Chapter 2

Depth sounding systems

2.1 Introduction

Sonar (*so*und *n*avigation *a*nd *r*anging) is the acronym identifying those systems that rely for their operation on the transmission and reception of acoustic energy in water. The term is widely used to identify all modern systems that propagate acoustic or electromagnetic energy into seawater to determine a vessel's speed or the depth of water under the keel. This book is not concerned with those specialized sonar techniques that are used for locating submerged objects, either fish or submarines. A navigator in the Merchant Navy is interested only in the depth of the water beneath the vessel, an indication of the speed of his ship and the distance run. See Chapter 3 for a description of speed logging equipment.

The first section of this chapter deals with the characteristics and problems that arise from the need to propagate energy in seawater.

2.2 The characteristics of sound in seawater

Before considering the problems of transmitting and receiving acoustic energy in seawater, the effects of the environment must be understood. Sonar systems rely on the accurate measurement of reflected frequency or, in the case of depth sounders, a precise measurement of time and both these parameters are affected by the often unpredictable ocean environment. These effects can be summarized as follows.

- Attenuation. A variable factor related to the transmitted power, the frequency of transmission, salinity of the seawater and the reflective consistency of the ocean floor.
- Salinity of seawater. A variable factor affecting both the velocity of the acoustic wave and its attenuation.
- Velocity of sound in salt water. This is another variable parameter. Acoustic wave velocity is precisely $1505\,\mathrm{ms}^{-1}$ at 15°C and atmospheric pressure, but most echo-sounding equipment is calibrated at $1500\,\mathrm{ms}^{-1}$.
- Reflective surface of the seabed. The amplitude of the reflected energy varies with the consistency of the ocean floor.
- Noise. Either inherent noise or that produced by one's own transmission causes the signal-to-noise ratio to degrade, and thus weak echo signals may be lost in noise.

Two additional factors should be considered.

- Frequency of transmission. This will vary with the system, i.e. depth sounding or Doppler speed log.
- Angle of incidence of the propagated beam. The closer the angle to vertical the greater will be the energy reflected by the seabed.

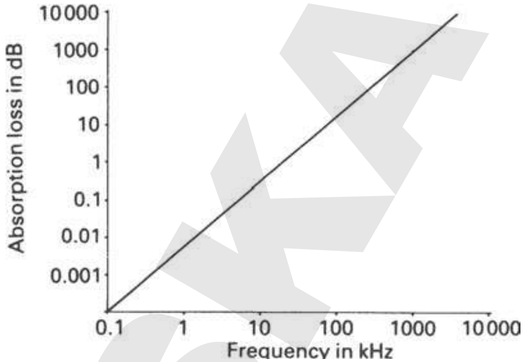

Figure 2.1 A linear graph produced by plotting absorption loss against frequency. Salinity of the seawater is 3.4% at 15°C.

2.2.1 Attenuation and choice of frequency

The frequency of the acoustic energy transmitted in a sonar system is of prime importance. To achieve a narrow directive beam of energy, the radiating transducer is normally large in relation to the wavelength of the signal. Therefore, in order to produce a reasonably sized transducer emitting a narrow beam, a high transmission frequency needs to be used. The high frequency will also improve the signal-to-noise ratio in the system because ambient noise occurs at the lower end of the frequency spectrum. Unfortunately the higher the frequency used the greater will be the attenuation as shown in Figure 2.1.

The choice of transmission frequency is therefore a compromise between transducer size, freedom from noise, and minimal attenuation. Frequencies between 15 and 60 kHz are typical for depth sounders fitted in large vessels. A high power is transmitted from a large magnetostrictive transducer to indicate great depths with low attenuation. Small light craft use depth sounders that transmit in the band 200–400 kHz. This enables compact electrostrictive or ceramic transducers to be used on a boat where space is limited. Speed logs use frequencies in the range 300 kHz to 1 MHz depending upon their design and are not strictly sonar devices in the true definition of the sense.

Beam spreading

Transmission beam diverging or spreading is independent of fixed parameters, such as frequency, but depends upon distance between the transducer and the seabed. The greater the depth, the more the beam spreads, resulting in a drop in returned energy.

Temperature

Water temperature also affects absorption. As temperature decreases, attenuation decreases. The effect of temperature change is small and in most cases can be ignored, although modern sonar equipment is usually fitted with a temperature sensor to provide corrective data to the processor.

