COOPERATIVE RESEARCH REPORT
No. 209

UNDERWATER NOISE OF RESEARCH VESSELS
Review and Recommendations

edited by

R. B. Mitson

ACOUSTEC
Swiss Cottage
5 Gunton Avenue
Lowestoft, Suffolk NR32 5DA, UK

International Council for the Exploration of the Sea
Palægade 2 - 4, DK-1261 Copenhagen K
Denmark

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1 INTRODUCTION

The formation of the Study Group on Research Vessel Noise came about because of increasing concern over the effects of underwater noise radiated from research vessels. Evidence has been steadily accumulating of adverse fish reaction to some vessels. For the purposes of fisheries research it is important that the natural distribution of fish should be disturbed as little as possible during population surveys, regardless of whether the sampling is by means of trawl, or acoustic methods. In this connection the statement has been made that, "scientists making underwater observations and measurements need quiet vessels for the same reason that astronomers have to site their telescopes on mountain tops, that is, to prevent the source of energy they need to measure from being obscured by other unwanted sources of this energy" (noise). The needs of the fisheries scientist go further, because they are seeking an elusive prey, sensitive to noise, not inanimate objects.

In 1993 the study group produced an interim report that was presented to the 81st Statutory meeting in Dublin (Anon. 1993). This stated that insufficient information was available at that time to fully address the terms of reference. It was concluded that a detailed study was needed of the published literature relating to ambient noise in the sea, fish hearing, fish reaction to noise and vessel noise. Members of the study group were requested to obtain copies of vessel noise signatures and to send these to the chairman. Where such signatures had not already been measured it was recommended that attempts should be made to do this, either by using established noise ranges, or by the provisional method outlined in the report.

During 1993/4 examination of the literature relating to ambient noise, fish hearing, reaction of fish to noise, ship's noise signatures and effects of noise on scientific echo-sounders has been undertaken. Where appropriate, data have been extracted and re-worked, or re-plotted, to provide a clearer understanding of the way the various factors interact. An important aspect has been the examination of information on fish hearing and the merging of data sets to show the equivalent pressure threshold sensitivities from infrasound* to ultrasound frequencies. In assessing the potential of noise to cause avoidance reactions of fish when vessels approach them there is no direct evidence on the precise nature of the stimulus. However, measurements of reaction range can be related to certain features of typical noise signatures. Due to greater loading on the engine and propeller, noise levels are raised when vessels are fishing, thus increasing the risk of scaring fish from the path of the vessel and the trawl. Other factors may also alter fish sensitivity to noise, e.g., whether they are feeding, or migrating, their physiological condition, water temperature, local light levels, etc.

Mention should be made of the concerns being expressed about the effects of increasing noise levels in the sea on marine mammals. However, dolphins such as *Tursiops truncatus* emit sounds with levels of greater than 200 dB re 1 μPa so there seems little likelihood that any noise from vessels, or from sonar devices used in fisheries acoustics would interfere with these creatures in normal circumstances.

Where acoustic surveys are undertaken, in addition to avoiding any disturbance of the natural distribution of the fish, it is necessary to ensure that the fish target strength distributions and echo-integrator results are free of bias due to high-frequency noise. Here the propeller is the main source but the flow in pumps and piping, hull roughness and hull protrusions can all add significantly to the noise signature. Ideally, it should be possible to detect signals down to the level of the ambient noise in the sea but as shown in Section 2 this is not a stable parameter, originating as it does from a variety of sources.

The propulsion power of vessels has continued to increase, it is now approximately twice that used 25 years ago and such an increase has potential for the production of higher noise levels. Individual noise signatures of some vessels have been examined with a view to describing the origins of radiated noise and relating these to engines, gearboxes, propellers, pumps, etc. Where possible, the characteristic noise spectrum of these items of machinery is demonstrated in terms of changes to the frequency and amplitude of the vessel signature. Some machinery configurations have the potential to produce higher noise levels than others but the extent of actual differences depends on many factors including the construction of the hull and particularly on the operational aspects of speed control. The latter effect is seen most clearly in the case of controllable pitch propellers (CPP's).

In practice it may be necessary for some form of compromise to be reached in setting an underwater radiated noise specification when a vessel is to be constructed (or chartered for a specific project). This document addresses the selection of such a compromise by discussing the factors involved and thereby outlining the possible consequences of not meeting the recommended levels.

The final report of the Study Group was discussed during a one-day meeting in Montpellier in April 1994 and was submitted to the 82nd Statutory Meeting held in St. John's Newfoundland (Anon. 1994b). It was accepted, subject to final review by the chairman of the Fish Capture Committee. The venue's for the meetings

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[*] Professor J.H.S. Blaxter has pointed out that the terms 'infrasound' and 'ultrasound' refer to classification bands of human hearing and have no direct relevance to fish hearing. However, they serve as a useful reminder of the frequencies being discussed so are retained in the text.

of the Study Group, a list of members names and the names of those who participated in the meetings is given in Appendix 3.

Note: To avoid undue repetition of pressure units in the text, sound pressure levels in the report are abbreviated to N dB. The definition is N dB re 1 μPa. When the sound pressure levels are given in relation to a source, e.g. radiated from a vessel, or transmitted by an echo-sounder, the reference distance is 1 metre. All source levels of a vessel refer to a 1 Hz bandwidth, i.e. N dB re 1 μPa (1 Hz band) at 1 m, unless otherwise stated.

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2 AMBIENT NOISE IN THE SEA

2.1 Introduction to ambient noise

The ultimate limit to detection of a wanted signal is ambient noise. Noise is the unwanted sound present in an acoustic measurement system. Ambient noise is that part of the noise independent of the observation system and always present in some form in the sea. Wanted signals in the present context may be defined as the echoes received by any sonar, or echo-sounder, especially those from fish being acoustically surveyed. But there is also a need to recognise that fish have good hearing capabilities and that their detection of sound will ultimately be limited by the level of ambient noise (Buerkle, 1968 & 1969). It is therefore important to recognise the sources of such noise, its variability in terms of frequency spectrum, level, locality and directionality.

Knudsen et al. (1948) published a report which surveyed and compiled the "principle available data on underwater ambient noise" to March 1944, it was condensed from a much longer, recently declassified, survey report. In scope, it covers sources and levels of noise under a variety of conditions and in widely separated localities. Later, the methods of noise generation are well-described by Ross (1976), whereas Wenz (1962) and Urick (1986) deal with levels of ambient noise. Short reviews of both the mechanics of noise generation and resulting ambient noise levels are found in McCartney (1971) and Urick (1983).

2.2 Sources of ambient noise

There are many sources of such noises which may be classified as either:

- *physical* - wind driven, turbulence, seismic, thermal, rainfall, seabed generated and icebergs;
- *biological* - animal sounds and movement;
- *man-made*- shipboard machinery, propeller, water flow around, and discharges from, the hull.

These diverse sources all contribute to the generation of background noise levels but the ambient level is not the result of noise sources alone; it also depends on propagation conditions and the absorption of sound in seawater (Francois & Garrison, 1982). Propagation is dominated by thermal conditions in the water, particularly the depth of the thermocline, but the structure of the seabed and sea surface also contribute substantially. Sound is transmitted easily into soft sediments, where it is largely absorbed, but is reflected from rock with much lower losses. Noise levels are reduced by absorption in both seawater and the seabed.

Low frequencies propagate for great distances with little absorption in seawater but the amplitude of high frequency components of noise is diminished. The resulting spectrum depends on the contributions of these different mechanisms of sound generation and conditions of local absorption. Sound generation is dominated by different physical phenomena in different frequency bands. Above 20 kHz, thermal noise (Mellen, 1952) is generated by molecular collisions. For frequencies between 200 Hz and 50 kHz the main controlling factor is the complex interaction of wind and sea surface. Surface ocean wave interaction (Hughes, 1976) and breaking waves with spray (Wilson, 1980) and Kerman (1984), have been identified as important sources of noise. Wind induced bubble oscillations and cavitation (Furduev, 1966; Ross, 1976) are also near-surface noise sources.

Local noise generated at the seabed may pose problems in the echo-detection of fish (Anon, 1927; Johnson & Muir, 1960; Millard, 1976; Harden Jones & Mitson, 1982; Thorne & Foden, 1988). This noise arises from the movements (collisions) of particles of sand, or gravel, caused by tidal action and covers a wide frequency band from below 30 kHz to above 300 kHz.

Ice in polar regions adds considerably to the noise spectrum, attenuating the effects of wind induced noise when the sea becomes frozen and increasing it in intermediate states. Both cracking ice and the collisions in pack-ice can add to the noise level. Lynch, et al. (1993) show examples of the different noise levels through the year due to the extent of ice in the Greenland Sea.

Ambient noise in the sea increases continuously as the lower frequencies, below about 50 kHz, are approached (Urick, 1983). From 200 Hz to 10 Hz shipping noise is dominant and it is important to remember that this forms part of the ambient noise spectrum. A single vessel carrying the sensing equipment, or operating close by, may give rise to a different spectrum. The major source of shipping noise is the propeller and other rotating machinery such as main engines, gearboxes, generators, or fans. Other sources exist, such as vortex shedding from the hull, noise generated by pipes open to, and discharging into the sea, and noise associated with the wake. Shipping noise is site specific, as illustrated by comparisons between sites on the Scotian Shelf and the Grand Banks by Zakarauskas, et al. (1990). Their study reports that choice of site has a critical effect on measured noise where the type of seabed sediment, and depth of the thermocline, dominate propagation. Wave and wind interactions were identified as the main natural influences, with shipping as the major low frequency factor.

Microseisms, or gravity waves, are the major natural source of infrasound (frequencies between 0.02 Hz and 20 Hz). Below 10 Hz the spectral slope is steep, increasing by about 12 dB per octave in the range 10 - 1 Hz and about 20 dB per octave below 0.1 Hz (Nichols, 1981). Among the suggested sources of this high level of infrasound are turbulence due to ocean currents and seismic motions of the ocean floor (Wenz, 1962;

Urick, 1974). The Mid-Atlantic Ridge, being an unstable area, may be an important source of sound because low-frequency noise can propagate over long distances with little attenuation, thus causing a pattern of infrasound in the sea with regional variation in the directional characteristics. Kibblewhite & Ewans (1985) describe wave-wave interactions as a major source of infrasound. Recent studies of data collected from Wake Island hydrophone arrays (McCreery, et al. 1993) in the North West Pacific Ocean have added to the understanding of very low frequency ambient sound levels. Fish can detect infrasound and Sand & Karlsen (1986) put forward the hypothesis that they may utilise information about the infrasound patterns in the sea for orientation during migration.

