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Bubbles in the ocean and their significance in ocean acoustics

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ABSTRACT

Gas bubbles in water are among the most efficient sources of sound in nature when they oscillate as monopoles and as such provide the mechanism of sound generation for a diverse range of sources from underwater physical and biological processes. These include most of the natural and some of the introduced sources of sound in the ocean and other water masses. Bubbles also have a high scattering cross section and substantially affect the propagation of underwater sound and enhance the detectability of objects containing bubbles. The underwater sound measured from natural bubbles can be inverted to make estimates of wind speed and rain fall integrated over an area of the water surface and can also provide insight into transfer of gases across the air sea interface. This paper will discuss why bubbles are so effective in these respects, how they are responsible for most of the ambient noise in the ocean through many different sources, and how they are important in extracting information about processes within the ocean and in the vicinity of the ocean surface.

BUBBLES AS SOURCES OF SOUND IN THE OCEAN

The source strength of sound radiated from movement of a fluid interface that forms the boundary between a contrast in density or sound speed or both (such as air and water) is proportional to (Cato, 1991)

$$s_L \approx \rho_w c_w^2 - \rho_a c_a^2 \qquad (1)$$

Here ρ_w and ρ_a are the densities in water and the gas respectively, and c_w and c_a are the sounds speeds in water and the gas respectively. The term ρc^2 is the bulk elasticity, the reciprocal of compressibility (Clay and Medwin, 1977). Hence a source formed by movement of a fluid interface with large contrast in compressibility, as in the case of air and water, has a high source strength. The sound radiated also depends on the velocity of the interface. The simplest example is the gas bubble in water, for which the interface is the surface of the bubble. When the bubble is oscillating radially it is an example of the simple source well known in classical acoustics. As such it forms a monopole source of sound, so is far more efficient than the dipole sources of sound that are often encountered. That and the high source level from the contrast in compressibility make gas bubbles in water very effective sources of sound.

The monopole radiation occurs when the surface of the bubble moves uniformly in a radial direction with the same speed in all directions. If the surface moves in a more complicated way, it will be a less efficient source, so it is the radial oscillation that dominates sound production. Much of the ambient noise in the ocean results from sources that are effectively oscillating gas bubbles.

NOISE FROM BREAKING WAVES

The earliest studies of ambient noise in the ocean showed that the noise of breaking waves across the ocean is a major component, extending over a broad frequency range from less than 100 Hz to more than 10 kHz (Knudsen et al, 1948). The actual mechanism of sound production was not determined until the 1980s when it was shown that the noise was generated by the oscillation of bubbles formed by the air entrained in the process of the wave breaking. Banner and Cato (1988) conducted experiments in a wave tank in which it was possible to carefully control the wave breaking. High speed photography synchronised with sound recording showed that sound was generated by the oscillation of bubbles immediately on formation by air entrainment. Larger scale tank experiments by Medwin and Beakey (1989) extended this work with transient breaking waves, closer to real ocean waves. Updegraff and Anderson (1991a and b) in an extensive series of observations of individual breaking waves at sea, found a similar dominance of noise from bubbles.

Figure 1 shows a summary of the main sources of noise in the Indo-Pacific region near Australia (Cato, 1997). The noise from breaking waves is shown as the broad band curves labelled “wind-dependent noise.” Wenz (1962) referred to noise from breaking waves as wind-dependent noise by because it was found that it correlated better with wind speed than with any measure of surface wave properties. The curves of Figure 1 are averages for the wind speeds shown.

