J Electroceram (2007) 19:339–347
DOI 10.1007/s10832-007-9059-9

Underwater acoustics: Propagation, devices and systems

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Received: 19 April 2006 / Accepted: 21 August 2006 / Published online: 21 February 2007

Abstract The word *acoustics* originates from the Greek word meaning "to listen." The original meaning concerned only hearing and sound perception. The word has gradually attained an extended meaning and, in addition to its original sense, is now commonly used for almost everything connected with rapidly varying mechanical vibrations, from noise to seismic and sonar systems, to ultrasound in medical diagnosis and materials technology. An important technical application of acoustics is related to undersea activities, where acoustic waves are used in much the same way that radar and electromagnetic waves are used on land and in the air-for the detection and location of objects, and for communications. The reason that acoustic rather than electromagnetic waves are used in seawater is simple: electromagnetic waves are strongly attenuated in salt water and would, therefore, have too short a range to be useful for most applications. This paper gives an introduction to underwater acoustics and an overview of the field of sonar engineering with emphasis on factors that affect range and performance.

Keywords Acoustic waves · Underwater acoustics · Sonar systems

1 Fundamentals of acoustic waves in fluids

Acoustic waves are mechanical vibrations. When an acoustic wave passes through a substance, it causes local changes in the density of the medium, as well as a local displacement of mass. This displacement leads to the formation of forces that create movement aimed at bringing the density back to the state of equilibrium. A simple analogy uses a chain of spring elements with the stiffness K and mass points with mass ρ. When the end of the chain is subjected to a displacement, the rest of the chain will also be displaced with a speed determined by the stiffness of the spring and the weight of the mass points. When a spring element with the length L is compressed by a small length ΔL, the result is a counteractive force F equaling $K(\Delta L/L)$, where K is the spring constant. The dimensions for F and K are in newtons, or kg·m·s^{-2}, and the mass is distributed by ρ kilograms per length unit, measured in kg/m. A simple dimension analysis shows that the displacement is propagated with a speed given by $c=(K/\rho)^{1/2}$. The analogy is simple, but the results are correct. These results also apply to acoustic wave propagation in gases and fluids, with K as the volume stiffness, measured in newtons per square meter (N/m^2) or pascals (Pa), and with ρ as the density of the medium, measured in kilograms per cubic meter (kg·m^{-3}).

The acoustic wave equation for fluids and gases is derived by the application of three simple principles.

- The continuity equation, or conservation of mass
- Newton's second law: force equals mass times acceleration
- The equation of state: the relationship between changes in pressure and volume

Application of these principles yields the linear acoustic wave equation

$$\nabla^2 p = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}. \quad (1)$$

Invited paper at POLECER International Conference, Piezoceramics for end-users II, March 5–8, 2006, Hafjell ,Lillehammer-Norway.

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Where ∇^2 is the Laplace operator and c is the sound speed at the ambient conditions, which can be defined as

$$c = \sqrt{\frac{K}{\rho}}. \tag{2}$$

Thus the sound speed is given by the square root of the ratio between volume stiffness and density, as we found was probable by simple reasoning at the beginning of this section. Both volume stiffness and density depend on the properties of the medium, and therefore on external conditions such as pressure and temperature. From the statements made before, we also understand that sound speed is a local parameter that may well be dependent on location, for instance when the sound speed varies with the depth in the water. Equation 1 gives the wave equation for sound pressure. The other important field variable is the particle velocity $\boldsymbol{u}$ (a vector) which is obtained from Newton's second law

$$\frac{\partial \mathbf{u}}{\partial t} = -\frac{1}{\rho}\Delta p. \tag{3}$$

1.1 Sound speed variations

In the preceding section, we found that the volume stiffness, or the bulk modulus, and the density of the medium give the sound speed. In the sea, both depend on ambient conditions, in particular water temperature, salinity, and the surrounding pressure or depth of the water.

In the literature there are several formulas for calculating sound speed in water. The following simplified formula is sufficiently accurate for most purposes:

$$\begin{aligned} c =& 1,448.6 + 4.618T - 0.0523T^2 \\ &+ 1.25(S - 35) + 0.017D. \end{aligned} \tag{4}$$

Here, c = sound speed (m/s), T = temperature (°C), S = salinity (pro mille), D = depth (m).

The range according to which the sound speed may vary is no more than about ±5%, though when it comes to sound propagation in seawater, this variation is very important, as we shall see later. In other contexts, however, the correct value of the sound speed is not important, so here we apply the nominal sound speed c=1,500 m/s and the nominal density ρ=1,000 kg/m^3.