Consistency of the seabed

The reflective property of the seabed changes with its consistency. The main types of seabed and the attenuation which they cause are listed in Table 2.1. The measurements were made with an echo sounder transmitting 24 kHz from a magnetostrictive transducer.

Table 2.1 Sea bed consistency and attenuation

Consistency	*Attenuation (dB)*
Soft mud	15
Mud/sand	9
Sand/mud	6
Sand	3
Stone/rock	1

These figures are typical and are quoted as a guideline only. In practice sufficient transmitted power will overcome these losses.

2.2.2 Salinity, pressure and the velocity of the acoustic wave

Since a depth sounder operates by precisely calculating the time taken for a pulse of energy to travel to the ocean floor and return, any variation in the velocity of the acoustic wave from the accepted calibrated speed of 1500 ms^{-1} will produce an error in the indicated depth. The speed of acoustic waves in seawater varies with temperature, pressure and salinity. Figure 2.2 illustrates the speed variation caused by changes in the salinity of seawater.

Ocean water salinity is approximately 3.4% but it does vary extensively throughout the world. As salinity increases, sonar wave velocity increases producing a shallower depth indication, although in practice errors due to salinity changes would not be greater than 0.5%. The error can be ignored except when the vessel transfers from seawater to fresh water, when the indicated depth will be approximately 3% greater than the actual depth. The variation of speed with pressure or depth is indicated by the graph in Figure 2.3.

It can readily be seen that the change is slight, and is normally only compensated for in apparatus fitted on survey vessels. Seasonal changes affect the level of the thermocline and thus there is a small annual velocity variation. However, this can usually be ignored.

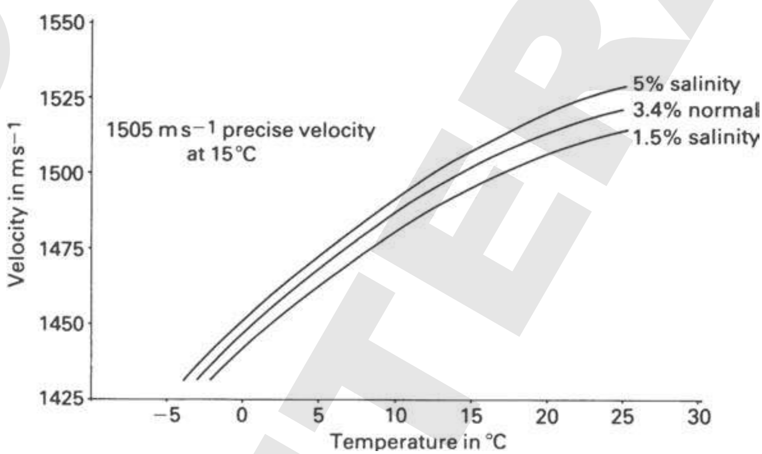

Figure 2.2 Graph showing that the velocity of acoustic energy is affected by both the temperature and the salinity of seawater.

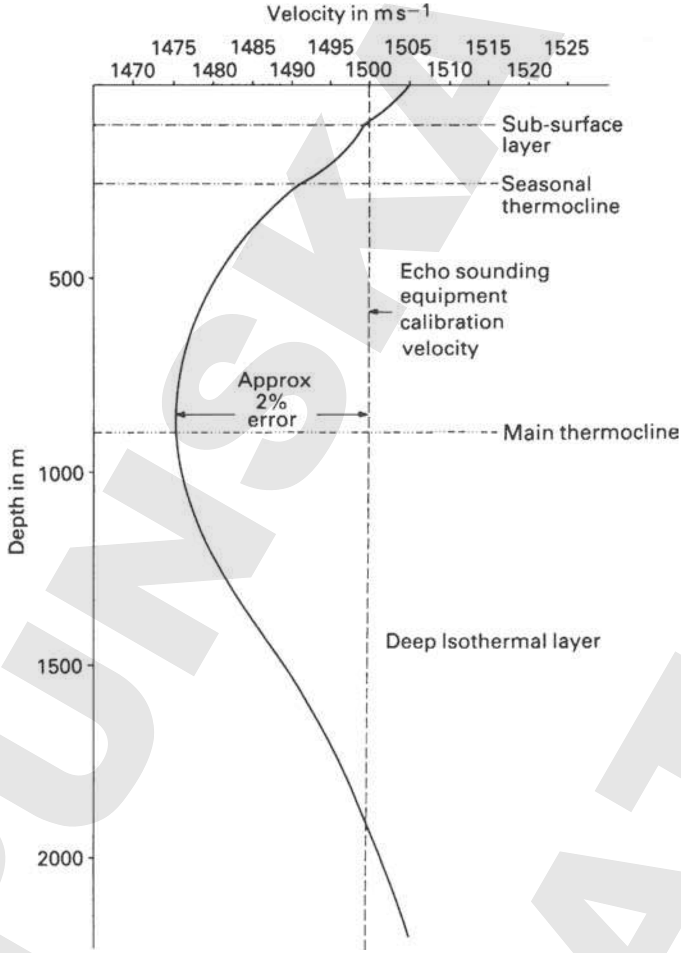

Figure 2.3 Variation of the velocity of acoustic waves with pressure.