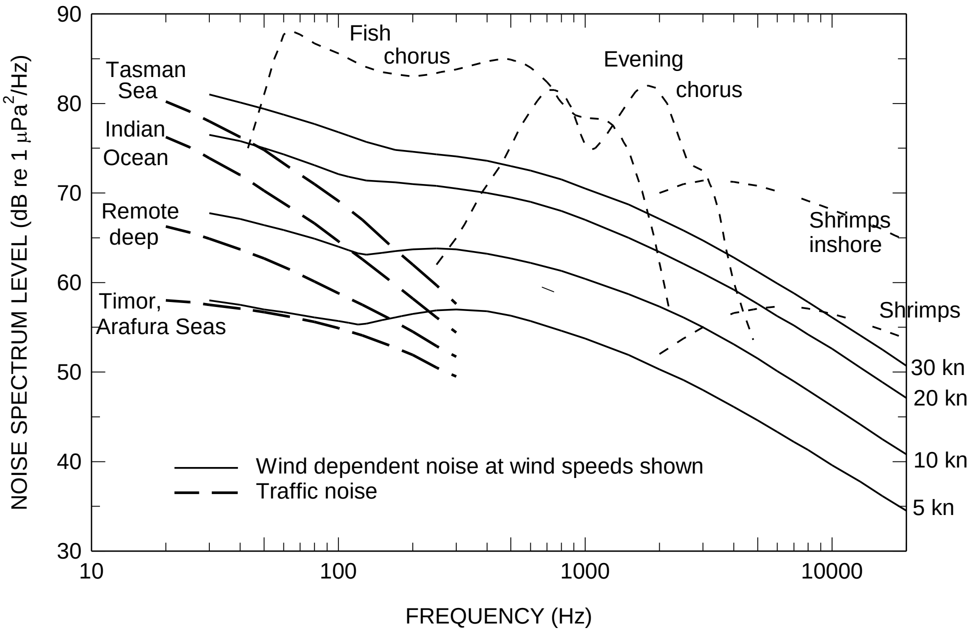

Figure 1. Summary of ambient noise in the Indo-Pacific region around Australia, showing the main components: wind dependent noise from breaking waves, biological choruses and traffic noise for the regions shown.

The bubbles form close to the sea surface where the air water interface provides a substantial mismatch in acoustic impedance. Acoustic reflection from the sea surface occurs with very little loss but with a reversal of phase, so that each bubble and its surface image effectively forms a dipole with maximum radiation downward. Hence the far field noise can be modelled as due to a surface distribution of dipoles with axes (of maximum radiation) normal to the sea surface, consistent with the source directionality inferred by Ferguson and Wyllie (1987) from directional noise measurements.

The resonant frequency of air bubbles in water is (Clay and Medwin, 1977)

$$f_R \cong \frac{3.25(1+0.1z)^{1/2}}{a} \qquad (2)$$

The multitude of bubbles in a breaking wave has sufficient spread of sizes to give a reasonably broad acoustic spectrum. Equation 2, however, implies that rather large bubbles are needed to produce sound at low frequencies. For example, at 100 Hz, the radius would be about 3.25 cm. It is evident in Figure 1 that there is a change in the shape of the wind-dependent noise spectra in the region 100 to 200 Hz. Since the measurements that demonstrated that individual bubble oscillations were the source of noise in breaking waves were confined to frequencies above 200 Hz, it has been suggested that some other kind of mechanism may be generating the noise at the low frequencies.

Carey and Browning (1988) and Prosperetti (1988) have independently provided theories of the mechanism of noise generation at low frequencies, involving the collective oscillation of clouds of bubbles. These clouds have been observed to extend to depths of several metres under breaking waves. The masses of bubbles do not significantly change the density in the cloud relative to the surrounding water, but they do significantly change the speed of sound.

Consequently, the boundary of the cloud is an interface between water of different sound speeds providing a difference in compressibility. If the surface of the bubble cloud moves, it will radiate sound with a source level dependent on the difference in the compressibility between the inside of the cloud and water, as indicated in the proportionality of Equation 1. In this case it will be dominated by the difference in sound speed.

The surf zone is well known as a source of noise both in the air and underwater. Wave breaking in surf also causes high levels of noise which may be audible some distance out to sea. Deane (1999) showed that close to the surf, the noise appears to be radiated from acoustic hot-spots at the ends of the breaking crest. More recent work is described in two papers in this proceedings: Deane (2010) and Deane and Czerski (2010).

NOISE FROM RAIN

Rain falling on the sea surface produces transient sounds as the droplets impact the surface, and also sounds from the oscillation of the air bubbles formed by the air that is entrained as the droplets break through the surface (Nystuen and Farmer, 1987). The noise generated by the impact and the bubble depends on the size of the drop, the impact speed and the angle of impact (which depends on the wind). Rain noise causes high levels noise over a very broad band from a few hundred hertz to tens of kilohertz and levels may be exceed the highest levels of wind dependent noise in this band.

