,9]. The experiments demonstrated that the length of the bubble layer can reach 1500m and its depth could be up to 10m.

Even if it was known that bubble generation in the wake of a ship is connected with turbulence generated by the ship, there is no developed theory for prediction of bubble concentration. Such a theory could be used for estimation of bubble concentration for various ships, propellers and speeds. It could predict possible distances of bubble detection. Also, temporal variation of bubble density can be used for ship classification and its speed estimations.

The first step in the development of this theory is to connect known theory of ship turbulent wake generation with results of experimental research. It was shown [10] that a shear-free turbulent model is a good approach to describe the turbulent wake behind a self-propelled body, or ship-wake. Later [11,12] this approach was extended to allow the wake turbulence parameterization by characteristics of the wake source.

There are limited field data available, and more can be collected in controllable conditions in a laboratory tank.. The bubble measurements using a ship model in a towing tank can be used for theory validation and for the determination of the theoretical model parameters.

For measurements of bubble density in the towing tank we applied a method based on the attenuation of acoustic waves in a wide frequency band (100-800kHz), which allows detection of bubbles with radii 4-32 μm. This frequency range is wider than was used in previous experiments at sea [13].

2 Experimental setup

A self-propelled ship model was used in experiments conducted at Stevens towing tank having length of 100m, width of 6 m and depth of 3m..

The ship model has a length 1.60 m, maximum width 0.3 m, and height about 0.2 m. The model was moved in the tank using a special control system to set the propeller rotation so as to keep the propulsion reaction on a supporting strut near zero. Different sizes and shapes of propellers were tested. In this paper we present results for two of them: propeller #2 has diameter of 0.09 m, and blade width of 0.04 m; propeller #3 has diameter of 0.105 m and blade width 0.025m (see Fig.1).

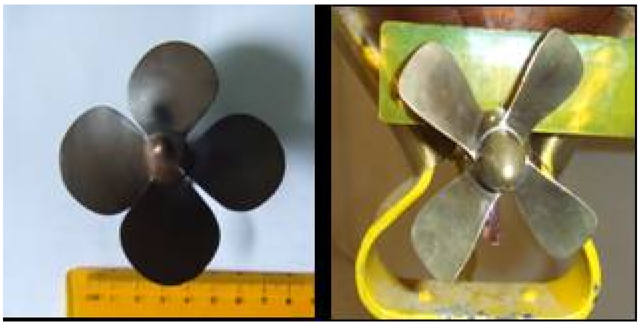

Fig.1 Two tested propellers (left panel –propeller #2, right panel #3)

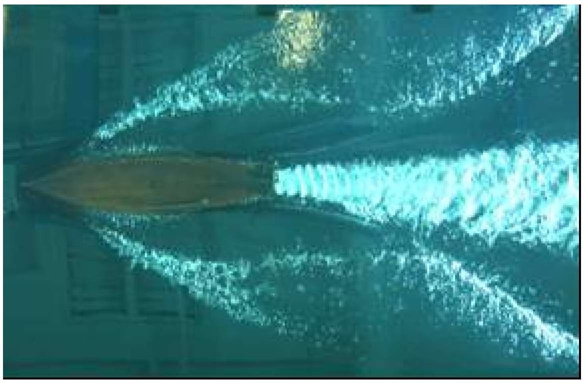

Fig.2. Picture of wake bubbles generated by the ship model made by an underwater camera.

For measurements of the bubble size distribution and the bubble density variation in time we used the measurements of sound attenuation at a short distance (0.2m) between transmitter and receivers that were placed parallel to the ship path.

The bubble-produced excess attenuation was measured over a wide frequency band using an acoustic radiation with a linear frequency sweep (Fig. 3(a)). A similar technique was described in [13] with a top frequency of 100kHz. In our experiments, the signal was received by the second sensor and sent to an electronic processing unit. To increase the signal-to-noise ratio and to cancel the influence of reflections, we cross-correlated the radiated and received signals. This gives the much shorter pulse shown in Fig. 3c.

