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Comparing whales to marine seismic sources: low frequency sound generation by fin whales

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SUMMARY

Whale calls have a similar frequency content to seismic airguns and hence communication between animals is likely to be disrupted by exploration activities. In addition, there is concern that seismic surveys can cause physical harm to whales. Comparing the sound pressure levels of natural whale calls and seismic sources is useful for assessment of the risk that behavioral changes or temporary or permanent physical harm may be caused if the seismic sources are too close. We find that whale calls recorded by tags attached to fin whales have comparable amplitudes to a marine vibroseis observed at a distance of 100 m and a seismic airgun at 1000 m. In addition, we discuss how whales may generate sound through resonance of their lungs in an analogous fashion to how the low frequency content of seismic airgun signals is generated through the resonance of the bubble of air ejected from the gun.

INTRODUCTION

There is significant concern about the impact of anthropogenic noise, a substantial amount of which is due to seismic surveys (Hildebrand, 2005), on marine life. Several studies have documented behavioral changes and temporary or permanent threshold shifts in the hearing of marine mammals as a result of exposure to seismic surveys (e.g., Gordon et al., 2003; Weilgart, 2013).

Fin whales generate a range of down-swept signals (Richardson et al., 1995; Aroyan et al., 2000) including characteristic low frequency pulses around 20 Hz with a duration of approximately one second and higher frequency sounds sweeping from 75 to 40 Hz (Barham, 1973; Watkins, 1981; Stimpert et al., 2015). These signals overlap with the frequency range of seismic surveys and hence environmental regulations have been imposed on marine seismic surveys out of concern that exploration activities may be harmful to whales or disruptive to their communication (Weir and Dolman, 2007; Compton et al., 2008). We compare the signals generated by seismic airguns and marine vibroseis with the observed whale calls.

We note that, despite significant interest in the impact of seismic surveys on whales, low frequency sound generation in whales remains an unsolved problem. Collecting data and performing experimental studies on marine mammals in general, and whales in particular, is fraught with difficulties. Novel studies have been performed on deceased animals in order to investigate physiological properties (e.g., Moore et al., 2011). However, these studies have been limited to smaller animals and the applicability of the results to live animals is debatable. Recent developments in multi-sensor acoustic recording tags (Johnson and Tyack, 2003; Johnson et al., 2009) and the ability to deploy these tags on live animals in the ocean (Goldbogen et al., 2014; Stimpert et al., 2015) have provided high resolution acceleration and acoustic data that can be used to constrain models of sound generation. Previous work has considered the possibility of cavities inside the whale acting as resonators (Barham, 1973; Aroyan et al., 2000). We further investigate this hypothesis and propose two possible mechanisms for sound generation; (1) impulsive excitation or (2) driven oscillation of the lungs. Further physiological work is need to investigate the validity of the two mechanisms.

WHALE CALLS

Multi-sensor acoustic recording tags, or DTAGs (Johnson and Tyack, 2003; Johnson et al., 2009) were attached to fin whales off the coast of southern California during the summer months of 2012 and 2013 (Goldbogen et al., 2014). The tags contain a hydrophone sampling at 240 kHz and a tri-axial accelerometer sampling at 200 Hz. They were attached to the outside of the whales in the vicinity of the lungs using suction cups.

Tags were attached to the whales for several hours and recorded several hundred calls before the tags detached. The calls displayed remarkable consistency over time and between animals. The characteristic call, illustrated in Figure 1, was a down-swept signal from approximately 30 Hz to 15 Hz over a duration of slightly less than one second. The majority of calls were recorded while the whales were at depths of 15-20 m (Stimpert et al., 2015). For more details on the data collection the reader is referred to Goldbogen et al. (2014) and Stimpert et al. (2015).

