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Research Article

Ballroom Music Spillover into a Beluga Whale Aquarium Exhibit

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It is not uncommon for modern aquaria to be built with special entertainment areas. There are no known measurements of sound spillover from such entertainment areas into underwater animal exhibits. Entertainment organizations typically prefer to play music for events at 95 and 100 dBA in a ballroom at Georgia Aquarium. Concern over the potential effects of the music and noise on animals in adjacent exhibits inspired an initial project to monitor and compare sound levels in the adjacent underwater exhibits against the typical in-air sound levels of the ballroom. Measured underwater noise levels were compared to modeled levels based on finite element analysis and plane wave transmission loss calculations through the acrylic viewing window. Results were compared with the model to determine how, if at all, the ambient noise level in the Cold Water Quest exhibit changed as a result of music played in the ballroom.

1. Introduction

Frequently, modern aquaria are built with special areas in which conferences, parties, and night functions can take place. For example, in Georgia Aquarium the Oceans Ballroom was built to entertain up to 1200 people. Many social functions held in this room include music played by disc jockeys or live bands that amplify the music to levels greater than 90 dBA for durations of approximately two hours. In many aquaria, these social spaces adjoin exhibits that accommodate various species of fish or marine mammals. At the Georgia Aquarium, the Oceans Ballroom adjoins the Cold Water Quest (Beluga Whale) exhibit. From the ballroom, the people participating in special events can see into the Cold Water Quest exhibit via a large acrylic viewing window. Sound from the ballroom propagates through the viewing window as well the concrete pool walls into the exhibit. This study investigates the sound propagation into the beluga exhibit through the acrylic viewing window.

Guidelines regarding sound exposure of animals in the wild are sketchy and fraught with debate over their derivation and applicability.

Reports to date on these issues include Southall et al. [1] and Finneran and Schlundt [2]. There are no specific laws or guidance which deals with the effect of prolonged exposure to sound on captive marine mammals. It has been observed that machinery noise is the most prominent contributor to underwater ambient noise observed in aquarium exhibits. The Cold Water Quest exhibit underwent an acoustic mapping during which the contribution of each pump, filter, and ozone, and protein tower was tested prior to animals being placed in the habitat to establish a baseline for noise generated by the exhibit life support system (LSS).

Audiologically, our knowledge of actual performance of the Beluga fully aquatic ear under prolonged periods of sound exposures at varying levels is poor at best. In order to establish specific guidelines based on empirical data for allowable limits for sound levels generated from the Oceans Ballroom, aquarium directors commissioned this study of the noise transfer from ballroom to exhibit via the ballroom window. Measurements of acoustic pressure were made in the Beluga exhibit as part of this study. Finite Element Modeling together with plane wave transmission calculations were used to model the sound transmission

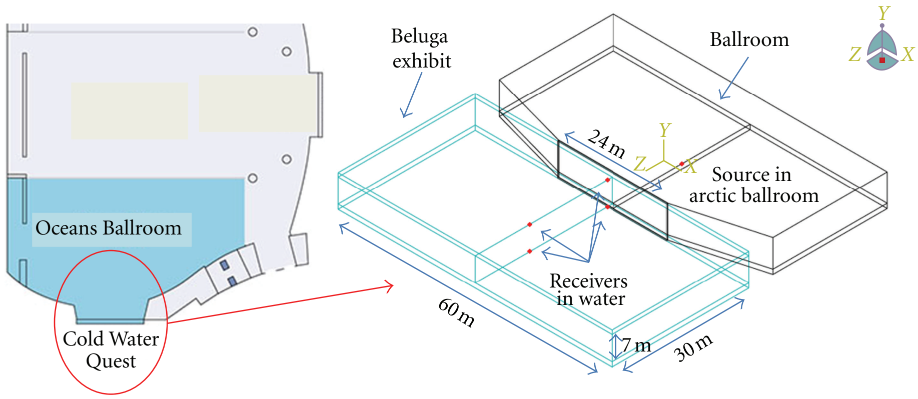


FIGURE 1: The geometry of the finite element model. The actual shape of the ballroom and the beluga exhibit is shown on the left. The acrylic window is 24 m wide.

