How can humans, in air, hear sound generated underwater (and can goldfish hear their owners talking)?

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The air/water interface at the top of a body of water is often treated from below as a pressure release boundary, which it closely matches. The small discrepancy in that match, however, is enough to enable humans in air to hear sounds generated underwater, which would not be possible across a pressure release boundary. A discussion of this phenomenon, designed for teaching purposes and using no more acoustics than would be contained in a first-year undergraduate syllabus in acoustics, leads to a discussion of whether goldfish can hear their owners speaking. The analysis is then used to illustrate the care needed when comparing sound levels in air and water, a process which continues to lead to erroneous statements in the media and some academic articles. © *2012 Acoustical Society of America*. [DOI: 10.1121/1.3681137]

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I. THE AUDIBILITY IN AIR OF UNDERWATER SOUND SOURCES

Reference is often made to the fact that little sound can penetrate the air/water interface from below because of the nearly pressure release conditions there for underwater sound, and the nearly rigid conditions for airborne sound from above. Indeed, before outlining a diffraction-based mechanism for predicting greater transmission of low frequency sound from compact underwater sources placed within a fraction of a wavelength of this interface, Godin[1] introduces such transmission as follows: "It is also frequently discussed in popular literature in connection with questions like 'Can we hear fish talk?' The conclusion is invariably that, because of a stark contrast in sound speeds in air ($c_a \approx 330$ m s^{-1}) and water ($c_w \approx 1500$ m s^{-1}) and especially in their mass densities ($\rho_a \approx 1.3$ kg m^{-3}, $\rho_w \approx 1000$ kg m^{-3}), only an exceedingly small fraction of the acoustic energy of an incident wave of the order of… a few hundredths of a percent, is transmitted through the interface…. Anecdotal evidence to the contrary such as low-frequency sounds heard in the air during the operation of naval sonars or observations of feeding sea birds locating fish in murky water, tended to be dismissed." Basing such dismissals on undergraduate level calculations of the type illustrated in this paper would be to undertake such calculations without sufficient depth, as will be shown. Although observations of the audibility in air of sound generated underwater are usually opportunistic, and therefore rarely calibrated, the interest and prevalence of in-air human observers when anthropogenic noise is generated underwater has created a body of reports of underwater sound that is audible in air.[2]

Leaving aside the proposition of low frequency effects discussed by Godin[3–5] and others,[6] here we present an undergraduate-level discussion to explain why human hearing can readily pick up sounds across the air/water interface. This can readily be demonstrated when bubbles are injected from nozzles underwater; or by the audible "plink" of a dripping tap; or (as can be heard in the movie accompanying Ref. 7) by the fact that 6 kHz center frequency sonar pulses emitted underwater can clearly be heard on the in-air microphone of a video recorder (such that after a day of testing the researchers believed, without objective record, that they heard wild birds *Sturnus vulgaris* mimicking these sonar pulses!).

As this treatise is designed for first-year undergraduate teaching, the scenario is restricted to that of plane waves normally incident on a (perfectly flat and smooth) planar interface (comments beyond this are restricted to square brackets). Such students are usually surprised that any perceptible sound transmission occurs across the air/water interface because the following calculation is basic for an acoustics courses. Students can characterize the impedance mismatch by considering the pressure amplitude reflection coefficient R for a plane wave approaching a perfectly flat air/sea interface from below at normal incidence $R = (Z_a - Z_w)/(Z_a + Z_w)$, where the specific acoustic impedance of air is $Z_a = \rho_a c_a \approx 429$ rayl (using the above values), and the specific acoustic impedance of water is $Z_w = \rho_w c_w \approx 1.5 \times 10^6$ rayl. Substituting these values into the above formulation, the value of R for a plane wave in water approaching the flat air sea interface vertically from below is -0.9994, which is close to -1, meaning that most of the energy (the proportion being R^2, here 0.9988) is reflected back into the sea, but with a phase change of π applied to the waveform (since $e^{j\pi} = -1$). Although this appears to show almost complete reflection, the discerning student could recognize that the proportion of energy transmitted into the air ($1 - R^2 \approx 0.0012$) represents a 30 dB loss, which is large but does not guarantee perfect sound insulation, as many room acousticians can attest.

