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SOURCES OF AMBIENT NOISE IN LITTORAL WATERS

L. BJØRNØ

Department of Industrial Acoustics
Technical University of Denmark
(Building 425, DK-2800 Lyngby, Denmark)

1. Introduction

During the so-called "cold war time", less than 10 years ago, the major interest in underwater acoustics was related to deep waters in particular in the North Atlantic and the Pacific Oceans where the deep-going, silent and very large, nuclear powered attack submarines of the "East" and "West" were operating. The considerably more silent regions of the deep waters were one of the main reasons for the particular emphasis on passive listening, use of towed arrays etc., during these years. The political situation changed drastically with the disappearance of the Warsaw Pact and the break down of the Soviet Union in the late eighties and early nineties. The need for operations in the deep waters was strongly reduced, but the Gulf War, the situation in the former Yugoslavia, the risk of local wars at other places around the World, and in particular the proliferation of small, diesel driven submarines developed for operation in shallow waters near their home bases gave rise to a considerably increased interest in underwater acoustical studies of the shallow water in the littoral areas. Active sonars became of increasing interest and as operations against hostile submarines, mine fields, etc. may take place in unknown waters far from the home bases, the concepts of "Rapid Environmental Assessment" were developed. Moreover, exploitation of resources in the Exclusive Economical Zone (EEZ) defined by several countries, and resources in and on the continental shelf, together with the defence of the boundaries for the territorial seas, the EEZ's and the continental shelf have led to a "deadly triangle" of economical growth, marine resources and naval arms, which have called for increased interests in the acoustics of the shallow waters of these zones. The turn in interests from the deep to the shallow littoral waters, however, showed the need for studies of sound propagation in regions where the influence of boundaries – seabed and sea surface –, of inhomogeneities in the water column, of considerable variations in temperature and salinity with decisive effects on the sound velocity profiles, and in particular of much higher levels and another spectral composition of ambient noise were prevailing. The ambient noise, frequently leading to a strongly reduced signal/noise ratio, is of importance at higher frequencies than in deep waters due to shorter ranges in shallow waters. Moreover, the sources of ambient noise constitute another "mix" in shallow than in deep waters. Therefore, the identification of sources of ambient noise has received renewed attention in shallow water areas.

It is a generally accepted fact that sound is generated in a fluid by any process which causes a non-steady pressure field to occur in the medium. Many different noise producing processes are active in the sea and their concerted action contribute to the *ambient noise level* measured. Thus ambient noise may be said to be *the residual noise background in the absence of any individual identifiable source* or that ambient noise is the natural noise environment at a measurement site. The ambient noise level is the intensity, in dB, measured at a measurement site using a nondirecional hydrophone and referred to the intensity of a plane wave having an rms pressure amplitude of 1 μPa. In spite of being measured in different frequency bands, ambient noise levels are always reduced to 1 Hz frequency band, and are then named the *ambient noise spectrum levels.*

Underwater ambient noise covers a very broad frequency range from below 1 Hz to several hundreds of kHz. Over this broad frequency range, the measured data show that ambient noise has different characteristics at different frequencies, with a different spectral slope and a different behaviour with varying external conditions, like for instance wind speed, in different parts of the spectrum. Pioneering works on measurement and description of ambient noise were done by a group of acousticians headed by V.O. Knudsen, who investigated ambient noise in the frequency range from 200 Hz to 50 kHz. Their results were first published in 1948 [1] and are summarized in a series of curves known as the *Knudsen Curves.* A discussion of the broad variety of sources contributing to the ambient noise level in the sea can be based on dominant orders of multipoles like monopoles, dipoles and quadrupoles, which may be treated in a mathematically rigorous way, but from a physical and conceptual point of view it is better to discuss the sources based on the characteristic mechanisms involved.

2. Sources of ambient noise

Sources of ambient noise to be discussed in some depth comprise among other things tides and hydrostatic effects of waves, seismic activities, sea surface phenomena like for instance surface waves and their breaking, wind, bubbles etc., precipitation contributions, large scale turbulence, biological activities, ice, shipping, off-shore activities, transducers and underwater explosions, thermal noise etc.