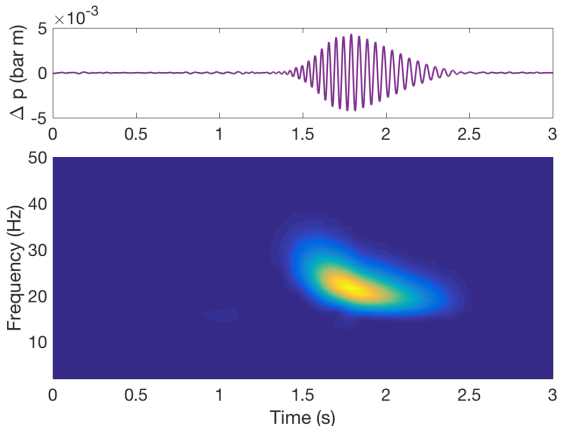


Figure 1: Acoustic data from the DTAG on whale bp12-294a (Goldbogen et al., 2014).

SEISMIC SOURCES

Seismic airguns are the predominant source used in marine seismic surveys. An airgun functions by discharging highly

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pressurized air into the water forming a bubble that expands and contracts. The signature is non-impulsive with a large peak from the initial expansion of the bubble and subsequent smaller peaks from the oscillations of the bubble. Tuned clusters of airguns (e.g., Dragoset, 2000) are used to increase the amplitude of the initial peak and generate destructive interference to reduce the bubble pulses.

Vibroseis works by moving an object up and down to transmit vibrations to the earth or water. Vibroseis is commonly used for land acquisition but the industry is still developing a fully operational marine vibroseis acquisition system. Vibroseis is thought to be less harmful to marine life as, compared to seismic airguns, it inputs a smaller amount of energy into the ocean over a longer period of time (Ogden, 2014).

We examine the pressure perturbation generated by three marine seismic soruces; (1) a marine vibroseis system, (2) a single 500 in^3 airgun and (3) a cluster of three 155 in^3 airguns. The data is from IAGC (1997).

COMPARING WHALE CALLS TO SEISMIC SOURCES

Seismic airguns and marine vibroseis are several orders of magnitude louder than the observed whale calls (Figure 1). We compare the whale calls recorded with the DTAG attached to the body of the whale with the pressure perturbation that would be recorded 100 m away from the marine vibroseis and 1000 m away from the two airgun signatures, assuming $1/r$ geometrical spreading (Figure 2).

We assume that a signal of comparable amplitude to the whale call will be unable to cause physical harm to the animal. This suggests that a whale 100 m away from a marine vibroseis or 1000 m away from a small away of airguns (a greater distance would be needed for a larger array of airguns) will not experience direct physical harm as a result of the seismic source. We note that this is only a rough estimation of how whales are harmed by seismic surveys. It is likely that the duration of exposure is important. Seismic surveys operate continuously for many hours whereas the whale signals are short lived and there are longer intervals between calls than between seismic shots. In addition, seismic airgun signals have a much faster onset than the emergent whale calls.

Seismic sources are likely to disrupt communication between whales. Figure 2 shows that seismic airguns generate substantial energy at the same frequency range as the fin whale calls. The marine vibroseis sweeps from low frequencies to high frequencies with energy peaking around 100 Hz. Therefore, marine vibroseis may be less disruptive to whale communication than seismic airguns as the animals can likely distinguish between their calls and the marine vibroseis signals based on the frequency content. However, in order for marine vibroseis to be commercially viable there is a need for improved low frequency content, which would be more disruptive to whale communication.

We note that the seismic sources are significantly more broadband than the whale call. Much of the high frequency energy