2.2.1 Biological sound sources

Biological sources of sound (noise) are common and are normally site specific. Tavolga (1964) edited a volume on this subject and Fish & Mobray (1970) provided a more analytical approach giving considerable data on individual signatures. Brawn (1961) gave details of the sound production of cod and recently Myrberg, et al. (1993) gave details of the sounds of bicolour damselfish. The literature on mammals as sources of underwater sound is extensive, and is well-documented in two books, Purves and Pilleri (1983) and Au (1993). Both provide an excellent source of information and further reference. Generally, dolphins and killer whales generate sound in the region 5 to 200 kHz, while some of the larger whales produce sound below these frequencies. Watkins, et al. (1987) report 20 Hz signals attributed to finback whales as do McCreery, et al. (1993) in their Wake Island study. Propagation losses due to absorption of sound above 10 kHz guarantees that biologically generated sound at these frequencies is not important except as isolated incidents when the animals are close to the observer.

2.3 Levels of ambient noise

There has been a steady upward trend in ambient noise levels since the end of World War II, partly because the number of ships has doubled but, more importantly, due to the dramatic increase in propulsion power for all types of vessel. As Ross (1993) points out, the level has gone up by around 0.5 dB per year since 1950, leading to an overall increase of more than 10 dB in some areas, the East and West Atlantic showing the highest levels.

Wenz (1972) and Urick (1986) give summaries of the spectrum levels of ambient noise. These are largely based on data from deep water although some continental shelf shallow waters are included. Figure 1 (after Wenz) covers 1 Hz to 200 kHz and gives a good indication of the likely noise levels but information on the levels of shipping and wind induced noise are less specific. In figure 2 the spectrum level, redrawn from Urick (1986), is shown from 1 Hz to 1 kHz. This is probably more useful for prediction, being explicitly labelled with wind speed and indications of shipping density. Urick describes these curves as “eyeball spectra” and suggests “they may be said to have some practical value whenever a grand average level, valid world-wide, is required”. Subsequent studies found results that differ only slightly from the levels predicted by Urick from 5 Hz to 1 kHz and these can be used as a guide. Above 1 kHz the curves from Wenz may be used, or the wind speed specific curves from Urick, extrapolated. The spectrum level decreases with frequency at 5 dB per octave to a minimum between 20 to 100 kHz, depending on wind speed. Above this frequency thermal noise is the dominant factor (Mellen, 1952) although it can be detected down as low as 20 kHz under favourable circumstances. Calculation of thermal noise can be made from Mellen (1952)

$$NL_{(\text{thermal})} = -15 + 20 \log f - DI - \log \eta \quad \text{in dB re } 1\ \mu\text{Pa}$$

where f = frequency in kHz; DI = directivity index of the receiving transducer, and η = transducer efficiency (%).

Ambient noise is anisotropic in some frequency bands, this is particularly so in the vertical plane and at high sea states. Becken (1964) made measurements between 750 Hz and 1.5 kHz at about 50 m depth (but similar effects have been noted up to 5 kHz) and obtained the distribution shown in Fig. 3.

The arrowhead shape of this figure is explained as follows: the arrow tip is directed normal to the surface and represents maximum intensity arriving from the surface direction. The tail indicates noise originating at the surface which has been specularly reflected from the seabed. At about ± 15° to the horizontal the marked null in the vertical distribution is due to two effects. First, contributions from the surface source, to the horizontal, or near horizontal distribution, arrive from greater distances than contributions to the off-horizontal distributions and have therefore experienced greater attenuation from spreading and absorption. Second, the level of radiation from the surface source in horizontal directions is more than 20 dB below the level of radiation in the downward directions.

Local effects in coastal areas can sometimes have a time-varying (due to tidal flow) influence on ambient noise levels, e.g. typical spectrum levels measured in the vicinity of large sandwaves (Harden Jones & Mitson, 1982) have been measured as shown below in Table 1.

Table 1. Noise levels generated by tidal action on sand ridges.

Frequency (kHz)	Noise level (dB re 1 μPa at 1 m)
30	98
100	75
300	127

This form of local noise can restrict the operation of sonars and cause misleading echoes to be recorded.

For the infrasound region the spectrum level of ambient noise in the sea, at 0.1 Hz ranges between 120 dB re 1 μPa (1 Hz band) at depths of 300 and 1200 m, to a maximum of 180 dB at a depth of 13 m (Nichols, 1981), with corresponding particle accelerations from less than 10^{-6} ms^{-2} to more than 10^{-4} ms^{-2}. Nichols' data were taken from bottom-mounted hydrophones, averaged over a 6-week period during calm summer weather off Eleuthera Island. Data with one year average levels presented by McCreery, et al. (1993) from sites near Wake Island in the NW Pacific, may also be appropriate, although levels from their bottom-mounted hydrophone at 5500 m are of uncertain origin and may be exaggerated below 1 Hz due to bottom generated noise. Graphs from both papers are replotted in figure 4.

More precise information on ambient levels of noise than that given above is difficult to achieve by calculation. Where noise levels are required more precisely, specific local measurements must be made, or the literature consulted to obtain information for given areas.

2.4 Summary

- Ambient noise forms the ultimate limitation to detection of "signals" at any receiving (listening) point whether it is an echo-sounder transducer, or the hearing organs of a fish.

- Its origins are diverse, arising from wind at the sea surface, seismic activity under the seabed, collision of particles close to the seabed, rainfall, animal sounds, thermal activity and, generated by ships.

- The frequency spectrum and intensity of noise depends greatly on its origins.

- Effects may extend for hundreds of km but are often very localised.

3. FISH HEARING

3.1 The importance of fish hearing

How fish perceive, use, and react to sound is of major importance in reaching conclusions about the appropriate allowable noise levels radiated from vessels. It is clear that fish can detect ship noise at long distances when the ambient levels are low but they are unlikely to react and move away unless the noise is relatively high, typically when the distance is a few hundred metres. Noise within a given band of frequencies, which exceeds certain levels, may have the potential to prejudice results from trawl and acoustic surveys carried out for fisheries research purposes. Because such a possibility exists, the literature on fish hearing thresholds is examined in this section of the report.

3.2 Fish hearing thresholds in relation to pressure and frequency

Initial investigation of fish hearing showed a limited bandwidth of sensitivity, typically centred in the region of 50 to 150 Hz. (Buerkle, 1967; Olsen, 1969; Chapman, 1973; Chapman & Hawkins, 1973; Chapman & Sand, 1974). When much of this experimental work on fish hearing took place, from the mid 1960's to mid 1970's, auditory thresholds were usually measured in terms of particle displacement, which was then converted to sound pressure (Fay, 1988). Sound pressure thresholds from this era are shown in Fig. 5 where the sensitivity of several species are plotted against frequency, indicating that those fish with swimbladders have the most sensitive hearing. Of the published data relating to the "commercial" fishes, all, with the exception of herring (Enger, 1967), have a relatively restricted frequency range, with a steeply increasing threshold at higher frequencies. The indications from these measurements are that the sensitivity was also decreasing at the lower frequencies, from, typically, around 20 or 30 Hz. This appears to indicate that hearing sensitivity below such frequencies is limited but the slope of decline is not obvious from these data. It should be noted that data from measurements of hearing thresholds on many fish were combined so some individual fish may have a sensitivity greater or less than that indicated. For example, Chapman & Hawkins (1973) used 43 cod from 21 to 47 cm to define a mean audiogram. The relationship between fish size and hearing is discussed in section 3.2.5.

3.2.1 Fish hearing mechanisms

The otoliths of the inner ear are responsible for sound detection. Each otolith organ consists of groups of sensory hair cells (the maculae) loaded by the crystalline bodies of the otoliths, which are denser than the surrounding tissues (Sand, 1974a; Hawkins & Horner, 1981; and Fay, 1984). Otolith movement in a sound wave will therefore be delayed relative to the maculae, thereby creating a shearing movement of the hair cells. These cells cannot be stimulated by sound pressure variations, as such, in the propagated wave, but only by the kinetic sound component of the wave, i.e. particle displacement, particle velocity, or particle acceleration. It has now been determined that the auditory stimulus for these sensory cells is particle acceleration (Lewis, 1984; Sand & Karlsen, 1986; and Kalmijn, 1988).

Sound reception in fish is not by the lateral line (Karlsen & Sand, 1987; Karlsen, 1992) although the lateral-line system has an important role in detecting local, low-frequency, water movements when the fish is very close to the source (probably a few body lengths, Denton & Gray (1983)).

3.2.2 Fish sensitivity to very low frequencies (infrasound)

Infrasound is defined as a wave phenomenon having the general characteristics of sound waves except that its frequency range is below that of sound audible to humans. Sand & Karlsen (1986) and others, have measured fish response to particle acceleration down to a frequency of 0.1 Hz, thereby showing that many fish are sensitive to infrasound (0.02 to 20 Hz). Measurements of very low frequencies are difficult for a number of reasons and the response curves for most species show a rise in the threshold of particle acceleration at around 1 Hz or above. Karlsen (1992b) states that the reason for apparent reduced sensitivity of plaice at 1 Hz is unclear but it could be due to masking by the increased respiratory activity of the fish, or by the accentuated background movements of the test chamber which had a resonant frequency of 4.7 Hz. Sand & Karlsen (1986) thought that the measured thresholds for cod above 1 Hz may have been masked by the background noise in the test chamber, resulting in a failure to link directly with higher-frequency data from Chapman & Hawkins (1973). However, the levels at 0.1 Hz are believed to be free of masking, or other effects, and workers making the infrasound measurements comment that the shape of the curves is less important than the biological results.

Enger et al. 1993, believe that the true response to particle acceleration is reasonably flat throughout the region down to 0.1 Hz (Fig. 6) although the actual threshold sensitivity level varies from species to species. On this basis and their belief that the thresholds are correct at 0.1 Hz, the particle acceleration levels at this frequency are used as a reference and recalculated in terms of sound pressure in dB re 1 μPa.

For practical purposes sound pressure is used to determine the effect of noise on fish. Taking threshold values of particle acceleration at 0.1 Hz for each species as the reference, the equivalent sound pressure levels may also be calculated for 1 Hz and 10 Hz. These levels show the slope of the hearing response threshold of cod and plaice at about 25 dB/decade, linking directly (Fig. 7) with data on sound pressure thresholds at 20 Hz and above (Mitson, in prep.). This figure also shows that salmon are less sensitive to sound and have a response slope of almost 35 dB/decade in the region below 20 Hz. No specific measurements have been made on the sensitivity of herring below 3 Hz but Blaxter, et al. (1981) measured the startle response of schools and plotted a relative pressure stimulus response curve against frequency between 3 Hz and 1 kHz. Taking the portion of curve with highest sensitivity (at ≈150 Hz) and relating it to previously measured levels (Enger, 1967) the ratios can be recalculated in terms of dB. These data have been added to Fig. 7 where the 'infrasound' and pressure thresholds have been re-plotted in terms of pressure levels to permit calculations of possible detection and reaction ranges of fish in relation to noise (Section 5).

