OBSERVATIONS AND EXPLANATION OF LOW FREQUENCY CLICKS IN BLUE WHALE CALLS

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ABSTRACT: A brief study has been conducted on the low frequency "clicks" and tones observed in calls recorded in recent years from Blue Whale aggregations at locations off the Rottnest trench. As has been suggested previously, it is concluded that the 20 Hz clicks most likely are the self-excitation of the bubble resonance of the gas within the lungs by the whale. This is probable, as the click waveform has the appearance of the decay of a resonance, and as there are no other conceivable mechanisms which might give rise to a resonance within a whale body at 20 Hz. This is explained with recourse to bubble physics, which are extended to include a treatment of both spherical and elongated bubbles, and to considerations of the effects of various depths at which a whale might call. The amplitude of the bubble oscillations required to generate the observed signal levels is shown to be surprisingly large, and appears to be close to the theoretical maximum for a resonant bubble driven by any means.

1 INTRODUCTION

Recordings of calls from Blue Whales (*Balaenoptera musculus*) are known to include low frequency components which may be tonal or impulsive "clicks"[1-5]. The signals are noteworthy for the high levels achieved (up to 190 dB re (1 μPa)^2 @ 1 m) at a low frequency range (centred about 20 Hz[1-5]). These features have been observed in Blue Whale calls recorded in recent years at locations off the Perth Canyon[5]. These observations are of interest to the Royal Australian Navy (RAN) as, firstly, causes of ocean ambient noise need be understood in relation to interference to the operation of passive sonar systems, and, secondly, it is desirable for RAN vessels to be aware of the proximity of Blue Whales and other marine mammals so that suitable separation distances may be achieved. This paper reports a brief study of low frequency 'clicks' observed in Blue Whale calls and investigates the mechanism by which these signals are generated. It has been suggested previously[2], that an air-filled resonator is likely to be the source and it is concluded here that the 20 Hz clicks most likely are the self-excitation of the ensemble gas bubble within the lungs by the whale. This is explained with recourse to bubble physics, which are extended to include a treatment of both spherical and elongated bubbles, and to considerations of the effects of various depths at which a whale might call. As is shown, the amplitude of the bubble oscillations required to generate the observed signal levels is surprisingly large.

1.1 MARITIME FAUNA INTEREST

At present, there is an increasing interest within the Australian Defence Force (ADF), and within defence forces internationally, in the welfare of the maritime environment. In particular, it is a desire of the ADF that it has the capability to conduct its maritime operations and maintain its related equipment in an environmentally responsible manner both within Australian waters and worldwide. The Environmental Protection and Biodiversity Conservation (EPBC) Act 1999 came into effect on 16 July 2000. This Act places requirements on the Department of Defence in regard to actions which are likely to have a significant impact on the environment anywhere in the world. For this reason, the Directorate of Environmental Stewardship has a requirement that relevant phenomena are investigated and essential principles are established. In the area of Defence maritime operations, relevant issues include the radiation of acoustic energy, particularly in regard to sensor and communication systems, and all relevant issues affecting the knowledge of the seasonal and diurnal distribution of marine fauna, and the susceptibility of marine fauna. Maritime Operations Division (MOD) is providing support to the ADF by providing scientific guidance and advice in these areas.

With reference to RAN activity within the West Australian Exercise Area (WAXA), the presence of Blue whales and Pygmy Blue whales (*Balaenoptera musculus brevicauda*) is of strong interest as the species are listed as "endangered" under the EPBC. MOD is providing scientific support to the Blue whale study funded by the Defence Materiel Organisation[6].