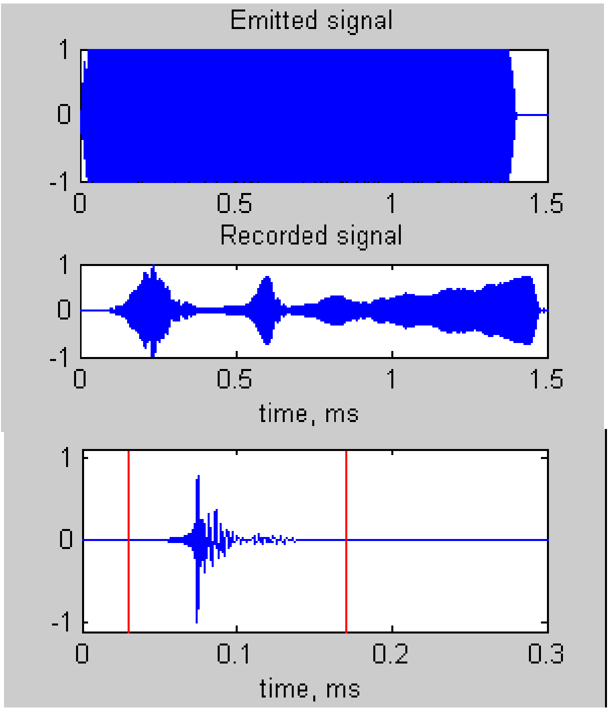

Fig. 3. Time tracks of signals used for bubble density measurements: (a) emitted signal; (b) recorded signal; (c) cross-correlation of emitted and recorded signals.

The cross-correlation was used for measurements of attenuation. This cross correlation was filtered using band pass filters. In this paper, we present results of measurements in 7 frequency bands from 100 to 800 kHz having width of 100kHz.

The attenuation of sound was measured by comparison of the band pass filtered cross-correlation of received signals in clear water $A_0(f)$ with amplitude of the same signal measured in water with bubbles $A_b(f)$. Attenuation of the wave was expressed in dB:

$$I = 20\log 10\left[\frac{A_0(f)}{A_b(f)}\right] \qquad (1)$$

In the bubble wake, bubbles of various sizes are present. They are descried by the bubble size distribution function *N(a)*, so *N(a)da* is number of bubble in volume unit having radii from *a* to *a+da*. Different units have been used in different papers for bubble density descriptions. In the first detailed tests conducted by the US Navy [1] bubble density was presented in cm^{-4}. In modern literature [2] bubble density is expressed in $m^{-3}\ \mu m^{-1}$ and $n(a)$ is reported as the number of bubbles per m^3 per micron radius increment.

For recalculation of the sound attenuation to the bubble density we can apply the widely used expression for sound attenuation of a signal with frequency *f* in a bubble layer [1,2,9].

$$\alpha(f) = \frac{c_0}{f}\int_0^\infty \frac{a\,\delta n(a)\,da}{(f_a^2/f^2-1)^2+\delta^2} \qquad (2)$$

In this equation, c_0 is the speed of sound in bubble-free sea water, *f* is the frequency of the applied sound field, a is the bubble radius,, f_a is the resonance frequency of a bubble with radius *a,* and δ is the damping parameter, α is attenuation coefficient in nepers per meter.

Equation (2) is a Fredholm integral equation of the first kind. An attempt to invert this equation to find the bubble-density distribution, $n(a)$, from measurements of attenuation over a range of frequencies leads to a complex system of integral equations, making direct calculations of $n(a)$ impractical. The simplifying assumptions presented in [1,14] gives an approximate solution of Eq.(2) under the following assumptions:

a) The damping bubble parameter δis a constant,
b) only those bubbles at resonance with the applied sound wave. contribute significantly to attenuation,
c) the bubble distribution changes slowly about the resonance radius, and
d) surface tension is negligible.

In terms of this resonance bubble approximation, the bubble density is connected with the attenuation produced by resonance bubbles by the relationship [14]:

$$n(a) = \frac{4.62 * 10^{-12} f_a^3 I}{L} \qquad (3$$

For bubbles near the surface, the resonance frequency of a bubble is connected with the bubble radius by relationship

$$f_a = \frac{3250}{a} \qquad (4)$$

where frequency is presented in kHz and bubble radius in μm.

The temporal variation of acoustic signal attenuation connected with bubble presence was measured at 10 points, positions of which are shown in Fig. 4.

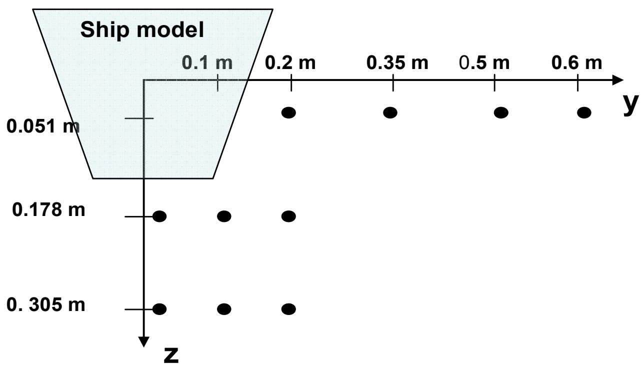

Fig.4. Schema of acoustic sensor placement.

