Modeling of Acoustic Attenuation of an Air Curtain

Prepared By

JASCO Research Ltd.

For

Stress Engineering Services

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1 BACKGROUND AND INTRODUCTION

Stress Engineering Services Inc is investigating the use of bubble curtains to reduce underwater sound pressure levels produced by airgun arrays that are commonly used as the seismic source for marine seismic survey programs. The acoustic modeling study described here was performed by JASCO Research Ltd to estimate the effectiveness of a specific air curtain configuration for absolute reduction of sound levels.

Airguns produce underwater sounds by rapidly releasing highly compressed air into the surrounding water. The pressurized bubble is initially small but starts to increase in size before undergoing damped oscillations. The resulting acoustic pressure wave is proportional to the pressure variation within the oscillating bubble. It has a high initial primary pressure peak corresponding to air release followed by a series of secondary peaks associated with the subsequent volume minima of the oscillating bubble. The secondary peaks are referred to as bubble pulses and these are undesirable from a seismic imaging perspective. The period between bubble pulses increases with the volume of the airgun chamber and airgun arrays use this feature to suppress bubble pulses by simultaneously firing multiple airguns with different volumes. The primary pulses occur at the same time so their pressures add coherently while the bubble pulses do not.

Airgun arrays are typically configured with the airguns laid out in one or more “strings” comprising sequences of in-line deployed airguns. Multiple strings are often towed side-by-side to provide a 2-dimensional array with all airguns on a constant depth plane. Planar airgun arrays produce highest sound pressure levels in the downward direction because the pressure pulses from all airguns add coherently only in that direction. However, high levels of sound are produced in all directions and this sound can lead to disturbance of nearby marine mammals. Air curtains have been proposed as a method of reducing sound levels in certain directions from airgun arrays. Air curtains have recently been employed to reduce sound levels produced by pile driving activities. That application is relatively more straightforward because the piles are stationary. The manifolds to be used for producing air curtains on the sides of airgun arrays will have to be towed on either side of the array at a depth greater than the airguns. The released air bubbles will move vertically upward due to buoyancy and horizontally due to water flow relative to the airgun array. Figure 1 depicts the relative positions of the manifolds and air curtains relative to a 3-string airgun array with 5 airguns in each string.