Section 2.3 showed that, as frequency decreases, infrasound ambient noise levels in the sea rise quickly at about 25 dB/decade between 10 Hz and 0.1 Hz, Nichols (1981). The rate of increase runs approximately parallel to that of the extended fish hearing curves of Fig. 7. Data from Nichols (1981) are similar at 300 and 1200 m depth and appear reliable, thus it can be compared to fish hearing curves. In contrast, Nichols data from a depth of 13 m and that from McCreery, et al. (1993) were presented with qualification and must be regarded as less reliable. Although the similarity of the slope of ambient noise to that of fish hearing cannot be verified, it is reasonable to postulate that fish develop hearing compatible with ambient levels.

3.2.3 Fish sensitivity to very high frequencies (ultrasound)

The dictionary definition of ultrasound is "above hearing" (i.e. the opposite to infrasound and again, this is only relative to human hearing). For the present purpose ultrasound may be regarded as any frequency above 10 kHz. This concept is introduced because recent work appears to indicate the response of some fish species to much higher frequencies than those discussed above. Occasional reports have been made that echo-sounders and sonars can cause an avoidance reaction in fish (e.g., Callon, 1971; Facay, et al. 1977). These have been treated cautiously, but because echo-sounders use frequencies typically two decades above the known hearing response of fish, it has been generally held that any reaction would be due only to the low-frequency "click" of the transmitted pulse envelope. Bercy & Bordeau (unpublished, 1987) looked at the output spectrum of a 38 kHz echo-sounder with a source level (SL) = 167 dB; the response was only 22.5 dB lower at 500 Hz. The echo-sounder output contained no unwanted components so the transducer was deemed to be responsible; however, the low frequency was also reported to be "relatively" directional and it is difficult to reconcile this with normal mechanisms of transduction.

Effects of low and high-frequency sound on blueback herring were investigated by observing their reactions when subjected to pulsed sources of various duration's, Nestler et al. (1992). Frequencies of 110 to 140 kHz with SL > 180 dB produced statistically significant avoidance responses. At 100 and 150 kHz the responses were reduced. Between 100 Hz and 1 kHz (SL = 160 to 175 dB) there were only short term startle responses. In free-field trials a single transducer at either 124.6 kHz (SL = 187 dB) or 130.9 kHz (SL = 200 dB) partially repelled fish that were about 60 m away for about 1 hour. The SL of acoustic survey scientific echo-sounders are typically 20 dB greater than the maximum level quoted by Nestler, et al. (1992).

Dunning, et al. (1992) used frequencies of 110 - 150 kHz (SL = 125 to 180 dB) to study the effect on groups of 25 alewife's in cages. Pulses at 110 and 125 kHz (SL = 175 dB) of 0.5 s duration at intervals of 1 s caused these fish to show a strong avoidance reaction during the day but little response at night. Similar results were obtained in response to a continuous tone of 125 kHz (SL = 172 dB) and a pulsed broadband sound of 117 - 133 kHz (SL ≈ 157 dB). When the pulsed sound was increased to ≈ 163 dB a fairly consistent daytime response was seen; fish did not become accustomed to this stimulus during a 150 minute observation period.

Astrup & Møhl (1993) used an echo-sounder (SL of up to ≈ 224 dB) to test the ability of 15 cod in the size range 18 - 36 cm to detect sound at 38 kHz. Classical cardiac conditioning was used and only fish that could be conditioned to sound between 200 - 300 Hz (currently considered as the upper end of the useful hearing range for cod) were tested for sensitivity to "ultrasound". All fish were positioned at a distance of 0.5 m from the transducer (the near-field extends to ≈ 3 m) and responded to 3 ms pulses of sound at an average threshold of 194.4 dB re 1 μPa. Shaped pulses were then used to reduce the wideband energy but the results were similar to those obtained with the normal echo-sounder pulse. Indications are that the cod were responding to the ultrasonic acoustic stimulation and not to secondary effects. The authors comment that fish may have developed this ability to alert them to the presence of echo-locating odontocetes which, on the basis of their results, would mean at ranges of 10 to 30 m.

No conclusions can be drawn from the present situation regarding fish sensitivity to "ultrasound", but it should be borne in mind that echo-sounder/sonar pulses may have an effect on the behaviour of fish very close to a vessel.

3.2.4 Fish directional hearing

Many fish possess acute directional hearing in both azimuth and elevation (Olsen, 1976; Hawkins & Sand, 1977; Buwalda et al. 1983; Schellart & Munck, 1987b). Engås, et al. (1991a) observed that acoustically tagged fish appeared to be able to predict the bearing of the ship as it approached and to sense the directionality of the "butterfly" pattern of the noise field in front of the vessel.

3.2.5 Hearing of fish in relation to size

Most experimental work on fish hearing has been on adults, probably because they are better able to withstand handling, so the hearing ability of fish of different ages, or size, has not been specifically investigated. Although the size of the swimbladder increases as the fish grows it evidently has no role in the perception of infrasound but acts as an amplifier at the higher frequencies (Sand & Enger, 1973; Sand & Hawkins, 1973; Blaxter et al. 1981). In fish such as gadoids, there is no specialised coupling to the labyrinth but they still use the swimbladder in hearing. It acts as a pressure-velocity converter, generating a scattered wave whose velocity amplification at the otolith may exceed that of the incident wave. Amplification is proportional to a^3 where a is the radius of a sphere equivalent in volume to the swimbladder.This implies that the hearing of cod may be size related, a factor that could have significance in trawl and acoustic surveys. Vessel noise could therefore cause a size dependent reaction amongst fish in the vicinity (see Section 5.4).

3.2.6 Swimbladder resonance

The swimbladder has a variety of functions including sound production and hearing. It is best known as a hydrostatic organ for maintaining the fish at neutral buoyancy for which purpose the volume is changed by secreting or excreting gas. McCartney & Stubbs (1971) and Sand & Hawkins (1973) found that the swimbladders of cod resonated at frequencies well above the hearing range of the fish, e.g., a 16 cm cod showed a resonance frequency of 1.1 kHz. No evidence appears to exist that high levels of sound at swimbladder resonance frequencies will affect the fish.

3.3 Summary

- Sound detection is by the otoliths of the inner ear which respond to the kinetic components of the sound wave rather than sound pressure. Particle acceleration is the true stimulus.

- Practical considerations dictate that threshold sensitivities are usually expressed in terms of sound pressure.

- Fish of the "commercial" species, i.e. cod, herring and similar types, have acute directional hearing extending over a frequency range of approximately 0.1 Hz to 1.2 kHz according to species.

- Maximum hearing sensitivity is typically in the range ≈ 20 - 300 Hz for most species, some may be able to detect high intensity ultrasound (>10 kHz).

- Peak sensitivity for herring is about 75 dB re 1 µPa between ≈ 20 Hz and 1.2 kHz. For cod a similar sensitivity applies from ≈ 100 - 300 Hz.

- Sensitivity to sound may increase in proportion to the size of fish that possess a swimbladder because this organ re-radiates sound waves to the otoliths.

4 VESSEL NOISE

Regulations govern the internal noise levels allowed in ships with very beneficial effects for those living and working onboard. No such regulations exist for noise radiated underwater and the low levels of internal noise in a modern vessel give the impression that the vessel is quiet in all respects. This is not the case and the purpose of Section 4 is to outline the sources and levels of underwater radiated noise found on a selection of fisheries research vessels.

4.1 The origins of underwater radiated noise

4.1.1 Engines

Over the past thirty years the propulsion power used for the operation of fisheries research vessels has typically doubled for the same size of vessel. This is bound to have had an impact on underwater radiated noise, although the levels have not necessarily increased in proportion (which would be equivalent to 6 dB in terms of pressure levels). All propulsion is by diesel engines as the "prime movers" and these come with a variety of specifications in terms of running speed, power output, number of cylinders, four-stroke or two-stroke operation and turbo-charging, all of which have a bearing on the noise signature. The cylinder firing rate, together with its harmonics might extend from a few Hz to several hundred Hz but whether or not these are evident will depend on the level of other contributions to the signature.

Noise frequencies can also change drastically if engine speed is used to control the speed of the vessel but this method is now rare. A common machinery configuration for several years, which has been carried over from commercial fishing vessel practice, is the combination of a diesel engine mounted directly onto the hull of a vessel, a gearbox similarly fixed, driving a CPP. This arrangement in its simplest form couples vibration from the engine and gearbox through to the hull where it is radiated as pressure waves. A modification is the isolation of the engine from the hull which helps to reduce the low-frequency noise levels. Details of the noise characteristically generated by these combinations are given in section 4.5.

4.1.2 Gearboxes

Gearboxes are often a source of high level noise, producing tones, seen on the 1 Hz band noise signature as an increase of the overall level centred on a particular frequency. Frequency will differ depending on the type of gearing and the speed of the input and output shafts. The graph from "Tridens" in **Fig. 8** is an example; the peak at 620 Hz is associated with gearbox "whine". A difficulty in the use of gearboxes is the inability to mount them with a satisfactory degree of isolation from the hull.

4.1.3 Propellers

Propellers are simple-looking devices but are extremely complex to design for a good performance, especially when compromise is necessary for the different loading conditions required for fisheries research purposes. It is beyond the scope of this report to look at the many designs available, merely to compare some general results obtained under working conditions.

Interaction of the propeller and hull is usually responsible for much of the lower frequency noise between ≈ 1 Hz and 1 kHz. This is generated by different mechanisms which include direct vibration imparted to the hull by rotation of the propeller shaft and, often more significant, the pressure pulses from the rotating propeller blade tips causing the excitation of nearby hull plates. These effects are common to both fixed-blade propellers and CPP's.

To ensure that the noise levels remain as low as possible, propellers should be inspected at each dry-docking. If there is damage, even in the form of small 'nicks', or cuts, on the edges of the blades these should be carefully "dressed out" by the repairers to reduce high frequency noise. More extensive damage such as bent or twisted blades will probably be dealt with as essential to the fuel-efficient running of the vessel.

a) fixed blade propellers

Some measurements (Fig. 9) from "Cirolana", a diesel-electric vessel built in 1970 with a fixed 4-bladed propeller illustrate this type of noise. There are no narrowband results for this vessel to give the true level of the tones making up the signature but the dynamic nature of the noise is clear when the vessel speed changes. At 6 knots the peak at 8 Hz appears to be associated with a propeller-excited hull resonance because at 9 knots a much higher level occurs at 7 Hz but at 12 knots it has subsided.