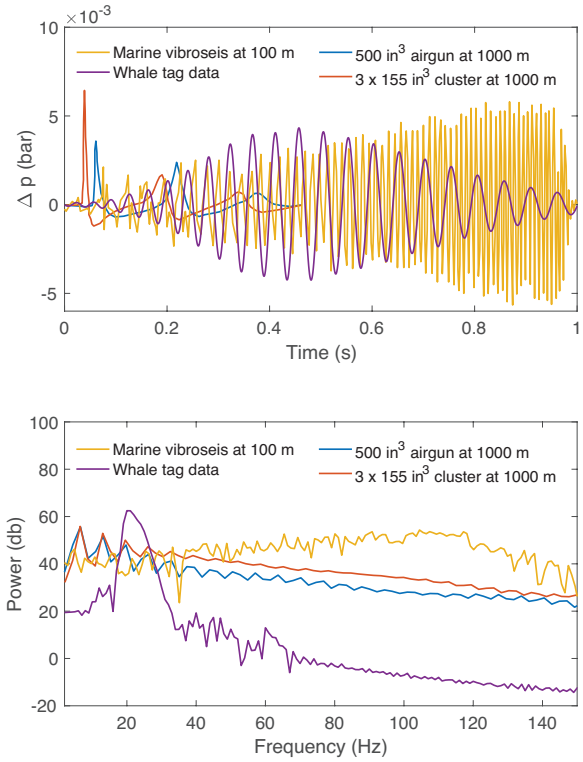


Figure 2: Comparison of whale call and marine seismic sources in the time (top) and frequency (bottom) domain. Marine seismic source data from IAGC (1997).

(above 150 Hz) generated by marine seismic sources is useless for seismic imaging as it is attenuated before it reaches the target or is scattered by the heterogeneous overburden (Watson et al., 2016). Hence, it is likely that marine seismic source designers will look at the lack of high frequencies in the whale calls with envy.

WHALE SOUND GENERATION

The mechanism of low frequency sound generation in whales remains an open question. There has been some previous work investigating the possibility of cavities inside the whale acting as a resonator. Barham (1973) demonstrated that the free oscillation of the lungs could explain the 20 Hz peak frequency observed in fin whale calls whereas Aroyan et al. (2000) argued that a Helmholtz resonator description with air moving between multiple cavities is a more appropriate description. We build upon the idea of Barham (1973) and develop a numerical model of the whale-lung system where the oscillation is forced by the contraction of muscles surrounding the lung.

The modeling approach is similar to that used to describe the oscillations of bubbles produced by seismic airguns (e.g., Ziolkowski, 1970; Brennen, 1995; de Graaf et al., 2014; Watson et al., 2016) where conservation of momentum of the fluid is solved and evaluated on the bubble wall. The whale-lung sys-

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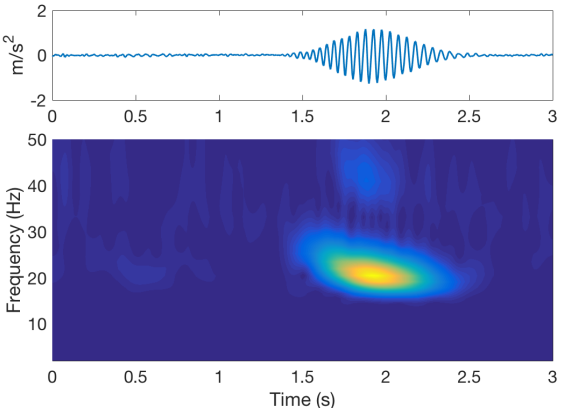


Figure 3: x-component of the accelerometer data from the DTAG on whale bp12-294a (Goldbogen et al., 2014).

tem is modeled as a lung surrounded by a membrane representing the net effect of the whale's body on the dynamics of the lung. We approximate the lungs as a sphere with a volume equal to the total lung capacity. In reality a whale has two roughly elliptical lungs. However, the spherical lung approximation is reasonable because we are only interested in low frequencies ($\sim$ 20 Hz). The radius of the lungs ($\sim$ 1 m) is far smaller than the wavelength at these frequencies of interest ($\sim$ 75 m) and hence the precise shape of the lungs is not important (Aroyan et al., 2000).

There are two major differences between the model presented here and that models used in seismic airgun studies. Firstly, the airgun bubble models describe the oscillation of an air bubble surrounded by water. Here, we are interested in a similar problem but with the air bubble surrounded by the membrane of the lungs as well as the water. This effect is parameterized into a surface tension term. Secondly, we consider that the motion of the lungs may be forced by contraction of muscles around the lungs. This adds a forcing term to the governing equation. The resulting governing equation is a combination of the Rayleigh-Plesset equation (Rayleigh, 1917; Brennen, 1995) with the modified Herring correction for the compressibility of the water (Herring, 1941; Cole, 1948; Vokurka, 1986) and the addition of the driving force:

