Attenuation of low frequency underwater noise using arrays of air-filled resonators

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ABSTRACT

This paper investigates the acoustic behavior of underwater air-filled resonators that could potentially be used in an underwater noise abatement system. The resonators are similar to Helmholtz resonators without a neck, consisting of underwater inverted air-filled cavities with combinations of rigid and elastic wall members, and they are intended to be fastened to a framework forming a stationary array surrounding a noise source, such as a pile driving operation, a natural resource production platform, or an air gun array. Previous work has demonstrated the potential of surrounding noise sources with arrays of large stationary encapsulated bubbles that can be designed to attenuate sound levels over any desired frequency band and with levels of reduction up to 50 dB [Lee and Wilson, Proceedings of Meeting on Acoustics **19**, 075048 (2013)]. Open water measurements of underwater sound attenuation using resonators were obtained during a set of lake experiments, where a low-frequency electromechanical sound source was surrounded by different arrays of resonators. The results indicate that air-filled resonators are a potential alternative to using encapsulated bubbles for low frequency underwater noise mitigation.

Keywords: Pile Driving, Helmholtz Resonators I-INCE Classification of Subjects Number(s): 12.2.3, 34.3

1. INTRODUCTION

The goal of this work is to investigate the efficacy of using air-filled, open-ended resonators to abate low frequency underwater noise and to compare their performance with large encapsulated bubbles. Previous work demonstrated the use of arrays of large tethered encapsulated bubbles to attenuate underwater sound in the 50 Hz to 1000 Hz frequency band from a variety of continuous and impulsive sources. [1–5] Air-filled encapsulated bubbles can be tethered to a framework surrounding a noise source, such as a pile driving operation or a natural resource production platform, to reduce radiated sound in a frequency band coincident with the peak sound levels emitted by the source. The volume of each encapsulated bubble in the array is designed so that its acoustic resonance occurs at a frequency near the low end of a chosen source's noise spectrum. Acoustic energy is damped near and above the encapsulated bubble resonance frequency primarily via phase incoherent acoustic re-radiation for the large bubbles sizes (approximately 10 cm in diameter) used in this application—energy from the sound wave goes into oscillating the bubbles in the array. While viscous and thermal damping also occur, they play a much smaller role for such large bubble sizes. Encapsulated bubbles that have a higher Q (quality factor) at resonance are better oscillators and can provide more sound level reduction from this radiation damping. The typical embodiment of an encapsulated bubble used in a noise abatement system is an air-filed rubber balloon. The encapsulating rubber shell is typically thick enough (~1mm–2 mm) that it can survive deployment and withstand the marine environment.

As an alternative to encapsulated bubbles, a potentially more effective type of resonator was developed, consisting of a container with a combination of rigid and elastic wall members and a single

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open end. The container is inverted so that the open end at the bottom forms an air-water interface, similar in concept to an air-filled underwater Helmholtz resonator without a neck, such that the air volume can undergo driven oscillations and sound can be re-radiated from the air-water interface at the opening and at the rubber sides. [6] The new resonator had rectangular box geometry with an open end on the bottom and a total enclosed volume of 216.8 cm^3. Instead of making all of the walls rigid, two vertical walls of new container consisted of thin rubber sheets (less than 1 mm thickness) to increase the amount of radiating surface area.

These new open-ended resonators were fabricated and tested in a series of laboratory and open-water experiments. The laboratory tank experiments were conducted to measure the resonance frequency and quality factors of both individual open-ended resonators and encapsulated bubbles. The new open-ended resonator was designed so that it had approximately the same resonance frequency as a selected size of encapsulated bubble (~110 Hz at an encapsulated bubble volume of 2671.5 cm^3), although the open-ended resonator had nearly double the quality factor Q of the encapsulated bubble. An additional feature of the new open-ended resonator is that it exhibits a second additional resonance below the primary resonance frequency. Attenuation measurements performed in a fresh water lake demonstrated that for a fixed void fraction, the array of open-ended resonators provided at least three times the amount of peak attenuation compared to an encapsulated bubble array of the same void fraction.