2.1. Tides and hydrostatic effects of waves

Tides and surface waves cause hydrostatic pressure changes of a considerable amplitude at very low frequencies. The magnitude of the tidally produced pressure changes around a hydrophone in water may be demonstrated by the fact that a 1 meter increase in the water height will lead to an increase in pressure of 10^4 Pa, or to 200 dB re 1 μPa. As the tidal motion spectrum is represented by about 2 cycles/day, it is of minor interest in relation to ambient noise. Tidal motion may, however, influence ambient noise measurements through changes in the temperature of the hydrophone environment, which may lead to pyroelectric effects in the piezoelectric hydrophone materials and thus to false measurements, and through tidal currents, which can lead to flow induced vibrations of the hydrophone and its support.

Studies of the influence of flow around a hydrophone on the noise generation has been performed by Strasberg. Three situations were studied: (1) a hydrophone held between the surface and the bottom in a turbulent flow, (2) a hydrophone resting on the bottom with a turbulent boundary layer flow above it and (3) a neutrally buoyant hydrophone floating with the mean speed of the current. The spectrum level L_p of the pressure fluctuations in dB re 1 μPa for a 1 Hz band can be expressed by:

$$L_p = A + B \log U - C \log f, \tag{1}$$

where U is the mean flow velocity in knots and f is the frequency in Hz. The following values were found for the constants A, B and C respectively. Situation (1): 117, 27, 17. Situation (2): 100, 57, 17. Situation (3): 67, 17, 27. The results show the importance of taking into consideration the influence of flow induced noise when ambient noise measurements below 5 Hz are being performed.

Surface waves are also sources of hydrostatic pressure changes in the sea. As the pressure amplitude falls off rapidly with increasing depth and with decreasing wavelength of the surface waves, the importance of surface waves as a source of hydrostatic pressure changes in deep water is low, while in shallow water a rough surface may have a dominating influence on pressure-sensitive hydrophones at low frequencies.

2.2. *Seismic activities*

Due to the fact that the earth is in constant state of *seismic* activity, earth unrest is causing low-frequency sound in the sea. Seismic activities range from contributions from large-scale intermittent sources like individual earthquakes (seaquakes) and distant volcanic eruptions to *microseisms*. Microseisms having a nearly regular periodicity of 1/7 Hz and a vertical amplitude of 10^{-6} m will lead to a pressure amplitude in the sea of 120 dB re 1 μPa [2]. Seismic unrest may also be found at frequencies above 10 Hz.

Also contributions from man-made activities like industrial plants, road transport, construction work etc. in coastal areas may, as seismic waves, propagate into shallow water areas close to the shore.

More than eighty years ago WEICHERT [3] proposed a close relation to exist between microseisms and ocean wave activity. In spite of the fact that several other mechanisms also have been proposed to account for the general microseisms, the most favoured mechanisms are nonlinear interactions between surface waves. Noise related to ocean microseisms dominates acoustic spectra at frequencies below 4–5 Hz. Ocean surface waves travelling in opposite directions in the vicinity of a storm or as a result of a reflection from a coast can generate a standing wave field. Unlike progressive surface waves, for which the pressure effects decay exponentially with depth, a standing surface wave field produces a mean second-order pressure effect at twice the frequency of the surface waves, that is unattenuated with the depth. The pressure amplitude produced by nonlinear surface wave interactions is proportional to the amplitude product of the interacting waves. This effect formed the basis of a theory developed by LONGUET–HIGGINS [4] for the formation of microseisms which lead to noise at infrasonic frequencies in the sea. Experimental verification of this theory has been given by HASSELMANN [5] and HUGHES [6].

Following the theory by Hasselmann it may be shown [7] that there should not only be a two-to-one frequency relation between seismic and ocean wave spectra, but the variance density spectral levels of the vertical component of the ground displacement should be proportional to the fourth power of the frequence of the interacting ocean waves, and to the square of the variance density level of the ocean wave components producing the exciting pressure field.

As shown in [8] low-frequency noise as for instance produced by microseisms may more readily be observed in boreholes than on or close to the seabed, due to the fact that the lower noise levels in the boreholes more than compensate for signal losses. However, existing seismic data in the 0.1 to 0.2 Hz frequency range show that a close relationship exists between the sound pressure at the seafloor and the seismic ground response [9].