from the ballroom to the beluga exhibit through the acrylic window, which were then compared with the previously established baseline measurements. This paper is organized as follows: Section 2 summarizes the measurements carried out in air and in water as part of this study. Modeling of the acoustic propagation from the ballroom to the beluga whale exhibit is described in Section 3. Specifically, the tests conducted to estimate the acoustic properties of the acrylic material are described in Section 3.1; finite element analysis approach is presented in Section 3.2; the plane wave transmission analysis is discussed in Section 3.3. Section 4 presents the conclusions of the present study.

2. Acoustic Measurements in Air and in Water

The life support system (LSS) in the aquarium consists of a number of pumps which help to recirculate the water in the exhibits. These pumps are the primary source of ambient noise in the aquarium. Ambient noise measurements were made with the LSS in the normal operating configuration prior to the ballroom noise assessment. This was done by means of recordings in the Cold Water Quest exhibit using Bruel & Kjaer Model 8103 hydrophones and an ST1400ENV data acquisition system, including one CR-1 hydrophone. B&K Hydrophones were calibrated by the manufacturer and the CR-1 by National Institute of Standards and Technology (NIST). The ST1400ENV acquisition system is a single channel 24 bit/48 kHz ultrasonic, multichannel recording system with sample rates of 96 kHz, and 192 kHz providing time-domain and 1/3 octave analysis. The CR-1 hydrophone has a linear (flat) frequency response range (± 3 dB) of 0.2 to 48 kHz (Cetacean Research Technology, 2012), when used with the Reson preamplifier with 100 MΩ input impedance and a useable Frequency Range of ($+3/-12$ dB) [kHz] 0.5 to 68 kHz (Cetacean Research Technology, 2012).

Recordings were taken at distances of one meter and 18.22 meters in a plane normal to the center of the window (one meter from the air-water interface and at the pool floor). The geometry of the ballroom, the beluga whale exhibit and the position of the acrylic window are shown in Figure 1. These ambient noise readings compared well with

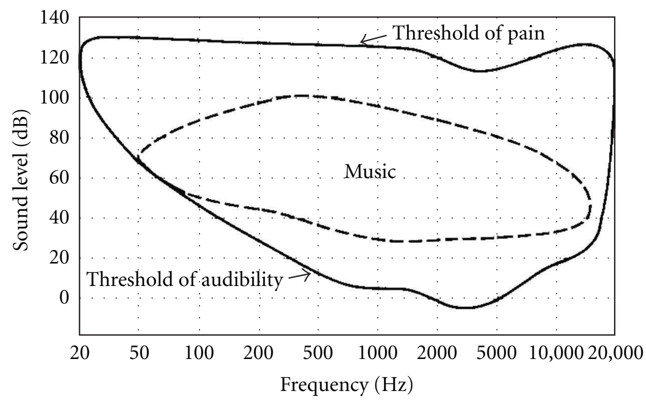


FIGURE 2: Dynamic range of music compared to human hearing range [3].

the original mapping values taken when the exhibit LSS was put into service.

Music selections were then played in the Oceans Ballroom by a disc jockey with speakers located at the usual location during events 15 meters from the acrylic glass window of the Cold Water Quest exhibit. The music was played such that the sound levels at the window face were 95 and 100 dBA, respectively. This was done to enable a determination of what sound levels of 95 and 100 dBA in-air on the ballroom side (where the people would be) would equate to on the water side of the acrylic glass window (where the marine mammals are). The music selections were typical of those that might be played at a wedding reception or party ranging from rock/rap to sedate popular and vocal music. Modeling was done in this study with the plane of the speaker facing directly onto the window. The specific sample frequencies selected for analysis in the musical selections ranged from 65 Hz to 14,000 Hz. These frequencies conform well to the approximate range of frequency and sound levels of music compared to the range of human hearing as shown in Figure 2 [3].