2. LABORATORY RESONANCE FREQUENCY AND QUALITY FACTOR MEASUREMENTS

Laboratory measurements of resonance frequencies and quality factors of individual open-ended resonators and encapsulated bubbles were made using the closed, water-filled tank apparatus and data analysis techniques described in Ref. 7. An individual open-ended resonator or encapsulated bubble was placed inside the tank apparatus, and a piston driven by an electromechanical shaker excited the acoustic response of the open-ended resonator or encapsulated bubble and of the tank. The pressure radiated by the resonator under test was measured by a hydrophone mounted inside the tank, and a spectral subtraction technique was used to estimate its frequency response. [7,8]

The resonance peaks for each of the resonator types are shown in Fig. 1. The resonance frequency f_0 corresponds to the maximum amplitude and the quality factor at resonance is given by $Q = f_0 / \Delta f$, where Δf is the width of the peak 3.01 dB down from the maximum amplitude. A single peak is observed in the resonance spectrum for the encapsulated bubble; however, two peaks occur in the open-ended resonator's response. The measured resonance frequencies and quality factors are listed in Table 1.

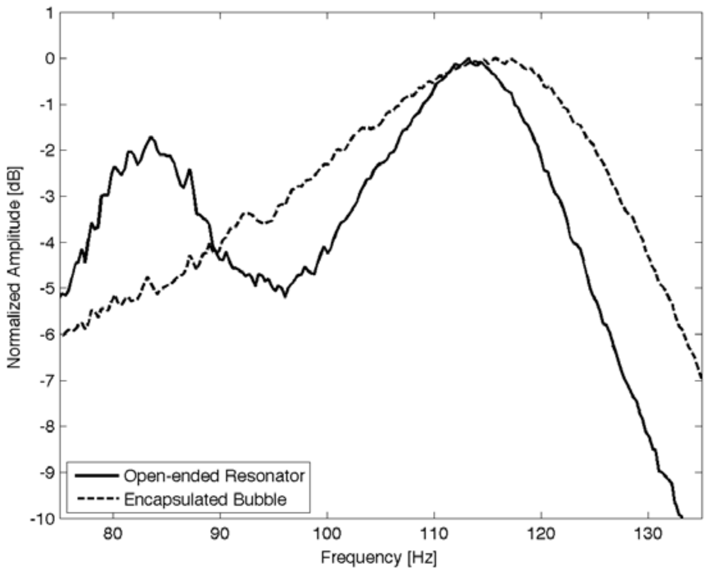

Figure 1 – Resonance spectra of an individual open-ended resonator and an encapsulated bubble measured in

a laboratory tank. Both types of resonators display resonance peak between 113 Hz and 116 Hz although the open-ended resonator design has a secondary lower frequency resonance at 83.6 Hz.

Table 1 – Resonance frequencies and quality factors for open-ended resonators and encapsulated bubbles

Resonator type	Primary resonance frequency [Hz]	Q at primary resonance	Secondary resonance frequency [Hz]	Q at secondary resonance
Open-ended	113.2	6.0	83.6	5.1
Encapsulated	115.7	3.6	–	–

The encapsulated bubble consisted of a rubber-shelled, air-filled balloon with a volume of 2671.5 cm^3. Such encapsulated bubbles have been the subjects of previous investigations, and their acoustic behavior is well predicted by Church's model. [4,7,9] The open-ended resonator has a primary resonance (highest amplitude resonance) at nearly the same frequency as the encapsulated bubble, but with a much smaller volume of 216.8 cm^3—about $1/12^{th}$ the volume of the encapsulated bubble. Compared to the encapsulated bubble, the open-ended resonator has a measured Q that is greater by a factor of 1.67. Additionally, the open-ended resonator exhibits a secondary, lower frequency resonance at 83.6 Hz with a similarly high Q. Although a detailed explanation of this remains the subject of further investigation, a potential reason for the discrepancy in acoustic behavior and between air volumes could be that while the air volume of the encapsulated bubble is fully constrained by its rubber shell, the air volume of the open-ended resonator is partially constrained by both a rigid member and rubber sheets in addition to having one unconstrained surface. The combined effects of the various impedances at the different boundaries of the open-ended resonator's enclosed air volume likely contribute to its unique acoustic properties.

3. OPEN-WATER ATTENUATION MEASUREMENTS

Attenuation measurements using arrays of both resonator types were conducted from an anchored, floating barge located in Lake Travis, a fresh water lake near Austin, Texas. Collections of either encapsulated bubbles or open-ended resonators were attached to netting stretched across the outer sides of a steel frame with height of 1.3 m and horizontal dimensions of 1.2 m by 1.2 m. Two additional vertical panels of netting were attached to the interior of the frame so that the resonators formed a three-dimensional volumetric array. Two steel weights were attached to the rigid framework to provide additional ballast. A US Navy J-13 low frequency reference projector was suspended in the middle of the resonator array, and the entire apparatus was submerged into the lake using an overhead gantry crane such that the center of the frame was at a depth of 1.2 m. A pre-deployment photograph of the apparatus with 96 open-ended resonators attached to it is shown in Fig. 2a. A High Tech, Inc. HTI-90 hydrophone was lowered into the water 11.5 m away from the resonator array. The acoustic pressure was measured in increments of 2 m, from 2 m to 20 m depth with and without the various resonator arrays present. The lake depths beneath the resonator array and hydrophone deployment sites were 20.9 m and 21.2 m, respectively. A schematic of the experiment configuration is shown in Fig. 2b.