2.3. Turbulence

The irregular and random motion of the water in turbulent currents of large or small scales is able to produce underwater noise. The pressure changes associated with the turbulence may be measured far from the turbulent region and will appear as a part of the ambient noise. However, the noise as such radiated from the turbulent region is not likely to be of significance due to its quadrupole character and thus its rapid fall-off with distance from the source region. A pressure sensitive hydrophone may, however, pick up the turbulent pressure when measurements are performed in the turbulent region. Pressure levels between 115 and 150 dB re 1 μPa related to flow velocities between 0.02 and 0.3 m/s have been suggested [10].

Low-frequency underwater noise may also be produced by turbulent pressure fluctuations in the *atmosphere* near the ocean surface [11, 12]. The induced noise field is related on a 1 : 1 frequency basis, with with the fluctuations in the existing turbulence field. It is concluded in [12] that atmospheric turbulence is the dominating source of wind generated noise above 5 Hz. Experimental results covering the frequency range below 10 Hz are, however, sparse, in particular due to experimental difficulties related to hydrophone installations, too short time periods of measurements done and the use of local test sites with too limited environmental data available.

2.4. Surface phenomena

It has been demonstrated at many occasions that low-frequency underwater sound is dependent on the *wind speed* for both deep and shallow water. The Knudsen spectra based on many observations gave relations between sea state or wind force and the level of underwater ambient noise. The frequency range over which wind speed via various noise producing mechanisms have an influence on underwater ambient noise is very broad.Local wind speed is the dominant factor controlling wind/wave noise for frequencies above about 500 Hz, while distant wind dominated sources may contribute essentially at frequencies below 500 Hz.

Apart from the fluctuating forces exerted on the sea surface due to the wind's turbulence, as discussed above, wind blowing over a rough surface may also generate sound which penetrates into the water [13].

Spectrum levels in the frequency range from 8.4 Hz to 3 kHz were studied by PIGGOTT [14] in shallow water on the Scotian Shelf off Nova Scotia. For most of the data in [14] the noise spectrum level $L(f)$ at a frequency f was found to be related to the wind speed V in miles per hour by the expression:

$$L(f) = A(f) + 20\,n(f)\log V, \tag{2}$$

where $A(f)$ is a frequency dependent threshold level, $n(f) = 2.1$ for frequencies below 50 Hz and $n(f) = 1.2$ for frequencies from 400 to 2000 Hz. These results show, that the sound pressure level is approximately proportional to the square of the wind speed below 50 Hz. As the wind speed dependent noise possesses a seasonal effect in shallow water, $A(f)$ in Eq. (2) varies by 3.5 dB from winter to summer. In general, shallow water, wind-generated noise and its characteristics, are highly variable and rather difficult to predict.

All surface phenomena leading to low-frequency ambient noise in the sea are more or less related to the influence of the wind. This also concerns the sound sources connected with (1) breaking of waves, (2) nonlinear wave-wave interaction and (3) bubbles.

Ambient noise studies in shallow water locations have frequently been made using buoyed hydrophones designed to move with the water mass and with a system to minimise the influence of surface motion. However, most measurements have been made with bottom moored systems comprising hydrophones on the bottom or buyoed up, and these systems have also included wind speed measurements at a buoy on the same mooring. Most data analysis have been in one third octave bands, corrected for bandwidth to provide average spectrum levels.

2.4.1. Breaking of waves. Wave breaking is a widespread phenomenon on the wind-driven sea surface, occurring over a wide range of length scales and appearing to play a major role in surface layer mixing and in underwater ambient noise generation. However, which mechanisms within the breaking waves, which actually generate sound, are not yet fully known.

On a large scale, the most common type of wave breaking process is related to the *spilling breaker*, which can be induced by steady flow over an obstacle. These breakers tend to entrain air bubbles at the lower end of the "roller". Among the progressive waves, another wave breaking type is characterized by the occurrence of *plunging breakers.* Plunging breakers will, before their short plunging state, demonstrate a bend-over cusp shape with jetting fingers along the leading edge. These fingers develop into streaks which appear to lengthen and ultimately to collapse into a violent moving region of bubbles and water along the leading edge. According to [15] the first detected sound should occur with the appearance of an air-water cloud (bubble cloud) pushed ahead by the waves. The sound level produced should also increase with the increasing size of the air-water cloud. The final stage of the breaker shows several foam lines produced in succession, each probably associated with a burst of sound. The produced sound level gradually decreases with these foam lines and a turbulent pool is left behind the wave. In a mixed sea, characterized by short surface waves riding on longer waves, the orbital compression by the long waves compels the short waves to steepen and to break near the long wave crests.