Music samples (sound shots) were played at 95 and 100 dBA in air as monitored for the duration of each song

(2–4 minutes) with a Bruel and Kjaer 2250 integrating sound level meter that met the standards IEC60804, IEC 61672, and ANSI S1.4. The Bruel and Kjaer 2250 was calibrated using a Bruel and Kjaer sound level calibrator Type 4223 at a frequency of 1 kHz at 94 dB in conformance with Class 1 specifications IEC 60942. The sound level meter was placed one meter away from the center of the acrylic glass window facing the DJ platform and speakers. The SLM was set on "slow" using the "A"-weighted scale. This allowed for a way to compare the in-air (dBA measurement) to the measurement made on the opposite side of the window taken one meter away from the glass on the water side (measured in dB re 1 micro Pascal). Although the ballroom was not populated during these measurements, they represent a conservative estimate of the transmission of loud music to the animals in the exhibit.

Each piece of music was analyzed to determine the frequency content. Recordings were again taken at distances of 1 meter and 18.22 meters in a plane normal to the center of the window (one meter from the surface air-water interface and at the pool floor). At each in-air sound pressure level, underwater recordings were simultaneously recorded in the Cold Water Quest exhibit. Visual observations were made of the behavioral activity of the animals during the testing.

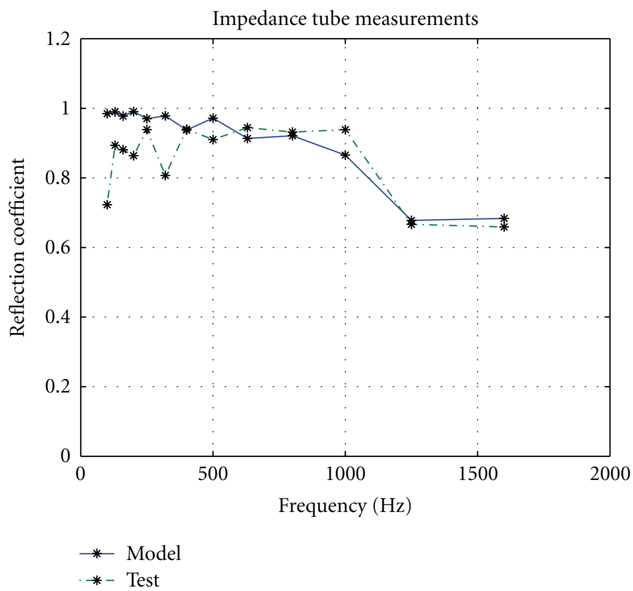


Figure 3: Impedance tube measurements made with the acrylic window sample. Comparison of the test data with finite element modeling is shown in the figure.

3. Modeling of Acoustic Propagation from the Ballroom to the Beluga Whale Exhibit Using Finite Element Method (FEM) and Plane Wave Analysis

Acoustic propagation from the ballroom (air) to the beluga exhibit (water) through the viewing window (acrylic) was modeled using the finite element method (FEM). Modeling was carried out using the commercial software package Abaqus [4]. The modeling geometry including the dimensions of the beluga exhibit and acrylic window is shown on the right panel in Figure 1. The shape of the ballroom and the beluga exhibit are shown on the left panel in Figure 1. The room height and water depth are 7 m, and the length of the window is 24 m. The thickness of the window is 0.27 m. Locations at which measurements were made during the field measurement program are also indicated in this figure at 1 m and 18 m from the face of the acrylic window. The acoustic source (speaker) is located at 1 m from the floor and 16 m from the acrylic window in the Oceans Ballroom (in air).

3.1. Acoustic Properties of the Acrylic Window. The acoustic properties of the acrylic window were determined by testing a sample in an impedance tube. The tests were conducted at the Dynamic Photomechanics Laboratory, Department of Mechanical Engineering and Applied Mechanics, at the University of Rhode Island. The test equipment consisted of a B&K standing wave apparatus (Type 4002) with a crystal type microphone (25 mV/Pa, 2 nF), frequency generator (Bendix advance technology center 343), four-channel phosphor oscilloscope (Tektronix TDS 3014), and a low noise preamplifier with band pass filter (Model SR560, Stanford research systems). The details of test procedure are discussed in detail by Tiwari et al. [5]