2 OBSERVATIONS OF BLUE WHALE CLICKS

A considerable body of knowledge exists concerning Blue Whale vocalisations. For example, Thode et al[4] report tonals at harmonically-related frequencies of 16 Hz (Source Level (*SL*) up to about 175 dB line level re (1 µPa)^2 at 1 m), 32 Hz (*SL* up to about 168 dB line level), 50 Hz (*SL* up to about 170 dB line level) and 67 Hz (*SL* up to about 160 dB line level). Thode et al suggest that an air-bubble type resonator within the animal may be the cause of the observed sounds, but suggest that the observed variation of frequency with depth of the animal (frequency proportional to depth squared) does not closely match the expectation for a bubble which is allowed to collapse with depth (frequency linearly proportional to depth).

Aburto et al[3] report tonals at 17 Hz with *SL* in the range 195 dB line level re (1 µPa)^2. Like Thode et al, Aburto et al report that the 17 Hz tonals are accompanied by higher harmonics of lower amplitude. Aburto et al report whale depth as nominally 30 m.

McCauley et al[5] have observed signals similar to those reported by Aburto et al and Thode et al, as shown in Figure 1. These show a tonal of extended duration at about 20 Hz, with higher harmonics at lower amplitude. McCauley et al have also observed "click" waveforms which consist of the decay of a tonal at about 20 Hz. An example of three consecutive 'clicks' from three different sources, is shown in Figure 2. The frequency spectra of these 'clicks' are shown on Figure 3. As the decay has a duration of about 0.75 seconds, and as the frequency is about 20 Hz, the quality factor *Q* for the oscillation is about 15.

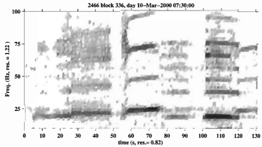

Figure 1: Spectrogram of Blue Whale call observed in the Perth Canyon. The 'call' is made up of three units, the first over 5–48 s, the second over 55–77 s and the third over 100–120 s. Distant calling whales are present in the background.

All of the observations reported above are consistent with the existence of a fundamental bubble resonance existing within the whale and with this resonance being intentionally excited by the animal to create a strong signal. The time series shown in Figure 2 are indicative of resonant decay of an oscillator, and the spectrogram shown in Figure 1 is indicative of non-linear radiation at a fundamental and harmonics. It is suggested that the harmonics of the base tone near 20 Hz result from the bubble resonance being driven to high amplitude levels.

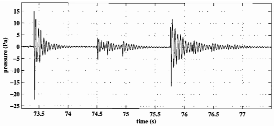

Figure 2: Time series of Blue Whale 'clicks' observed in the Perth Canyon. Using a variant of a method described by Cato (1998) for utilising multipath signals, the first 'click' was estimated to come from an animal at 2160 m horizontal range from the receiver and 260 m depth and the third signal from an animal at 805 m range and 200 m depth.

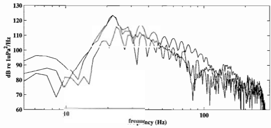

Figure 3: Power spectra of the three 'clicks' shown in Figure 2.

A bubble resonance is the most likely explanation for these observations as there are no other conceivable mechanisms which might give rise to a resonance within a whale body at about 20 Hz. At this frequency the wavelength is 75 m. With an average Blue Whale body length of about 25 m, and diameter no greater than about 5 m, a distributed impedance resonant device is unlikely and a lumped element device almost certainly is the cause. The latter may be formed by a summation of the air within the lungs of the whale, acting as a compliance, and the surrounding body tissue and/or water in the ocean as an inertance.

3 BUBBLE PHYSICS

A gas bubble contained underwater will have a single mode of resonance at a frequency for which the inertance of the effective surrounding mass (of whale tissue and water) is matched to the compliance of the gas within the bubble. For spherical bubbles in water, the frequency of resonance f_r of the air bubble is given by

$$f_r = \frac{1}{2\pi r_s}\sqrt{\frac{3\gamma P}{\rho_w}}. \qquad (1)$$

where r_s radius of gas bubble, m

γ ratio of specific heats for gas in bubble ($\gamma = 1.4$ for air)

P hydrostatic pressure, Pa

ρ_w density of water/body tissue surrounding the bubble, kg m^{-3}

This is the same as the equation in Urick, page 251[7], equations (7.55) and (10.14) of Kinsler et al[8], and corresponds with the expression given by Sims[9]. Based on equation (1), combinations of resonant frequency, bubble radius and operating depth are shown in Table 1.