Standing waves break in a different manner [16]. The crests can become unstable, throwing droplets into the air, or overturning symmetrically on either side. In extreme cases the trough of the wave collapse, throwing up a water jet of high velocity.

Prior to wave breaking, low-frequency sound in the frequency range from 2 to 200 Hz may be generated by the interaction between surface waves and turbulence, this being the case for sea states low enough that breaking of waves do not occur [17].

Breaking of wind generated waves can also produce noise by the action of surf on beaches. Measurements of surf zone generated noise performed at a distance of 5 km from a beach in Australian northern waters showed a level fluctuation between 67 and 82 dB re 1 $\mu Pa^2/Hz$ (from 50 Hz to 500 Hz), due to a 1 m surf [47].

2.4.2. Nonlinear wave-wave interaction. Nonlinear interaction between ocean waves has been of interest, not only to seismologists as mentioned above, but also to the oceanographers due to the fact that this interaction mechanism most probably leads to a self-stabilization of the ocean wave spectrum. The second-order effect involved in the surface wave motion by two waves progressing in opposite directions and thereby forming a standing wave, has been demonstrated to be the dominant mechanism of noise generated in the frequency range from 0.1 to 5 Hz [18]. Experimental evidence in [18] shows that the greatest wind related noise levels occur when a 180° shift in the direction of the wind of long duration brings a growing sea into direct opposition with the one already established. While the two wave fields interact, the underwater low-frequency noise level remains very high, but it drops rather fast to a level some 20 dB lower as the new wave field becomes dominant, thus reflecting the nonlinear wave-wave interaction process influence on the underwater noise level.

2.4.3. Bubbles. Surface waves breaking in shallow water produce *clouds of bubbles* which persist below the sea surface as identifiable acoustic targets for periods of several minutes. They are carried and dispersed by the near surface turbulence, and may serve to identify fluid regions directly affected by the breaking waves which produce them. The distribution of the bubble clouds after their formation is a function of the properties of the bubbles themselves as well as of the turbulence. Apart from breaking of waves, bubble clouds in the uppermost layer of the ocean may also be produced by precipitation, break-down of organic materials, and ship traffic, where bubbles in wakes may persist for hours. Beside the obvious acoustic influence from the bubble clouds, they play an important role in the air-sea interaction processes as for instance in the exchange of gas, in production of sea salt aerosols, in electrical charge exchange and in chemical fractioning in addition to the net upward flux of organic materials and bacteria [19].

Observations over the past have shown that the size distribution of bubbles after normalization by depth and wind dependence, follows a power law dependency on radius. Estimates of the slope with increasing bubble radius vary from −3.5 to −5 [20, 21]. The number of bubbles also decreases with the depth z, approximately as $\exp(-zk^{-1})$, where k is some scaling length. As shown in [22] the total number of bubbles increases very rapidly with speed U_{10} (measured at 10 m height above the sea surface). A relation showing as rapid an increase as $(U_{10})^{4.5}$ has been suggested. The bubbles present near the sea surface resonate over a broad frequency range. Using the Rayleigh-Plesset equation, which describes the radial dynamics of a spherical bubble of radius $R(t)$ in an incompressible liquid of density ϱ, leads to

$$R\ddot{R} + 3/2\,\dot{R}^2 = 1/\varrho[p_i - p_\infty[1 + F(t)] - 2\sigma/R]. \tag{3}$$