Reflection coefficient values computed using the impedance tube were compared with finite element modeling (Figure 3). The objective of this exercise was to tune the material/acoustic properties of the acrylic to match the measurements. Once we identified the correct material/acoustic properties for the acrylic (shown in Table 1), we used the same properties for our main modeling task (finite element modeling of acoustic propagation from ballroom to beluga exhibit through the acrylic window). Rayleigh damping coefficients were applied based on the assumption that first mode has 1% and sixth mode has 10% of the damping ratio. In addition to the modeling of full geometry, we also evaluated the attenuation of sound in the acrylic. We modeled the propagation of sound through acrylic with the estimated material properties using FEM and calculated the loss in dB/m for normal incidence at different frequencies. Figure 4 shows the frequency dependence of attenuation in acrylic for the analyzed frequencies.

The continuous lines in Figure 4 are the linear fit to the data. The slopes of the linear fits are different for frequencies below and above 1000 Hz. The equations of the linear fit are as follows:

$$\begin{aligned} \alpha_2(\text{dB/m}) &= 0.0022\,f + 11.734; \quad f < 1000\,\text{Hz}, \\ \alpha_2(\text{dB/m}) &= 0.0106\,f + 5.6227; \quad f \geq 1000\,\text{Hz}, \end{aligned} \tag{1}$$

where α_2 is the attenuation in dB/m at the frequency, f in Hz. These values of α_2 were used in our subsequent analysis.

3.2. Finite Element Analysis of Acoustic Propagation. After estimating the acoustic and material properties of the acrylic, the propagation of sound from the ballroom to the beluga

Table 1: Material and acoustic properties used for modeling using the finite element method.

Material	Density (ρ, kg/m^3)	Young's modulus (E, GPa)	Poisson's ratio (ν)	Bulk modulus (K, GPa)	Speed of sound (m/s)
Air	1.2	—	—	0.000147	350
Water	1020	—	—	2.295	1500
Acrylic	1175	5.5	0.37	—	2870
Concrete	2400				3600

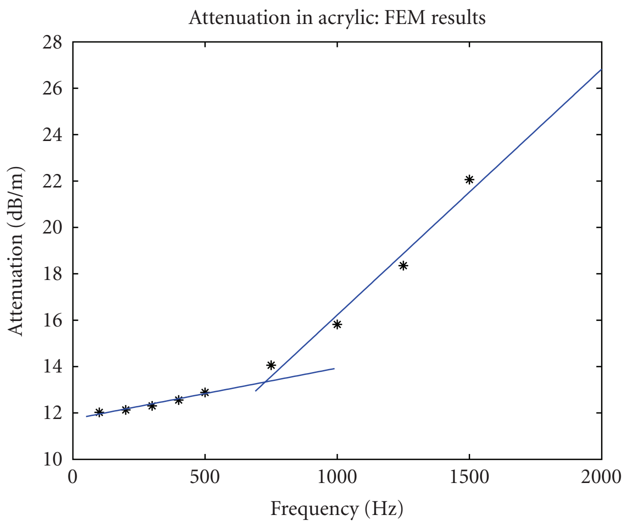
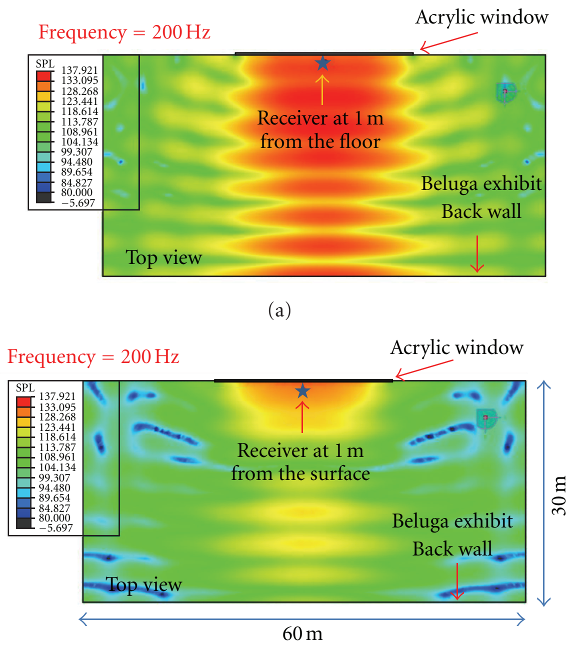


Figure 4: Estimated frequency dependance of attenuation in acrylic. The losses were computed using FEM modeling.