1.2 Harmonic waves

We will often treat signals and waves with sine or cosine form, also called harmonic signals and waves. Formally, we move from the time domain to the frequency domain by using the Fourier transformation pair,

$$\begin{aligned} \Phi(\omega) &= \int_{-\infty}^{\infty} \phi(t) \exp(-i\omega t)\mathrm{d}t, \\ \phi(t) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} \Phi(\omega) \exp(i\omega t)\mathrm{d}w. \end{aligned} \tag{5}$$

The angular frequency is ω=2πf, with f being the frequency in Hz.

The wave equation in the frequency domain, called the Helmholtz equation, is thereby expressed as

$$\left[\nabla^2 + \left(\frac{\omega}{c}\right)^2\right] p = 0. \tag{6}$$

The acoustic wave number κ and the wavelength λ are defined by:

$$\kappa = \frac{\omega}{c} = \frac{2\pi}{\lambda}. \tag{7}$$

Analysis in the frequency domain means that we assume a solution of the wave equation in the form $\Phi(\omega)\exp(i\omega t)$. After this solution is found, the solution in the time domain, and consequently the time response, is found by using the second transformation in Eq. 5. The last step is often not necessary when we treat signals with narrow frequency bandwidths. Examples of this appear in conventional active sonar, which uses a bandwidth rarely exceeding approximately 10% of the center frequency, where a solution for the carrier frequency tends to be sufficient. Examples of the opposite are to be found in seismic applications, where the signals typically are transients with relatively broad frequency bands and, therefore, demand solution of a Helmholtz equation for a wide frequency band, followed by a transformation back to the time domain.

1.3 Plane waves

For plane waves propagating in the x-direction, the wave equation becomes

$$\frac{\partial^2 p(x,\omega)}{\partial x^2} = -\kappa^2 p(x,\omega). \tag{8}$$

The solution is of the form

$$p(x,\omega) = A\exp[i(-\kappa x + \omega t)] + B\exp[i(\kappa x + \omega t)]. \tag{9}$$

The first term describes a wave propagating in the positive x-direction with amplitude A and the second term is a wave in the negative x-direction with amplitude B.

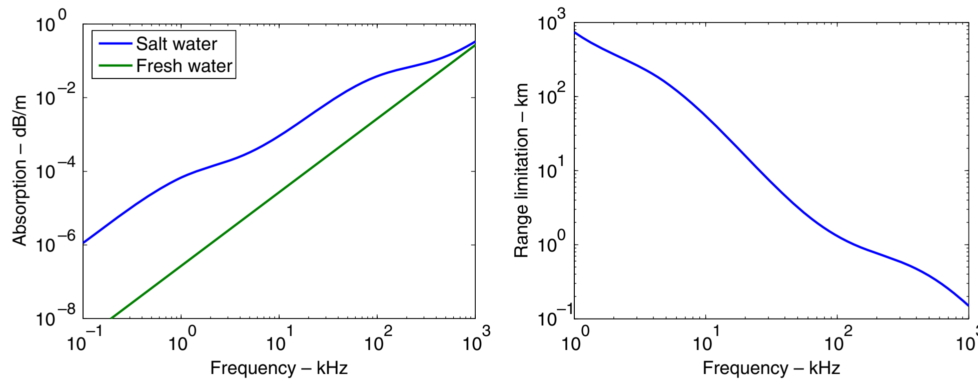


Fig. 1 Acoustic absorption in fresh and salt water, (*left*) plotted in dB per meter as function of frequency. Range for which the absorption will amount to 20 dB (*right*)

The solution for the particle velocity is, from Eq. 3

$$u_x(x,\omega) = \frac{A}{\rho c}\exp\left[i(-\kappa x + \omega t)\right] - \frac{B}{\rho c}\exp\left[i(\kappa x + \omega t)\right]. \tag{10}$$

The product of the density and the sound speed is the specific acoustic impedance $Z = \rho c$. The intensity of a plane wave is generally given as the product of the pressure and the particle velocity, $I = p\ u_x$, and therefore the intensity becomes

$$I = \frac{p^2}{\rho c} = (\rho c)u_x^2, \tag{11}$$

It is assumed in the expressions above that the amplitudes are given as the effective values.

