BUBBLE SCREEN EXPERIMENT AT RAFAEL ACOUSTIC TANK FACILITY

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1 INTRODUCTION

There is a growing interest to acoustical properties of bubble containing liquids in a scientific community. There are numerous reasons for that, starting from medical ultrasound research to military sonar performance inside a surface layer, containing bubbles. The presence of bubbles changes drastically acoustic properties of water, including strong losses in a wide range of acoustical frequencies, phase velocity dispersion, nonlinear wave mixing and frequency multiplication.

2 THEORY

2.1 BUBBLE SIZE DISTRIBUTION CALCULATION BY TRANSMISSION LOSS MEASUREMENT

To find a transmission loss for an acoustic signal passing a layer containing bubbles, we use a traditional technique developed in a classical work of R. Wildt [1]. If I is the sound intensity in the incident sound beam, the rate at which sound energy is lost by each bubble is $\sigma_e I$, so total increment in sound intensity is

$$dI = -IN\sigma_e dx \tag{1}$$

where N is bubbles volume concentration, σ_e is a single bubble extinction cross-section. Integration of (1) gives

$$I_1 = I_0 \exp(-N\sigma_e h) \tag{2}$$

where h is a bubble screen width, I_0 and I_1 - sound intensities before and after transmission through bubble screen. So, total extinction cross-section $S_e = N\sigma_e$ can be found by the following expression:

$$S_e = \frac{\log(\frac{I_0}{I_1})}{h\log(e)} \tag{3}$$

On the other side, extinction cross-section can be found by resonance bubble approximation in the following form (see [1, p. 470]):

$$S_e = \frac{2\pi^2 R_r^3 n(R_r)}{\eta_r} \tag{4}$$

here R_r is the radius of a bubble which is in a resonance with an acoustic signal, $n(R_r)$ is the bubble size distribution, i.e. a number of bubbles with a given size per unit volume, η_r is a resonance value

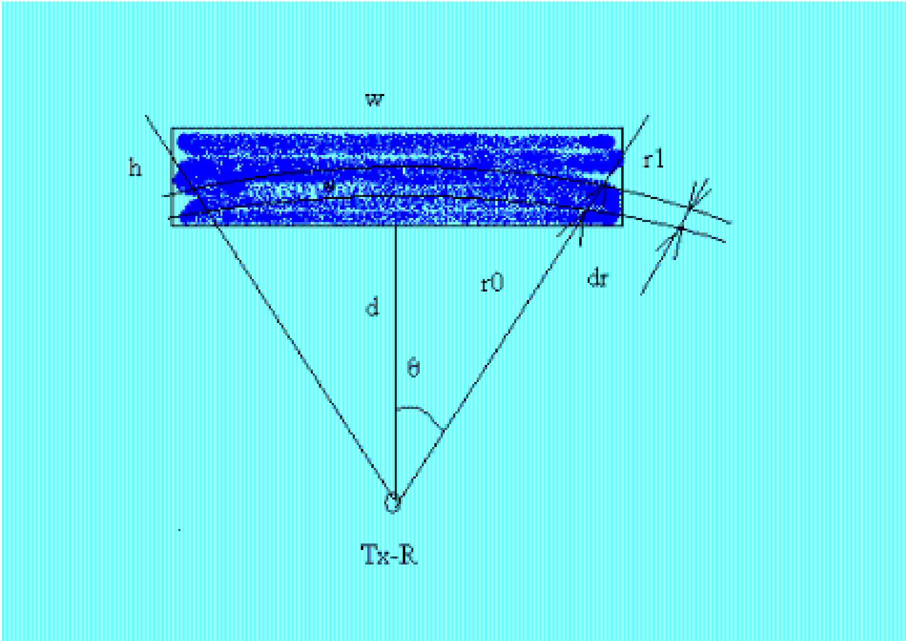


Figure 1: Bubble layer reflection experiment geometry

of relative bubble radius to acoustic wavelength, $\eta = 2\pi R/\lambda$. Theoretical analysis shows that a resonance bubble radius R_r is related to acoustic frequency f as