[In practice, measurements rarely show this value because the conditions assumed for this first year undergraduate problem are not met: the waves are not planar, the direction of incidence is not normal, the interface is rough, shallow

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[a)] Author to whom correspondence should be addressed. Electronic mail: tgl@soton.ac.uk water will generate multiple reflections, and inhomogeneities (e.g., bubbles[8] or aerosols) complicate the boundary. While awareness of this in a first year undergraduate is desirable, detailed calculations[9–14] are beyond that syllabus.]

Returning to the undergraduate's calculation of a 30 dB loss, the ability of the human ear to hear sounds in air that were made in water does not rely simply upon the ability to detect sound even after 30 dB attenuation. The 6 kHz sonar source generated zero-to-peak acoustic pressure amplitude of $p_{\mathrm{i}} = 20$ kPa at 2 m range, corresponding to an intensity in water I_{20} of this 20 kPa plane wave of $I_{20} = p_{\mathrm{i}}^2/(2Z_{\mathrm{w}}) \approx 133\ \mathrm{Wm}^{-2}$. For comparison let us also consider a more usual wave of zero-to-peak acoustic pressure amplitude $p_{\mathrm{a}} = 5$ kPa, which will have a plane wave intensity I_5 underwater of $I_5 \approx 8.33\ \mathrm{Wm}^{-2}$. If these waves were normally incident on the air/water interface, the intensities ($I_{20}^{(\mathrm{air})}$ and $I_5^{(\mathrm{air})}$, respectively) transmitted into the air are $(1 - R^2 \approx 0.0012)$ times the above intensities, i.e., $I_{20}^{(\mathrm{air})} \approx 0.16\ \mathrm{Wm}^{-2}$ and $I_5^{(\mathrm{air})} \approx 0.01\ \mathrm{Wm}^{-2}$. Assuming plane waves in air, these intensities (ignoring A-weighting or issues of subjective loudness) would be normalized to an intensity of $I_0 = 10^{-12}\ \mathrm{Wm}^{-2}$ to indicate levels in air of $I_{20}^{(\mathrm{air})} \approx 10\log(0.16/10^{-12}) = 112$ dB and $I_5^{(\mathrm{air})} \approx 10\log(0.01/10^{-12}) = 100$ dB, which would be audible if the ear were in the proximity of the air/water interface.

The sonar sources used in the above calculation were powerful, which begs the question of the minimum audible normally-incident plane wave underwater that we could hear, in air. Given that the minimum threshold for hearing in humans at 1 kHz is taken to be $I_{\min}^{\mathrm{air}} = 10^{-12}\ \mathrm{Wm}^{-2}$, the intensity of the normally incident plane wave in water would be $I_{\min}^{\mathrm{water}} = 10^{-12}/0.00120 \approx 8.33 \times 10^{-10}\ \mathrm{Wm}^{-2}$, equivalent to a zero-to-peak acoustic pressure amplitude in water of $p_{\min}^{\mathrm{water}} = \sqrt{2I_{\min}^{\mathrm{water}} Z_{\mathrm{w}}} \approx 0.05$ Pa. Since the literature[15] indicates a zero-to-peak acoustic pressure amplitude in the water of $p_1 \sim 5$ Pa at $r_1 = 1$ cm from a single $\sim$ mm-sized bubble injected underwater, the feasibility of hearing such emissions in air is clear (spherical spreading losses and adjustment of the reflection coefficient for spherical waves meeting a plane boundary[16] indicate that the sound of such a bubble being injected could still be heard at a range of order 1 m from the nozzle). Audibility in air does not require explanations based solely on coupling through the ground or ship hull, although this can also occur.