Table 1: Diameter of a spherical air-filled bubble for resonance frequency and operating depth (shading indicates source at shallow depth, depth in wavelengths, λ)

Operating depth d (m)	resonance frequency f_r (Hz) 10	20	50	100	200	500
1	0.678 m 0.0067λ	0.338 m 0.013λ	0.136 m 0.033λ	0.068 m 0.067λ	0.034 m 0.133λ	0.0136 m
2	0.708 m 0.013λ	0.354 m 0.027λ	0.142 m 0.067λ	0.070 m 0.133λ	0.036 m	0.0142 m
5	0.792 m 0.033λ	0.396 m 0.067λ	0.158 m 0.167λ	0.078 m	0.040 m	0.0158 m
10	0.914 m 0.067λ	0.456 m 0.133λ	0.182 m	0.092 m	0.046 m	0.0182 m
18	1.080 m 0.120λ	0.540 m	0.216 m	0.108 m	0.054 m	0.022 m
30	1.292 m 0.20λ	0.646 m	0.258 m	0.1292 m	0.064 m	0.026 m
50	1.582 m	0.790 m	0.316 m	0.158 m	0.078 m	0.032 m
80	1.938 m	0.968 m	0.388 m	0.194 m	0.096 m	0.038 m
120	2.328 m	1.164 m	0.466 m	0.232 m	0.116 m	0.046 m

The shading in Table 1 identifies bubbles which are located at a depth less than ¼λ. This is significant as the resistive part of the radiation impedance, for a constant volume velocity source, has a depth dependence, and hence the maximum possible radiated sound power will also be depth dependent (eg. Section 4.1.4 of Brekhovskikh and Lysanov[10]). The radiation of sound from a small source of constant volume velocity, at shallow depth, d, may be considered as from a dipole composed of two small sources each of the same strength. Here[10], the acoustic pressure release at the ocean surface gives rise to a reflection which may be considered to come from an anti-phased image source. The ratio, x, of the sound power radiated into the water by the dipole source, to the sound power radiated by a source at infinite depth may be shown to be (eg. equation 4.1.24 of Brekhovskikh and Lysanov[10])

$$x = 1 - \frac{\sin(2k\,d)}{2k\,d} \approx \frac{8\pi^2}{3}\left(\frac{d}{\lambda}\right)^2 \quad \text{for sources very close to the surface.} \qquad (2)$$

where k is the acoustic wavenumber (radian frequency/speed of sound in seawater, in m^{-1}).

For non-spherical bubbles, different but similar expressions for resonance frequency will apply. For example, the frequency of resonance f_r for a cylindrical air bubble of radius r_c m and long length, contained within water/tissue was derived by the lead author as

$$f_r = \frac{1}{2\pi\,r_c}\sqrt{\frac{2\gamma\,P}{\rho_w\left(-\ln[k r_c]\right)}} \approx \frac{1}{2\pi\,r_c}\sqrt{\frac{2\gamma\,P}{5\rho_w}}. \qquad (3)$$

This was obtained by, first, deriving the radiation impedance of a cylinder from cylindrical radiation functions and, then, finding the frequency at which the inductive impedance component, per unit length of cylinder, cancelled the capacitive impedance component of the gas in the cylinder. Equation (3) is similar to a generalised expression derived by Zhang[11].

At a given depth, it may be surmised that an animal may exhibit some control over the shape of the ensemble bubble, and thus vary the resonance frequency. For example, it is conceivable that an ellipsoidal bubble might be formed – the expression for a cylindrical bubble then representing an extreme case of elongation. If such an elongation occurs for a given mass of gas, the cylindrical radius r_c must of necessity be much less than the radius of the sphere r_s. In the limit of a very long cylinder being formed there will then be an increase in the resonance frequency of the bubble.