3 Results of measurements

3.1 Time variation of bubble concentration

The conducted experiments demonstrated that after the ship passing, the attenuation of an acoustic signal first increases and than rapidly decreases to a relatively small level. The first strong attenuation is probably produced by relatively large bubbles that rapidly rise to the surface. Relatively lower longer time attenuation is probably produced by small bubbles. The same categorization of the bubbles in wakes to large and small bubbles was used to explain the field experiments described in [4]. The concentration of small bubbles decays much more slowly than the concentration of large bubbles. This is probably due to the slow spreading and dissolving of small bubbles. The example of such attenuation variation is shown in Figs. 5, 6 for two tests with the same experimental conditions.

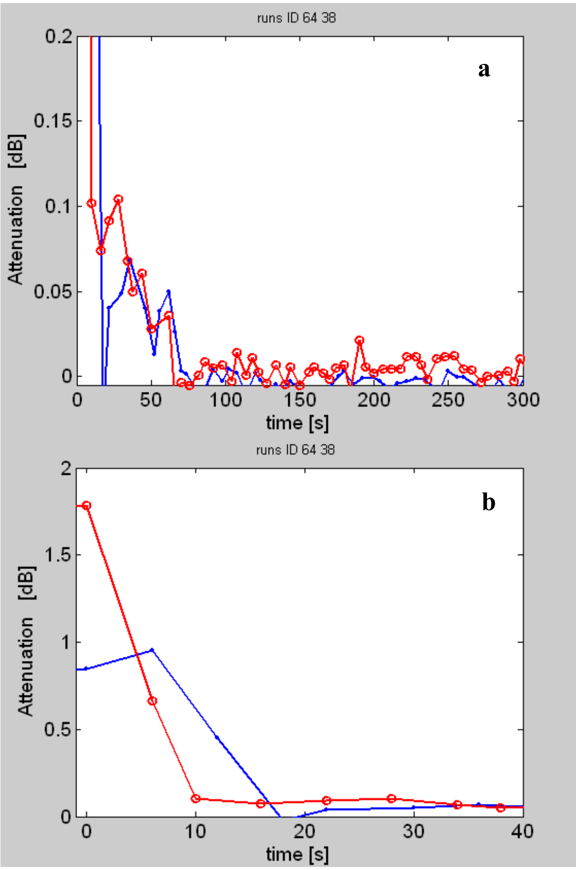

Fig.5. Measured variation of sound attenuation in the frequency band 700-800kHz for two similar tests at depth 5.08 cm and distance 20cm from ship path axis. Propeller #2, model speed 2.74m/s. Fig 5a shows the long time record where the bubbles are detected for time up to 70 sec. Fig 5b shows the initial part of the record where large bubbles are detected with lifetimes of up to 15 sec.

Fig. 6. presents the time dependence of acoustic attenuation measured in these two tests in a log-log scale showing that the time dependence of attenuation produced by small bubbles can be interpolate by the theoretical dependence:

$\alpha \sim t^{-2/3}$ (see theoretical part below)

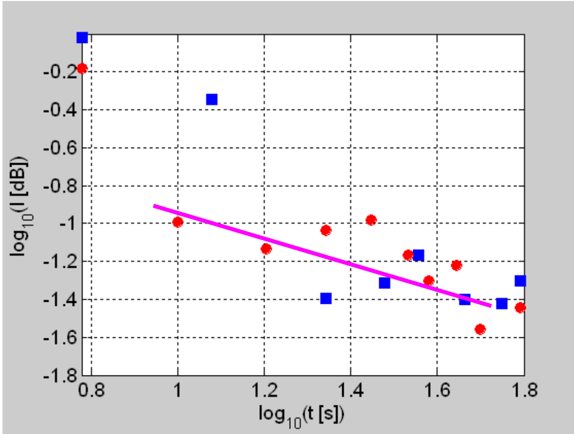

Fig.6. Time dependence of acoustic wave attenuation (Fig.5) presented in log/log scale. Solid line shows theoretical dependence $\alpha \sim t^{-2/3}$.