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{p - p_\infty}{\rho_\infty} + \frac{R\dot{p}}{\rho_\infty c_\infty} - \frac{2S}{\rho_\infty R} - \frac{\sigma}{\rho_\infty}, \qquad (1)$$

where R, $\dot{R} = dR/dt$, and $\ddot{R} = d^2R/dt^2$ are the effective radius, velocity, and acceleration, respectively, p is the spatially uniform pressure inside the lung and ρ_∞, p_∞ and c_∞ are the constant density, ambient pressure, and speed of sound respectively. p_∞ is calculated assuming hydrostatic pressure and using the depth data provided by the tag (18.6 m for the data displayed here). S is the surface tension constant and σ is the potentially time-varying compressive stress from the muscles surrounding the lungs. The pressure is related to the effective radius by the ideal gas law,

$$p = p_0 \left(\frac{R_0}{R} \right)^{3k} \qquad (2)$$

where p_0 and R_0 are the equilibrium pressure and radius, respectively, and k is the polytropic index (equal to 1.4 for an adiabatic process).

The total lung capacity at the surface, V_a, is taken as 1540 L which is the average of the measurements performed by Scholander (1940) and Leith and Lowe (1972) on excised lungs (Piscitelli et al., 2013). The equilibrium pressure inside the lung at depth, p_0, is equal to the hydrostatic pressure plus the contribution from surface tension, $p_\infty + 2S/R_0$. The equilibrium radius is determined by solving,

$$\frac{nQT_0}{\frac{4}{3}\pi R_0^3} = p_\infty + \frac{2S}{R_0} \qquad (3)$$

where T_0 is the body temperature of the whale, n is the number of moles of air inside the lungs and Q is the universal gas constant. The number of moles is determined from evaluating the ideal gas law at the surface, $p_a V_a = nQT_a$, where subscript a indicates atmospheric values.

Impulsive Excitation

A possible mechanism for sound generation in whales is an impulsive excitation of the lungs followed by decay with oscillations at the resonant frequency of the lungs, which is approximately 20 Hz. The measured displacements are extremely small (sub millimeter) compared to the radius of the lungs (several tens of centimeters). Therefore, the governing equation (equation 1) can be linearized around R_0 and p_0 to give,

$$R_0\Delta\ddot{R} + \frac{3kp_0}{\rho_\infty c_\infty}\Delta\dot{R} + \left(\frac{3kp_0}{\rho_\infty R_0} - \frac{2S}{\rho_\infty R_0^2} \right)\Delta R = -\frac{\sigma}{\rho_\infty}. \qquad (4)$$

By comparison with the canonical equation for a damped harmonic oscillator, the characteristic decay time of the oscillations is,

$$\tau = \frac{2R_0}{3k}\frac{\rho_\infty c_\infty}{p_0}. \qquad (5)$$

For the model parameters of interest, $\tau \approx 0.4$ s which is of the same order of magnitude as the duration of the observations, suggesting that an impulsive force and subsequent ringing could be the mechanism for fin whale sound generation.

The impulsive excitation model does not explain the emergent onset or the changing frequency throughout the call. Nonetheless, we note that the similarity between decay time and resonant frequency of a harmonic oscillator and that of the observations is an intriguing coincidence that warrants further investigation. We speculate that the emergent onset could be due to air flowing across a vibrating membrane between cavities while the resonant frequency of the lungs depends on the radius and hence would decrease with expansion of the lungs,

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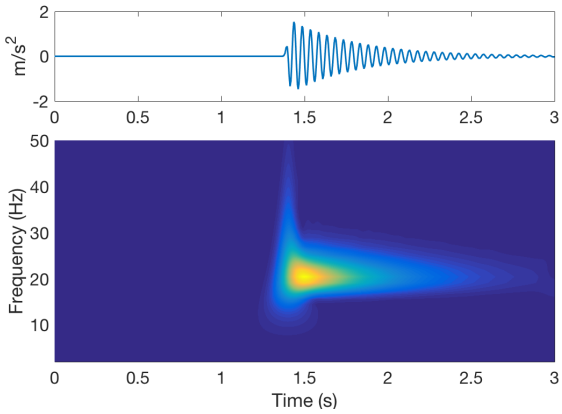


Figure 4: Simulated acceleration of whale lung for impulsive excitation. The impulsive excitation is approximated as a gaussian with a mean of 1.4 s and a standard deviation of 0.009 s.

such as from mass flow into the lungs or muscular expansion. Further work is needed to investigate the validity of these mechanisms.