3.1 DEPTH DEPENDENCE

The data shown in Table 1 do not relate to a bubble formed by a single breath taken at the ocean surface. We may arrive at an expression for the variation of resonance frequency f_r with depth d for a given mass of air m taken at the surface by substituting for spherical bubble radius r_s in equation (1) and for cylindrical bubble radius r_c in equation (3) using the perfect gas relation $PV = mRT$[12]. If we then assume that a given air mass will be compressed isothermally (rather than adiabatically) as a whale varies its depth (as the air within cavities such as the lungs is in contact with body tissue which itself will not vary greatly in temperature), we may arrive at expressions for resonance frequency at depth f_r in terms of resonance frequency at the surface f_{rs}. For a spherical bubble we have

$$f_r / f_{rs} = \left[P_a + \rho_w\,g\,d / P_a\right]^{\frac{5}{6}} \approx \left[1.0 + d/10\right]^{\frac{5}{6}}. \qquad (4)$$

For a cylindrical bubble,

$$f_r / f_{rs} = P_a + \rho_w\,g\,d / P_a \approx 1.0 + d/10. \qquad (5)$$

where P_a is atmospheric pressure (Pa) and g is acceleration due to gravity (m s^{-2}). Equation (4) has been used to generate the data in Table 2.

Table 2: Variation of resonance frequency for spherical air-filled bubble of fixed mass lowered in depth, with isothermal compression (shading indicates source at shallow depth)

Operating depth d (m)	resonance frequency near surface f_{rs} (Hz) 5	10	20	50	100	200
1	5.4 Hz	10.8 Hz	22 Hz	54 Hz	108 Hz	216 Hz
2	5.8 Hz	11.6 Hz	23 Hz	58 Hz	116 Hz	232 Hz
5	7.0 Hz	14.0 Hz	28 Hz	70 Hz	140 Hz	280 Hz
10	8.9 Hz	17.8 Hz	36 Hz	89 Hz	178 Hz	356 Hz
18	11.8 Hz	23.5 Hz	47 Hz	117 Hz	235 Hz	470 Hz
30	15.9 Hz	31.7 Hz	63 Hz	158 Hz	317 Hz	634 Hz
50	22 Hz	44.5 Hz	89 Hz	222 Hz	445 Hz	890 Hz
80	31 Hz	62.4 Hz	125 Hz	312 Hz	624 Hz	1248 Hz
120	42 Hz	85 Hz	170 Hz	425 Hz	850 Hz	1700 Hz

From Table 2, it is clear that quite a variation in resonance frequency is expected across the range of depth values at which whales were reported to be present whilst vocalising at about 20 Hz. In particular, a rise in resonance frequency of a factor of about 1.8 is expected in going from 10m depth to 30m depth.

3.2 BEHAVIOUR OF BUBBLE AT RESONANCE

A universal measure of the performance of a resonant system is the quality factor, Q, (e.g. section 1.10 of Kinsler et al[8]). This is a measure of the damping in the system. Q defines the sharpness of a resonance in relation to the frequency of excitation. It may be shown that it is the same as the amplification provided by the resonator (Kinsler et al show this for the case of a Helmholtz resonator). Further, the greater the amplification, the narrower the frequency band over which the resonance is encountered. The quality factor may be defined as[8]

$$Q = \frac{\omega_r}{\omega_2 - \omega_1} = \frac{f_r}{\Delta f} = \tfrac{1}{2}\,\omega_r \tau = 1/\eta_a \qquad (6)$$

where Q quality factor
ω_r resonant frequency, radians s^{-1}
ω_2, ω_1 frequencies above and below ω_r, respectively, for which radiated power is half the value at resonance (that is, - 3 dB), radians s^{-1}
Δf 3 dB bandwidth, Hz
τ relaxation time, s
η_a acoustic radiation loss factor (for example, equation (7.17) in Bies and Hansen[13])