Both the sonar source and the injected bubble can therefore be detected by the human ear in air. The reason is that water is very stiff, so that large pressures can be generated within it. If plane waves are assumed to approach a planar boundary at normal incidence, the first year undergraduate will calculate that the air/water interface provides a 30 dB loss for normal incidence, which is large but insufficient to insulate the airborne listener from the underwater sounds because of the sensitivity of the human ear.

II. CAN GOLDFISH HEAR THEIR OWNERS SPEAK?

Similar calculations can be undertaken by first year undergraduates who can be provided with (or asked to find) the hearing threshold for marine creatures to assess the audibility underwater of in-air sounds. Under the same undergraduate-level restrictions outlined in Sec. I, the reflection coefficient $R = (Z_{\mathrm{a}} - Z_{\mathrm{w}})/(Z_{\mathrm{a}} + Z_{\mathrm{w}})$ simply changes sign if Z_{a} and Z_{w} exchange places, so that the transmission coefficient for intensity $(1 - R^2)$ is the same as it was for the transmission of normally incident plane waves from water into air. However because the reflection coefficient is close to $+1$, and the student may suggest that the boundary is close to rigid, and that as a consequence the acoustic pressure amplitude in the air and water next to the interface will be double that of the incident wave (the normal-incidence pressure reflection coefficient T equals $R + 1$ in the usual manner[15]). This argument is used in Ref. 16 to argue why fish should easily be able to hear sounds generated in air, stating "[t]hus, while the acoustic pressure decreases approximately 2000 times for the wave transmitted from water into air, it increases by a factor of two for the wave transmitted from air into water. As a consequence, fish can perceive air noise well, while we cannot hear the sound of fish." While the first sentence is correct, the jump to the conclusion of the second is too great. It would need reference to the intensities usually emitted by the sources, the ambient noise, the sensitivities of the receivers, and details of what parameter they are sensitive to. Likening the air/water interface to a rigid/free boundary is unhelpful for the undergraduate considering audibility, since all the information is contained within the discrepancy of reality from the rigid/free limits. In the above case, the doubling of pressure at the interface of a rigid boundary, whilst correct, cannot be the sole basis for an argument on audibility. This is because, whilst some fish species are sensitive to particle velocity and some to pressure, the ability of the wave to do mechanical work on a sensor some distance from the air/water interface depends on the acoustic intensity, which depends not just on the doubled pressure but also on the specific acoustic impedance of the medium, as shown in the preceding section.

The ratio of the intensities of the normally incident plane waves in water and air (I^{water} and I^{air}, respectively) depends on their acoustic pressure amplitudes (p^{water} and p^{air}, respectively) as follows:

$$\frac{I^{\mathrm{water}}}{I^{\mathrm{air}}} = \frac{(p^{\mathrm{water}})^2/(2Z_{\mathrm{w}})}{(p^{\mathrm{air}})^2/(2Z_{\mathrm{a}})}. \tag{1}$$

If indeed the student is modeling the boundary with water, for a sound wave in air, as a rigid interface for which $R = 1$, then by the definition of the rigid interface $Z_{\mathrm{w}}/Z_{\mathrm{a}} \to \infty$ and the intensity of the propagating wave in the water is zero, despite the fact that the pressure is doubled. As the intensity is zero, no energy capable of doing mechanical work on a sensor can propagate away from the boundary into the second medium. Because the boundary with water from air is not perfectly rigid, there is some transmitted wave intensity. However in terms of calculating the intensity of the wave in the water from Eq. (1), the doubling of the pressure amplitude at the boundary is more than offset by the fact that $Z_{\mathrm{w}}/Z_{\mathrm{a}} \approx 3497$: although the ratio $(p^{\mathrm{water}})^2/(p^{\mathrm{air}})^2$ provides a multiplicative term of close to 4 in Eq. (1), when the ratio

Z_w/Z_a is also included the net effect is that $I^{\text{water}}/I^{\text{air}} \approx 4/3497 \approx 0.0012$. This retrieves (as suggested above) the same $(1-R^2)$ intensity transmission coefficient as was derived in Sec. I for normally incident plane waves propagating from water into air. It implies that the same 30 dB of insulation occurs when sound in air is transmitted into the water as occurs from water into air (noting from the comments in Sec. I that this may not be observed with rough boundaries, point sources, etc.).