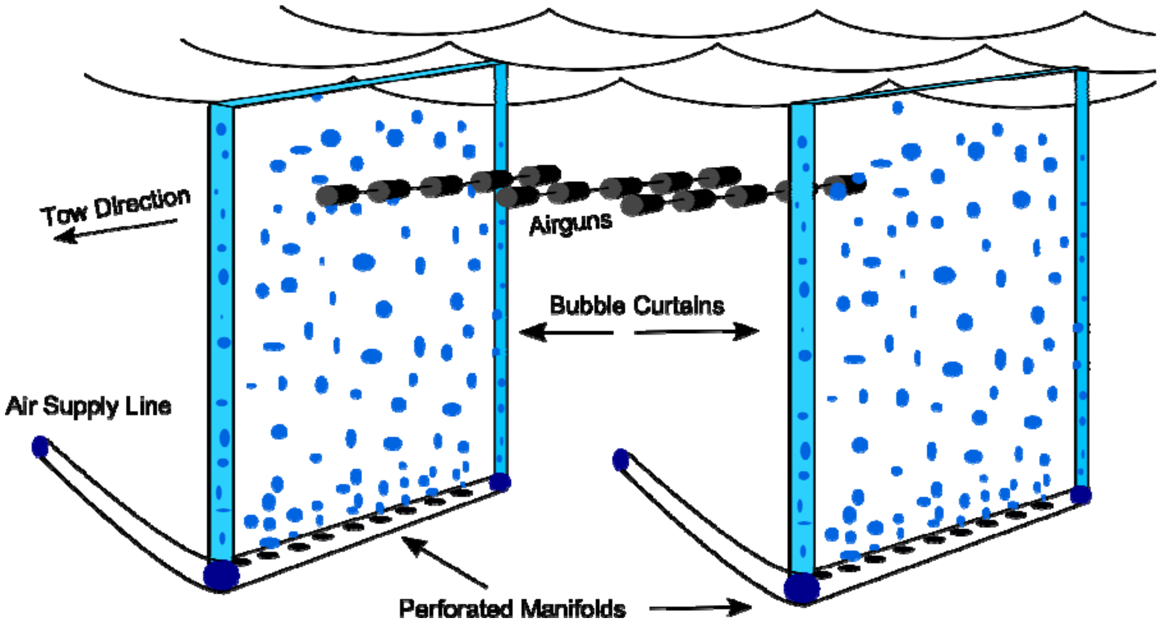


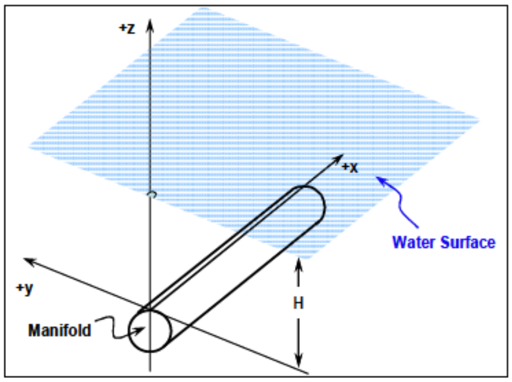
Figure 1: Positions of manifolds and curtains relative to a towed airgun array.

2 PURPOSE

The purpose of this acoustic modeling study is to predict the absolute pressure reduction as a function of sound frequency that could be achieved by a specific air curtain configuration. The specific configuration is described by two 201 foot (61.3 m) - long manifolds deployed on either side of the airgun array and towed at 60 feet (18.3 m) depth. This scenario was chosen based on fluid-dynamic modeling by Warren Jones (Figure 2) that predicted the fractional volume of water that would occur as a function of depth in the region above the manifolds. The bubble density decreases perpendicularly across each curtain according to a square exponential decay function. The distance perpendicular to a vertical plane passing through the manifold axis at which the bubble density reaches 1/e (~0.37) of its on-axis density is 2.4 m at 15.2 m depth and 0.58 m at 3.7 m depth.

AIR CURTAIN DESIGN	Created: Warren T. Jones, Ph.D.	12/4/08 10:02 AM
Solution #64	Last Revision	12/11/08 2:07 PM

Max Speed of Sound Ratio c/c_w (-)	Depth of Manifold [H] (ft)	Number of nozzles per ft [n] (1/ft)	Diameter of nozzle exit [d] (in)	Manifold Pressure [Pm] (psia)	Diameter of manifold [Dman] (in)	Pressure at Manifold End (psia)	Flow Rate (scfm)	Total Pneumatic HP at manifold (hp)	Rise Time (sec)	Manifold length (ft)	Manifold Position in front of array (ft)	Total Number of Nozzles (-)	NumSteps (-)
0.07	60	3	0.125	58.40212	8.986533	57.23408	4933.793	423.1036	15.4867557	201	141	603	20000



z (ft)	Avg s (-)	sm (-)	b (ft)	λb ft
0	1			
3	0.110072	0.13759	0.348	0.4698
6	0.061522	0.076902	0.696	0.9396
9	0.04353	0.054412	1.044	1.4094
12	0.034204	0.042755	1.392	1.8792
15	0.028539	0.035673	1.74	2.349
18	0.024764	0.030956	2.088	2.8188
21	0.022099	0.027623	2.436	3.2886
24	0.020141	0.025176	2.784	3.7584
27	0.018668	0.023334	3.132	4.2282
30	0.017543	0.021928	3.48	4.698
33	0.016681	0.020851	3.828	5.1678
36	0.016027	0.020033	4.176	5.6376
39	0.015542	0.019427	4.524	6.1074
42	0.015203	0.019003	4.872	6.5772
45	0.014993	0.018741	5.22	7.047
48	0.014905	0.018631	5.568	7.5168
51	0.014936	0.01867	5.916	7.9866
54	0.015089	0.018862	6.264	8.4564
57	0.015376	0.019219	6.612	8.9262
60	0.015812	0.019765	6.96	9.396

Average volume fraction of air = $\overline{s}$

$$s_m(z) = 1.25\,\overline{s}(z)$$
$$b = 0.116z, \quad \lambda = 1.35$$
$$s(z,y) = s_m(z)\exp\left[-y^2/(\lambda b)^2\right]$$

Figure 2: Fluid dynamic model of air curtain bubble density and volume fraction versus depth and distance off curtain axis. Modeling results provided by Warren T. Jones.

3 APPROACH

Sound propagation and back-scattering in bubbly water has been studied extensively in problems encountered in acoustic oceanography and ultrasonic imaging (Leighton 1994). Even a very small fractional volume of air bubbles in water can significantly change the sound speed. The primary reason for this effect is that the compressibility of bubbly water is much greater than for regular water. Sound pressure waves incident on the boundaries of bubbly water layers can be reflected strongly due to the large change in sound speed and acoustic impedance across the boundaries. Bubbles also can absorb energy from acoustic pressure waves if the natural frequency of bubble oscillation is similar to that of the incident pressure wave. The natural resonant frequency of bubbles depends on their radii and depth. The latter affect generally is important at low frequencies only for large bubble sizes; bubble diameters corresponding to resonant frequencies 100 Hz and 500 Hz respectively are 3 cm and 6 mm. It is quite possible that these large bubble sizes could be produced by the air curtain system considered here.