In equation (6), the relaxation time τ is the time for oscillations to decay in amplitude by $1/e$, following the cessation of excitation. The relaxation time τ, in seconds, then follows as

$$\tau = 2Q/\omega_r = Q/(\pi f_r) \qquad (7)$$

The oscillations decay exponentially with time. There are about Q/π oscillations of the decaying resonator within time τ. Thus, there are Q oscillations within time $\pi\tau$, after which the amplitude of oscillation has decayed by the factor $1/e^{\pi} \cong 0.043$. So, a rule-of-thumb approximation is that there are Q oscillations, lasting $\pi\tau$ or Q/f seconds, in the decay of the tonal pulse. The waveforms shown for the 20 Hz "clicks" in Figure 2 then indicate a value of Q of about 15.

The appropriateness of this measured value Q of 15 (same as 23 dB amplification) may be seen from the data shown in Table 3. These data show the amplification achieved in the case with no damping caused by the bubble housing. For an ideal spherical bubble, the damping or quality factor $Q = c_w\sqrt{\rho_w/(3\gamma P)}$, where $\gamma \cong 1.4$ is the ratio of specific heats for the gas within the bubble, c_w is the speed of sound in the water. The values of Q shown in Table 3 are slightly less than this, as they have been prepared by taking into account extra damping caused by heat transfer at bubble walls, as discussed by Devin[14]. Note that no account has been taken here of the reduction in radiative damping for sources at shallow depths.

The values shown in Table 3 indicate a variation in amplification with, mainly, depth with the amplification ranging from 36 dB near the surface, to 26 dB at 120 m depth. Significant damping is to be expected due to body tissue and internal lung tissue, so the lower observed value for Q of 15 (23 dB) is reasonable.

Table 3: System amplification factor Q for spherical air-filled bubble of indicated resonance frequency and deployment depth (shading indicates source at shallow depth)

operating depth d (m)	resonance frequency f_r (Hz) 10	20	50	100	200	500
1	64 (36 dB)	62 (36 dB)	58 (35 dB)	55 (35 dB)	50 (34 dB)	43 (33 dB)
2	62 (36 dB)	60 (36 dB)	56 (35 dB)	53 (34 dB)	49 (34 dB)	42 (32 dB)
5	56 (35 dB)	54 (35 dB)	51 (34 dB)	48 (34 dB)	45 (33 dB)	39 (32 dB)
10	49 (34 dB)	48 (34 dB)	46 (33 dB)	43 (33 dB)	40 (32 dB)	35 (31 dB)
18	42 (32 dB)	41 (32 dB)	39 (32 dB)	37 (31 dB)	35 (31 dB)	32 (31 dB)
30	35 (31 dB)	35 (31 dB)	33 (30 dB)	32 (30 dB)	30 (30 dB)	28 (29 dB)
50	29 (29 dB)	29 (29 dB)	28 (29 dB)	27 (29 dB)	26 (28 dB)	24 (27 dB)
80	25 (28 dB)	25 (28 dB)	24 (28 dB)	24 (27 dB)	23 (27 dB)	21 (27 dB)
120	20 (26 dB)	20 (26 dB)	19 (26 dB)	19 (26 dB)	18 (25 dB)	17 (25 dB)

3.3 FEASIBLE SOURCE LEVELS OF 20 HZ TONE

The maximum source level (SL) which an animal may achieve by exciting the resonance of its body and lung ensemble gas may be estimated by considering the physical limits to oscillation.