(b)

Figure 5: Sound pressure levels (SPL) re 1 μPa at 200 Hz. (a) shows the plan view of the levels at 1 m from the tank floor whereas (b) shows the plan view at 1 m from the surface. The asterisks indicate the location of the two measurement hydrophones.

habitat through the acrylic window was modeled for low frequencies. For reasonable accuracy of FEM result, at least six representative internodal intervals of acoustic mesh should fit into the shortest acoustic wavelength in the analysis [6]. We have used the smallest mesh size computationally feasible, and we compared and validated by matching the model result and measurement. The properties of the different media involved are listed in Table 1. The walls of the beluga tank were modeled as concrete with appropriate density, sound speed, and acoustic impedance (Table 1). Global mesh size for all parts is 1 m and local mesh size for the acoustic medium between acrylic window and source is 0.5 m. Analysis used 47880 quadratic elements for the air, 104711 quadratic elements for the water, and 168 quadratic elements for the acrylic window. The internodal interval for a quadratic element is half the element size [6] (i.e., 0.25 m in our modeling).

We executed a "direct-solution steady-state dynamic analysis" available in the Abaqus Step module to get pressure field/history output as a function of frequency. 3D quadratic elements were used to model the beluga exhibit, ballroom, and acrylic window with appropriate material properties. A source generated in the Abaqus Load module with 0.1 m radius generating acoustic pressure (equivalent to 100 dBA) at 1 m from the floor and 16 m from the acrylic window was applied. Rayleigh damping coefficients, $\alpha = -0.0365$ and $\beta = 0.0077$, were applied based on the assumption that first mode has 1% and sixth mode has 10% of damping ratio (matching the attenuation properties estimated from the impedance tube analysis).

Figure 5 shows the results of the finite element modeling at 200 Hz. The sound pressure levels (SPL) predicted by the FEM analysis at 1 m height from the floor of the tank is shown in the top panel of Figure 5. The bottom panel, on the other hand, shows the SPL at 1 m below the water surface. The acrylic window is located centrally at the top side of each of the panels, and the asterisks show the location of the receiver at 1 m from the window. The levels are 133 dB and 138 dB at the two locations (top and bottom) at 1 m distance from the acrylic window as shown in the figure. This is slightly less than the measured level (140 dB) at the receiver at 1 m from the window.

The steady state dynamic response at 1000 Hz was computationally challenging due to the smaller wavelengths involved which in turn demands smaller mesh sizes. We had to limit the analysis to the beluga exhibit alone in this case. We applied the acoustic pressure directly at the acrylic window (eliminating the air medium) and modeled

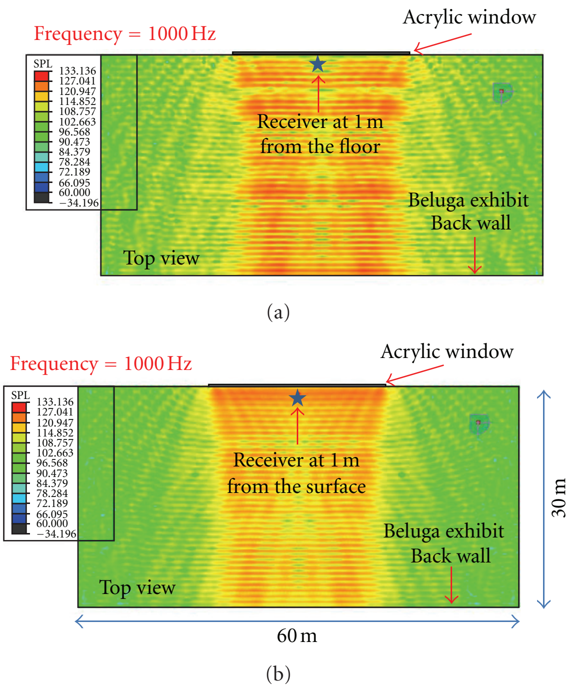


Figure 6: Sound pressure levels (SPL) re 1 μPa at 1000 Hz. (a) shows the plan view of the levels at 1 m from the tank floor whereas (b) shows the plan view at 1 m from the surface. The asterisks indicate the location of the measurements at 1 m from the acrylic window.