Driven Oscillation

An alternative sound generation mechanism is driven oscillation of the lungs through a time-varying compressive stress. The compressive stress is calculated from the data by taking the Fourier transform of equation 4 and solving for σ,

$$\left(-\omega^2\rho_\infty R_0 - \frac{2S}{R_0^2} + \frac{3kp_0}{R_0} + i\omega\frac{3kp_0}{c_\infty}\right)\Delta\hat{R} = \frac{\hat{\sigma}}{\rho_\infty} \quad (6)$$

where ω is the angular frequency. The surface tension parameter, S, is unknown. We assume that that whales have evolved to generate sound efficiently and hence the value of S is chosen to minimize the amplitudes of the compressive stress, $\sum\sigma^2$.

The driven oscillation model is able to match the observations exactly as there are an infinite number of free parameters. Further physiological work is needed to determine if there are muscles in the whale capable of driving the oscillations of the lungs at $\sim$20 Hz.

CONCLUSION

We present high resolution hydrophone and accelerometer data from tags attached to fin whales in the hope that those in the seismic industry may be able to utilize this data to better quantify the impact of seismic surveys on whales.

The pressure perturbation generated by seismic airguns and marine vibroseis are compared to fin whale calls. The seismic signals are of a similar frequency range to fin whale calls and are several orders of magnitude louder. It is noted that we are examining small seismic sources and are likely underestimating the amplitude of signals produced by conventional surveys that often employ up to thirty airguns. However, the tag data

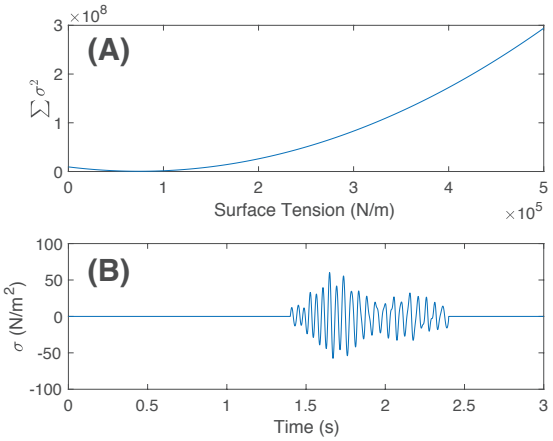


Figure 5: (A) Sum of the squared amplitudes of the compressive stress required to force the lung oscillations to match the data for various values of the surface tension parameter, S. The optimal value of S is 7.5×10^4 N/m. Future work should compare this estimation to the mechanical properties of whale tissues. (B) Compressive stress as a function of time inverted from the data for $S = 7.5\times10^4$ N/m.

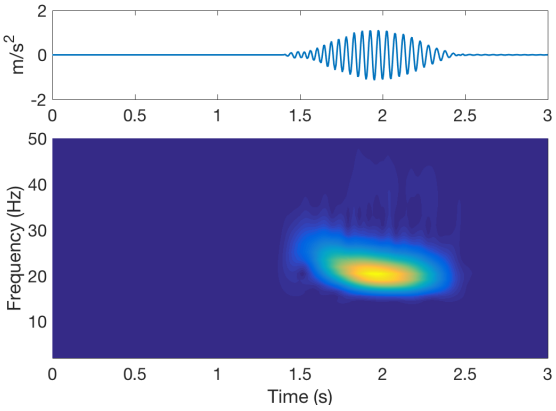


Figure 6: Simulated acceleration of whale lung for the time-varying compressive stress shown in Figure 5.

does not necessarily represent the loudest calls that fin whales can generate.

We speculate on possible mechanisms for generation of the whale calls. Further work needs to be done to link the mathematical model to whale biology. However, studies on smaller marine animals and on deceased whales have limited applicability to the physiology of live whales while performing measurements on live whales is extremely challenging. Therefore, mathematical models, such as the work presented here, can provide important insight and help to guide future physiological studies.

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