1.4 Absorption

The absorption of sound in sea water depends on many factors; the most important being the temperature and the salinity. Figure 1 shows the absorption coefficient, expressed in dB per meter as function of frequency, calculated for a temperature of 15 degrees for fresh water and for salt water with a salinity of 3.5%. The absorption increases very rapidly with frequency and this means that transmission over long ranges requires relative low fre-

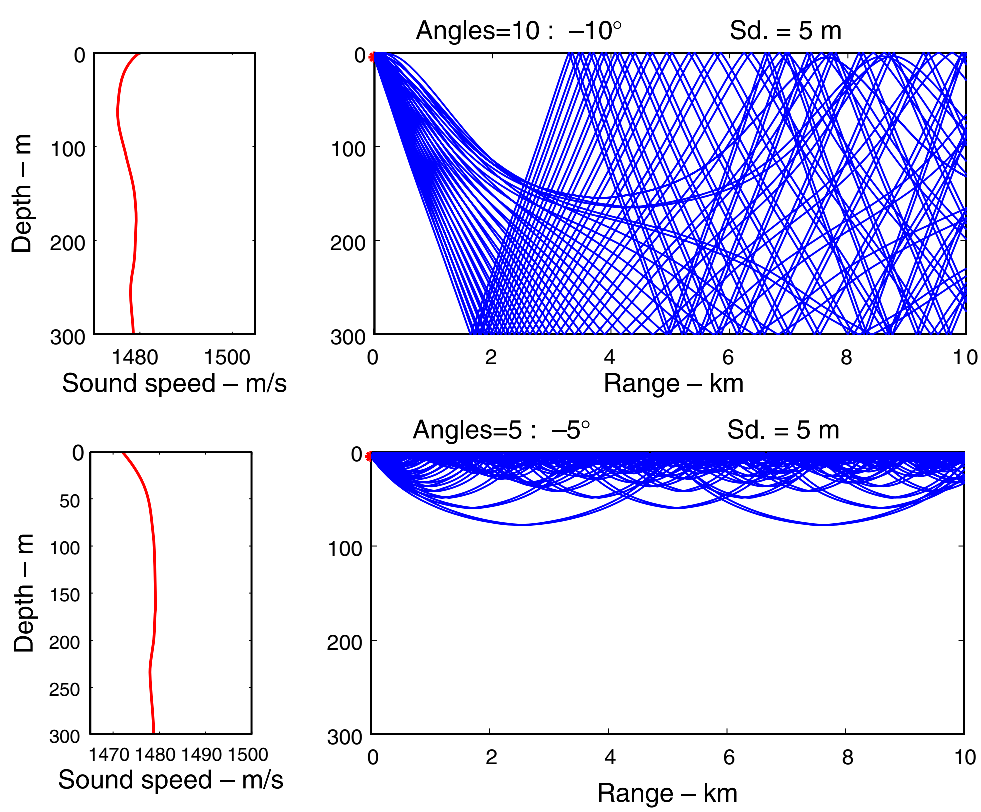


Fig. 2 Examples of ray tracing for the Norwegian Sea under typical summer conditions (*upper*) and winter conditions (*lower*). Source depth is 5 m (*hull mounted*)

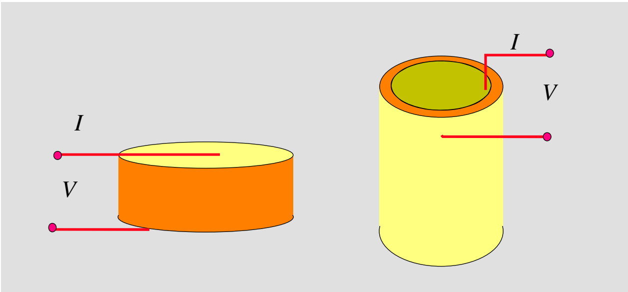


Fig. 3 Examples of transducer elements: *left*, a disk and *right*, a cylindrical tube

quency; the frequency dependency of acoustic absorption is very important for the choice of frequency.

As an indication how range may vary with frequency we have in Fig. 1 also plotted the range for which the salt water absorption will amount to 20 dB.

1.5 Sound radiation from a spherical source

A point source radiates sound in all directions with the same intensity, and at a sufficient large distance r from the source the radiated wave is locally plane. The total radiated power W is the integral of the intensity over a spherical surface of radius r and consequently the sound pressure p at a distance r from a sound source radiating an output power of W (watts) under spherical conditions is:

$$p^2 = \frac{\rho c W}{4\pi r^2}, \tag{12}$$

or in dB,

$$20 \log p = 10 \log \left(\frac{\rho c}{4\pi}\right) + 10 \log W - 20 \log r. \tag{13}$$

With c=1,500 m/s and ρ=1,000 kg/m^3, the numerical value of the equation's first term is approximately 50.8, so that the sound pressure at a distance r from an omnidirectional source that transmits the power W acoustically into the water with the same intensity in all directions becomes

$$20 \log p = 170.8 + 10 \log W - 20 \log r \quad \text{dB(re } 1\,\mu\text{Pa)}, \tag{14}$$

when using the reference 1 μPa=10^{-6} Pa.