$$R_r = \frac{1}{2\pi f}\sqrt{\frac{3\gamma P_0(1+\rho_w g d/P_0)}{\rho_w}} \tag{5}$$

where P_0 is ambient atmospheric pressure, $\gamma = 1.4$ is air adiabatic constant, ρ_w is water density, $g = 9.8\ m/sec^2$ is Earth acceleration constant, d is water column depth. So, η_r can be found by the following relation:

$$\eta_r = \frac{2\pi R_r f}{c} = \frac{1}{c}\sqrt{\frac{3\gamma P_0(1+\rho_w g d/P_0)}{\rho_w}} \tag{6}$$

here c is sound velocity in water. Combining equations (3) and (4) we get the following final expression for $n(R_r)$:

$$n(R_r) = \frac{\eta_r \log(\frac{I_0}{I_1})}{2\pi^2 R_r^3 h \log(e)} \tag{7}$$

2.2 BUBBLE SIZE DISTRIBUTION CALCULATION BY REFLECTED SIGNAL MEASUREMENT

Experimental setup for measuring bubble size distribution by a reflection from bubble layer is shown at Figure 1.

Scattering sound intensity due to a single bubble is given by

$$I_s = \sigma_s \frac{I_0}{4\pi r^2} \tag{8}$$

where σ_s is scattering cross-section, I_0 is an incident sound intensity, r is a distance from the bubble. So, intensity of sound scattered by a short sound pulse which coincides the bubble layer is given by

$$I_s = \int_0^{2\pi} \frac{\sigma_s I_1 N}{4\pi} d\varphi \int_0^{\theta} \sin(\theta) d\theta \int_{r_0}^{r_1} \frac{1}{r^2} dr \tag{9}$$

here we used the following symbols: I_1 - source sound intensity at unit range, N - bubbles volume concentration, θ- bubble layer angular half-width, $\theta = \arctan\left(\frac{w}{2d}\right)$,$w$ - bubble layer width, d - distance to a bubble layer, r_0, r_1 - acoustic pulse front positions. Expression (9) can be simplified to

$$I_s = \frac{1}{2} I_1 N \sigma_s (1 - \cos(\theta)) \left(\frac{1}{r_0} - \frac{1}{r_1}\right) \tag{10}$$

On the other side, scattering cross-section by using RBA (see once again [1, p. 472]) is given by

$$\sigma_s = \frac{2\pi^2 R_r^3 n(R_r)}{N \delta_r} \tag{11}$$

here δ_r is bubbles damping at resonance. Substituting (11) into (10) we get the following expression for $n(R_r)$:

$$n(R_r) = \frac{I_s \delta_r}{I_1 \pi^2 R_r^3 (1 - \cos(\theta)) \left(\frac{1}{r_0} - \frac{1}{r_1}\right)} \tag{12}$$

To be more accurate, equation (10) does not take into account a time dependent development of the scattered signal amplitude, and has no losses due to passage through bubble layer in both directions. An improved version of this equation should look like this one:

$$I_s = \frac{1}{2} I_1 N \sigma_s (1 - \cos(\theta)) \left(\frac{1}{r_0} - \frac{1}{r_1}\right) \exp(-4 \frac{\pi^2 R_r^3}{\eta_r} \int n(R_r, r) dr) \tag{13}$$

The last equation let us to restore a space dependant bubble distribution $n(R_r, r)$ by inversion of time dependent scattered intensity $I_s(t)$.

3 EXPERIMENT

3.1 EXPERIMENT SETUP AND MEASUREMENTS

The measurements were conducted ar RAFAEL acoustic tank facility (ATF). The tank length is 20 m, width is 10 m, and depth is 10 m. Experiment setup is shown at Figure 2.

Acoustic transmitter and two receivers for reflected and transmitted through bubble screen signals were aligned at depth of 5 m in the acoustic tank. Custom designed bubble generator, consisting of 6 ceramic panels with air pumped through the panels was placed at the bottom at the middle between transmitter and receiver. Bubble source in action is shown at Figure 3.