Various numbers of each resonator type were attached to the test framework to achieve different void fractions. The void fraction is given by the expression $\beta = NV_{res}/V_{tot}$, where N is the number of resonators, V_{res} is the volume of an individual resonator, and V_{tot} is the total volume contained within the test framework. Void fractions of 0.08%, 0.17%, 0.34%, 0.67%, and 1.01% were obtained using 8, 16, 32, 64, and 96 open-ended resonators. Using 8, 16, and 32 of the larger volume encapsulated bubbles, void fractions of 1.03%, 2.07%, and 4.14% were achieved.

Narrowband spectra (4096 FFT points, 0.488 Hz resolution bandwidth) of the measured acoustic pressure for each case are plotted in Fig. 3. The spectra are normalized such that highest pressure in the baseline case (the iteration with no open-ended resonators or encapsulated bubbles present) is equal to 0 dB. As the number of resonators of either type increases, and hence the void fraction, is increased, the overall sound level received at the hydrophone is reduced. For the highest void fraction cases, the sound level reduction near the individual resonator resonance frequency is great enough that the signal level is coincident with the ambient noise floor. Sharp lines occurring in the spectra at 60 Hz and higher harmonics are due to acoustic noise radiated by vibrating electrical transformers attached to the deck of the test barge; hence this noise is not attenuated by the resonator array since its source is located outside of the array. Increased spectral levels occurring below the individual resonator resonance frequency are due to enhanced coupling of the source signal into the lake waveguide through collective in-phase oscillations of the resonator array.

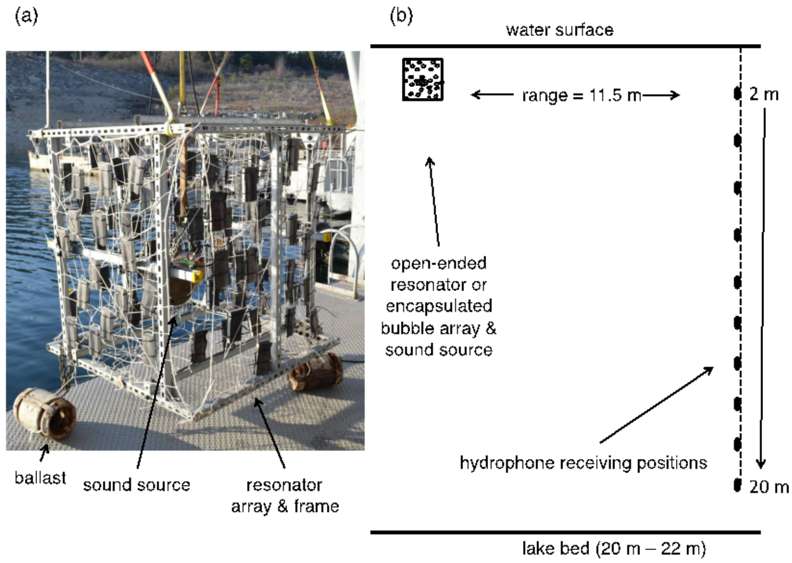

Figure 2 – (a) Photograph of open-ended resonator array with 96 resonators attached to test framework prior to being deployed. The J-13 sound source was suspended in the center of the array. (b) Schematic of the sound source and receiver configuration used in the lake experiment.