All propellers are vulnerable to a phenomenon known as "singing" although modern designs are now less prone to this problem. The "Explorer" had a propeller that "sang" at 830 Hz which gave a level 10 dB above the average when the vessel was free-running. When trawling the "singing" was swamped by propeller cavitation.

b) controllable pitch propellers (CPP's)

This type of propeller has been fitted to many vessels and continues to be used despite the penalty it imposes in terms of high underwater radiated noise levels. The "Gadus Atlantica" is a noisy vessel with a very high overall level (exceeding 170 dB at low frequencies). Noise ranging was carried out before and after the fitting of a Kort nozzle around the propeller but with no measurable effect on the noise signature. In this case the propeller blades were of unusual design, probably optimised for a specific operational requirement but unsuited to work where reasonable noise levels are needed.

There is ample evidence to show that the underwater noise level can increase very dramatically for changes in propeller speed and pitch but especially when pitch is suddenly altered. Figure 10 (after Gjestland, 1971) shows the measured far-field noise of a purse seiner during a simulated catching routine. This demonstrates that the sudden alteration of pitch from 1.0 to 0.26 produced results of different magnitudes at the three discrete frequencies monitored, i.e., the process was frequency selective. The curves at 100 Hz and 1 kHz are of significance in relation to possible fish reaction, with the change in levels at 100 Hz being dramatic and occurring at, or close to, the most sensitive part of the hearing threshold for several species. Similar effects were obtained from a modern CPP (Fig. 11) used for the new "Tridens" where frequency bands from 126 to 260 Hz and 1 to 10 kHz were monitored (de Haan, 1992). Again it is seen that dramatic changes occur as the propeller pitch angle is changed.

4.2 Machinery configurations

Despite wide variations in the use of individual machines there are two principal configurations and the purpose of this section is to briefly cover their salient points (4.2.1 and 4.2.2). Operational requirements dictate the major design factors such as size of vessel and the power needed to drive it, plus the electrical services that are so important today. Almost every vessel has some parts of her specification that are different to those of the next vessel, consequently there is little consistency in overall design.

4.2.1 Diesel/gearbox/CPP

With this configuration it is normal to have an engine driving a gearbox with typically two speeds and the output shaft of the gearbox coupled to the propeller. In some cases an intermediate shaft from the gearbox is used to drive a generator but this leads to unstable electrical supplies and restricts flexible operation of the vessel because driving speeds are then fixed. The purpose of a controllable pitch propeller is to provide a smooth speed control for the vessel. From a mechanical and operational viewpoint this method of speed control works well but it is clear from the evidence that it is most unsatisfactory when underwater radiated noise is considered. Also, when noise reduction techniques are considered, the diesel-gearbox-CPP system is inherently limited, particularly because of the propeller characteristics and the need for firm mounting of the gearbox. The noise signature of the new "Dr Fridtjof Nansen" has shown that, despite great care in vessel design and the provision of a large diameter propeller (3.8 m), the diesel/gearbox/CPP configuration is not capable of achieving low levels of underwater radiated noise (Anon. 1994a).

4.2.2 Diesel-electric

Diesel-electric installations have one or more diesel engines driving electrical generators which provide power for propulsion and other services. Some of the power from the generators is connected to one or more electric motors directly connected to the shaft of a fixed-blade propeller. System's may be DC/DC, AC/DC or AC/AC. The first two options can provide smooth control from very low creeping speed up to full power and the same may be achieved with AC/AC systems following the introduction of the cycloconverter principle, although this has yet to be proved. No data appear to be available for the radiated noise levels of vessels using this form of propulsion.

Diesel-electric vessels were first built in the 1960's, including the "Sir William Hardy", the "Bjarni Sæmundsson" and "Cirolana". Noise signatures exist for the latter two but the overall signature levels (1 Hz band) do not differ markedly from other vessels of the period. However, with modern technology the diesel-electric system has the potential to achieve much better noise reduction and is capable of meeting the levels that a fisheries research vessel might be expected to attain, based on the foregoing evidence in this report. An example is "Corystes", Kay, et al. (1991). There is also the point that the usual presentation of noise signatures disguises characteristics (fast rate of change of levels as occur with CPP's) which have the potential to scare fish.

4.2.3 Relative operational features

A prime operational requirement in fisheries research is the ability to change speed smoothly between periods of free-running, slow speed steaming, manoeuvring, towing and trawling. Being able to stop the rotation of the propeller is often considered desirable without having to stop the main engine. Given the correct combination of machinery both diesel/gearbox/CPP and diesel-electric systems can provide suitable speed control.

a) diesel/gearbox/CPP

In normal operation the propeller shaft rotates continuously with speed being regulated by the change of propeller pitch but even at zero pitch there is some "creeping" movement of the blades due to leakage in the hydraulic control valves. For this machinery configuration the engine/s must be sited towards the rear of the vessel, thereby reducing flexibility of layout. Typically, two engines are coupled into a gearbox with a power takeoff. Gearboxes are inefficient in the transfer of power, they are also noisy, and it is difficult to isolate them from the hull. In order to obtain sufficient power two or more diesel-driven alternators must also be installed, especially if a bowthruster is run (the shortcomings of shaft-driven generators have been outlined above).

b) diesel-electric

A diesel-electric system is compact and the engines can be sited anywhere in the vessel. Because no direct mechanical coupling is needed to transfer power from the engine it is easy to isolate the engine/generator from the hull on resilient mounts. High efficiency of power conversion by silicon-controlled-rectifiers helps to keep fuel costs relatively low. The installed horsepower can be lower with a diesel-electric system, e.g., the balance of power can be switched to the bowthruster when a vessel is on station with only one engine running. There is also versatility in providing electrical power for all purposes, although separate "clean" supplies are needed for scientific equipment. The voltage is more stable for dynamic positioning (no voltage dips) and there is a reduced possibility of "blackout". Reliability is enhanced due to the constant speed and loading at which the engines can be run and this keeps the engines in better condition with the number of hours between overhauls being approximately doubled.

Diesel-electric propulsion has been used for fisheries research vessels since the late 1960's but only for a small minority of vessels. In view of its apparent advantages the question must be asked, "why so few"? There are two responses: first, the initial expense is about 1.2 times the cost of a diesel/gearbox/CPP configuration: second, the problem of underwater radiated noise has been ignored.

4.3 Underwater radiated noise signatures

A dictionary definition of a signature is, "Any sign that indicates the presence, or activity, of a person, group, or thing". The term is used here to denote the levels of underwater radiated noise against frequency for research vessels. This signature is dependent on a number of factors that combine to determine the overall character of underwater radiated noise. They include such things as the cylinder firing rate of diesel engines and the propeller shaft and blade rate, plus low-frequency resonance's due to the hull of the vessel being excited by vibration from these sources. Vessels of the same design may have similar but not necessarily identical signatures because of differences in the machinery and its running state, the construction of the hull and, in particular, the propeller. In addition, the speed of the vessel and the load being carried, or towed, both play an important part in determining the frequency spectrum and the pressure levels of the signature. Before arranging to have the signature measured it is normal to assume that the vessel is in good condition, e.g., the rudder is not "rattling" etc.

4.4 Noise ranging reports

4.4.1 Current noise signatures and their limitations

Most noise ranging reports contain signatures in the form of averaged curves which are derived from measurements, usually made in a third octave bandwidth, then converted to a 1 Hz band for convenience of calculation and comparison. Some of the results in noise ranging reports cover the frequency band of measurement from 1 Hz to 100 kHz, now regarded as the normal requirement for fisheries research purposes, although many older data series are more restricted. It is standard practice to have measurements made at selected speeds (see Appendix 1 on measurement procedure). The free-running signature at 11 knots is very useful for comparative purposes and gives an insight to a vessel's performance, but it does not necessarily convey sufficient information for a detailed assessment of the potential to fulfil all fisheries research tasks. A shortcoming of many noise ranging reports is the lack of low-frequency narrowband data. This is a matter that needs to be highlighted and arrangements made for its inclusion when future noise ranging is specified and undertaken. It is also necessary to devise trials that will ensure an adequate measure of the rate of change of noise level for important operational conditions of the vessel, including the heavily loaded state of towing a trawl or other operations where many changes of speed are made. This applies particularly when (CPP's) are in use (see Appendix 1).

4.4.2 Directional aspects of noise

A vessel travels on a pre-defined course when being noise-ranged. Hydrophones are located in a suitable configuration to take measurements which are corrected for distance to the vessel. The angle of measurement on each side is about 20 - 30° from the horizontal because of the position of the hydrophones relative to the vessel. Normal practice is to average the measurements from port and starboard sides, which may disguise the fact that a vessel is particularly noisy on one side compared to the other. This is illustrated in Fig. 12 from an early noise ranging of "Corystes", where the port side is seen to be about 6 dB (2 times) above the level of the starboard side in the frequency range 80 to 260 Hz. Clearly, if the measurement included all angles going from port to starboard sides under the vessel there would be variation due to the machinery layout and the individual contribution from machines. This brings up the matter of higher noise levels radiated from the hull directly below the engines. Low-frequency noise of this origin can be quite directional, concentrating the energy vertically downwards and steps should be taken to control it by suitable methods of construction. Arrangements should also be made to measure it in keel aspect. Most noise ranges are now equipped with bottom-mounted hydrophones for this purpose.

4.4.3 Precision and repeatability of noise signature measurements

A high proportion of underwater radiated noise reports originate from Naval facilities and are based on virtually identical measurement techniques, which gives confidence in the relative precision obtained. For example a vessel was built in Norway and noise-ranged before delivery to New Zealand. Soon after arriving there a further ranging was carried out with results within about 1 dB of those obtained in Norway.

4.4.4 Fisheries research vessel noise signature database

Twenty-two underwater radiated noise signatures for fisheries research vessels are currently available in the form of reports, although only those taken in the past twenty years are in similar technical format. These reports cover the period from 1960 to 1994, so some vessels are now out of service but others are in operation for which there are no data and there are a few, for which data exist but is not available to the Study Group.

Most reports include measurements of noise levels against vessel speed over frequency bands that have widened over the years. Usually there is scant information about the machinery and propeller but in a few there are detailed descriptions of these items, together with analyses of their contributions to the vessel's signature. Such information is valuable in building up a picture of the most, or least, effective combinations of machinery in combating excessive noise levels.