We used series of pulsed harmonic signals with frequencies starting from 20 kHz and up to 200 kHz that were transmitted trough bubble screen produced by the bubble generator. Along with transmitted signals we have registered signals reflected from bubble layer. Because of natural non-stability of bubble cloud produced by our bubble generator we have repeted experiment for each frequency 50-100 times and then averaged results.

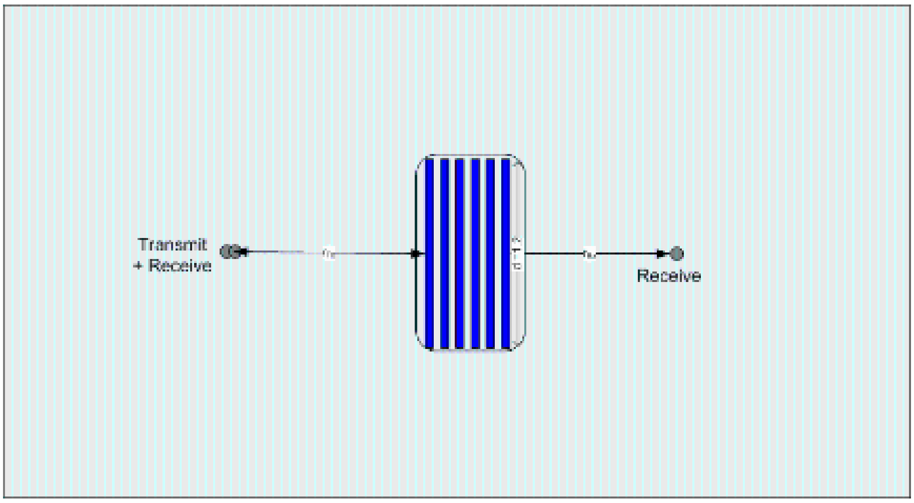
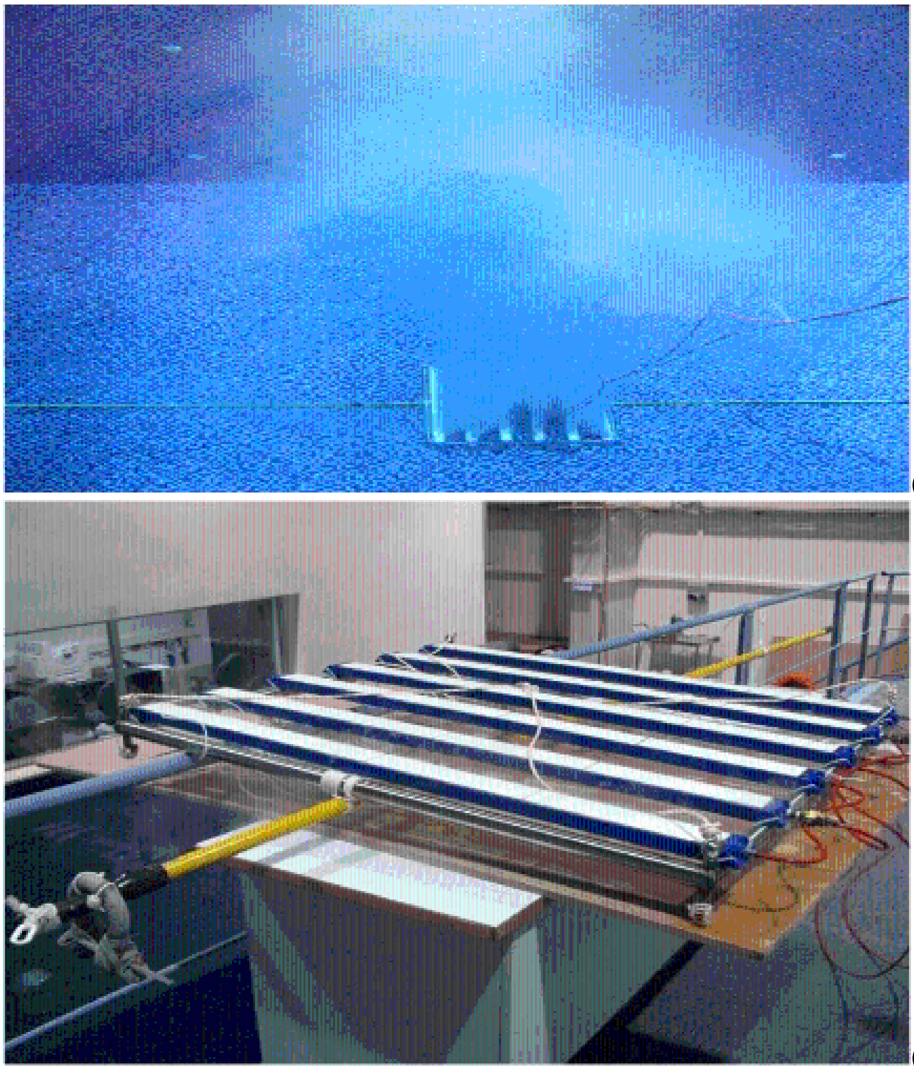


