The University of British Columbia

Physics 438 Assignment # 6: ACOUSTICS

SOLUTIONS:

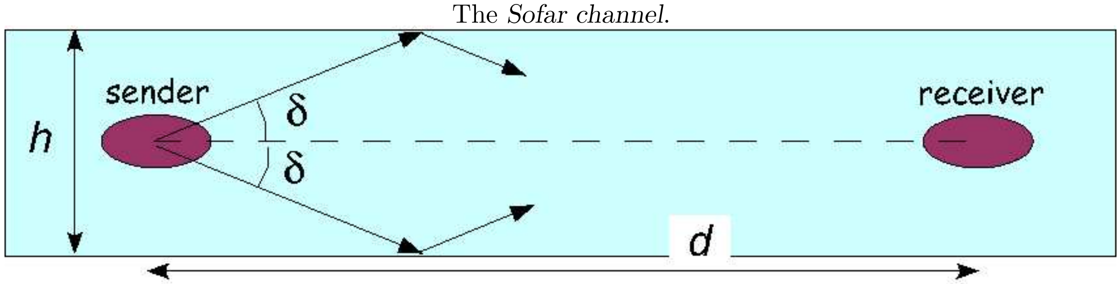
Thu. 15 Mar. 2007 — finish by **Thu. 29 Mar.**

1. SHARK ATTACK: A diver makes a deep dive wearing a facemask that covers eyes, nose and mouth. At 35 m depth he suddenly notices a shark cruising towards him; he lets out a short shriek at the top of his voice with an intensity of 95 dB. What is the intensity of his voice transmitted into in the water just outside his face mask? (Neglect the acoustic impedance of the lens of his face mask; just consider the transition of sound from the air to the water).[1] **ANSWER**: A diver at a depth of 35 m will encounter a pressure of 4.5 atm (1 extra atm per 10 m depth). That means the pressure is 4.5 times higher than at sea level. From the ideal gas law $pV = nRT$ we see that (for constant temperature T and volume V) the molar concentration $n/V = p/RT$ is proportional to the pressure p, and so is the density ρ. Since the pressure is increased by a factor of 4.5, the density is increased by a factor of 4.5 as well. Since the impedance Z is defined as $Z = \rho v$ (where v is the velocity of sound in air, which is approximately independent of pressure), this means that the impedance of air at 35 m depth is likewise increased by a factor of 4.5. From $I_{\text{trans}} = 4.5 \times (Z_{\text{a}}/Z_{\text{w}}) \times I_{\text{a}}$ we get $I_{\text{trans}} = 7 \times 10^{-7}$ W/m^2 which corresponds to $\boxed{\text{55 dB}}$.

2. LONG DISTANCE TALK OF WHALES:

(*a*) Determine the critical angle of total internal reflection for sound waves in the *Sofar channel*. What is the beam angle 2δ (critical angle of TIR) into which an animal should emit its voice in order to match the *Sofar channel* sound wave guide?

The *Sofar channel*.



(*b*) Suppose a whale in the *Sofar channel* talks to a friend 2000 km away. The animal emits a sound signal of power $P = 1.2$ W and frequency $f = 10$ Hz into a conical beam with the half angle δ calculated above. What is the *intensity* of this sound wave at a distance $d = 2000$ km? Express your result as a sound level β [in dB] using $I_{\text{ref}} = 10^{-12}$ W/m^2. With reference to Fig. **7.16** on p. 254 of the textbook, assume $h = 800$ m. Consider both the spreading of the wave with distance and the attenuation due to absorption. **ANSWER**: A full solution is on pp. 259-260 of the textbook.

(*c*) Determine the displacement amplitude s_0 and the pressure amplitude Δp_0 of the sound signal at the distance $d = 2000$ km. **ANSWER**: A full solution is on pp. 259-260 of the textbook.

(*d*) How long does it take for the message to travel from the sender to the receiver? **ANSWER**: A full solution is on pp. 259-260 of the textbook.

3. VOICES:

(*a*) Assume that elephants and mice roar like organ pipes, closed at one end. What is the lowest frequency of their voices? (*Hint:* You must guess or find from physiology texts the length of their "trumpets".) **ANSWER**: For a pipe of length L, closed at one end and open at the other, the n^{th} "mode" has $lambda_n = 4L/(2n-1)$ and $f_n = v/\lambda = (2n-1)(356 \text{ m/s})/(4L)$, where we assume moist air at 37°C. The lowest frequency mode has $n = 1$. The "organ pipe" of a typical human is taken to be about 17 cm, or about

[1] *Hint:* you must first find the pressure and density at that depth. Look at sections **9.2**, **9.2.1** and **9.2.9** in the textbook.