Here the dots denote time derivatives, p_∞ is the static pressure, σ is the surface tension and p_i is the internal pressure in the bubble. The exitation function, due to variation in ambient pressure caused by waves or turbulence, has been denoted by the dimensionless function $F(t)$. A rough estimate based on Eq. (3) of the natural frequency of the bubble oscillations is given by expression (4):

$$\omega_0 = R_0^{-1}\left[\frac{3\gamma p_\infty}{\varrho}\right]^{1/2} \tag{4}$$

where R_0 is the equilibrium radius of the bubble and where ω_0 is the angular frequency in the bubble vibration. From Eq. (4) a natural frequency of 100 Hz may be ascribed to a bubble having a radius of about 0.03 m. As most bubbles produced near the sea surface are much smaller, the individual bubble contribution to the low-frequency noise level in the sea is small. However, the collective oscillations of the bubbles in the bubble cloud near the sea surface may generate low-frequency sound. It is well-known, that a small amount of bubbles in water significantly changes the bulk compressibility of the water, while not drastically changing the density. These changes lead to a considerable variation in the speed of sound in the bubble-water mixture. If the volume fraction of air is β, which is considered to be small, the speed of sound in the bubble-water mixture may be found from:

$$C_m = C_w\left[1 + \frac{\beta\chi_a}{\chi_w}\right]^{1/2} \tag{5}$$

where C and χ denote the speed of sound and the adiabatic compressibility, respectively. The indices m, a and w denote mixture, air and water, respectively. For $\beta = 0.001$ the speed of sound in the mixture will be about 320 m/s. If a bubble cloud in water is assumed to have a linear dimension L this cloud may be considered as a system of coupled oscillators with the frequency of the lowest mode given by:

$$f_0 = \frac{C_m}{L} \tag{6}$$

which for naturally ocurring values of L may lead to rather low frequencies [52, 53].

As mentioned earlier, turbulence generated noise in pure water is of quadrupole character and turbulence is, therefore, forming a very weak source of sound. The presence of bubbles will, however, amplify the turbulence produced noise by conferring to it a monopole nature. The magnitude of this intensity amplification can be estimated to be of the order of (C_w^4/C_m^4), [23]. In this way, through the presence of bubbles, turbulence can contribute a significant amount of ambient noise up to frequencies of the order of several tens of Hz.

2.5. Precipitation

In particular *rain*, but also *hail* and *snow*, falling on a sea surface have turned out to be considerable contributors to the ambient noise level in the sea. The underwater sound spectrum generated by rain has frequently a shape which can be distinguished from other sources of sound in the sea, and the relationship between the spectral levels and the rainfall may be quantified. Rainfall is a climatic factor of great importance and, therefore, measurement of rainfall has a high priority. However, it has been estimated that about 80% of the Earth's precipitation occurs over the ocean where the smallest number of weather stations are located. Measurements of underwater sound have, therefore, been proposed as a way for determination of the amount of rain falling on the sea surface [24]. A prospective future procedure for rainfall measurements could include underwater ambient noise measurements at certain geographical locations combined with the use of satellite observations and the use of weather radar. However, there still appears to be a long way to this goal. Several attempts to describe the underwater noise spectra produced by rainfalls of various magnitudes have been made over the years [25–29], but a considerable deviation did exist between rain noise data produced by various scientists.

Possible sources of underwater sound caused by *single droplets* of rain are the transient introduction of the droplet into the water, the secondary splashes by water droplets thrown up by the entry and oscillations of air bubbles trapped near the surface and oscillations of cavities open to the atmosphere.

The individual contributions to the underwater noise spectrum from these mechanisms are strongly influenced by factors related to the droplet size, shape and movement before it hits the water surface. Among these factors shall in particular be emphasized: The equivalent raindrop diameter, the size distribution of the raindrops, the shape of the raindrops, the wind velocity and its profile, surface tension and raindrop temperature, and, frequently, the conditions under which the measurements took place. Underwater sound generated by *multiple raindrop impacts* on a water surface will be influenced by the interaction between the individual impacts, which will comprise water droplets falling on a not-plane (random shape) water surface, drops falling in and out of phase leading to phase cancellation, resonance etc. The noise generated by multiple raindrop impacts is possibly the field of rain noise generation where most research is still needed. Not only extensive experimental studies have to be performed, but a theoretical (numerical) basis has also to be established. Recently, experimental evidence was created for the strong influence of *surface tension* on the noise level produced by *real rain* (multiple impacts) [30–32]. The results show, that a considerable part of the noise produced by raindrops falling on a sea surface is caused by the pulsation of bubbles trapped near the surface. For instance, the characteristic spectral amplitude of rain noise around 14 kHz is caused by formation and pulsations of small bubbles produced by raindrops having a diameter between 0.8 and 1.1 mm. These bubbles are formed near the water surface by closure of cavities produced by impact of raindrops and under the influence of the surface tension. Only raindrops in the size range mentioned above are leading to bubble formation at all impacts. By adding small amounts of detergents to water, thus reducing the surface tension, a very remarkable reduction in the rain took place and the characteristic spectral amplitude around 14 kHz disappeared, see Fig. 1.