Figure 2: Bubble screen experiment setup



(a)

(b)

Figure 3: Bubble source used in an experiment. (a) - installed and activated in the ATF bottom; (b) - before installation

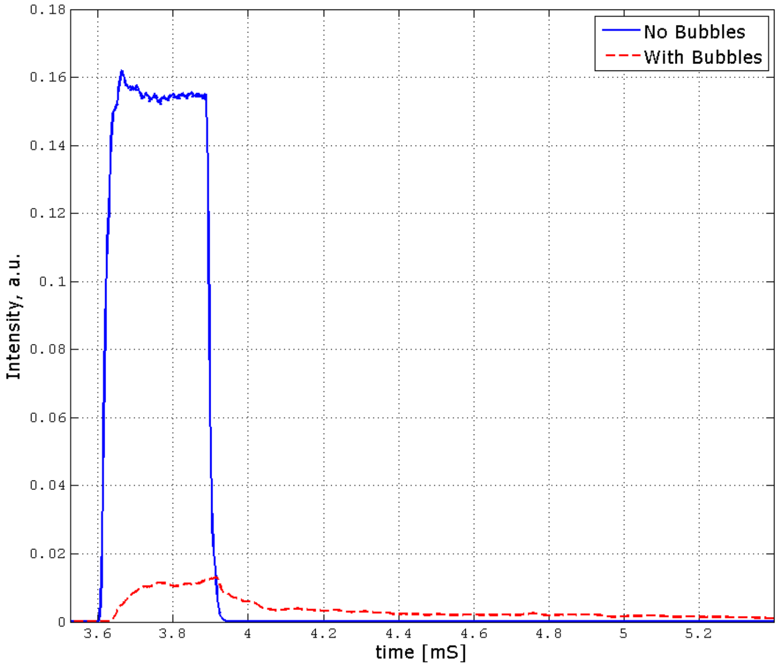


Figure 4: Passed signal intensity without (solid blue line) and with (red dash line) bubble screen

We have used narrow band passed filters centered near the frequency of transmission on each receiver. Both receiver signals were then digitally sampled and recorded. A typical envelope shapes of the transmitted signal recorded without and with bubble source are shown at Figure 4. One can see that a presense of bubble screen dramatically reduces the intencity of the passed signal and also causes some delay.

A typical envelope shapes of the reflected signal recorded without and with bubble source are shown at Figure 5. As it can be seen from Figure 5, there is no reflection without bubbles and there is a weak and broaden reflected signal when bubble screen is present.

3.2 DATA PROCESSING AND RESULTS

Experiment data for signals passed through bubble screen was processed and averaged over repetitions and systemized by four transducer types used. This data was compared to signal amplitudes registered without bubble screen. In order to obtain bubble distribution over size using RBA method, we used expression (7). The result of data processing for transmitted signals is shown at Figure 6.