Sound attenuation due to excitation of individual bubble oscillations is complex and depends on the distribution of bubble sizes in the bubbly liquid region. Although resonance absorption is likely an important effect, we have neglected it in this initial examination. Here we only consider the macroscopic effect of reduced acoustic impedance in the bubbly layer on the reflection and transmission coefficients through the layer. Leighton shows that when the frequency of the incident acoustic wave is much less than the bubble oscillation frequency then the sound speed C in the bubbly layer can be computed according to

$$C = C_w \left(1 + \frac{\{VF\}}{2} \frac{C_w^2 \rho_w}{C_a^2 \rho_a}\right)^{-1} \quad \text{Eq.1}$$

where C_w is the water sound speed, ρ_w is the water density, C_a is the air sound speed, ρ_a is the water density and VF is the fractional volume occupied by air bubbles.

The specific approach taken here is to model the reflection and transmission coefficients as a function of frequency through a homogenous bubble layer that has reduced sound speed and density. The specific assumptions made here were:

1. Bubble layer thickness of 1.5 m was chosen based on the distance at which the density factor had decreased to 1/e of its on-axis value. This was based on the decay function value at 5 m depth (corresponding to common airgun array operating depth).
2. Bubble layer fractional air volume of 0.028 is used. It is the fluid-dynamic model predicted value at 5 m depth.
3. Bubble layer sound speed was computed using Eq. 1 with the following parameter values: C_w = 1500 m/s, ρ_w = 1020 kg/m^3, C_a = 343 m/s, ρ_a = 1.2 kg/m^3 and VF = 0.028. Eq. 1 gives C = 6.6 m/s but to be conservative we have increased the value by an order of magnitude; the value for sound speed in the bubble layer used for this study is 66 m/s.
4. Bubble layer density was chosen based on the sum of the products of relative fractions of water and air at 5 m depth and their respective densities. This gives 991 kg/m^3.

A one-dimensional problem was considered in which a plane acoustic wave of frequency f is incident on the bubble layer from angle θ as shown in Figure 3.

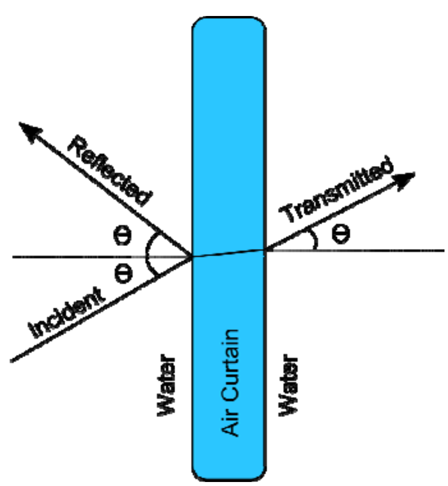


Figure 3: Diagram of Incident, Reflected and Transmitted Acoustic Paths.

The transmission coefficient T represents the ratio of amplitudes of the transmitted wave to the incident wave. This coefficient in decibels indicates how much signal attenuation will be produced by the air curtain. The transmission coefficient was computed using the well-known theoretical formula for sound transmission through a fluid layer having different acoustic impedance than the fluid on either side (e.g. Jensen et al. 2000 and Brekhovskikh 1960). This is an exact formulation for fluid layers. The acoustic impedances of the water and air curtain layers were computed from their respective sound speeds and densities and from the angle of propagation in each layer. The angles of propagation were computed from Snell's law.

4 RESULTS

The transmission loss through the bubble curtain was computed as a function of frequency using the method described in Section 3. The results for incident angles 0 degrees, 30 degrees, 60 degrees and 89 degrees are shown in Figure 4. The 89 degree result is labeled as 90 degrees.