2.2.3 Noise

Noise present in the ocean adversely affects the performance of sonar equipment. Water noise has two main causes.

- The steady ambient noise caused by natural phenomena.
- Variable noise caused by the movement of shipping and the scattering of one's own transmitted signal (reverberation).

Ambient noise

Figure 2.4 shows that the amplitude of the ambient noise remains constant as range increases, whereas both the echo amplitude and the level of reverberation noise decrease linearly with range. Because of beam spreading, scattering of the signal increases and reverberation noise amplitude falls more slowly than the echo signal amplitude.

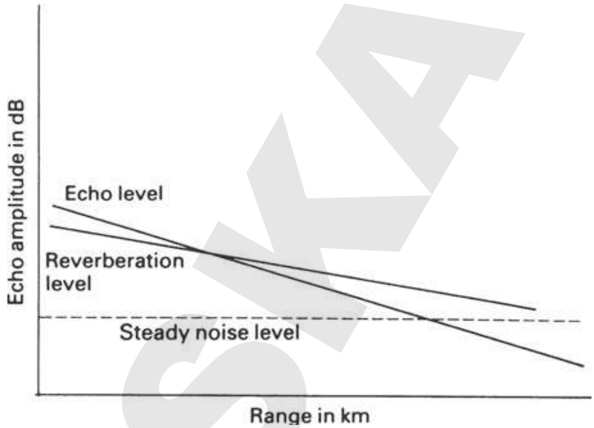

Figure 2.4 Comparison of steady-state noise, reverberation noise and signal amplitude.

Ambient noise possesses different characteristics at different frequencies and varies with natural conditions such as rainstorms. Rain hitting the surface of the sea can cause a 10-fold increase in the noise level at the low frequency (approx. 10 kHz) end of the spectrum. Low frequency noise is also increased, particularly in shallow water, by storms or heavy surf. Biological sounds produced by some forms of aquatic life are also detectable, but only by the more sensitive types of equipment.

The steady amplitude of ambient noise produced by these and other factors affects the signal-to-noise ratio of the received signal and can in some cases lead to a loss of the returned echo. Signal-to-noise ratio can be improved by transmitting more power. This may be done by increasing the pulse repetition rate or increasing the amplitude or duration of the pulse. Unfortunately such an increase, which improves signal-to-noise ratio, leads to an increase in the amplitude of reverberation noise. Ambient noise is produced in the lower end of the frequency spectrum. By using a slightly higher transmitter frequency and a limited bandwidth receiver it is possible to reduce significantly the effects of ambient noise.

Reverberation noise

Reverberation noise is the term used to describe noise created and affected by one's own transmission. The noise is caused by a 'back scattering' of the transmitted signal. It differs from ambient noise in the following ways.

- Its amplitude is directly proportional to the transmitted signal.
- Its amplitude is inversely proportional to the distance from the target.
- Its frequency is the same as that of the transmitted signal.

The signal-to-noise ratio cannot be improved by increasing transmitter power because reverberation noise is directly proportional to the power in the transmitted wave. Also it cannot be attenuated by improving receiver selectivity because the noise is at the same frequency as the transmitted wave. Furthermore reverberation noise increases with range because of increasing beamwidth. The area covered by the wavefront progressively increases, causing a larger area from which back scattering will occur. This means that reverberation noise does not decrease in amplitude as rapidly as the transmitted signal. Ultimately, therefore, reverberation noise amplitude will exceed the signal noise amplitude, as shown in Figure 2.4, and the echo will be lost. The amplitude of both the echo and reverberation noise decreases linearly with range. However, because of beam spreading, back scattering increases and reverberation noise amplitude falls more slowly than the echo signal amplitude. Three totally different ‘scattering’ sources produce reverberation noise.