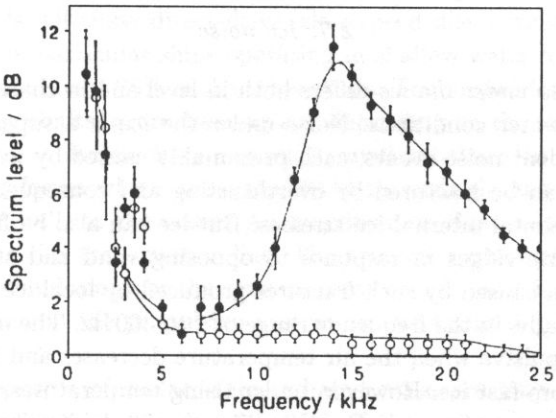

Fig. 1. Acoustic power spectra of real rain falling into clean water (closed circles) and water with sulfo detergent added (open circles). Here, dB reference level is arbitrary [32].

2.6. Biological activities

Biological noise sources are many and varied. The frequency range of the various biological sounds is very wide, from about 20 Hz to more than 300 kHz. The principal sources of low-frequency biological sound are marine mammals, mainly whales and porpoises [33]. Some of the sounds generated are used for echolocation, for detection of food, and for communication between the species, but the functions of many sounds are not known. Naturally, because of their biological origin, such sounds have diurnal and seasonal cycles. Groups of mammals such as whales can generate such loud, continuous sounds as to raise the ambient noise level significantly.

One of the best known biological noise sources is the snapping shrimp which abounds in shallow waters in latitudes less than 40°. They were first described by KNUDSEN *et al.* [1] for frequencies up to 20 kHz. Recent measurements have, however, shown that shrimps are a dominant source of noise from frequencies of a few kHz to at least 300 kHz [47].

In most shallow waters there is a general background of biological noise, but the most pronounced effect is due to the choruses that result when a great number of animals are calling at the same time. Such choruses cover various parts of the spectrum and they typically increase the spectrum levels by 20 dB or more. The choruses may be considered to belong to two general categories. The first category is the diurnally varying type of chorus which occurs a few hours per day at approximately the same time of the day. The evening chorus occurring for a few hours after sunset is the prevailing. However, similar choruses are sometimes observed near sunrise and occasionally at other times of the day. The other type of chorus sounds result from fish and are often related to their spawning. These, less predictable choruses, may occur for longer periods of the day and they often have pronounced seasonal relations, which differ considerably between the species. Many fish use their gas-filled swim bladder and their drumming muscles to generate sound, thus being able to produce a considerable sound pressure level.

2.7. Ice noise

Underwater noise *under the ice* differs both in level and in characteristics from that measured in open-water conditions. Noise under the ice is a superposition of a large number of independent noise events, each presumably caused by *ice fractures* of one or another kind. Ice can be fractured by overthrusting and consequent flexural straining in response to horizontal internal ice stresses. But ice can also be fractured by turning moments on pressure ridges in response to opposing wind and current stresses [37]. Acoustical radiation caused by such fractures produced by local ice motion is supposed to lie, at least partially, in the frequency range of 1 to 300 Hz. The noise has been found to be spiky and impulsive when the air temperature decreases and tensile fractures are formed in solid, shore-fast ice. However, under rising temperatures, the spiky character of the noise disappears and a more Gaussian like amplitude distribution is found [38].

Also *vibration* of the ice may produce low-frequency sound. Wind blowing over the rough ice surface becomes turbulent and transmits varying pressures to the ice and through it, to the water. Wind produced sound is more prominent under a noncontinuous ice cover than under a continuous one. Vertical ice motions measured with seismometers mounted on the ice generally correlate with ambient noise levels at 60 m depth at 50 Hz [39]. Another type of noise due to the ice motion is an almost sinusoidal signal 7 Hz and a variable amplitude, which is attributed to standing wave patterns between the surface and the seabed [40].