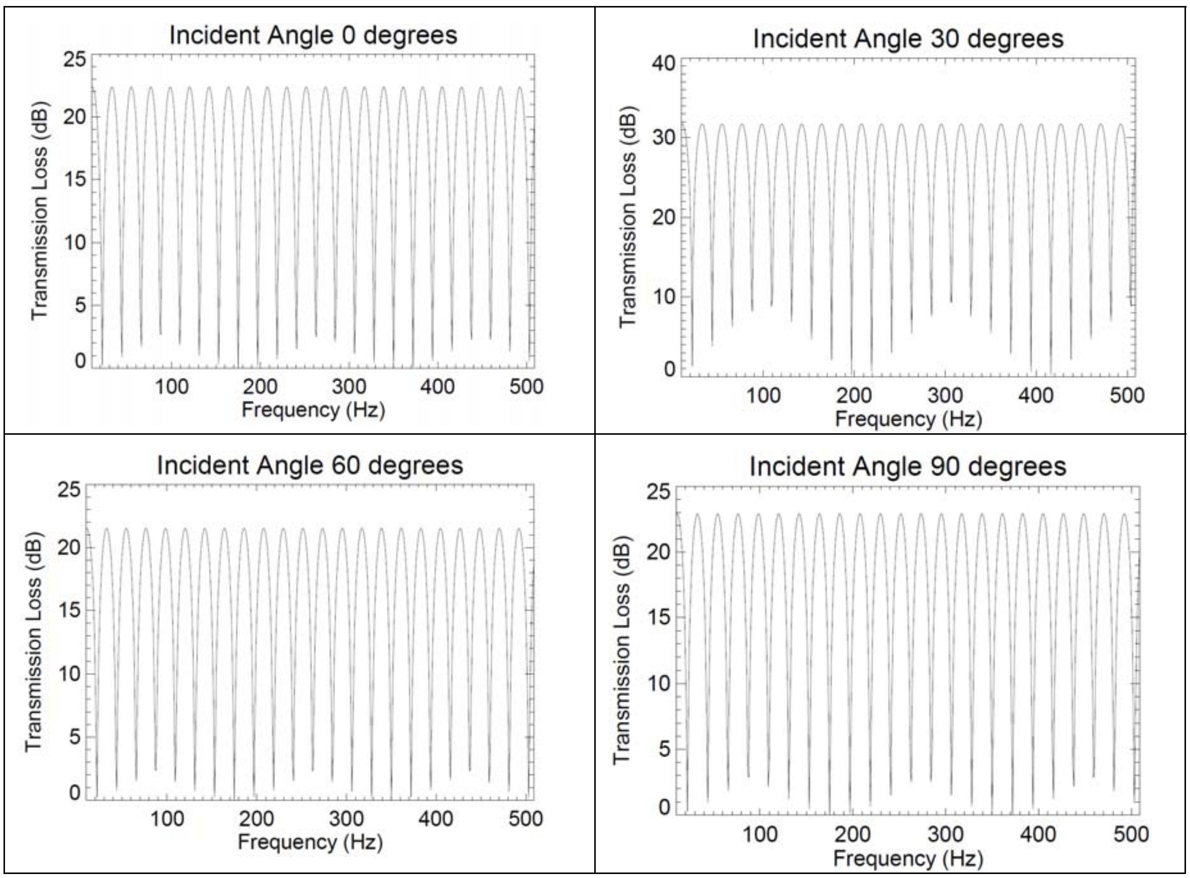


Figure 4: Transmission loss incurred by sound propagation through the air curtain bubble layer for four angles of incidence.

5 SUMMARY

Figure 4 shows the predicted acoustic transmission loss for sound transmission through the bubble curtain configuration described in Section 2 with several additional assumptions presented in Section 3. The acoustic transmission loss was predicted as a function of frequency for frequencies up to 500 Hz and for incident angles onto the bubble curtain layer of 0 degrees, 30 degrees, 60 degrees and 89 degrees. The results are plotted in Figure 4. Transmission loss values versus frequency were observed between 0 dB and 32 dB for the four incident angles tested. All four incident angles showed similar frequency variation whereby the transmission loss function cycled between 0 dB to the maximum (22 dB to 32 dB) with a period of 22 Hz. This frequency corresponds with ½-wavelength layer effect; the wavelength in the air curtain layer at 22 Hz is 3 m which is twice the layer thickness. The frequency of the loss minima do not change appreciably with incident angle because the wave propagation angle in the low speed bubbly layer is near perpendicular to the boundaries for all incident angles. We also examined the maximum loss value as a function of angle. The maxima for the four angles presented in Figure 4 were between 22 dB and 32 dB. The transmission loss maxima however can have greater variation than apparent at the four angles examined. Transmission loss at 11 Hz, and likely multiples of that frequency, ranged from 22 dB to 65 dB when incident angle was stepped through 1 degree increments between 1 and 89 degrees.

Insofar as sound level reduction is concerned, the bubble curtain scenario examined here could reduce the spectral levels for most frequencies by more than 10 dB. The absolute reduction appears to vary cyclically with frequency but there was not a trend with frequency. This result is likely due to our assumption of no absorptive losses within the bubble curtain layer. Losses incurred by exciting individual bubble resonances were not addressed in this study and those would be in addition to the impedance loss mechanism considered here. Those resonant losses would be frequency dependent and influenced by the similarities between bubble resonant frequencies and the airgun array sound frequency spectrum. The bubble resonant frequencies are dependent on the bubble size distribution.

6 LITERATURE CITED

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