From the presented results is seen that there is the large variation of the acoustic attenuation for same experimental conditions.

3.2 Large bubble spatial distribution for various propellers and speed

For estimation of large bubble spatial distributions, the maximum attenuation, which occurred a short time after ship passing, was presented for various spatial points for various propellers and model speeds. Figures 7 shows the spatial distribution of maximal sound attenuation for propeller #3 and speed model of 2.74m/s.

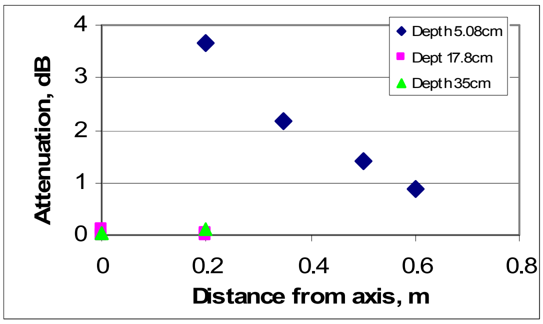

Fig.7. Dependence of maximal attenuation on distance from axis for various depths for model speed 2.74 m/s, propeller #3, band of filtering 200-300kHz.

It is seen that large bubbles were generated is relatively shallow subsurface layer and large bubbles do not penetrate to the depth of 17.8 and 35 cm

Fig.8 presents dependence of measured attenuation produced by large bubbles on distance from axis. The measurements were conducted at depth of 5.08 cm for various model speed and propellers.

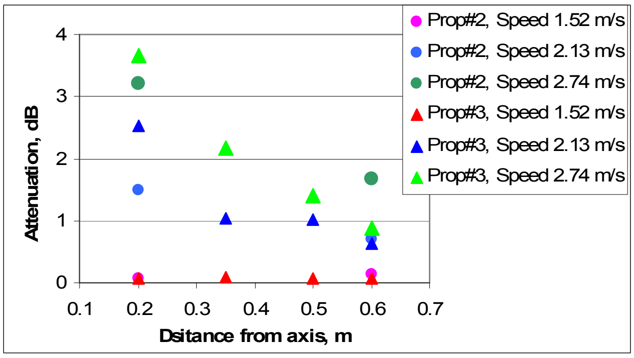

Fig.8. Maximal sound attenuation produced by large bubble at various distances from the axis at depth 5.08 cm for various propellers and speeds. Band of filtering 200-300kHz.

3.3 Small bubble size distribution and gas volume content

Filtering in several frequency bands allows the estimation of bubble size distributions. Fig. 9 shows the time dependence of attenuation measured for the model with propeller #2 moving with speed 2.74m/s, for the point at distance 20 cm from the axis and depth 5.08 cm. It is seen that for time up to 60 s the attenuation of all bubbles is roughly the same. This means that according the formulas (3) and (4) bubble size distribution is proportional to $a^{-3.}$

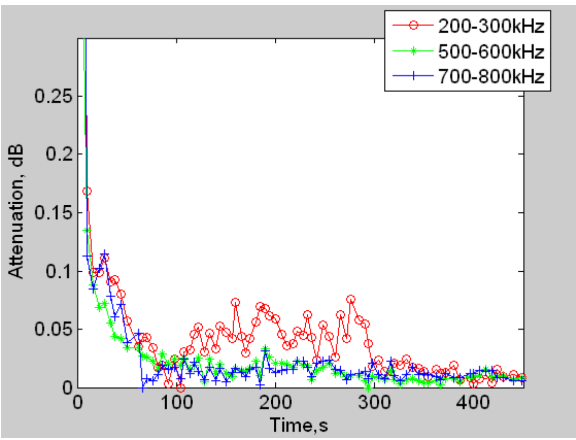

Fig. 9. Acoustic attenuation temporal variation in three frequency bands 200-300kHz, 500-600kHz, 700-800kHz measured at the point at distance 20 cm from the axis and depth 5.08 cm. Model with propeller #2 was moved with speed 2.74m/s

Eq. (3) can be used for estimation of bubble density. For example, bubble density for time about 40 s after ship passing is about 4 10^4 $m^{-3}\mu m^{-1}$ for bubbles with radii around 13 µm. This density is a bit higher than ambient bubble density in the ocean, which was measured by Medwin in San Diego ([2], fig.8.4.5c). In the presence of relatively strong wind, the bubble density can by much higher ([2], fig.8.4.5a]. The rough estimation of total gas volume (void fraction) can be made based on the assumption that the maximal size of bubbles is about 30 µm (resonance bubble frequency 110kHz) and attenuation is about 0.5dB/m for higher frequency. In this case the estimation of void fraction of small bubbles gives the value 3 10^{-9}.This does not include possible contribution of relatively large bubbles, which was not investigated.