2.8. Shipping

A major source of underwater ambient noise, primarily in the frequency range of 10 to 500 Hz, is shipping. *Distant ship traffic* is a principal source of low-frequency noise in the range of 20 to 150 Hz. Such traffic may take place at distances up to 1000 km or more, thus competing with *distant storms* as sources of low-frequency noise [27]. Even if ship traffic generates sound over a broad frequency band, the propagation over distances of several hundreds of km or more will attenuate sound at higher frequencies, and only low-frequency sound will be received from distant shipping. This also means, that the spectral composition of the sound received from ship traffic at short distances will be different from sound produced by distant shipping.

The acoustic power produced by a ship is only a small fraction (frequently less than 1/1,000,000) of the mechanical power used for moving the ship. A modern submarine proceeding at slow speed produces on the order of 10 mW acoustic power, while surface ships generally radiate from 5 to 100 W of acoustic power [42]. Since each ship is operated in a wide variety of configurations from unloaded to fully loaded, at various speeds and in varying mechanical conditions, the sound generated by a ship can vary over a wide frequency band.

The principal sources of radiated sound from ships are: (1) the propulsion system; (2) the propeller; (3) the auxiliary machinery; (4) the hydrodynamic effects and (5) the hull movements. Three types of power plants are now commonly used in merchant ships: (1) Geared steam turbines; (2) direct-drive, slow-speed diesels and (3) geared medium-speed diesels. Of these direct-drive, slow-speed diesel constitute about 2/3 of all ships at sea and in particular ships operating in shallow water areas. Steam turbine driven ships constitute about 25% of the ships at sea. The *propulsion system* contains in general large rotating shafts, gears, bearing and depending on the ship type, reciprocating engines, turbines, or electric drive motors. A small unbalance in one of these devices results in oscillating forces which are transmitted through the machine structure, the foundations and the hull, to the water. An amplification due to structural resonances may take place along this transmission line. The acoustic signals generated in this way are normally narrowband tonals at the systems rotational frequencies and their harmonics. Broadband signals in the propulsion system are for instance generated by friction forces.

The dominant sources of surface-ship radiated noise are *propeller cavitation* and propeller singing. It is estimated that 80 – 85% of the noise power radiated into the water by surface ships comes from the propeller cavitation. There are two types of radiation from cavitating propellers, low frequency tonals and a broad continuum [42, 43]. The tonals are radiated up to the first 10 harmonics of the blade frequency and are usually dominating for frequencies below about 40 to 50 Hz. The continuum controls the spectrum above 50 Hz, generally peaking between 50 and 150 Hz. Above 150 Hz, the spectrum decreases with frequency at about 6 dB per octave. Both the tonals and the continuum are modulated at the shaft rotational frequency, and the continuum is even more strongly modulated at the blade frequency [42]. Cavitation, i.e. stable and transient, may form in the low-pressure regions on the propeller blades as surface cavitation or as tip-vortex cavitation. Because the onset of cavitation is related to ambient pressure as well as to the speed of the propeller, cavitation noise decreases with depth and increases with speed. Also the shape of the propeller blades has a strong influence on the onset of the cavitation, and even small variations in geometry may separate propellers with and without cavitation. While cavitation noise is a major component of the noise signature of surface ships and of submarines operating close to the sea surface, submarines travelling at sufficient depths may avoid propeller cavitation.

In addition to propeller cavitation noise, tonal components may be produced by vibrational excitations of the propeller blades by the stratified flow in the wake of the ship. The occurrence of *singing propellers* is visible as spectral lines in the noise spectra. Also amplitude modulations of the cavitation spectra at the propeller blade rate may frequently be found to characterize certain ship types and their propellers.

Auxiliary machinery like pumps, blowers, electrical generators etc. will primarily produce tonal components due to dynamic unbalances in rotating components. As these devices normally are operating at constant speed, the sound produced is, in general, relatively stable in amplitude and frequency.

The *hydrodynamic noise sources* also include cavitation produced along the ships hull, in valves, in pipe bends, in hydraulic machinery etc. This broadband noise is transmitted through machine structures, along pipes, through bulkheads and sea valves into the water. Water flow past struts may induce structural vibrations through processes of unbalanced vortex shedding off the trailing edge of a strut. These vibrations radiate sound into the sea. Turbulent flow along the hull structure may couple pressure fluctuations back to the hull, thus producing vibrations and sound radiation.