We will illustrate the relevant values by using an example. A very high sound pressure in water is one that equals one atmospheric pressure—that is, p=10^5 Pa. Sound pressure of this magnitude is only to be found in the immediate proximity of a powerful sonar that is operating close to the so-called cavitation limit. With this sound pressure, the particle velocity becomes $u_x = p/(\rho c) = 0.067\text{m/s}$. The intensity is $I = 0.5(pu) = 0.33 \cdot 10^4 \text{W/m}^2$, or I=0.33 W/cm^2. Note that the particle velocity is considerably lower than the sound speed, even under such high sound pressure.

1.6 Ray acoustics

Ray acoustics studies and ray tracing calculations are the simplest means for assessment of sound propagation in the sea. Ray acoustics is based on Snells's law and the assumption that the sound follows rays that are normal to surfaces with the same phase. When generated from a point source in a medium with constant sound speed, the phase fronts form surfaces that are concentric circles, and the sound follows straight paths that spread out from the sound source. If the speed of sound is not constant, the sound rays will follow curved paths rather than straight ones.

Figure 2 shows ray paths in the Norwegian Sea during typical summer and winter conditions, respectively. The sound speed profiles are shown at the left sides of the figures; the source depth is 5 m. For the summer profile, we notice that the direct sound's range is very limited because it is bent downward. In the winter the propagation conditions are quite different. For shallow source depths, the sound rays have a marked upward curve, with possibilities of good sonar coverage for shallow targets.

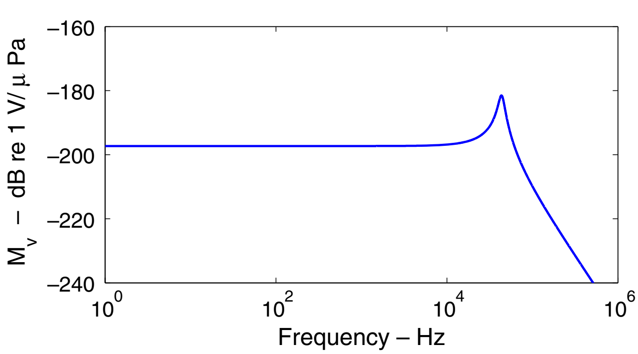


Fig. 4 Typical receiver sensitivity of a ring hydrophone using a tube element with diameter 10 mm and height 20 mm

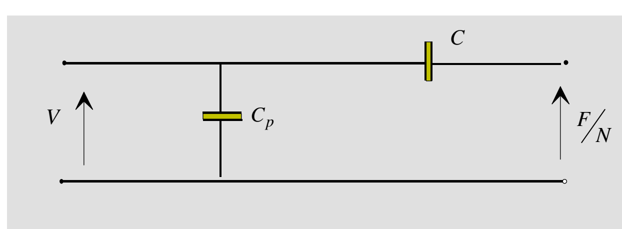


Fig. 5 Circuit diagram equivalent to the ring hydrophone, for frequencies far below the resonance frequency

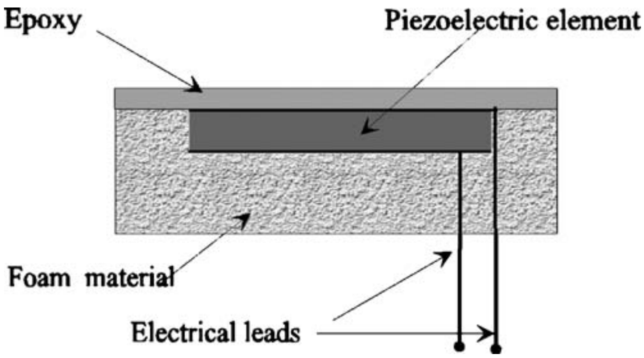


Fig. 6 Half-wavelength transducer in 33-mode

2 Piezoelectric transducers

In nearly all applications of underwater acoustics piezoelectric transducers are used for both transmission and reception. Figure 3 shows two frequently used types of ceramic elements. The left side shows a piezoelectric disk with a conductive metal layer attached to both major surfaces. An element of this type is usually used in the *thickness mode*, or the *33 mode*.