A practical limit is reached when the amplitude of oscillation is so large that the acoustic pressure p' and condensation s' of the air, the latter being the fractional density change, cease to be linearly related by the adiabatic bulk modulus (see, for example, chapter 5 of Kinsler et al[8]). That is, density changes caused by the acoustic oscillations must be small in relation to the mean density of air, that is, s' must be small. In practice, large amplitudes of condensation will give rise to non-harmonic gas oscillations and additional damping (reduced amplification Q). The limit may be assumed to be a condensation Δs, numerically equal to the maximum relative density change. A practical limit may be assumed $\Delta s \cong 0.2$ (a peak level, not rms.)

The maximum possible source levels, as dB re (1 μPa)^2 (line) for resonant frequencies and bubble diameters given in Table 1, are shown in Table 4. Note that the SL for shallow sources as shown in Table 4 has been reduced in accordance with a sound power reduction as given by equation (2). For non-shallow sources, the mean-square SL values were calculated based on the following expression for peak radiated pressure level, p, at 1 m:

$$p = \gamma \Delta s \, r_s \rho_w g \, (d + 10) \text{ Pa at 1 m} \qquad (8)$$

This expression is effectively the same as equation (4.47) of Ross[15].

The source levels indicated in Table 4 are the maximum possible, acoustically, let alone physiologically. Note that some definitions of SL may ascribe higher values to sources at shallow depth, as transmission modelling which accounts for Lloyd mirror, and is based on such values, will result in the same radiated power. It is remarkable indeed that a source level of 195 dB has been reported by Aburto et al for animals at about 30 m depth. Based on the 2nd column within Table 4 this is only about 10 dB less than the estimated maximum. As such, the corresponding condensation Δs ~ 0.06, corresponding pressure amplitude within the bubble and in the

Table 4: Maximum possible SL for driven spherical air-filled bubble of indicated resonance frequency and deployment depth (shading indicates source at shallow depth)

operating depth d (m)	resonance frequency f_r (Hz) 10	20	50	100	200	500
1	168 dB	168 dB	168 dB	168 dB	168 dB	163 dB
2	175 dB	175 dB	175 dB	175 dB	173 dB	165 dB
5	185 dB	185 dB	185 dB	181 dB	176 dB	167 dB
10	195 dB	195 dB	191 dB	185 dB	179 dB	171 dB
18	205 dB	204 dB	196 dB	190 dB	184 dB	176 dB
30	214 dB	208 dB	200 dB	194 dB	188 dB	180 dB
50	220 dB	213 dB	206 dB	200 dB	193 dB	186 dB
80	225 dB	219 dB	211 dB	205 dB	199 dB	191 dB
120	229 dB	224 dB	216 dB	210 dB	204 dB	196 dB

surrounding tissue within the whale is $|p'| = \gamma \Delta s P \approx 34$ kPa, that is 210 dB.

3.4 INSONIFICATION OF BUBBLE BY WHALE

The observations of clicks indicates a sudden displacement of a resonant system and subsequent decay. However, for tonals of duration 5 – 10 seconds or so, it is feasible that a whale may provide a continual excitation and allow the quality factor to build the signal to maximum level. As such, there will be a finite time required for the bubble to respond fully – a build-up time. This "resonance build-up time" T_b follows from equation (7) as

$$T_b = Q/f_r \tag{9}$$

where T_b is time for CW response of bubble to build up to 96% of steady state amplitude, following commencement excitation, in seconds. Values of pulse build-up time are shown in Table 5 for different values of Q and resonance frequency. For the observed $Q \approx 15$, 0.75 seconds build up time is required at 20 Hz.

Table 5: Resonance build-up time, T_b, seconds

quality factor, Q	resonance frequency f_r, Hz 5	10	20	50	100
3	0.6 s	0.3 s	0.15 s	0.06 s	0.03 s
5	1.0 s	0.5 s	0.25 s	0.10 s	0.05 s
10	2.0 s	1.0 s	0.5 s	0.2 s	0.1 s
15	3.0 s	1.5 s	0.75 s	0.30 s	0.15 s
20	4.0 s	2.0 s	1.0 s	0.4 s	0.20 s

It is conceivable that a whale might excite its lung air bubble using a frequency sweep (frequency modulation (FM)). This FM sweep must be at rate, in Hz/s, which is sufficiently slow to permit the bubble to reach maximum amplitude of oscillation. In particular, the frequency must not sweep more than about the 3 dB bandwidth within the build-up time T_b.