the propagation in the acrylic and water only. The pressure which was applied at the window came from our full modeling (200 Hz). The results obtained at 1000 Hz are shown in Figure 6 with measurement locations indicated again using "*". The sound pressure levels are 121 dB and 126 dB at the two locations (top and bottom) at 1 m distance from the acrylic window. As mentioned earlier in this section, for reasonable accuracy the internodal interval should be less than or equal to one-sixth of the acoustic wavelength. This condition is satisfied using quadratic elements up to 1000 Hz. At 1000 Hz, the wavelength ($\sim$1.5 m) is equal to six times internodal interval in our modeling using quadratic elements. This condition will not be satisfied at frequencies over 1000 Hz. Hence, we believe that the results shown in Figures 5 and 6 for frequencies 200 Hz, and 1000 Hz are reasonably accurate. Full modeling using FEM becomes computationally onerous at frequencies higher than 1000 Hz. So, we used a plane wave modeling using the material and attenuation properties estimated previously. The plane wave modeling is discussed in Section 3.3. In a perfectly rigid walled waveguide, as the one analyzed in this study, only plane waves propagate if the frequency of the sound is sufficiently low [7]. At higher frequencies standing waves will be generated depending on the dimensions of the waveguide and the wavelength of the sound. The evidence of the presence of standing wave patterns can be observed in the FEM results shown in Figure 5 (200 Hz) and Figure 6 (1000 Hz). It should be noted that the plane wave modeling, discussed in Section 3.3, is bound to break down at higher frequencies. Depending on the location of the receiver relative to a node or antinode of a standing wave, the plane wave model may underestimate or overestimate the acoustic pressure. It should also be noted that the walls of the tank are not perfectly rigid, and not perfectly reflecting, hindering the generation of standing waves to some extent. This factor supports the plane wave assumption to some extent and hence justifies the analysis discussed in Section 3.3.

3.3. Plane Wave Modeling of Propagation through Acrylic Window. As discussed in Section 3.2, the finite element analysis approach becomes computationally unsustainable at high frequencies due to small mesh sizes. Hence, we modeled the propagation from air (medium 1) through acrylic window of thickness h_2 (medium 2) to the water (medium 3) with a plane wave transmission coefficient for plane waves with an angle of incidence of 0 deg. The intensity transmission coefficient is given by [7]

$$\mathfrak{I}_{13} = \frac{4}{2 + r_{31}\cos(k_2 h_2)^2 + (r_{23} + r_{13})\sin(k_2 h_2)^2}, \quad (2)$$

where $r_{31} = r_3/r_1 + r_1/r_3, r_{23} = r_2^2/(r_1 r_3)$, $r_{13} = r_1 r_3/r_2^2$ are constants and $k_2 = \omega/c_2$, $r_1 = \rho_1 c_1$, $r_2 = \rho_2 c_2$, $r_3 = \rho_3 c_3$ are the wave numbers in the acrylic, and the characteristic impedances of the air, acrylic, and water, respectively. The pressure transmission coefficient for the same arrangement of air, acrylic, and water is given by [8]

$$T_{13} = \frac{T_{12} T_{23} \exp(-j2\phi_2)}{1 + R_{12} R_{23} \exp(-j2\phi_2)}, \quad (3)$$

with the pressure transmission coefficient from air to the acrylic given by $T_{12} = 2r_2/(r_2 + r_1)$, the pressure reflection coefficient from air to acrylic given by $R_{12} = (r_2 - r_1)/(r_2 + r_1)$, the pressure reflection coefficient from acrylic to water given by $R_{23} = (r_3 - r_2)/(r_3 + r_2)$, and the pressure transmission coefficient from acrylic to the water given by $T_{23} = 2r_3/(r_3 + r_2)$, and $\phi_2 = k_2 h_2 - j\alpha_2 h_2$. The parameter α_2 is the attenuation coefficient of the acrylic, which was determined previously by the FEM analysis (Figure 4).