20% of the length of the "trunk" of the body. Thus if the mouse's body (not counting legs or head) is about 5 cm then we would expect $L_{\rm mouse} \approx 0.01$ m, giving $f_1(\text{mouse}) \approx 356/0.04$ or $\boxed{f_1(\text{mouse}) \approx 8900 \text{ Hz}}$. A bigger mouse should have a lower voice. The elephant is another story, since its "trumpet" may or may not include the long trunk. If it does *not* include the trunk, then a 4 m long elephant may have $L_s \approx 0.8$ m, giving a "high low" of $\boxed{f_1(\text{elephant, mouth-talking}) \approx 111 \text{ Hz}}$. If we assume the elephant is good at "talking through its nose" then we must add a trunk length of about 1.7 m to get $L_\ell \approx 2.5$ m, giving a "low low" of $\boxed{f_1(\text{elephant, nose-talking}) \approx 36 \text{ Hz}}$.[2]

(*b*) Bass singers produce sounds somewhat like Helmholtz resonators, where the lips and mouth from a pipe shaped opening of area A (a few cm^2) and length L in which a plug of air resonates, driven by the flow of air from the lungs. Suppose a certain singer has a lung volume $V = 7.5$ liters and he opens his mouth to $A = 1.5$ cm^2. To what length L does he have to shape his "mouth pipe" in order to produce the frequency $f = 65$ Hz, and what tone is that?[3] **ANSWER**: Equation (9.41) says $f = (v/2\pi)\sqrt{A/LV}$. Solving for L gives $L = (v/2\pi f)^2 A/V = [(356 \text{ m/s})/(2\pi \times 65 \text{ Hz})]^2 \times (1.5 \times 10^{-4} \text{ m}^2)/(7.5 \times 10^{-3} \text{ m}^3) = 0.0152$ m or $\boxed{L = 1.52 \text{ cm}}$.[4] The tone can be looked up: low-low C or C_2 [two octaves below "middle C" (C_4)] is listed as 65.41 Hz and the nearest other tones are B_1 at 61.74 Hz and $C_{\sharp 2}/D_{\flat 2}$ at 69.30 Hz, so the baritone is a little off-key at C_2.

(*c*) When frogs croak they blow up a part of their skin above an air sack. Approximate the skin (typically $A = 10^{-4}$ m^2, $m = 10^{-5}$ kg) as a piston driven by an air spring in a cylinder, and determine what sound frequency this device would produce. Compare this frequency to the frog data in Fig. **9.28** on p. 346 of the textbook, and comment. **ANSWER**: Here, since the effective oscillating mass is given, we use the equation (9.37) for the frequency for a piston with mass m: $f = (v/2\pi)\sqrt{\rho A/mL}$. Assuming a cylinder depth of $L = 1$ cm (*i.e.* similar to the diameter of the tympanum) we get a frequency of roughly $\boxed{1800 \text{ Hz}}$ which could be an *E. portoricensis* or possibly an *E. coqui* (see p. 346 of the textbook).

(*d*) Name three animals *other than* mammals, frogs or birds that produce sounds; at least one of these should be under water, and at least one on land.[5] **ANSWER**: Our good friend the mole cricket is joined by a chorus of other *insects* who make sounds by rubbing their legs together (evidently with tremendous enthusiasm!). In the water one finds *shrimps* making noise by *cavitation* as they snap their tails. Reef *fish* make quite a racket too, as they crunch bits of coral or barnacles with their teeth. (Anyone who has been snorkeling in the presence of either is familiar with these relatively boring sounds.) Whether these sounds are used for communication is an open question.

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[2] This would be good for long-distance communication, since lower frequencies are more weakly attenuated.

[3] The tone sf A has the frequency $f_{\mathsf{A}} = 440$ Hz. One octave corresponds to a factor of 2 in frequency. Each of the 12 semitones within one octave differs from its neighbor by the frequency ratio $2^{1/12}$. For instance, $f_{\mathsf{F}}/f_{\mathsf{E}} = 2^{1/12}$ and $f_{\mathsf{A}}/f_{\mathsf{G}} = 2^{2/12}$.

[4] This may seem rather short, but there are several reasons: first, the lungs are not a fixed-volume container — they are elastic, and the effective volume has been increased to take this into account; second, the "piston" air column is not the whole mouth and throat, but just the region with the small area A specified — which corresponds to a diameter of only about 1.4 cm, which in turn is (not so surprisingly) about the same size as our calculated L. The vibrating "mass on a spring" is just the air between the baritone's teeth and lips.

[5] Actually this question could lead to a nice project: *How* do they make the sound (PHYSICS), and *why* do they do it (ZOOLOGY)?