Also shown in Fig. 3 is a piezoelectric tube with a conductive metal layer on the inner and outer cylinder surfaces. A tube like this is often used as a hydrophone or acoustic receiver, but will also work as transmitter. The first resonance of a tube is the frequency where the circumference of the tube is equal to the acoustic wavelength in the tube. The receiving sensitivity, expressed as dB rel. 1 volt/μPa, of a typical hydrophone is shown in Fig. 4. The resonance frequency is this case about 50 kHz, the diameter of the tube is 10 mm, the length is 20 mm, and the low frequency receiving sensitivity is −197 dB rel. 1 volt/μPa. For frequencies much below the resonance frequency the equivalent circuit diagram is simply composed of two capacitors as shown in Fig. 5.

A common transducer for high-frequency application is the piezoelectric disk with an epoxy layer in the front, towards the water, and with a backing of a porous material with acoustic properties like air, Fig. 6. The resonance frequency is the frequency where the thickness of disk equals half the acoustic wavelength of the ceramic.

Larger transducers used in sonar and echo sounders are constructed as shown in Fig. 7. A number of smaller vibrator elements of the form shown at the left side are mounted to form the larger plane projector shown in the right hand side of the figure. The element consists of one piezoelectric disk (or more) with a head facing the water and a backing element behind the disk. An axial bolt, which also ensures a mechanical prestress, keeps the elements together. The vibrator works in the 33-mode.

3 Acoustic antennas, directivity of lines and plates

Underwater acoustic transducers are normally given a size and form to obtain spatial directivity in transmission and reception. For instance, a rectangular antenna with dimensions L_x and L_y will have a two-dimensional beamwidth of approximately

$$\Delta\Omega = \frac{\lambda^2}{L_x L_y} = \frac{\lambda^2}{A_a}. \tag{15}$$

In this expression A_a is the effective radiation area of the projector, and the expression is valid also for other shapes than the rectangular shape.

A consequence of transmitting the sound mainly in a limiting angle is that the sound level on the beam axis becomes higher then when the same power is transmitted omnidirectionally. This is illustrated in Fig. 8, where we compare the maximum of a directional antenna $I(\theta=0)$ with the uniform intensity of the point source. An omnidirectional source transmitting the same power would have given the intensity I_{ref} at distance equal to $I_{\mathrm{ref}}=W/(4\pi r^2)$.

The directivity factor of a planar antenna is therefore

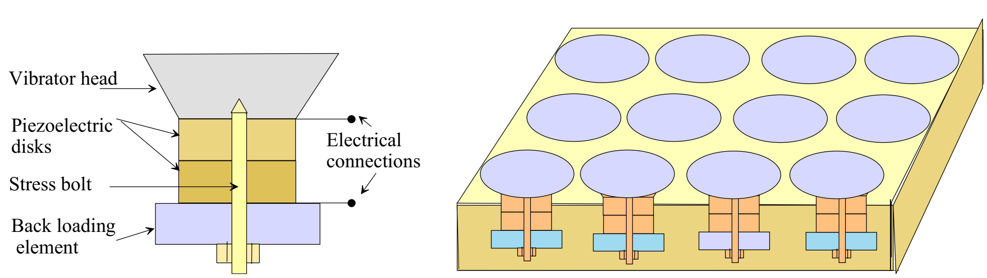
$$D = 4\pi\frac{A_a}{\lambda^2}. \tag{16}$$

The directivity index DI is defined by the logarithmic ratio

$$\mathrm{DI} = 10\cdot\log D. \tag{17}$$

The source level SL of an acoustic source is defined as the sound pressure level in dB relative to 1 μPa at a reference distance of r_0=1 m. The source level of a sound source with

Fig. 7 A common design for a larger underwater transmitter/receiver. *Left*, the device is composed of many elements; *right*, the elements are mounted together in a plate. Together they constitute the complete transducer



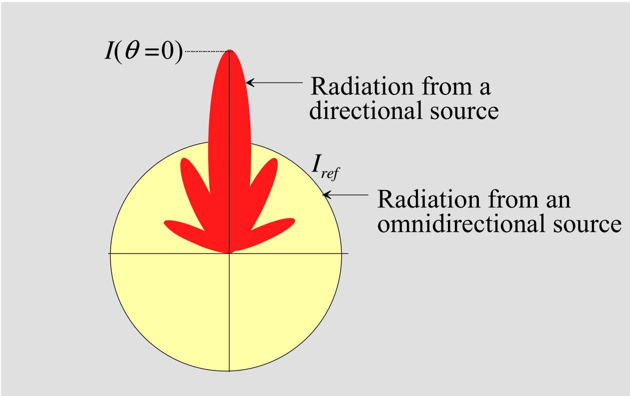


Fig. 8 The directivity factor is defined by comparing the maximum intensity $I(\theta=0)$ of a directional antenna with the intensity of a point source with intensity I_{ref}

directivity index DI and acoustically radiating a power W (watts) is therefore

$$\begin{aligned} \mathrm{SL} &= 10 \log\left(\frac{\rho c}{4\pi}\right) + 10 \cdot \log W + \mathrm{DI}. \\ &= 170.8 + 10 \cdot \log W + \mathrm{DI}. \end{aligned} \tag{18}$$