Measurements at depth 17.8 and 35 cm did not show the presence of large bubbles, but small bubbles can penetrate to this depth due to turbulence spreading. Fig. 10 presents the time dependence of attenuation for the depth 17.8 cm under the ship path for propeller #3 and speed 2.13 m/s. It can be seen that there is a similar level of attenuation for all presented frequencies.

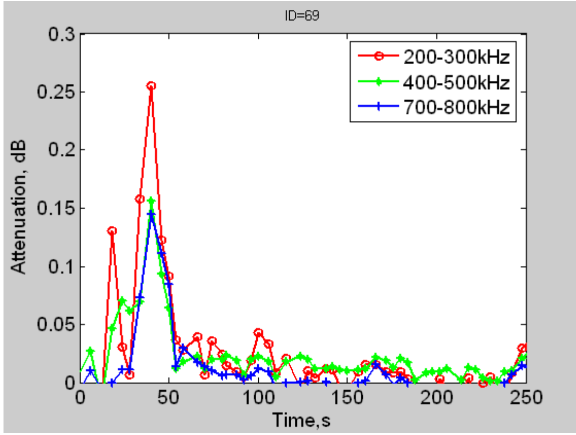

Fig. 10. Acoustic attenuation temporal variation in three frequency bands 200-300kHz, 400-500kHz, 700-800kHz. model with propeller #3 moved with speed 2.13m/s for the measured point under the model path at depth 17.8 cm.

It is worth mentioning that the small bubbles penetrate to this depth for time about 40 s and their estimated void fraction is even higher than in the previous case and reaches 8 10^{-9}.

4 Turbulent model and comparison with experiment

We have employed the turbulent-wake theory [10,11] for the data interpretation. This model can not be applied to describe behaviour of larger bubbles. Therefore, we will apply it for estimation of temporal variation of small bubble concentrations. Because the micro-bubbles with radii less than 30 µm have a rising speed less than 0.2 cm/s [8] the rate of bubble degradation is low enough so that the micro-bubbles in the wake turbulent field can be assumed as a passive admixture of the wake water body. Hence we have coupled the wake theory with the bubble turbulent diffusion in the wake as a passive admixture. In this case the total bubble mean concentration in a wake cross-section obeys the bubble mass-conservation law. That means that the mean bubble concentration decays with inverse proportionality to the area of wake cross-section. According to the wake theory the wake radius increases in time proportional to t^n, where the power coefficient n is in the range $0 < n < 0.5$ [10,11] . Then the cross-section area of turbulent wakes increases in proportionality to t^{2n} , and the mean bubble concentration decays as t^{-2n}. As is seen from Fig. 6, the bubble concentration decay in time for all collected data can be approximated by function that is proportional to $t^{-2/3}$, therefore the coefficient $n=0.33$. This result agrees with the theoretical prediction on limitations for the coefficient n and known numerical values of n for surface ships which are about $n = 0.2 – 0.3$. Hence, this result is qualitatively consistent with theoretical conclusion and quantitatively with known estimates of this coefficient.

5 Conclusion

The acoustic system, based on sound attenuation in a wide frequency band (100-800kHz) was used for measurements of bubble concentration in the wake of a self-propelled ship model in the Stevens towing tank. It was found that the ship model can generate two kinds of bubbles: one kind consists of large bubbles that rise rapidly to the surface and with a lifetime that does not exceed 15 seconds. The second kind, the smaller bubbles can be detected much longer and their size distribution is in a range from 4 to 32 microns. This was estimated from the sound attenuation data using bubble resonance theory. In many cases bubble size distribution was proposition to a^{-3}. Bubbles with radii around 10-20 microns were observed for up to five minutes

As observed in experiments the temporal variations of bubble concentration can be approximated as $t^{-2/3}$. This power law is qualitatively consistent with theoretical conclusion and quantitatively with known estimates of the model parameters.

The attenuation technique used in this work is a scientific tool for measurements of bubble concentrations in wide range of bubble sizes. From the perspective of best sensitivity of bubble detection, nonlinear acoustic methods look preferable, as they that can detect even single bubbles with radii around few microns [15,16]. Application of these methods can extend the bubble wake detection time.

Acknowledgments

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