If the attenuation coefficient is set to zero, it is straightforward to demonstrate that the intensity transmission coefficient and the pressure transmission coefficient are related by

$$\mathfrak{I}_{13} = |T_{13}|^2 \frac{r_1}{r_3}. \quad (4)$$

The acoustic intensity in the water and air are related by

$$I_3 = \mathfrak{I}_{13} I_1, \quad (5)$$

and the intensity level (or sound pressure level) in the water is

$$\mathrm{SPL}_3 = 10 \log \frac{I_3}{I_{\mathrm{ref-water}}}, \quad (6)$$

where $I_{\mathrm{ref-water}} = (1\mu Pa)^2/r_3 = 6.5 \times 10^{-19}\ \mathrm{W/m^2}$.

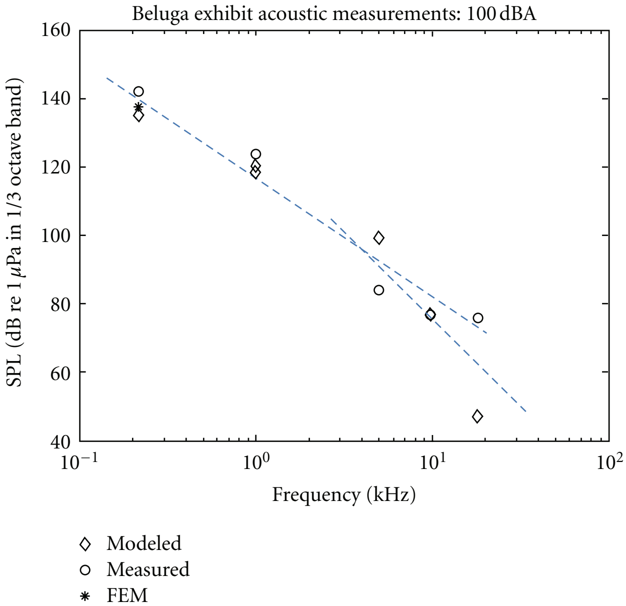


Figure 7: Measured (circles) and modeled (diamonds) SPL in a 1/3 octave band in the aquarium for given music in the ballroom with a SPL of 100 dBA at frequencies 215, 1000, 5000, 10000, and 14000 Hz. Full FEM modeling was carried out for two lowest frequencies (215 Hz and 1000 Hz). The FEM results (asterisks) compare well with the measured values and plane wave modeling. The dashed lines are linear fits to the data/model in two frequency bands.

For the 100 dBA test, the measured and modeled sound pressure levels are shown in Figure 7. Measured (circles) and modeled (diamonds) SPL in a 1/3 octave band in the aquarium for given music in the ballroom with a SPL of 100 dBA at frequencies 215, 1000, 5000, 10000, and 18000 Hz are shown in the figure. Full FEM modeling was carried out for two lowest frequencies (215 Hz and 1000 Hz). The FEM results (asterisks) compare well with the measured values and plane wave modeling. Plane wave modeling predicts the levels well at lower frequencies. At higher frequencies there is disagreement but a full FEM analysis at these frequencies becomes extremely burdensome computationally due to the smaller mesh sizes associated with smaller wavelengths.

During subsequent tests Beluga behavior was monitored for abnormalities such as avoidance, swimming patterns that were varied from what has been described as the "norm" by the aquarium keepers and trainers, vocalization changes from the norm and changes in eating habits. No significant changes in any behaviors were noted other than some avoidance of the window and random swimming during music sound shots at 100 dBA.