The numerical factor in Eq. 18 applies to water. For example, a sonar with a 20 dB directivity index and a 1 kW acoustic power has a source level of 220.8 dB relative to 1 μPa. Although we use a reference distance of 1 m in the source level definition, the sound level is not necessarily measured at that distance. Usually, it is necessary to measure the sound level at a much greater distance.

4 Sonar systems

Figure 9 provides a sketch showing a hull-mounted sonar transmitting a sound beam and receiving an echo from a target. In addition to one or more possible echoes, this sonar will receive noise from various sources, as well as reverberation from the sea bottom, sea surface, or other objects in the water. The echo can be detected only when its sound level is higher than those of the noise and reverberation.

4.1 Resolution measures

Angular resolution is defined as the sonar system's capability to distinguish between two equally large targets at the same distance, but having a small difference in bearing. Angular resolution is determined by the beam-width, as two targets can only be separated from each other if the angular distance between them is at least equal to the beamwidth. A uniformly weighted line antenna with the length L has a beamwidth and angular resolution of approximately

$$\Delta\theta = \frac{\lambda}{L}. \tag{19}$$

The range resolution is the ability to distinguish between two equally large targets lying in the same direction, but with a small difference in distance. For a sonar with pulse length ΔT, the two echoes will not overlap at the time of arrival if the radial separation between them is at least

$$\Delta r = \frac{c\Delta T}{2}. \tag{20}$$

This means we have to apply short pulses for a good range resolution if we are using a simple sinusoidal pulse. However, by using a modulated pulse with bandwidth B, for instance an FM pulse, the compressed effective pulse length after matched filter reception is $\Delta T \approx 1/B$, and the range resolution is

$$\Delta r = \frac{c}{2B}. \tag{21}$$

Doppler resolution If a target has a radial velocity relative to the sonar, the echo signal will have a frequency, or Doppler, shift that can be measured and then used to determine the target's relative radial velocity. When a radial velocity component v exists between sonar and target, the frequency shift of a transmitted signal with the frequency f_0 is

$$\Delta f = \frac{2v}{c} f_0. \tag{22}$$

In order to distinguish between two targets having a small velocity difference Δv, the receiver must be able to carry

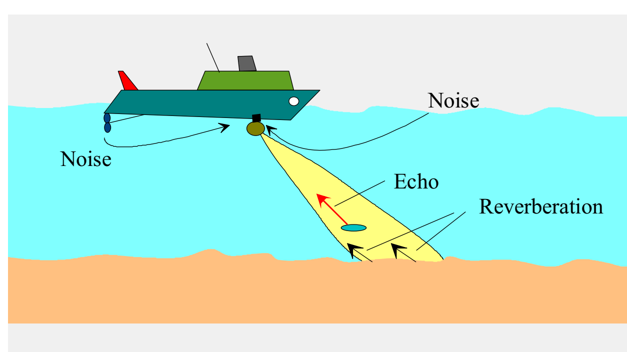


Fig. 9 Searching for an object with a hull-mounted sonar in an environment having both noise and reverberation

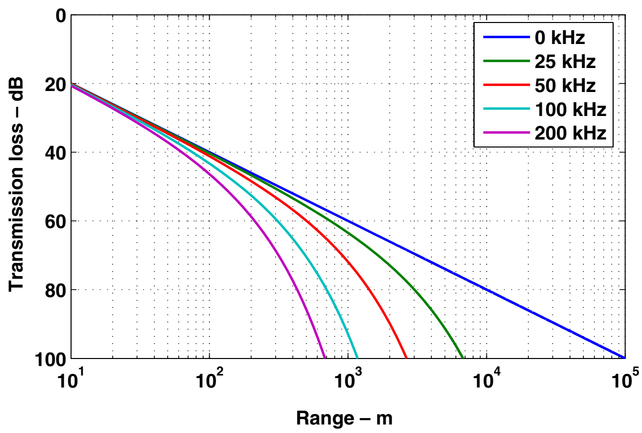


Fig. 10 Transmission loss as function of range for the frequencies of 0, 25, 50 100 and 200 kHz. The transmission loss includes spherical spreading and absorption according to Eq. 27

out a frequency analysis of a received signal with a bandwidth, or frequency resolution, better than the frequency shift given in Equation (22). This means that the processing bandwidth B must be

$$B < \frac{2\Delta v}{c} f_0. \tag{23}$$

The time duration T of the transmitted signal then must be

$$T > \frac{c}{2\Delta v f_0}. \tag{24}$$

We see that a good resolution in both range and velocity can impose contradictory demands. If good resolution in both range and Doppler is required, we will have to use modulated signals with a time-bandwidth product (BT) that is greater than unity.