The 3 dB bandwidth is given by $\Delta f = f_r/Q$. The time for the resonance to build up is Q/f_r. Thus, the tone must sweep more slowly than a rate of about $(f_r/Q)^2$ Hz/s. These rates are shown in Table 6 for combinations of Q and resonance frequency in Table 5. For example, at 20 Hz, with $Q = 15$, an animal must sweep more slowly than 1.8 Hz/s.

Table 6: Maximum sweep rate for FM insonification of target, $(f_r/Q)^2$ Hz/s

quality factor, Q	resonance frequency f_r, Hz 5	10	20	50	100
3	2.8 Hz/s	11 Hz/s	44 Hz/s	280 Hz/s	1100 Hz/s
5	1.0 Hz/s	4 Hz/s	16 Hz/s	100 Hz/s	400 Hz/s
10	0.25 Hz/s	1.0 Hz/s	4 Hz/s	25 Hz/s	100 Hz/s
15	0.11 Hz/s	0.44 Hz/s	1.8 Hz/s	11 Hz/s	44 Hz/s
20	0.06 Hz/s	0.25 Hz/s	1.0 Hz/s	6.2 Hz/s	25 Hz/s

4 AIR CAVITIES WITHIN WHALES

The largest air cavity in a whale is the lung, and although no dimensions appear to be available for a blue whale, Slijper[16] reports that the lungs of a 23 m long fin whale have maximum capacity of 2000 litres, equivalent to 1 m^3 per lung. Fin whales are similar to blue whales in morphology and the size of this specimen is similar to the range reported for pygmy blue whales[17] of 21-22 m. It seems reasonable, therefore, to use the dimensions of a fin whale lung as representative of that of a pygmy blue whale. A spherical air cavity of 1 m^3 diameter would have a radius of 0.62 m. Slijper's diagram of the fin whale lung, however, shows it to be closer to a tapered cylindrical in shape than to a sphere, a representative diameter being roughly $^1/_4$ of the length of the cylinder. Such a cylinder of volume 1 m^3 would have a radius of 0.34 m. The resonant frequencies for these dimensions for various depths can be calculated from equations (1) and (3). For the sphere of 1 m^3, the resonant frequency is 7.4 Hz at 10 m depth and 10.5 Hz at 30 m depth. For the cylinder it is 5 Hz at 10 m depth and 7.0 Hz at 30 m. These simple calculations give estimates that are of the right order of magnitude for the lowest frequencies of sounds observed from blue and fin whales. A more realistic model would need to take account of effects of the internal tissues of the lung. In addition, the reduction in volume of the lung can be expected to be more than calculated by equations (4) and (5) as the increased pressure would cause some of the air to be dissolved in tissues and fluids of the body, giving higher resonant frequencies than calculated above.

5 CONCLUSIONS

By examining some data recordings of Blue Whale vocalisations, the postulation of a bubble resonance phenomenon being exploited by animals to produce low frequency clicks and tones has been revisited. By examining the relevant physics of underwater resonant bubbles, many aspects of the generation of the observed signals have been examined. It is concluded that a resonance of the ensemble of gas within a whale's lungs and the surrounding body tissue and seawater is, in fact, the most probable cause of the very high amplitude, very low frequency sounds which have been observed. Estimated resonant frequencies and amplitudes are of the right order of magnitude. It does appear that Blue Whales may produce a sound of such intensity that it is within about 10 dB of a postulated maximum for a resonant bubble excited by any means. It would also appear that the process of driving a low frequency fundamental near 20 Hz generates significant, but lesser, sound intensity at harmonics of the fundamental.

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