One can see that results obtained by using different transducers (due to wide range of frequencies used from 20 up to 200 kHz) overlap closely, giving good repeatability of the results.

A similar approach was used to process reflection data. Experiment data for signals reflected from bubble screen was processed and averaged over repetitions and systemized by four transducer types used. This data was compared to signal amplitudes registered without bubble screen. In order to obtain bubble distribution over size using RBA method, we used expression (12). The result of data processing for transmitted signals is shown at Figure 7.

Space dependent bubble distribution was restored by inverse calculation using method described by equation (13). The result is shown at Figure 8.

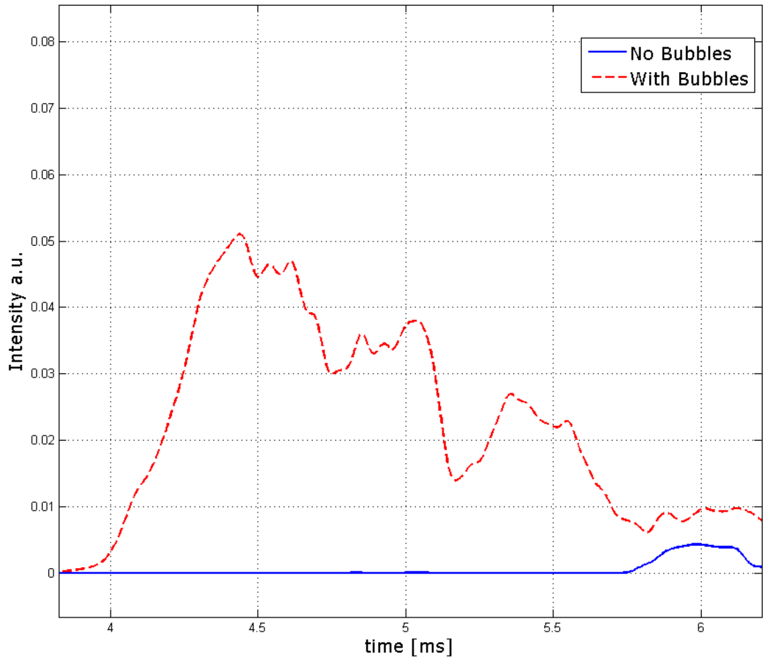


Figure 5: Reflected signal intensity registered without (solid blue line) and with (dash red line) bubble screen present