The student could use the analysis of normal incident plane waves as follows. Human speech generating, say, 60 dB in air ($I^{\text{air}}_{\text{speech}} = 10^{-6}$ Wm^{-2}) will produce an intensity in water (assuming normally incident plane waves) of $I^{\text{water}}_{\text{speech}} = 10^{-6} \times 0.0012 = 1.2 \times 10^{-9}$ Wm^{-2}, and therefore a zero-to-peak acoustic pressure amplitude of $P^{\text{water}}_{\text{speech}} = \sqrt{2I^{\text{water}}_{\text{speech}} Z_W} \approx 0.06$ Pa. This is around one order greater than the minimum audible acoustic pressures usually quoted for a goldfish,[17] implying speech could be just audible to a goldfish given low noise (for example, when the aerator is turned off).

[Departures from the simple undergraduate model of plane waves normally incident on a flat smooth interface mean that in reality the attenuation might be reduced, as outlined in Sec. I. This would imply easier audibility for sounds generated by the goldfish's owner, more so when vibrations communicated by tank walls are included (and hence the sense in warnings against stimulating fish by tapping on tank glass). Such a topic could be included if the scenario in this paper is extended to a project for deeper learning. Other topics might include discussion with students that some fish are sensitive to particle velocity, rather than pressure, although because the swim bladders of goldfish are attached to their hearing organ, they are believed to sense pressure[18] (perhaps in addition to particle velocity).]

III. RECURRING ERRORS IN THE MEDIA

Using these simple calculations, first year undergraduates can not only investigate the care with which the air/water boundary must be treated, but also illustrate the effect that the differing sound speeds and densities in air and water have upon the intensities there. These, and the differing baseline units for normalization, are the reason why a standard 61.5 dB adjustment is made when comparing dB levels in air to those in water, although in reality when zoology is involved this is likely to be just the first stage in a yet-to-be defined adjustment that takes into account the nuisance caused, etc.[19–21] Lack of application of this 61.5 dB adjustment (or its possible future successor), and lack of appreciation of the fallacy of comparing dB levels in air at the point of measurement with source levels in water (quoted as a proxy sound field 1 m from the source center, even if such a sound field does not exist), continue to produce erroneous statements in the media comparing the levels of natural and man-made sounds in water with sounds in air which strike the public as being spectacularly loud. Recent examples include the description of sonar as being "as loud as 2000 jet engines";[22] and when academics (who had taken into account only the use of differing normalization intensities in air and water, neglecting the differences in density and sound speed) produced erroneous calculations which led to media suggestions that the sound of the penis of the 2 mm-long freshwater insect *Micronecta scholtzi* rubbing against its abdomen underwater "reached 78.9 decibels, comparable to a passing freight train."[23] Indeed a cavalier attitude to loudness can occur even when sound source and receiver are both in air, for example when describing a grunting tennis player "who at 101 decibels is almost as loud as a lion's 110 decibel roar."[24]

There is a great deal of work to be done in countering these misconceptions, work which would not be required if intensity, rather than dB, had been used to measure the intensities of acoustic fields.