- Surface reverberation. As the name suggests, this is caused by the surface of the ocean and is particularly troublesome during rough weather conditions when the surface is turbulent.
- Volume reverberation. This is the interference caused by beam scattering due to suspended matter in the ocean. Marine life, prevalent at depths between 200 and 750 m, is the main cause of this type of interference.
- Bottom reverberation. This depends upon the nature of the seabed. Solid seabeds, such as hard rock, will produce greater scattering of the beam than silt or sandy seabeds. Beam scattering caused by a solid seabed is particularly troublesome in fish finding systems because targets close to the seabed can be lost in the scatter.

2.3 Transducers

A transducer is a converter of energy. RF energy, when applied to a transducer assembly, will cause the unit to oscillate at its natural resonant frequency. If the transmitting face of the unit is placed in contact with, or close to, seawater the oscillations will cause acoustic waves to be transmitted in the water. Any reflected acoustic energy will cause a reciprocal action at the transducer. If the reflected energy comes into contact with the transducer face natural resonant oscillations will again be produced. These oscillations will in turn cause a minute electromotive force (e.m.f.) to be created which is then processed by the receiver to produce the necessary data for display.

Three types of transducer construction are available; electrostrictive, piezoelectric resonator, and magnetostrictive. Both the electrostrictive and the piezoelectric resonator types are constructed from piezoelectric ceramic materials and the two should not be confused.

2.3.1 Electrostrictive transducers

Certain materials, such as Rochelle salt and quartz, exhibit pressure electric effects when they are subjected to mechanical stress. This phenomenon is particularly outstanding in the element lead zirconate titanate, a material widely used for the construction of the sensitive element in modern electrostrictive transducers. Such a material is termed ferro-electric because of its similarity to ferro-magnetic materials.

The ceramic material contains random electric domains which when subjected to mechanical stress will line up to produce a potential difference (p.d.) across the two plate ends of the material section. Alternatively, if a voltage is applied across the plate ends of the ceramic crystal section its length will be varied. Figure 2.5 illustrates these phenomena.

The natural resonant frequency of the crystal slice is inversely proportional to its thickness. At high frequencies therefore the crystal slice becomes brittle, making its use in areas subjected to great stress forces impossible. This is a problem if the transducer is to be mounted in the forward section of a large merchant vessel where pressure stress can be intolerable. The fragility of the crystal also imposes limits on the transmitter power that may be applied because mechanical stress is directly related to power. The power restraints thus established make the electrostrictive transducer unsuitable for use in depth sounding apparatus where great depths need to be indicated. In addition, the low transmission frequency requirement of an echo sounder means that such a transducer crystal slice would be

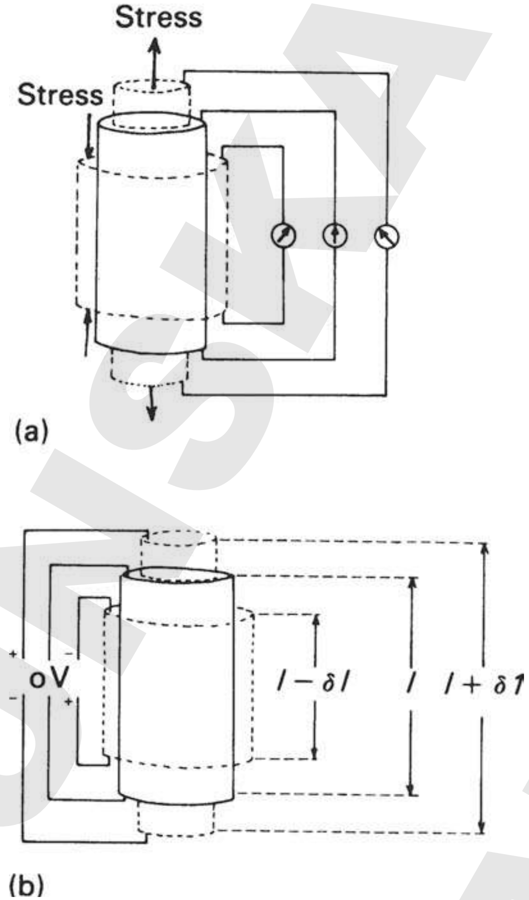

Figure 2.5 (a) An output is produced when a piezoelectric ceramic cylinder is subjected to stress. (b) A change of length occurs if a voltage is applied across the ends of a piezoelectric ceramic cylinder.

excessively thick and require massive transmitter peak power to cause it to oscillate. The crystal slice is stressed by a voltage applied across its ends, thus the thicker the crystal slice, the greater is the power needed to stress it.