Low-frequency sound radiation from *hull motions* may involve the whole hull. The hull may experience a rigid-body motion in which it retains its shape and either vibrates in position in response to an external alternating force, or rotates about an axis. Moreover, the hull may vibrate in a beam-like flexural mode (whipping) and it may vibrate in a dominantly longitudinal mode, in which the two ends move out of phase in an accordionlike motion. At somewhat higher frequencies, but still below 300 Hz, whole compartments may resonate and emit sound as a cylindrical shell vibrating in a rigid cylindrical baffle [42]. Low-frequency radiation from hull structures is much more important for submerged vehicles, for which the image cancellation, as found for surface ships, is much reduced and for which the propeller cavitation may be absent.

Since the noise radiated is a function primarily of ship size and speed, the ships with the highest propulsion powers are probably the noisiest. A rough estimate of the total overall noise power level produced by an individual surface ship may be obtained using expression (7):

$$L_s = 186 + 15 \log \mathrm{SHP}/10^4 \quad (\mathrm{dB}) \tag{7}$$

where SHP is the Shaft Horse Power corresponding to the ship's speed. Generally, the total power radiated below 100 Hz exceeds that radiated above 100 Hz by about 6 dB.

The various sources of noise in and around a ship are individually related to the ship. Some sources may be absent by certain ships and some sources may be more expressed and the concerted action of all these noise sources form the "noise fingerprint" of the ship.

2.9. *Other man-made sources*

In recent years, a new, major, low-frequency source in shallow waters has raised the ambient noise levels below 100 Hz, occasionally by as much as 20 dB. The source is the explosion-like pulses used during seismic surveying and produced by boomers, air guns, underwater explosions etc. These sources cover a broad frequency range, but with a considerable acoustic power situated at low frequencies. One seismic profiler may transmit the same acoustic power into ambient noise as nearly 300 merchant ships together. Moreover, the significance of off-shore oil exploration as a source of ambient noise is enhanced by the fact that locations on the shallow water parts of the continental shelf for such activities are often optimum for propagation of sound to distant receivers. Drilling, communication and transport activities related to off-shore work produce sound having some of the same features as shipping.

The use of *underwater explosions* and other high-intensity sound sources involve bubble pulsations at low frequencies, but of high intensities. Depending on the depth of the explosion, from 10% to 50% of the energy available in the explosive is radiated as sound [44]. Also boomers and electrical discharges over a spark gap contribute low-frequency sound, in particular due to bubble formation or exitation [45].

2.10. Thermal noise

At elevated frequencies, i.e. above 100 kHz the thermal noise becomes of importance as a major part of underwater ambient noise. As shown by MELLEN [46], the thermal noise of the molecules of the sea places a limit on hydrophone sensitivity at high frequencies. The equivalent noise spectrum level at ordinary sea temperatures produced by thermal noise may be expressed as [2]:

$$NL = -15 + 20 \log f \quad (\text{dB re1}\,\mu\text{Pa}) \tag{8}$$

where f is the frequency in kHz. The noise is increasing with frequency at a rate of 6 dB/octave and it leads to a frequency dependent threshold for the minimum observable sound pressure level in the oceans.

3. Conclusions

Ambient noise in shallow water regions is caused by a broad variety of sources, frequently not all being active at the same time. The spectra and the directivity of the ambient noise are strongly influenced by the type of source producing the noise. Therefore, source identification and ranking are major tasks in the study of ambient noise. The advances in underwater acoustic propagation modelling have given rise to progresses in development of computer models for calculation of vertical and horizontal directivity, spectral levels etc. of ambient noise, based on assumptions of type and distribution of sources, in particular the two main sources of noise, shipping and wind [48]. Moreover, most recently and exciting application of the ambient noise has been suggested [49] comprising the use of the local ambient noise as the signal for probing the seabed and for detection of objects in the water column and on and in the seabed. Experimental results have in a convincing way [50] confirmed the applicability of ambient noise for underwater acoustical studies by exploitation of the concept of "Acoustical daylight", and advanced ambient noise imaging systems are now being built [51].

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