4. Conclusions

Music sounds at 90 dBA, 95 dBA, and 100 dBA (levels preferred by disc jockeys contracted at the Georgia Aquarium) were played in the Oceans Ballroom and sampled in the Cold Water Quest exhibit to determine what corresponding sound levels were within the exhibit. Measured underwater noise levels were compared to modeled levels based on finite element analysis and plane wave transmission loss through the acrylic viewing window. Results compared well with the model at low frequencies; however at high frequencies greater attenuation in the acrylic window was measured than was expected and hence lower underwater noise levels were measured. No significant animal behavioral signs were indicated at any of the tested levels. This testing provides at least preliminary data for aquarium husbandry and veterinary staff members to use in the care of these animals in the captive habitat. Testing showed that adjoining room noise of 90 and 95 dBA transmitted through the viewing window has no adverse effect on animals within the exhibit.

Results indicate that the music played in the Oceans Ballroom could clearly be heard in the Cold Water Quest exhibit. In playbacks of the underwater recordings of sound shots, the music was clearly audible to the human ear and the selections were even clearly identifiable at 95 dBA and 100 dBA through the hydrophone.

There is a tendency for entertainers and party attendees to prefer listening to music at intensities that are higher than considered safe for the human ear. When sound is intense enough, whether it be industrial noise or music, irreparable damage can occur to the microscopic hearing nerve receptors. As sound pressure levels increase, any type of sound becomes potentially hazardous to the ear of all animals based upon an interaction of the physical sound pressure levels and the length of time exposed to the sound. As such, when setting safe limits for sound exposure, acousticians and audiologists use the sound level/temporal trade-off values set by the Occupational Safety and Health Administration (OSHA) for industrial noise exposure [9]. OSHA has recommended a scale through which the time a worker can be safely exposed to sound is decreased as the intensity of the sound is increased. The maximum exposure without hearing protection is set at 85 dB sound pressure level (SPL) for an eight hour time period. The length of safe exposure time is cut in half for every 5 dB that the sound is increased.

Based on psychological and physiological data related to marine mammal noise exposure ([2]), it would appear prudent in situations where elevated noise levels are prolonged, to attempt to maintain noise levels within the exhibit (marine-life side of the acrylic window) to under 120 dB re 1 uPa at frequencies of 1 kHz or above. This is coincident with ballroom sound pressure levels of no greater than 95 dBA. This is the same level listed as OSHA's cut-off for safe exposure for a two-hour duration—the typical duration of social events at the Georgia Aquarium.

References

[1] B. L. Southall, A. E. Bowles, W. T. Ellison et al., "Marine mammal noise exposure criteria: initial scientific recommendations," *Aquatic Mammals*, vol. 33, no. 4, article 1, 2007.

[2] J. J. Finneran and C. E. Schlundt, "Frequency-dependent and longitudinal changes in noise-induced hearing loss in a bottlenose dolphin (*Tursiops truncatus*)," *Journal of the Acoustical Society of America*, vol. 128, no. 2, pp. 567–570, 2010.

[3] T. D. Rossing, *The Science of Sound*, Addison-Wesley, New York, NY, USA, 2nd edition, 1990.

[4] Abaqus Unified FEA, http://www.3ds.com/products/simulia/portfolio/abaqus/latest-release/.

[5] V. Tiwari, A. Shukla, and A. Bose, "Acoustic properties of cenosphere reinforced cement and asphalt concrete," *Applied Acoustics*, vol. 65, no. 3, pp. 263–275, 2004.

[6] *Abaqus Analysis User's Manual*, Dassault Systèmes Simulia, Providence, RI, USA, 2011.

[7] L. E. Kinsler, A. R. Frey, A. B. Coppens, and J. V. Sanders, *Fundamentals of Acoustics*, John Wiley & Sons, New York, NY, USA, 1999.

[8] C. S. Clay and H. Medwin, *Acoustical Oceanography: Principles and Applications*, John Wiley & Sons, New York, NY, USA, 1977.

[9] Occupational Safety and Health Administration (OSHA), "Occupational noise exposure: hearing conservation amendment, final rule, 29CFR1910. 95, 48," Federal Register 9738–85, 1983.