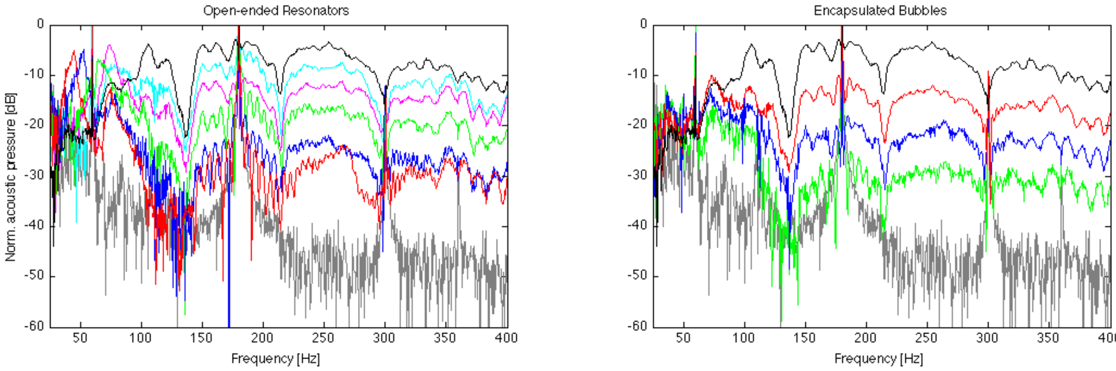

Figure 3 – Example measured acoustic pressure from a hydrophone 11.5 m away and at a depth of 10 m for the various configurations of open-ended resonators and encapsulated bubbles. Left: Open-ended resonators arrays—$N = 8$, $\beta = 0.08\%$ (light blue), $N = 16$, $\beta = 0.17\%$ (magenta), $N = 32$, $\beta = 0.34\%$ (green), $N = 64$, $\beta = 0.67\%$ (dark blue), and $N = 96$, $\beta = 1.01\%$ (red). Right: Encapsulated bubble arrays—$N = 8$, $\beta = 1.03\%$ (red), $N = 16$, $\beta = 2.07\%$ (dark blue), and $N = 32$, $\beta = 4.14\%$ (green). The black solid lines in both plots correspond to the baseline spectrum, and the grey dashed lines show the ambient noise spectrum. The red solid lines in both plots correspond to the arrays with approximately 1% void fraction.

The narrowband spectra for each resonator or baseline case were divided into 25-Hz-width frequency bins, and the mean amplitude was computed for each bin. These band levels for each case were then averaged over each of the receiver depth positions. To estimate the band level reduction for each resonator array, the band levels for a particular case were subtracted from the baseline band levels. The resultant depth-averaged band level reductions are plotted in Fig. 4 for three different cases: 1.01% void fraction array of open-ended resonators, 1.03% void fraction array of encapsulated bubbles, and 4.14% void fraction array of encapsulated bubbles. For a fixed void fraction of ~1%, the open-ended resonators provided at least three times the peak reduction in the band closest to the resonance frequencies of the two types of resonators centered at 114 Hz. The increased attenuation of the source signal is both due to the higher Q of the open-ended resonators and also likely to an increased impedance mismatch around the source from the higher number of air-filled resonators. The band level reduction provided by the 4.14% void fraction encapsulated bubble array is comparable to the 1.01% void fraction open-ended resonator array for frequencies up to about 1 kHz. For higher frequencies the reduction from the encapsulated bubble array falls off to zero while the open-ended resonator continues to provide at least 10 dB of reduction up to approximately 1.8 kHz. As the wavelength approaches the array size at these higher frequencies, scattering effects may become important, and the comparatively larger number of the smaller open-ended resonators per wavelength may enhance the scattering effects. Finally, the sub-resonance band level increase is more pronounced with the open-ended resonator array than in the encapsulated bubble cases. This effect is also likely enhanced by the greater number of open-ended resonators in the array, which could potentially increase the efficiency of the in-phase collective oscillations of the array below the individual resonator resonance frequency.

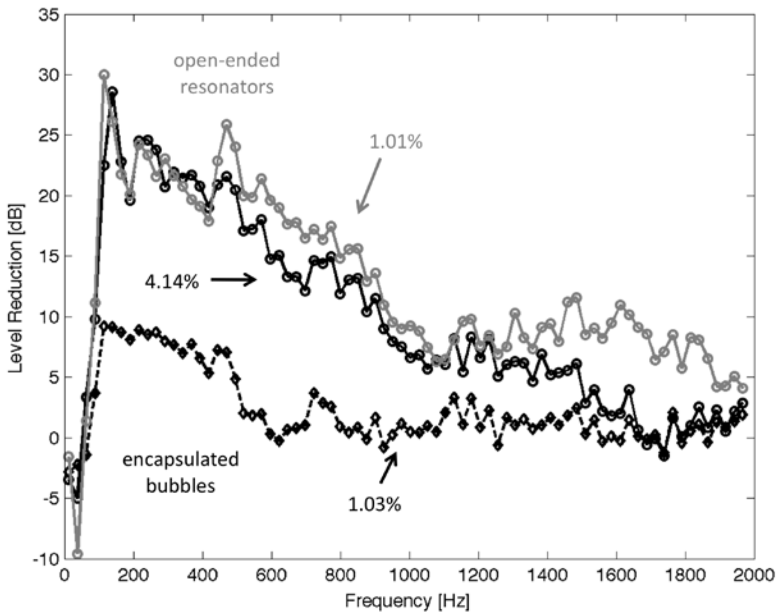

Figure 4 – Depth-averaged band level reduction for three different array cases: 96 open-ended resonators, β = 1.01%, 8 encapsulated bubbles, β = 1.03%, and 32 encapsulated bubbles, β = 4.14%. The frequency bands each had a width of 25 Hz.