4.5 Typical research vessel noise signatures

4.5.1 Noise signatures when free-running

Examination of eight signatures compiled by Ojak (1988) shows the noise characteristics of these vessels to be similar in the region above 260 Hz although the levels vary by about 10 dB: below 260 Hz the variation is about 20 dB. All measurements were made between 1967 and 1971 and five of these reports refer to research vessels. Two of the signatures are from vessels running at 11 knots, another signature from one of the same vessels is at 16 knots, but no information on speed is given for the rest. Signatures of the two research vessels running at 11 knots are shown in Fig. 13, together with those of two vessels built within the past five years. The latter serve to illustrate that no significant improvements in reduction of underwater radiated noise have been made in the majority of recently built vessels. This is not surprising because, for the most part these vessels have used the same type of construction, machinery and propeller as used for commercial fishing vessels.

4.5.2 Noise signatures when fishing

Measurements were made of the noise levels from an Aberdeen bottom trawl and a pelagic trawl towed by "Explorer" (Chapman & Hawkins, 1969) but the pelagic trawl was found to be ripped from wing to codend after behaving strangely during the trials so the results are not given here. **Figure 14** shows the levels from the bottom trawl, being towed at 3.66 knots, taken when it was 10 m from the hydrophone and corrected to 1 m distance. At frequencies up to 2 kHz the vessel noise was dominant but the trawl noise was then greater to the maximum frequency measured of 10 kHz.

A comparison is made in Fig. 15 between "Tridens" towing a 12 m beam trawl at 7.8 knots, a GOV trawl at 4.6 knots, and the noise levels at 11 knots survey speed (de Haan, 1992). The overall increase in levels when trawling is sufficiently high as to almost swamp the 520 Hz tone which dominates at survey speed. It is interesting to note that for the beam trawling condition there is an increase of about 13 dB at 160 Hz above the survey level at the same frequency but when using the GOV trawl a decrease of around 8 dB can be seen.

4.6 Vessel self-noise

The term "self-noise" usually denotes noise received by the echo-sounder or sonar which arises from the noise generated on, or by the ship. This noise is due to the presence of the ship and not the surrounding medium alone. The noise manifests itself in the signal voltage from the transducers which results from it being moved through the water. It is important to keep a clear distinction between "self" and "radiated" noise. The echo-sounder is normally situated within the near-field of these sources and its pickup is very different from that radiated in the far-field but there is no simple correlation between the far and near fields. It is not possible to define self-noise of the ship without reference to the echo-sounder, nor of the echo-sounder, without reference to the ship. Basic mechanisms which provide self-noise are also capable of radiating noise into the sea.

4.7 Summary

- Many vessels built or used for fisheries research do not have a noise specification.
- Fisheries research vessels are being built with high underwater radiated noise levels.
- Controllable pitch propellers are incompatible with the noise requirements for research vessels
- Diesel-electric propulsion has the best capability for low noise levels and has other advantages.

5. FISH REACTION TO VESSELS

5.1 Recognition of the noise problem

The Directorate of Fisheries in Norway formed a Vessel-Noise Committee in 1967 to investigate "noise problems in fisheries" and their report was subsequently published, Anon (1969a). The background was the generally held view that: (a) noise may scare fish; (b) noise can make it difficult to find fish; (c) noise can be inconvenient for the crews of vessels. There were three main conclusions, (a) that a wide interest was evident in the investigation of noise problems on fisheries vessels (b) a recommendation should be made to include in these investigations a means of noise reduction (c) simple measurement methods should be established for routine control of vessel noise levels.

When fishing vessels were first mechanised, fishermen feared that the noise created by the engine and propeller would scare fish away. With the increase of purse seining and other fishing methods, using higher powered vessels, there were marked differences in the reported catching power. Fishermen quickly concluded that fish were scared away by vessel noise, particularly when sudden changes in propeller RPM and pitch occurred. Measurements taken by Gjestland (1971) and de Haan (1992) support these observations (see section 4, Figs. 10 & 11). A number of fishing vessels and research vessels had their noise signatures measured about 1971, (Simrad, Bulletin No. 8, unpublished). These measurements also confirmed that high noise levels and a rapid rate of increase of noise occurred with controllable pitch propellers.

A meeting was held at FAO in Rome (1968) and reported the following year, Anon (1969b). It was agreed that a bibliography be prepared and FAO was requested to sponsor the reproduction of a suitable standard text on underwater noise to be used as a general introduction to the subject. Shortly after, W. Ojak was appointed as the André Mayer research fellow to investigate "Vibration and Noise on Fishery Research Vessels". This was the title of his report published in May 1972. It gives a detailed, technical analysis of the origins of noise, its distribution inside and outside a vessel, as well as the frequencies and levels for different items of machinery. Possible reasons for fish reaction to certain characteristics of the noise field are also discussed.

5.2 Possible stimuli to fish reaction

The 1993 report of the ICES Noise Study Group listed various possibilities for the noise stimulus, or stimuli, that might be responsible for causing a fright reaction in fish. It is now clear from the published literature that the soliton can be discounted, because of its limited range of influence close to the hull of the vessel and, whose effectiveness is confined to very shallow waters. Fish are also unlikely to react to infrasound beyond a few metres from the source, except for the upper end of the band (10 - 20 Hz). Other possible forms of stimulus, listed in 1993, remain as potential sources of fright reaction, with the ability to cause fish to take avoiding action in the horizontal, or vertical planes, relative to the vessel. High intensity ultrasound (section 3.2.3) emanating from echo-sounders or sonars may stimulate changes in behaviour very close to a vessel.

There are indications that tones, wide-band pressure levels, or pressure gradients can cause avoidance reaction. Most of the evidence, though, points to the amount of noise energy contained within the most sensitive hearing band of a particular species. What is certain is that fish do at times, take avoiding action from vessels and many reports substantiate this behaviour under various circumstances. Such action is mostly attributed directly to noise radiated from these vessels. However, other factors, such as feeding behaviour, migration, water temperature, the prevailing light levels, or vessel lights at night (Halldorsson, 1983; Ona & Toresen, 1988a) may influence the magnitude of any reaction.

5.3 Basis of reaction range estimates

In making an assessment of the possible reaction of fish to ship noise it is necessary to examine fish hearing thresholds from Section 3 in relation to the known noise characteristics of vessels given in Section 4. From these factors it is necessary to determine the probable frequencies and levels at which reaction may occur.

The noise field radiated from a vessel and surrounding a fish can be predicted at the position of the fish from *a priori* knowledge of the vessel's noise signature and by making some assumptions about its' propagation. Spherical spreading of acoustic waves is assumed, although at very low frequencies and in shallow water, the wavelengths may be comparable to the depth and the results therefore modified. When fish are seen to react to a vessel the range from the ship to the fish is noted (the reaction range) and the propagation loss calculated. The level in the vicinity of the fish at the time of the reaction can be estimated from the known noise level of the vessel, within the fish's sensitive frequency band, minus the propagation loss. Some observations in the following sub-sections have been recorded from vessels for which noise measurements are unknown so the signature of a typical, similar vessel is used to estimate reaction levels.

For the purpose of this report experimental evidence is taken from a number of published accounts. These relate to various fish species but for simplicity, the threshold hearing responses of only two species, cod and herring, are used to illustrate potential reaction ranges in later subsections. Of the "commercial" species these two appear to be the most sensitive to sound and many of the reports of fish avoidance behaviour are based on investigations concerning these particular or closely related species. Under conditions of high ambient noise levels there will be some masking of fish hearing and this is likely to reduce the reaction ranges.

5.4. Size-related hearing in fish?

Examination of data from Engås, et al. (1993a & b) shows that when a population of cod, at a mean depth of 260 m, were subjected to high sound intensity from seismic airguns at about 80 - 150 Hz, more large fish moved away from the area than small ones. The ratio of fish (in 5 cm size classes) present in the area before the sound transmissions commenced to those left after the transmission had ceased, is shown in Table 2 (Mitson, in prep.)

Table 2. Reaction of cod to seismic airguns

size class (cm)	35- 40	45-50	55-60	65-70	70-75
ratio of numbers before/after firing	2.5	3.1	3.75	5.3	5.6

5.5 Measurements and observations of fish behaviour in relation to vessel noise

The extent of a reaction exhibited by fish to the noise of a vessel depends on various factors including the species, its physiological condition and its immediate environment. The manifestation of a reaction is when the fish tries to move to a lower intensity noise field as quickly as possible. Pelagic fish may dive away from the source or, if in schools near the surface, they may avoid it by breaking up and passing on either side (perhaps simultaneously increasing their depth). As for demersal fish, Shevelev, et al.(1989) reported that cod at about 50 m depth, in 200 m of water, were driven down by the noise of "Pinro" until the density on the bottom and in reach of the trawl had increased substantially. It seems likely that demersal fish in shallower water and already on, or close to, the bottom will make lateral movements out of the vessel's path if the noise levels are sufficiently high.

5.5.1Lateral avoidance and increase in depth by deep schools

An echo-sounder transducer was placed at 45 m depth looking downwards by Olsen, et al. (1983a). When a vessel running at 15 knots passed directly overhead, hibernating herring schools at 60 - 95 m below the transducer immediately moved and left a void through the full depth extension of the school. For a different vessel similar effects were noted for spawning cod and for polar cod and capelin during the feeding season where yet another vessel was used. These authors thought the reaction shown by cod in the very "noisy" Lofoten area was remarkable, indicating that most species will react to an approaching vessel if its noise level is high. Reaction was reduced with increased swimming depth of the fish and decreasing speed of the vessel. The noise signature of the vessel used for the polar cod and capelin studies is known so noise levels can be predicted at the range of the fish. Initially, the top of the school was at 147 m but the fish reacted strongly to the passage of the vessel and disappeared from beneath its track. When seen again the top of the school (looking more dispersed) was at about 155 m.

Although hearing thresholds are not known specifically for polar cod and capelin it is assumed that they are similar to those of cod and herring. On this basis the noise level is ≈ 28 to 34 dB above the hearing thresholds from 40 - 250 Hz, at ranges between 100 and 200 m.

5.5.2 Increase in swimming speed and lateral avoidance

Omni-directional sonars now allow fish swimming speeds to be measured, in addition to the distances at which fish take avoiding action from the path of a vessel. Avoidance reactions reported for cod, polar cod, capelin and herring (Olsen, 1971; Olsen, et al. 1983a & b; pacific mackerel, Neproshin, 1979) were similar to those from sardine and mackerel, Diner & Masse (1987); herring and sprat, Misund & Aglen (1991) and jack mackerel, *Trachurussimmetricus murphyi*, Goncharov, et al. (1989). The latter worked three different geographical areas with the same vessel and each area showed a different reaction distance (Table 3)

Table 3. Observations of jack mackerel schools

Area	mean length of fish	schools		vertical reaction	
	cm	No. seen	No. avoided ship	depth before	depth after
1	34	87	40	36 ± 8.7	62 ± 9.4
2	36	145	35	36 ± 5.7	63 ± 8.3
3	39	65	65	28 ± 3.8	62 ± 10.7

The schools were dense with dimensions of 20 - 27 m long by 10 - 20 m high. As the vessel approached, some of the larger concentrations broke into two parts, passing the vessel one on each side. In **Fig. 16** the reaction to the approaching vessel is seen as an increase in fish swimming speed in relation to the distance from the vessel for the three areas. The calculated mean reaction distances are: area 1 = 84 m; area 2 = 134 m and area 3 = 341 m.