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[1] O. A. Godin, "Sound transmission through water–air interfaces: New insights into an old problem," Contemp. Phys. **49**, 105–123 (2008).
[2] National Marine Fisheries Service, Office of Protected Resources, "Assessment of acoustic exposures on marine mammals in conjunction with USS Shoup active sonar transmissions in the Eastern Strait of Juan de Fuca and Haro Strait, Washington, 5 May 2003" (January 21, 2005).
[3] O. A. Godin, "Anomalous transparency of water-air interface for low-frequency sound," Phys. Rev. Lett. **97**, 164301 (2006).
[4] O. A. Godin, "Transmission of low-frequency sound through the water-to-air interface," Acoust. Phys. **53**, 305–312 (2007).
[5] O. A. Godin, "Low-frequency sound transmission through a gas–liquid interface," J. Acoust. Soc. Am. **123**, 1866–1879 (2008).
[6] B. E. McDonald and D. C. Calvo, "Enhanced sound transmission from water to air at low frequencies," J. Acoust. Soc. Am. **122**, 3159–3161 (2007).
[7] T. G. Leighton, D. C. Finfer, G. H. Chua, P. R. White, and J. K. Dix, "Clutter suppression and classification using twin inverted pulse sonar in ship wakes," J. Acoust. Soc. Am. **130**(5), 3431–3437 (2011).
[8] I. N. Didenkulov and A. M. Sutin, "The influence of the subsurface bubble layer on wind ambient noise generation," in *Natural Physical Sources of Underwater Sound*, edited by B. R. Kerman (Kluwer, Dordrecht, The Netherlands, 1992).
[9] A. A. Hudimac, "Ray theory solution for the sound intensity in water due to a point source above it," J. Acoust. Soc. Am. **29**, 916–917 (1957).
[10] M. Weinstein and A. Henney, "Wave solution for air-to-water sound transmission," J. Acoust. Soc. Am. **37**, 899–901 (1965).
[11] H. Medwin and J. D. Hagy, "Helmholtz-Kirchhoff theory for sound transmission through a statistically rough plane interface between dissimilar fluids," J. Acoust. Soc. Am. **51**, 1083–1090 (1972).
[12] R. J. Urick, "Noise signature of an aircraft in level flight over a hydrophone in thesea," J. Acoust. Soc. Am. **52**, 993–999 (1972).
[13] R. Young, "Sound pressure in water from a source in air and vice versa," J. Acoust. Soc. Am. **53**, 1708–1716 (1973).
[14] D. Bordelon, "Sound pressure in air from a source in water and vice versa," J. Acoust. Soc. Am. **55**, 869–870 (1974).
[15] T. G. Leighton, *The Acoustic Bubble* (Academic Press, London, 1994), pp. 22–25,194, Fig. 3.23.
[16] L. M. Brekhovskikh and Yu. P. Lysanov, *Fundamentals of Ocean Acoustics*, *Springer Series on Wave Phenomenon*, 2nd ed., edited by L. B. Felsen (Springer-Verlag, Berlin, 1990), pp. 66, 76–83.
[17] M. E. Smith, A. S. Kane, and A. N. Popper, "Acoustical stress and hearing sensitivity in fishes: Does the linear threshold shift hypothesis hold water?" J. Exp. Biol. **207**, 3591–3602 (2004).
[18] M. E. Smith, A. S. Kane, and A. N. Popper, "Noise-induced stress response and hearing loss in goldfish (*Carassius auratus*)," J. Exp. Biol. **207**, 427–435 (2004).
[19] P. H. Dahl, J. H. Miller, D. H. Cato, and R. K. Andrew, "Underwater ambient noise," Acoust. Today **1**, 23–33 (2007).
[20] D. C. Finfer, T. G. Leighton, and P. R. White, "Issues relating to the use of a 61.5 dB conversion factor when comparing airborne and underwater anthropogenic noise levels," Appl. Acoust. **69**(5), 464–471 (2008).

[21] D. H. Cato, "The effects of noise on marine animals in the context of their natural acoustic environment," in *Proceedings of 20th International Congress on Acoustics*, I.C.A. 2010, Sydney, Australia (August 23–27, 2010).

[22] The New York Times editorial, "Sonar Over Whales," November 15, 2008, http://www.nytimes.com/2008/11/15/opinion/15sat3.html (Last viewed 19 September 2011), p. A20.

[23] BBC Nature News, "'Singing penis' sets noise record for water insect," June 30, 2011, http://www.bbc.co.uk/nature/13958630 (Last viewed 19 September 2011).

[24] The Daily Mail, "The grunt stops here: Tennis officials plan crackdown on noisy players," June 14, 2009, http://www.dailymail.co.uk/news/article-1192948/The-grunt-stops-Tennis-officials-plan-crackdown-noisy-players.html (Last viewed 19 September 2011).