4.2 The sonar equations

The sonar equations, a set of relatively simple equations, allow us to evaluate various environmental factors, as well as the sonar systems' specifications and properties. These equations allow evaluation of sonar performance based on knowledge of the acoustic environment and the sonar's characteristics. Essentially, we use the sonar equations to determine the level of the signal that is to be detected and to estimate the level of background noise and reverberation.

For active sonar, the echo level EL is given by

$$\mathrm{EL} = \mathrm{SL} - 2\mathrm{TL} + \mathrm{TS}, \tag{25}$$

where *SL* is the transmitter's source level, which is defined by Equation (18), 2TL is the two-way transmission loss, and TS is the target strength. All the terms are given in logarithmic units (dB), so that addition and subtraction replace multiplication and division.

The echo has to compete with noise; the noise level NL is given by

$$\mathrm{NL} = \mathrm{NSL} + 10\log B - \mathrm{DI}_m. \tag{26}$$

Here NSL is the spectral level of the noise, B is the bandwidth of the receiver, and DI_m is the directivity index of the receiving antenna. When the noise is isotropic, DI_m is given by Eqs. 16 and 17. In general, the noise has directional properties, which means that the noise level depends on the receiving direction; and the effective noise contribution must be estimated by integrating the product of the noise's relevant directional distribution and the antenna's directivity. An active sonar will often be limited by reverberation because of reflections from the surface, seabed, or particles in the water mass, but reverberation will not be discussed in this text. For the target to be detected, the echo must exceed the noise or reverberation by a certain detection threshold, which is defined as the difference between the echo level and the noise or reverberation level necessary for the probability of detection to be acceptable, while keeping the probability of false alarm sufficiently low.

4.3 The transmission loss

The transmission loss is determined by the sound speed variation in depth and range, which again is determined by oceanographic conditions: the water's temperature, salt content, and density. If sound propagation involves interaction with the sea surface or the seabed, the properties of these boundaries also may have a significant impact on transmission loss. In order not to complicate the discussion too much, in this section we will apply a very simple transmission model. For transmissions in relatively deep

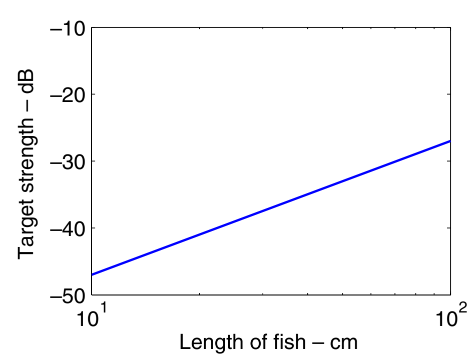


Fig. 11 Target strength of cod as a function of the fish's length

Table 1 Parameters for a hypothetical sonar.

Frequency, f_0	50 kHz	Wavelength, λ	3 cm
Beam angle, $\Delta\theta$	10°	Directivity index, DI	25 dB
Transducer area, A	230 cm^3	Circular disk with radius a	8.5 cm
Pulse power, W_f	2 kW	Acoustic power, W_a	1 kW
Pulse length, ΔT	1 ms	Range resolution, Δr	0.75 m

water and at short distances, we can often assume spherical sound propagation, which along with absorption gives the transmission loss

$$\mathrm{TL} = 20 \cdot \log\left(r/r_0\right) + \alpha(r - r_0), \tag{27}$$

where r is the distance between the transmitter and receiver and r_0 is a reference distance which is usually selected to be equal to 1 m. This expression can be applied with caution to short-distance transmissions, where sound refraction does not play a major role and where there are no interfering reflections from the seabed or sea surface. In Fig. 10 we show the transmission loss according to Eq. 27 using the absorption values from salt water shown in Fig. 1.