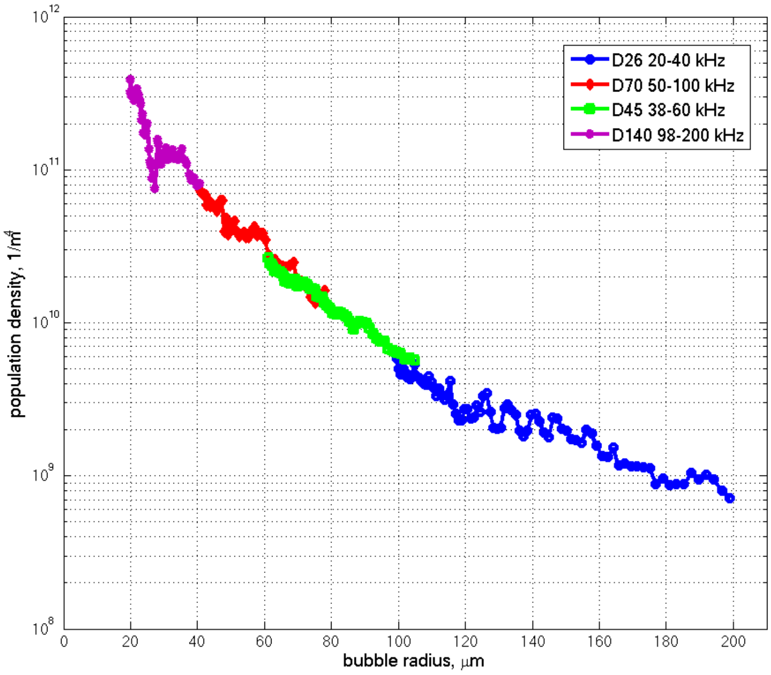


Figure 6: Bubbles size distribution calculated using transmission data with RBA

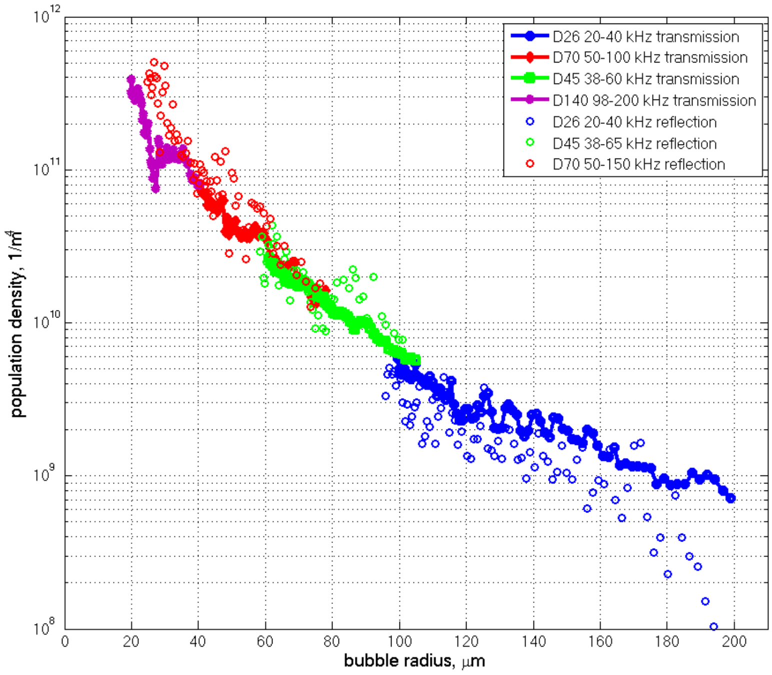


Figure 7: Bubbles size distribution calculated using transmission and reflection data with RBA

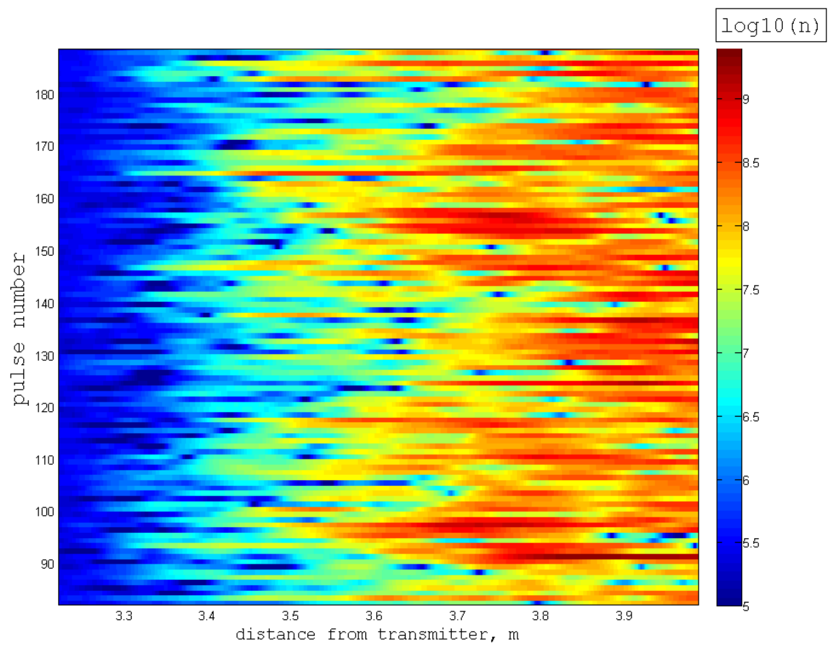


Figure 8: Bubbles distribution in space and time restored by reflection inversion

ACKNOWLEDGEMENTS

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