Because ballast weight is required to hold down both the open-ended resonators and the encapsulated bubbles, there is an advantage to having a given level of reduction achieved through a reduced void fraction array of open-ended resonators. Approximately four times less ballast is required to submerge the 1.01% void fraction open-ended resonator array than the 4.14% encapsulated bubble array. The broadband level reductions for the 100 Hz to 1 kHz frequency range and each of the open-ended resonator and encapsulated bubble cases are plotted versus the amount of ballast needed to just make each array negatively buoyant, shown in Fig. 5. The 4.14% void fraction encapsulated bubbles array requires nearly an order of magnitude more ballast to attain negative buoyancy compared to the similarly performing 1.01% void fraction open-ended resonator array. In practice, noise abatement systems made from these open-ended resonators would have reduced manufacturing, shipping and deployment costs compared to equivalent-performance encapsulated bubble systems because of the reduced need for ballast.

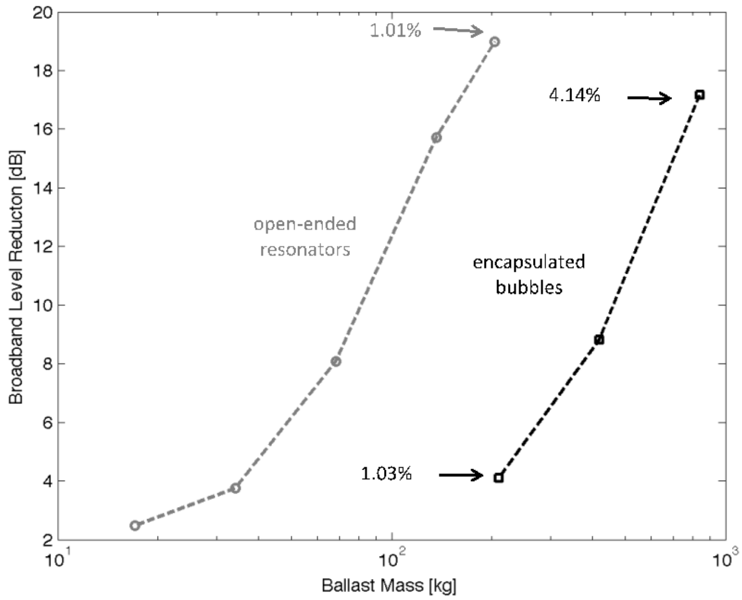

Fig. 5: Mean sound level reduction in the 100 Hz to 1000 Hz band plotted versus the minimum ballast mass needed to submerge each array. On such a plot, systems with curves shifted to the left are lighter, and less expensive to build, ship, and deploy.

4. SUMMARY

A new prototype open-ended resonator design was developed and tested for the purpose of incorporating arrays of the resonators into an underwater noise abatement system. Individual resonators were designed to have a resonance frequency near 100 Hz, similar to encapsulated bubbles that were used in previous noise abatement systems. Laboratory measurements confirmed that open-ended resonator had a resonance frequency at 113.2 Hz compared to the resonance frequency of the encapsulated bubbles used in the testing with resonance frequencies of 115.7 Hz, but at only one-twelfth the air volume of a single encapsulated bubble. Furthermore, the new resonator possesses a second resonance frequency at 83.6 Hz not exhibited by the encapsulated bubble. The Q values for both resonances of the open-ended resonator are 1.5–2 times larger than that of the encapsulated bubble, indicating that the new resonator is a comparatively better oscillator. Attenuation measurements conducted in a lake confirmed that the an array of open-ended resonators can provide at least three times the amount of peak sound level reduction than an encapsulated bubble array of the same void fraction. Additionally, an open-ended resonator-based noise abatement system has the potential to achieve a target amount of underwater sound attenuation, but at four times less required ballast weight than an equivalently performing encapsulated-bubble-based system due to the increased acoustic efficiency of the open-ended resonator design.

ACKNOWLEDGEMENTS

This work was supported by AdBm Technologies. KML, PSW and MSW have equity ownership in AdBm, which is developing and commercializing underwater noise abatement technology related to the research being reported here. The terms of this arrangement have been reviewed and approved by the University of Texas at Austin in accordance with its policy on objectivity in research.

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