NOISE FROM VESSELS

Vessels of all sizes are widely distributed across the oceans and apart from the noise that is evident from a passing ship, they also contribute to a nondescript background noise known as *traffic noise* (Wenz, 1962). Ships across an ocean basin can contribute to traffic noise and it generally depends on the shipping densities and propagation conditions of the region. Averaged traffic noise from different areas around the Indo-Pacific region near Australia is shown in Figure 1 and widespread variation in noise levels between the regions is evident. In the Tasman Sea off the east coast of Australia, noise levels approach those of high shipping density area near North America (Wenz, 1962). Traffic noise is a general background noise and is nondescript in the sense that the ships contributing are not detectable individually.

There are many sources of noise in vessels (Ross, 1976) including the noise from the engine and gearing, but one that makes a substantial contribution is cavitation caused by the movement of the propeller. Cavitation is formed when the pressure fluctuation becomes comparable to the static pressure, so that the negative or low pressure side of the fluctuation cancels the static pressure and the total pressure approaches zero. As the pressure in water becomes very small, cavities are formed around small inhomogeneities. These are bubbles containing water vapour and they quickly collapse, each producing a pulse of sound. Cavitation bubbles are quite visible in the wake of an outboard motor, for example.

SOUNDS OF MARINE ANIMALS

The efficiency of an oscillating gas bubble as a source of sound is exploited by marine animals in their generation of sound. One of the best known sources of noise is the ocean is the snapping shrimp which in large numbers produce a general broad band noise field (Johnson, et al., 1947). Examples of the spectra are as shown in Figure 1. There are a number of species of snapping shrimp and they occur in large numbers in temperate and tropical waters (latitudes less than about 40°) and water depths less than about 60 m. These shrimps have one claw that is disproportionately large, and they produce a sharp transient sound by snapping this enlarged claw. Their numbers are so large that the snapping of claws results in a continuous crackling or "sizzling" sound which can dominate the ambient noise in the frequency range of a few kilohertz to at least 300 kHz (Cato and Bell, 1992). The click is very sharp and intense. The actual mechanism of sound production by the movement of the enlarged claw had been a matter of speculation for many years until Versluis et al. (2000) showed that the click was actually produced by the collapse of a cavitation bubble. The claw moves so fast as it closes that a cavitation bubble is formed in its wake and this is was produces the intense noise.

Many species of fish have a gas filled sac known as a swim bladder. The acoustic impedance of flesh is much closer to that of water than to gas, so this swim bladder can function as a gas bubble in water. Many species of fish make use of the swim bladder both for enhancing hearing and for generating sound (Tavolga, 1964). Sounds may be generated by excitation of the bladder in short bursts by attached muscles or by interconnecting bone. The effect is a series of sounds rather like drumming or knocking. The chorus labelled "fish chorus" in Figure 1 was caused by these type of sounds from a large number of fish. The bladder may also be excited by rapid contraction of muscles attached to the swim bladder at a rate similar to the resonant frequency of the bladder. This results in a sustained tonal signal.

Baleen whales, the large filter feeding whales, produce a range of sounds and many cover a relatively small frequency band, suggesting that some resonance process is involved, thought the mechanism of sound production has not been established. Baleen whales have a large laryngeal sac or diverticulum (tens of centimetres long) that could function as a gas filled sac resonator (Quayle, C.J, 1991; Reidenberg and Laitman, 2007) and contribute significantly to the sound production by these whales. Calculations of the range of frequencies and source levels that could be achieved by oscillation of air cavities in a blue whale are consistent with those observed (Jones et al., 2003).

BUBBLES AS SCATTERERS OF SOUND

Gas bubbles in water cause significant scattering of acoustic waves. They have a very high scattering cross section in the region of their resonant frequency. Scattering by masses of bubbles can affect the propagation of sound by providing significant attenuation. For example, the bubbly water left behind breaking waves in surf can result is very high attenuation over short distances (Deane, 1999). Fish swim bladders contribute significantly to their scattering of sound and thus to their detection by fish finding sonar.

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