The electrostrictive transducer is only fitted on large merchant vessels when the power transmitted is low and the frequency is high, a combination of factors present in Doppler speed logging systems. Such a transducer is manufactured by mounting two crystal slices in a sandwich of two stainless steel cylinders. The whole unit is pre-stressed by inserting a stainless steel bolt through the centre of the active unit as shown in Figure 2.6.

If a voltage is applied across the ends of the unit, it will be made to vary in length. The bolt is insulated from the crystal slices by means of a PVC collar and the whole cylindrical section is made waterproof by means of a flexible seal. The bolt tightens against a compression spring permitting the crystal slices to vary in length, under the influence of the RF energy, whilst still remaining mechanically stressed. This method of construction is widely found on the electrostrictive transducers used in the Merchant Navy. For smaller vessels, where the external stresses are not so severe, the simpler piezoelectric resonator is used.

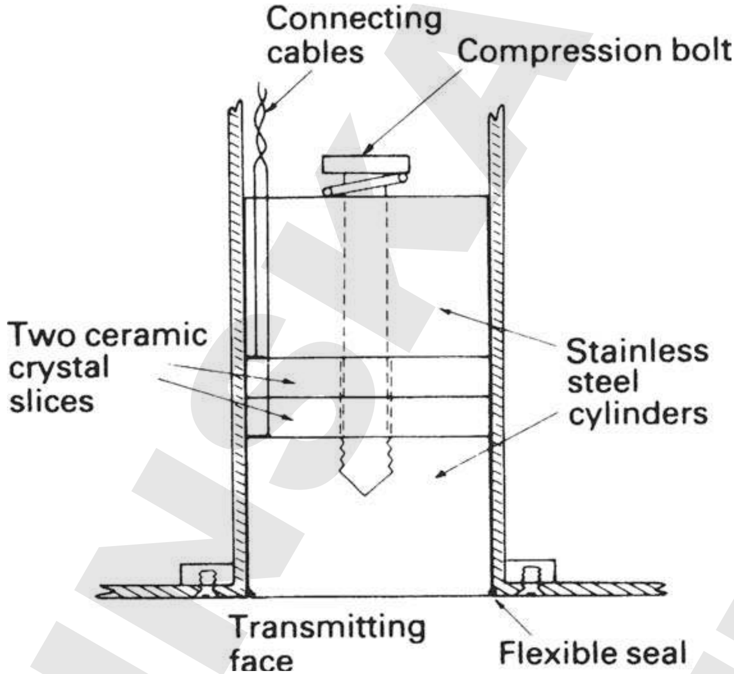

Figure 2.6 Construction details of a ceramic electrostrictive transducer.

2.3.2 Piezoelectric resonator

This type of transducer makes use of the flexible qualities of a crystal slice. If the ceramic crystal slice is mounted so that it is able to flex at its natural resonant frequency, acoustic oscillations can be produced. The action is again reciprocal. If the ceramic crystal slice is mounted at its corners only, and is caused to flex by an external force, a small p.d. will be developed across the ends of the element. This phenomenon is widely used in industry for producing such things as electronic cigarette lighters and fundamental crystal oscillator units for digital watches. However, a ceramic crystal slice used in this way is subject to the same mechanical laws as have previously been stated. The higher the frequency of oscillation, the thinner the slice needs to be and the greater the risk of fracture due to external stress or overdriving. For these reasons, piezoelectric resonators are rarely used at sea.

2.3.3 Magnetostrictive transducers

Figure 2.7 shows a bar of ferromagnetic material around which is wound a coil. If the bar is held rigid and a large current is passed through the coil, the resulting magnetic field produced will cause the bar to change in length. This slight change may be an increase or a decrease depending upon the material used for construction. For maximum change of length for a given input signal, annealed nickel has been found to be the optimum material and consequently this is used extensively in the construction of marine transducers.