5.5.3 Lateral avoidance by near-surface schools

Diner and Masse (1987) made many observations of fish in relation to their research vessel and found that pelagic fish schools took strong avoiding action at ranges between about 150 to 400m but typically at greater that 200 m. Big schools of 100 m, or more across, tended to break into two and pass either side of the vessel as in the report by Goncharov *et al.* (1989). Table 4 gives details of some of the observations. Reaction distances given below are those at which avoiding action started. The vessel was "Thalassa", which is very noisy and this is reflected in the reported reaction distances of between 150 and 400 m.

TABLE 4. (DINER & MASSE, 1987)

Species	Month	Speed of vessel (knots)	Reaction distance (m)
sardine	February	8.5	200 - 300
mackerel	April	7	300 - 400
sardine	May	6.5	≈150

5.5.4 Reaction to the pattern of the vessel's noise field

Acoustically tagged cod, two = 55 cm, one = 45 cm were observed by Engås et al. (1991a) from the 30 m "Fjordfangst" of 165 HP. The vessel was initially towing a bottom trawl at 1 ms^{-1} in depths of 15 - 20 m but the work was later repeated with similar results in 40 m of water. When the vessel was far away from the fish their movements were small and appeared to be unrelated to the vessel. At 200 m range the presence of the vessel caused the fish to "swim calmly along in front" but at around 100 m the swimming pattern became restless until the fish being observed suddenly increased its swimming speed to about 2 ms^{-1}, giving a rapid diagonal burst forward and out of the track of the vessel. This was judged to be a clear avoidance reaction to the approaching vessel.

In two experiments the fish maintained an almost constant distance of ≈ 60 - 70 m directly ahead of the approaching vessel. The initial reaction was again a rapid diagonal burst forward and out of the vessel's track. At about 50 m to the side of the trackline these fish suddenly turned, crossed the midline and swam diagonally forward about 50 m on the opposite side, turned again and repeated this behaviour several times. It seems that these fish used their directional hearing capability to sense the "wings" of the typical butterfly pattern noise field around the vessel which has a near null at the bow and for 30 - 40° either side. Being a low-powered vessel the noise levels are potentially less than for the more typical research vessel therefore the reaction range of about 100 m is rather lower.

5.5.5 Reaction by lateral avoidance and diving

Ona & Chruickshank (1986) and, Ona (1988), using a 60 m vessel of 3400 HP, but running at a power of about 1000 HP for the trawling operation at 3 knots, observed that cod, *Gadus morhua*, and haddock, perceived noise from this vessel and that they reacted to it at a range of about 200 m. At this range the fish immediately made avoiding movements horizontally and vertically, towards a noise field of lower intensity. The fish were at 20 to 60 m depth and a vigorous diving reaction was evident at the moment the propeller was above them. When towing a pelagic trawl at about 3 knots a similar vessel produces a level of ≈ 151 dB at 150 Hz. At 200 m range this is reduced by propagation losses to about 105 dB, i.e., ≈ 30 dB above the hearing threshold for cod at that frequency.

5.5.6 Reaction to a discrete tone

Nicholson, et al. (1992) investigated the effect on fish catches of an usual feature possessed by "Corystes". This is the ability to switch on or off at will an intense tone at 300 Hz (and its harmonics) approximately 33 dB above the average free-running noise level of the vessel. A series of 190 trawl tows at different depths, <50 m and >50 m, with different gears, Granton and beam trawls, during daylight and in the dark, were made at various tidal states and direction. During the experiment, 15 of the commoner species of fish were caught in numbers varying from tens to hundreds per 30 minute tow and a statistical model was applied to determine the relative effects of trawling with the tone switched on and off. Results showed that catches of haddock in deep water were significantly greater (by 20%) when the 300 Hz tone was switched off. Haddock have a hearing response which is still at maximum sensitivity at 310 Hz but then starts to decrease rapidly (Chapman, 1973). No significant effects were evident for other species.

No noise signature was available for the vessel when towing a trawl so it was uncertain what changes in noise level might occur as a result. Emery & Beach (1994, unpublished) made measurements to observe if changes occurred in noise levels under trawling conditions. Towing an Engels 800 pelagic trawl with codend liner, or blinder (small mesh netting) at 3 knots was compared to the free-running state at 4 to 5 knots. Absolute values were not obtained but the relative measurements showed average increases of about

5 dB up to approximately 4 kHz and around 10 dB thereafter. The "Corystes" is a noise-reduced vessel with low levels between 25 Hz - 1 kHz so the reported increase in noise due to trawling (at the lower frequencies) may be less than for some other FRV's. When trawling, the 300 Hz tone increased by ≈ 7 dB to a level ≈ 40 dB above the hearing threshold of haddock at 65 m depth. Haddock have a slightly lower maximum sensitivity than cod but a marginally increased frequency response around 300 Hz.

5.6 Reaction range

It is clear from the observations and measurements in Section 5.5 that avoidance behaviour by fish in relation to vessel noise may result in a combination of actions but that the effect is to change the natural distribution pattern of fish around and, or, below a noisy vessel. There were many different vessels reporting these data in relation to a number of species of fish but the indications are that where vessels caused a reaction it was at ranges of between 100 - 200 m: for particularly noisy vessels it was up to 400 m. Numerous factors are involved which will have had a bearing on the particular reaction distance, e.g. some vessels were free-running whilst others were trawling. Regardless of the specific circumstances these distances are too great and the aim should be to reduce them to approximately 10 to 20 m.

To put the reported results from Section 5.5 into context, the known level from a vessel that can be classed as having "medium to high" radiated noise is used as a reference to illustrate likely reaction distances for cod. Fig. 17 shows the hearing threshold for cod with associated lines indicating levels that are 20, 30 and 40 dB higher. The vessel is "Tridens" whose radiated noise level at 150 Hz is 151 dB when free-running at 11 knots (de Haan, 1992). From this the reduction in noise level is calculated at the listed ranges of 10 to 500 m, represented by the dotted lines.

In the most sensitive region of hearing, around 150 - 250 Hz, the noise is seen to be 20 dB above threshold at 500 m and is 40 dB above at 50 m. The same vessel has a higher level of 154 dB at ≈ 500 Hz in the averaged 1 Hz band spectrum (which is due to the gearbox). The true level may be even higher but cod have a low sensitivity at this frequency so are unlikely to be affected. Herring though, have a much wider band of hearing and retain high sensitivity to about 1.2 kHz. For herring, at 500 Hz and the level of 154 dB the ranges would be about 1.6 times greater than those shown in Fig. 17.

What happens to the noise field level when a trawl is being towed has been investigated over the years, with an early report due to Aslanova (1958) followed by, (Chapman & Hawkins, 1969; Chapman, 1970; Buerkle, 1974 and 1977; Ona & Godø, 1990; Ona, 1988; Ona & Toresen, 1988 a and b; Nunnalee, 1991; de Haan, 1992; Emery and Beach, 1994) to quote from an incomplete list. Section 4 contained examples of noise signatures for some vessels towing fishing gear and it is clear that for a given vessel there will be an increase over the free-running state of between 5 and 15 dB. This needs to be taken into account when estimating possible reaction distances from the normally available free-running signature.

5.7 Determining the low-frequency noise specification

It is a serious disadvantage for a fisheries' research vessel to cause avoidance reaction in fish at such significant distances (and depths) as 100 - 200, or more metres. Obviously there is a limit to the amount by which noise can be reduced but it should be the aim for vessels used in fisheries research to approach to within about 20 m before the fish take avoiding action. Using this criterion Fig. 18 has been developed so that a low-frequency level can be set for the noise specification in Section 7. In this figure the 30 and 40 dB levels above the most sensitive region of the hearing frequency band for herring and cod have been used to determine the slope of a line. When this is projected to 1 m range it gives the maximum allowable level of radiated noise from a vessel (132 dB re 1 μPa (1 Hz band) at 1 m). For the purpose of applying this value to the radiated noise specification the frequency bandwidth of the herring is used, being the widest.

5.8 Summary of fish reaction to vessels

Evidence is overwhelming that fish show a positive avoidance reaction to vessels when the radiated noise levels exceed their threshold of hearing by 30 dB or more.

Reaction range varies from 100 - 200 m for many typical vessels but 400 m for noisy ones.

The aim is to reduce this to 10 - 20 m

Vessel noise levels increase by 5 - 15 dB when fishing.

Other factors, both physical and physiological, play a part in determining the noise level that will trigger an avoidance response from fish.

6. ACOUSTIC SURVEY INSTRUMENTATION

6.1 Potential effects of vessel noise on acoustic fish stock estimation

6.1.1 Low-frequencies

It was shown in Section 5 that fish avoidance behaviour in relation to a vessel is due to high levels of low frequency noise and the first requirement for acoustic survey is that the surveying vessel causes no undue disturbance to the natural distribution of the fish. This means that they must not be frightened from the path of the approaching vessel so that they would be missed by the acoustic beam. Nor must they be caused to dive when directly below the vessel because of the induced tilt angle which would reduce the measured target strength (Olsen, 1971; Foote, 1980; Olsen, et al. 1983b;) thereby resulting in the population being underestimated. Although low-frequency noise can cause fish to move away from the vicinity of a vessel it is the high frequency component of the noise that has the potential to affect acoustic measurements by the echo-sounder and hence bias the collected data.

6.1.2 High-frequencies

Acoustic instruments are used for many purposes in fisheries research but the most demanding application in terms of performance is the quantitative assessment of fish stocks. Scientific echo-sounders developed for this purpose have the capability to detect objects ranging from very small, single organisms, to large schools of fish. High sensitivity is necessary to achieve this, plus a large dynamic range of 160 dB (a maximum to minimum signal ratio of 10^8 to 1). One of the key functions in acoustic surveys is the measurement of target strength distributions of individual fish, or organisms, to obtain size distributions. This information is used in calculating the population biomass and in helping to determine the species composition.

Most of the acoustic instrumentation operates at high frequencies, above 10 kHz. Only noise generated at these higher frequencies has the potential to degrade the system performance, by obscuring the measurements of single fish echoes and adding to the integral signal obtained from fish aggregations.