4.4 The echo level

The strength of the echo from a target is characterized by its *target strength* (TS) defined by the reflected intensity divided by the incident intensity as

$$\mathrm{TS} = 10 \cdot \log\left(\frac{I_r}{I_i}\right), \tag{28}$$

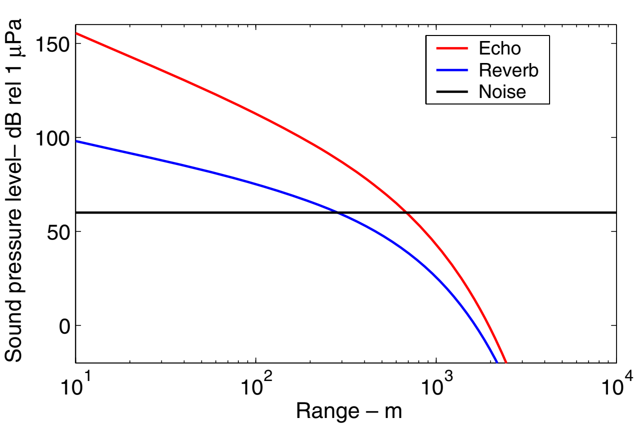


Fig. 12 Echo level EL, reverberation level RL, and noise level NL as functions of the distance to a target for which TS=−30 dB

The target strengths of many objects have been determined experimentally, for instance, careful measurements have been obtained of many fish species. For instance, a simple relation between a fish's length and its target strength is an equation of the form

$$\mathrm{TS} = 20 \log(l) + A, \tag{29}$$

where l is the length in cm and A is a constant. For cod and for a sonar frequency of 38 kHz, the appropriate vale of A is found to be −67 dB. Figure 11 shows the target strength as function of length for cod using Eq. 29.

4.5 Noise

Oceanic acoustic noise is generated from a number of sources with different frequency ranges. The noise that originates from ocean waves, rain and other not-indefinable sources can be considered as the natural background noise called ambient noise. Noise is usually characterized by the noise spectral level (NSL), which is the intensity in dB when measured in a 1 Hz frequency band with reference to the intensity of a plane wave with 1 µPa sound pressure. In order to find the total noise level, we must integrate across the receiver's bandwidth. However, for relatively small bandwidths, such integration can be replaced by multiplication by the bandwidth (which is the same as addition on the decibel scale), as was done in Eq. 26. The mean ambient noise level often follows a group of curves called Knudsen curves. According to these curves, with increasing frequency the ambient noise declines at about 17 dB per decade. Thermal noise may dominate at higher frequencies (that is, above 100–200 kHz) since with increasing frequency such noise increases by 20 dB per decade.

In water with ship traffic or other human activity, the noise produced from such activity will probably dominate and ship noise can have clear spectral lines created by the blade frequency of the propeller and associated harmonics. This noise may be detected and identified by passive military sonar at very long distances. In addition to the ambient noise, there will also be self-noise generated by the machine and propellers of one's own vessel, the movements of the vessel,

Table 2 Nominal range and transducer size for typical sonar systems.

Type	Frequency (kHz)	Wavelength (cm)	Transducer size (cm*cm)	Range (km)
Long	10	15	150*150	30
Medium	50	3	30*30	2
Short	200	0.75	7.5*7.5	0.3

or noise hydrodynamically generated by water flow across the transducers.

5 Example of analyses of active sonar

We will now apply the sonar equations to analyze a typical sonar system. The example is a hypothetical, not representations of any existing sonar, but the parameters and the performance is fairly realistic, and typical of real sonar systems. Table 1 gives the parameters and other relevant information for a sonar intended for midrange applications.

Figure 12 shows the echo level and the noise level as function of range for an object with a target strength of −30 dB and a sonar with specifications given in Table 1. The calculations show that the sonar will be reverberation-limited—that is, the reverberation level will be higher than the noise level up to a distance of about 250 m. Thereafter, the level of the noise will be higher than that of the reverberation. With a detection threshold of 10 dB, we find that the maximum range for detection of a target with target strength TS=−30 dB is approximately 500 m.

Several changes are possible in order to increase this sonar's detection range. The most effective is to use a lower frequency. However this will have the effect of increasing the size and the cost of the system to, may be, prohibitive levels. In Table 2 we have calculated the typical ranges of three hypothetical systems, for short, medium and long ranges, using respectively, 10, 50 and 200 kHz.

The range is defined as the distance where the one-way absorption loss equal 20 dB. It is furthermore assumed that all systems have the same directivity with a beam width of 0.1 radians (=6°) and that the noise level is the same for all frequencies. From the table we understand that very long ranges are possible by using sufficiently low frequencies, but maintaining high angular resolution may require transducer with prohibitive size and cost.

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