As the a.c. through the coil increases to a maximum in one direction, the annealed nickel bar will reach its maximum construction length $(l+\delta l)$. With the a.c. at zero the bar returns to normal (l). The current now increases in the opposite direction and the bar once again constricts $(l-\delta l)$. The frequency

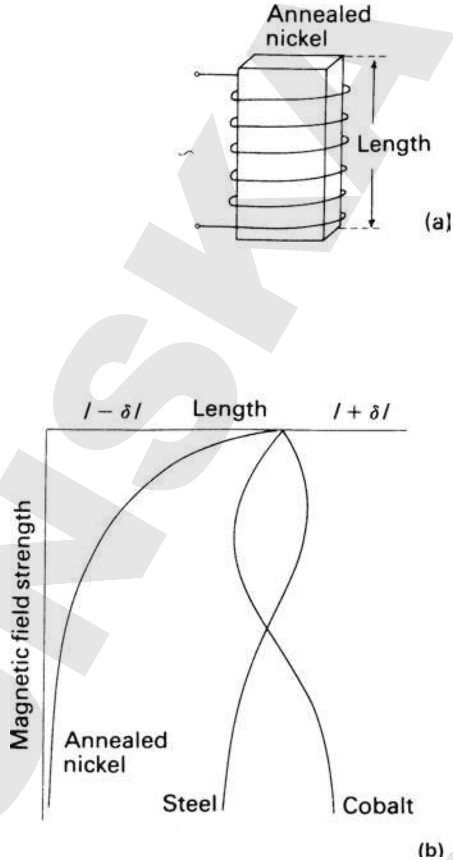

Figure 2.7 (a) A bar of ferromagnetic material around which is wound a coil. (b) Relationship between magnetic field strength and change of length.

of resonance is therefore twice that of the applied a.c. This frequency doubling action is counteracted by applying a permanent magnet bias field produced by an in-built permanent magnet.

The phenomenon that causes the bar to change in length under the influence of a magnetic field is called 'magnetostriction', and in common with most mechanical laws possesses the reciprocal quality. When acoustic vibrations cause the bar to constrict, at its natural resonant frequency, an alternating magnetic field is produced around the coil. A minute alternating current is caused to flow in the coil and a small e.m.f. is generated. This is then amplified and processed by the receiver as the returned echo.

To limit the effects of magnetic hysteresis and eddy current losses common in low frequency transformer construction, the annealed nickel bar is made of laminated strips bonded together with an insulating material. Figure 2.8 illustrates the construction of a typical magnetostrictive transducer unit. The transmitting face is at the base of the diagram.

Magnetostrictive transducers are extremely robust which makes them ideal for use in large vessels where heavy sea pounding could destroy an unprotected electrostrictive type. They are extensively used with depth sounding apparatus because at the low frequencies used they can be constructed to an acceptable size and will handle the large power requirement of a deep sounding system. However,

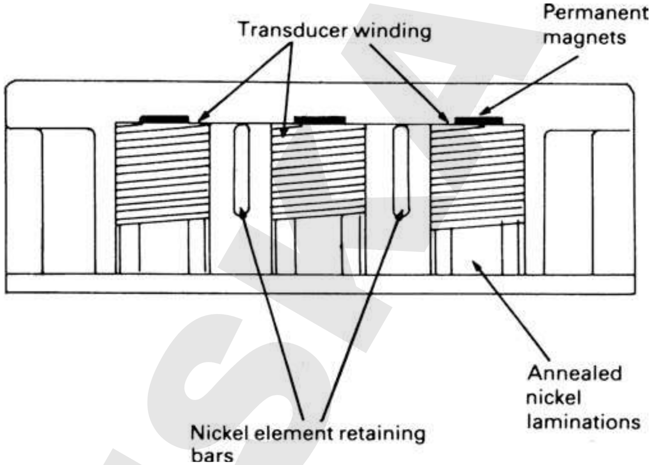

Figure 2.8 Cross-section of a magnetostrictive transducer. (Reproduced courtesy of Marconi Marine.)

magnetic losses increase with frequency, and above 100 kHz the efficiency of magnetostrictive transducers falls to below the normal 40%. Above this frequency electrostrictive transducers are normally used.

2.3.4 Transducer siting

The decision of where to mount the transducer must not be made in haste. It is vital that the active face of the transducer is in contact with the water. The unit should also be mounted well away from areas close to turbulence that will cause noise. Areas close to propellers or water outlets must be avoided.

Aeration is undoubtedly the biggest problem encountered when transducers are wrongly installed. Air bubbles in the water, for whatever reason, will pass close to the transducer face and act as a reflector of the acoustic energy.

As a vessel cuts through the water, severe turbulence is created. Water containing huge quantities of air bubbles is forced under and along the hull. The bow wave is aerated as it is forced above the surface of the sea, along the hull. The wave falls back into the sea at approximately one-third the distance along the length of the vessel from the bow. A transducer mounted aft of the position where the bow wave re-enters the sea, would suffer badly from the problems of aeration. Mounting the transducer ahead of this point, even in the bulbous bow, would be ideal. It should be remembered, however, that at some stage maintenance may be required and a position in the bulbous bow may be inaccessible.