Noise at echo-sounder frequencies is mostly propeller induced and it varies with vessel speed. An example is given in Fig. 19 where measurements have been made through the EK500 echo-sounder at 18 and 38 kHz. In order to keep noise levels low, the speed must sometimes be lowered, thus reducing the overall efficiency of data collection by restricting the area covered, or by increasing the time taken. This high frequency noise is predominantly due to propeller cavitation but various other sources may also contribute, e.g. flow-noise from hull apertures, pump outlets, or projections of structures, or instruments.

With fixed-blade propellers cavitation often starts very suddenly, at a critical speed, or loading. For CPP's, which normally cavitate to some extent throughout the full set of operating conditions, it changes with blade pitch and propeller shaft speed settings. Few data appear to have been published on such limitations although much anecdotal evidence is available. Figure 20 is a curve of an echo-integrator output which indicates the steep rise in noise level when propeller cavitation becomes severe but it should be noted that for many vessels this will occur at lower speeds, 9-10-11 knots.

6.2. Detection and processing fish echoes in relation to noise

The most commonly used frequency is 38 kHz. Partly because of the large number of target strength measurements that have been made, the vast experience accumulated over many years of survey, and the range capability of this frequency, it has become an international standard for acoustic surveys. Therefore, the allowable high frequency underwater radiated noise from a research vessel has to be based on what is an acceptable level at this frequency. Recently, there has been an increasing tendency to also use lower frequencies, e.g., 18 kHz and even 12 kHz so these must be given some consideration. Although 120 and 200 kHz are also used, vessel noise levels are normally too low to be of consequence at such high frequencies.

Detection of echoes from fish, particles and organisms is ultimately limited by the ambient noise level which is usually related to the wind-induced seastate at frequencies below about 80 kHz. The maximum possible noise from this source at 38 kHz is about 40 dB (1 Hz band) but, more typically, 30 dB. At 12 kHz the level is ≈ 40 - 50 dB and at 18 kHz is ≈ 38 - 45 dB.

It is necessary to remember that underwater radiated noise picked up by a transducer can increase significantly when the vessel goes into shallow waters where the bottom is hard. For this reason it is necessary to ensure that adequate measurements of the noise are made via the echo-sounder when in such a situation. In most instances the TVG, which suppresses the system gain at shallow depths, will act to reduce or restrain the effect of noise even though the general level has increased due to the proximity of the seabed.

6.3 Determining the high-frequency noise specification

Another, almost universal standard is the use of an EK500 scientific echo-sounder for acoustic survey purposes. The following search for the acceptable vessel noise level is therefore based on this equipment in a similar configuration to that being used by some research organisations. The transducer is towed at about 15 m range from the propeller so the rear of the transducer is exposed to the noise field. It has a sensitivity approximately -36 dB relative to the front face. Normal system settings are used, i.e. the bandwidth is 3.8 kHz.

Taking the ambient noise as 30 dB, the band level of noise is obtained by adding 10 log 3800 = 36 dB giving a figure of 66 dB. With a receiving sensitivity of -186 dB re 1 V per 1 μPa the ambient noise voltage at the transducer terminals will be ≈ 1 μV. A reasonable figure for the vessel noise received by the transducer at 11 knots might therefore be 2 μV, and, back-calculating this to the acceptable noise source at the propeller gives 95 dB (1 Hz band). (note that this level is slightly lower than that attained by "Johan Hjort"). From Fig.19 the level measured on "Bjarni Sæmundsson" at 38 kHz (hull-mounted transducer) is ≈ 1μV.

Assuming a normal source level of 226 dB re 1 μPa at 1 m, the echo levels from fish of three target strengths are calculated and plotted in Fig. 21. These levels are shown in relation to the previously determined vessel noise at 38 kHz and against the effective ranges for a signal-to-noise ratio (SNR) of zero and 10 dB, other ranges can be predicted by interpolation. An adequate SNR must be allowed because of the extremely dynamic nature of noise, especially when it originates from the propeller.

Although the ICES FAST Working Group has informally recommended that the lowest practical aim (smallest target) for detection by survey echo-sounders should be -80 dB, it is clear from Fig. 21, that, for the stated conditions, the range of detection would be very small.

The choice of 95 dB for the specification at 38 kHz is based on a practical situation but it should be remembered that acoustic coupling between the noise source in a vessel and a transducer can be very variable, not only when a towed transducer is used. This is due to such factors as the possibility of reflection from parts of the underwater structure, pickup on transducer sidelobes and surface and bottom scattered noise. The recent practice of placing transducers in a centreboard may offer an opportunity for masking them from propeller noise.

In Section 5 it was determined, on the basis of likely fish reaction levels, that the noise level should average ≈132 dB over the frequency band from 20 Hz to 1.2 kHz. For practical considerations it was to reach 130 dB at 1 kHz, so, running a line from 130 dB at 1 kHz to 95 dB at 38 kHz gives a level at 18 kHz of 102 dB. Vessel noise levels at 12 kHz are likely to be about 3 dB higher than those at 18 kHz but the latter frequency is used here for reference purposes. Taking into account the distance from propeller to transducer, the bandwidth and the sensitivity of the transducer at the rear it can be calculated that this would produce a noise voltage of 2.8 μV. For comparison, the noise level measured at 18 kHz on the "Bjarni Sæmundsson" (Fig. 19) running at 11 knots, gives 3.5 μV at the transducer.

6.4 Summary

- Scientific echo-sounders have high sensitivity and a wide dynamic range so it is vitally important that their transducers work in a low noise field
- The acceptable vessel noise level at high frequencies has been determined as

  $= 130 - 22 \log f_{kHz}$
- At 38 kHz this gives a level of 95 dB re 1 μPa (1 Hz band).
- At 18 kHz it is 102 dB re 1 μPa (1 Hz band).
- Noise at echo-sounder frequencies is normally speed dependent.
- If vessel speed has to be reduced due to noise the overall efficiency of the survey is reduced.

7. ESSENTIAL NOISE REQUIREMENTS FOR RESEARCH VESSELS

7.1 The purpose of a noise specification

There are two vital aims for noise reduction in fisheries research vessels. The first is to ensure that fish do not swim out of the path of the vessel as it approaches; nor must the radiated noise cause an artificial concentration of fish below the vessel. It is necessary to ensure that these effects do not occur, regardless of the method of sampling, whether it is by trawl, or acoustics. The second aim is to prevent noise from being integrated as signal, or from contaminating the fish echoes received and processed by acoustic survey equipment.

7.2 Proposed noise specification: all vessels used for fisheries research

Observations reported in previous sections show that vessel noise has the potential to bias the sampling of fish populations thereby confirming the need to build noise reduced vessels. To achieve this we propose the specification shown in Fig. 22. This is based primarily on two factors as discussed in Sections 5 and 6 respectively: (a) fish avoidance reaction and (b) acoustic surveys. These separately determine the low frequency and high frequency portions of the specification. Levels of noise that will cause fish to react adversely to the approach of a vessel control the low frequency portion of the spectrum. For the present purpose these levels are related to the hearing threshold of cod and herring. Of the "commercial" species these fish have a similar, high sensitivity to noise although herring maintain this over a wider range of frequencies than cod.

For the high-frequency levels an acceptable performance at 38 kHz is the primary requirement, although there is also consideration of lower frequencies such as 12 and 18 kHz that are now being used more often.

The graph in Fig. 22 should be regarded as a conservative specification for noise-reduced vessels because it represents the best performance of the vessel when new. As vessels age, mechanical wear in machinery causes higher levels of noise to be generated (Mitson, 1993). A more stringent specification may be required if the effects of ageing machinery and increased noise levels during trawling are taken into account.

Figure 23 illustrates that the proposed specification is practical and realisable by comparing the 11 knot signatures of two recently built vessels and displaying these against the proposed specification. The upper curve relates to a vessel with some noise reduction measures ("Dr Fridtjof Nansen") and the lower to a noise-reduced vessel ("Corystes").

7.2.1 Low-frequency levels of noise

The low-frequency level shown in Fig. 22 was determined as 132 re 1 μPa (1 Hz band) @ 1 m in Section 5.7 together with an explanation given in conjunction with Fig. 18. This level is effective for both cod and herring and is applicable over the whole of the hearing band of maximum sensitivity for herring (because of their wider bandwidth). For practical reasons the specification is not shown as a continuous line at a level of 132 dB. It is encompassed within the slope of the graph from 135 dB at 1 Hz to 130 dB at 1 kHz to minimise the difficulties to designers and builders in meeting the essential noise requirement.

7.2.2 High-frequency levels of noise

The high frequency levels were determined in Section 6.3 by referring to typical ambient noise levels and placing the acceptable noise level just above (≈ 6 dB). When this is back-calculated to the transducer a level of 95 dB re 1μPa (1 Hz band) at 1 m at 38 kHz is obtained. The ranges at which three target strength classes of fish can be detected and their signals adequately processed in relation to vessel noise is given in Section 6.3 for the given set of equipment operating conditions. At 18 kHz the vessel level was set at 102 dB and the line through the level at this frequency and 38 kHz intersects with the low-frequency specification at 1 kHz (130 dB). Most vessel noise signatures start to "roll off" after 1 kHz at a rate of about 20 dB per decade and coincidentally the high-frequency line of the specification gives a similar slope.

7.3 Checking vessel performance by noise ranging

When previous sections of this report are considered it becomes clear that more than one form of noise measurement is required for a full assessment of the vessel's capability to avoid the potential problems. For the purpose of contractual arrangements in the specification, building and acceptance of a new vessel a single graph is acceptable for the immediate future. This graph forms the proposed underwater radiated noise specification to be achieved at a free-running speed of 11 knots. This is a frequently used speed and operating condition for acoustic survey so a measure of echo-sounder performance is possible. It also facilitates the comparison of vessels because the majority of noise ranging reports include such a measurement.

In addition to this commonly used and accepted measurement a series of noise signatures should be obtained to cover all the important speeds and conditions of operation, including trawling. Such data will be beneficial, not only in identifying the characteristics of the particular vessel, but should, by comparison, enable economic choices to be made in terms of machinery and construction for future designs.

When fishing gear is used the evidence indicates that the vessel's overall noise level increases by between 5 and 15 dB over free-running levels. Depending on the characteristics of the vessel there may also be differences in the frequency distribution of this noise relative to the free-running condition. It is therefore important to determine the frequency response when trawling to allow estimation of possible fish avoidance reaction and the contamination of acoustic or trawl survey data.

7.3.1 Specification for noise ranging

When the noise ranging requirements for a vessel are specified it is recommended that the following measurements are included.