A second source of aeration is that of cavitation. The hull of a vessel is seldom smooth and any indentations or irregularities in it will cause air bubbles to be produced leading to aeration of the transducer face. Hull irregularities are impossible to predict as they are not a feature of the vessel's design.

2.4 Depth sounding principles

In its simplest form, the depth sounder is purely a timing and display system that makes use of a transmitter and a receiver to measure the depth of water beneath a vessel. Acoustic energy is transmitted perpendicularly from the transducer to the seabed. Some of the transmitted energy is reflected and will be received by the transducer as an echo. It has been previously stated that the velocity of sound waves in seawater is accepted to be $1500\,ms^{-1}$. Knowledge of this fact and the ability to measure precisely the time delay between transmission and reception, provides an accurate indication of the water depth.

$$\text{Distance travelled} = \frac{\text{velocity} \times \text{time}}{2}$$

where velocity = $1500\,ms^{-1}$ in salt water; time = time taken for the return journey in seconds; and distance = depth beneath the transducer in metres. Thus if the time taken for the return journey is 1 s, the depth of water beneath the transducer is 750 m. If the time is 0.1 s the depth is 75 m, and so on.

The transmitter and transducer, must be capable of delivering sufficient power and the receiver must possess adequate sensitivity to overcome all of the losses in the transmission medium (seawater and seabed). It is the likely attenuation of the signal, due to the losses described in the first part of this chapter, which determines the specifications of the equipment to be fitted on a merchant vessel.

2.4.1 Continuous wave/pulse system

The transmission of acoustic energy for depth sounding, may take one of two forms.

- A continuous wave system, where the acoustic energy is continuously transmitted from one transducer. The returned echo signal is received by a second transducer and a phase difference between the two is used to calculate the depth.
- The pulse system, in which rapid short, high intensity pulses are transmitted and received by a single transducer. The depth is calculated by measuring the time delay between transmission and reception.

The latter system is preferred in the majority of applications. Both the pulse length (duration) and the pulse repetition frequency (PRF) are important when considering the function of the echo sounding apparatus.

Continuous wave system

This system is rarely used in commercial echo sounding applications. Because it requires independent transmitters and receivers, and two transducer assemblies it is expensive. Also because the transmitter is firing continually, noise is a particular problem. Civilian maritime echo sounders therefore use a pulsed system.

Pulsed system

In this system the transmitter fires for a defined period of time and is then switched off. The pulse travels to the ocean floor and is reflected back to be received by the same transducer which is now switched to a receive mode. The duration of the transmitter pulse and the pulse repetition frequency (PRF) are particularly important parameters in this system

The pulse duration effectively determines the resolution quality of the equipment. This, along with the display method used, enables objects close together in the water, or close to the seabed, to be recorded separately. It is called target or echo discrimination. This factor is particularly important in fish finding apparatus where very short duration pulses (typically 0.25 or 0.5 ms) are used.

Echo discrimination *(D)* is:

$$D = V \times l \text{ (in metres)}$$

where V = the velocity of acoustic waves, and l = pulse length.

For a 0.5 ms pulse length:

$$D = 1500 \times 0.5 \times 10^{-3} = 0.75\,\text{m}$$

For a 2 ms pulse length:

$$D = 1500 \times 2 \times 10^{-3} = 3\,\text{m}$$

Obviously a short pulse length is superior where objects to be displayed are close together in the water. Short pulse lengths tend to be used in fish finding systems.

A short pulse length also improves the quality of the returned echo because reverberation noise will be less. Reverberation noise is directly proportional to the signal strength, therefore reducing the pulse length reduces signal strength which in turn reduces noise. Unfortunately, reducing the signal strength in this way reduces the total energy transmitted, thereby limiting the maximum depth from which satisfactory echoes can be received. Obviously, a compromise has to be made. Most depth sounders are fitted with a means whereby the pulse length can be varied with range. For shallow ranges, and for better definition, a short pulse length is used. On those occasions where great depths are to be recorded a longer pulse is transmitted.

For a given pulse length, the PRF effectively determines the maximum range that can be indicated. It is a measure of the time interval between pulses when transmission has ceased and the receiver is awaiting the returned echo.

The maximum indicated range may be determined by using the following formula:

$$\text{Maximum range indication } (r) = \frac{v \times t}{2} \text{ (in metres)}$$

where v = velocity of sound in seawater ($1500\,\text{ms}^{-1}$) and t = time between pulses in seconds. If the PRF is one per second (PRF = 60), the maximum depth recorded is 750 m. If the PRF is two per second (PRF = 120) the maximum depth recorded is 375 m.

The maximum display range should not be confused with the maximum depth. For instance, if the PRF is one per second the maximum display range is 750 m. If the water depth is 850 m, an echo will be returned after a second pulse has been transmitted and the range display has been returned to zero. The indicated depth would now be 100 m. A system of ‘phased’ ranges, where the display initiation is delayed for a pre-determined period after transmission overcomes the problem of over-range indication.

2.4.2 Transmission beamwidth

Acoustic energy is radiated vertically downwards from the transducer in the form of a beam of energy. As Figure 2.9 shows the main beam is central to the transducer face and shorter sidelobes are also produced. The beamwidth must not be excessively narrow otherwise echoes may be missed, particularly in heavy weather when the vessel is rolling. A low PRF combined with a fast ship speed

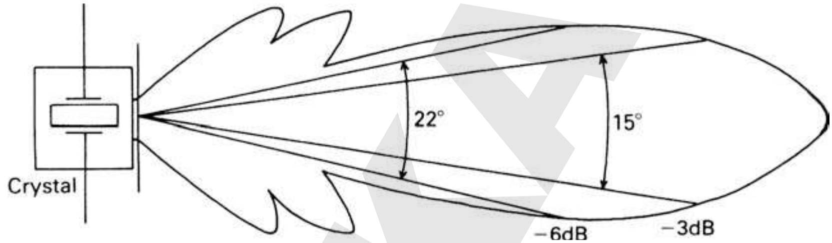

Figure 2.9 Transmission beam showing the sidelobes.

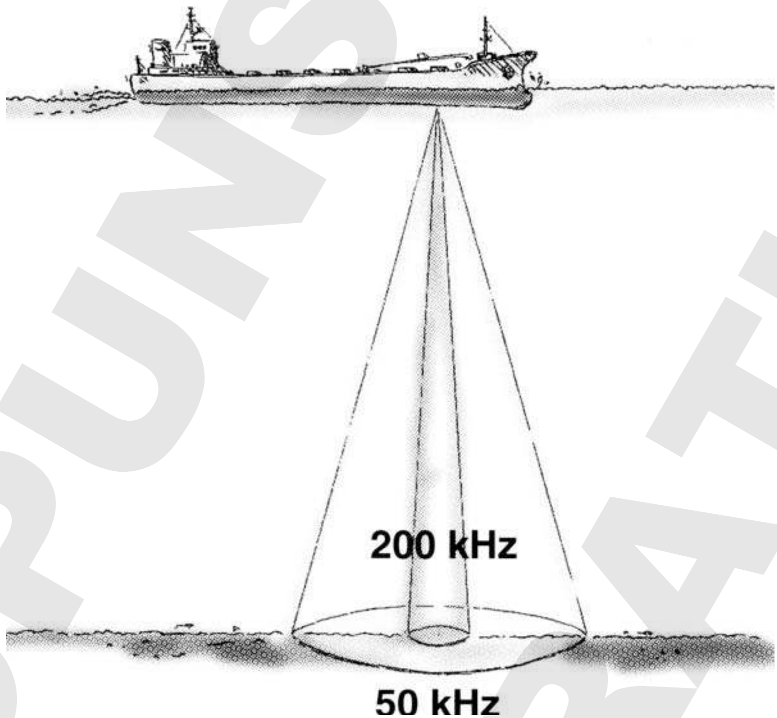

Figure 2.10 Typical beamwidths for echo sounders transmitting low and high frequencies. (Reproduced courtesy Furuno Electric Co. Ltd.)

can in some cases lead to the vessel 'running away' from an echo that could well be missed. In general, beamwidths measured at the half-power points (–3 dB), used for depth sounding apparatus are between 15° and 25°. To obtain this relatively narrow beamwidth, the transducer needs to be constructed with a size equal to many wavelengths of the frequency in use. This fact dictates that the transducer will be physically large for the lower acoustic frequencies used in depth sounding.

In order to reduce the transducer size, and keep a narrow beamwidth, it is possible to increase the transmission frequency. However, the resulting signal attenuation negates this change and in practice a compromise must once again be reached between frequency, transducer size and beamwidth. Figure 2.10 shows typical beamwidths for a low frequency (50 kHz) sounder and that of a frequency four times greater.