1. Free-running at survey speed (11 knots) and intermediate speeds as required
2. Towing a mid-water trawl
3. Towing a bottom trawl

Narrow band measurements up to 5 kHz should be made in each case.

7.4 Summary

- The proposed noise specification for vessels used in fisheries research is:

  a) $135 - 1.66 \log f_{Hz}$ from 1 Hz to 1 kHz

  (based on a mean level of 132 dB re 1 μPa (1 Hz band) at 1 m, from 20 Hz to 1kHz)

  b) $130 - 22 \log f_{kHz}$ from 1 kHz to 100 kHz

  it is shown graphically in Fig. 22.

- At low-frequencies the level specified above should prevent avoidance of vessels by cod, herring and similar species at ranges in excess of ≈ 20 m.
- High frequency levels are determined primarily by the need to detect and process fish signals at 38 kHz for acoustic survey and to prevent noise being integrated as signal.
- Noise ranging should encompass the sets of conditions detailed in Section 7.3.1. That is, from 1 Hz to 100 kHz, measurements to be presented as dB re 1 μPa (1 Hz band) at 1 m. Narrowband measurements in appropriate bandwidths up to 5 kHz.

8. REPORT SUMMARY

To compile this report we have examined the factors pertaining to underwater radiated noise from vessels used to conduct fisheries research. A brief summary of the salient points is given below.

Ambient noise forms the ultimate limitation to detection of sound by fish or echo-sounder. The origins of ambient noise are diverse and the intensity and frequency distribution depend greatly on the source. Effects are often local but can extend for hundreds of km. Normally ambient noise levels are unlikely to have a significant effect on fish hearing or fish detection excepting under severe weather conditions.

Fish detect sound by the otoliths of the inner ear. Species such as cod, herring and similar types have acute directional hearing but the critical frequency band of high sensitivity hearing is between ≈ 20 -300 Hz for cod and ≈ 20 Hz to 1.2 kHz for herring. For fish with swimbladders sensitivity may increase in relation to size.

Vessels to be used for fisheries purposes are being built without a noise specification and with little or no noise reduction. Controllable pitch propellers (CPP's) generate noise having great variability in frequency and amplitude; efforts to design low-noise versions have been unsuccessful. This type of propeller is incompatible with noise levels required by fisheries research vessels. Consideration of the machinery configurations currently used comes down in favour of a diesel-electric plant used in conjunction with a fixed blade propeller as being the means to obtain satisfactorily low noise levels.

Overwhelming evidence has been presented that fish show an avoidance reaction to vessels when the radiated noise levels exceed their threshold of hearing by 30 dB or more. Environmental and physiological factors play a part in determining the noise levels that will trigger an avoidance reaction in fish. For many vessels fish avoidance reaction distances are 100 - 200 m but for the noisiest 400 m is likely. Noise levels typically increase by about 5 - 15 dB when vessels are fishing.

Scientific echo-sounders have high sensitivity and a wide dynamic range so their transducers need to work in a low noise field if full benefit is to be gained. Noise at echo-sounder frequencies is vessel speed dependent. If it is necessary to reduce speed through excessive noise the efficiency of the survey is reduced, e.g. it will take longer to complete a given area, or the area covered will be smaller than required.

At low frequencies this specification aims to reduce the avoidance reaction of fish from ranges of 100 - 200, (or even 400 m) down to 20 m or less. At high frequencies the proposed levels are based on preventing noise contamination of fish echoes at 38 kHz although 18 kHz levels have also been considered.

On the basis of the evidence contained within the report a graph is given of the proposed minimum noise specification for an FRV (Fig. 22). This is intended to apply to both research vessels and charter vessels used for fisheries research purposes.

9. RECOMMENDATIONS

a) Vessels engaged in fisheries research, whether FRV's, or charter vessels, should conform as closely as possible to the proposed noise signature, i.e.

1Hz to 1 kHz = $135 - 1.66 \log f_{Hz}$

1 kHz to 100 kHz = $130 - 22 \log f_{kHz}$

these specifications are shown graphically in Fig. 22 of this report.

b) The proposed noise levels should be used as a reference when preparing the specification of new vessels and then implemented in the design.

c) Vessels should be noise-ranged on a regular basis, or when any significant damage is thought to have occurred to the propeller.

d) Noise measurements should be used to assess possible limitations of vessels in connection with the work they are required to perform.

e) Careful observations should be carried out whenever possible to relate the known (measured) characteristics of a vessel to any observed avoidance behaviour of fish, or to noise affecting acoustic survey equipment. Any such results should be reported through the normal international channels.

10. REFERENCES

Anon. 1927. Sound ranging with reference to ultrasonic parasitic noises. Hydrogr. Rev., 4(2): 157-9

Anon. 1969a. Fisheries vessels and noise. Report from the Vessel-Noise Committee of the Directorate of Fisheries, Bergen, Norway. English trans. by H. P Knudsen (1993). 15pp

Anon. 1969b. Underwater noise as a problem to fisheries. FAO Fish. Rep. 76. Rome

Anon. 1993. Report of the Study Group on Research Vessel Noise Measurement. ICES. C.M.1993/B:5; Fish Capture Committee. 9pp

Anon. 1994a. Underwater and structureborne noise measurements and analyses for M/S "Dr Fridtjof Nansen", unpublished report.

Anon. 1994b. Report of the Study Group on Research Vessel Noise Measurement. ICES. C.M.1994/B:5; Fish Capture Committee. 55pp

Aslanova, N.E. 1958. A study of the behaviour of fishes in the zone of action of fishing gear. Min. of Agr., Fish. & Food translation. N.S. No. 15. From The Behaviour of Fish and Commercial Searching, Trudy, VINRO 36: 33 - 51

Astrup, J. and B. Møhl. 1993. Detection of intense ultrasound by the cod *GADUS MORHUA*. J. Exp. Biol. 182: 71-80

Au, W.W.L. 1993. The Sonar of Dolphins, Springer-Verlag New York. 277pp

Becken, B.A., 1964. Directional distribution of ambient noise in the ocean. Scripps Inst. Oceanogr. Rep. 61-4

Bercy, C. and B. Bordeau. 1987. Physiological and ethological reactions of fish to low frequency noise radiated by sounders and sonars. Int. Symp. Fisheries Acoustics. Seattle, Wash. USA, 22-26 June. unpubl. 14p

Blaxter, J.H.S., J.A.B. Gray and E.J. Denton. 1981. Sounds and startle response in herring shoals. J. Mar. Biol. Assoc. U.K. 61(4): 851 - 870

Blaxter, J.H.S., 1981. The swimbladder and hearing. In "Hearing and sound communication in fishes" ed W.N. Tavolga, A.N. Popper, R.R. Fay., Springer, NY. Chap. 3: 61-71

Brawn, V.M. 1961. Sound production by the cod. (*Gadus callarias*). Behaviour 18: 239-255.

Buerkle, U. 1967. An audiogram of the Atlantic cod, *Gadus morhua* L. J. Fish. Res. Bd. Can.24 (11): 2309-2319

Buerkle, U. 1968. Relation of pure tone thresholds to background noise level in the Atlantic cod, (*Gadus morhua*). J. Fish. Res. Bd. Can. 25 (6): 1155-1160

Buerkle, U. 1969. Auditory masking and the critical band in Atlantic cod (*Gadus morhua*). J.Fish. Res. Bd. Can. 26: 1113-1119

Buerkle, U. 1974. Gill-net Catches of Cod Gadusmorhua L.) in Relation to Trawling Noise. Mar. Behav. Physiol. (2): 277-281

Buerkle, U. 1977a. Detection of trawling noise by Atlantic cod (*Gadus morhua* L.) Mar. Behav. Physiol. 4: 233-242

Buwalda, R.J.A., Schuijf, A. and A.D. Hawkins, 1983. Discrimination by the cod of sounds from opposing directions. J. Comp. Physiol. 150: 175-184

Callon, L. 1971. Notes sur le chalutage pélagigue du areng et l' utilsation du sonar. In Modern Fishing Gear of the World. Ed. H. Kristjonsson. Fishing News (Books) Ltd. London

Chapman, C.J. and A.D. Hawkins. 1969. The importance of sound in fish behaviour in relation to capture by trawls. FAO Fisheries Report 62 (3): 717-729

Chapman, C.J. 1970. Ship noise and hearing in fish. Scot. Fish. Bull. 33: 22-24

Chapman, C.J. 1973. Field studies of hearing in teleost fish. Helgoländer wiss. Meeresunters, 24: 371-390.

Chapman, C.J. and A.D. Hawkins., 1973. A field study of hearing in the cod (*Gadus morhua*). J. Comp. Physiol. 85: 147-167.

Chapman, C.J. and O. Sand., 1974. Field studies of hearing in two species of flatfish *Pleuronectes latessa* (L.) and *Limanda Limanda* (L.) (Family Pleuronectidae) Comp Biochem. Physiol., 47A: 371-385

Denton, E.J. and J.A.B. Gray. 1983. Mechanical factors in the excitation of clupeid lateral lines. Proc. Roy. Soc. London Ser. B 218: 1-26

Diner, N. and J. Masse. 1987. Fish school behaviour during echo survey observed by acoustic devices. ICES C.M. 1987/B:30; 41pp

Dunning, D. J., and Quentin E. Ross., Geoghegan, P., Reichle, J.J., Menezes, J.K. and J.K.Watson. 1992. Alewives Avoid High-Frequency Sound. Nth Am. J. Fish Mngt. 12 (3):407-416

Emery, A. and M.H. Beach. 1994. Measurement procedure and preliminary results of underwater acoustic noise spectra from RV "Corystes" in the 10 Hz to 20 kHz frequency band with the ship in unloaded and loaded modes. MAFF. Fisheries Laboratory, Lowestoft, unpublished report, 11 pp.

Engås,A., Soldal, A.V., and J.T. Øvredal. 1991a. Avoidance reactions of ultrasonic tagged cod during bottom trawling in shallow water. ICES Fish Capture Comm. C.M. 1991/B:41;9pp

Engås, A., Misund, O.A., Soldal, A.V., Horvei, B. and A. Solstad. 1991b. Fish Behaviour and Vessel Noise: Catch Data Comparisons, Noise Analysis, and Playback Experiments. Can. J. Fish. Aquat. Sci.. (in press)

Engås, A., Løkkeborg, S., Ona, E. and A.V. Soldal. 1993b. Effects of seismic shooting on catch and catch availability of cod and haddock. Fisken og Havet, NR 9 - August 1993

Enger, P.S. 1967. Hearing in herring. Comp. Biochem. Physiol. 22: 527-538

Enger, P.S., H.E. Karlsen, F.R. Knudsen and O. Sand., 1993. Detection and reaction of fish to infrasound. ICES mar. Sci. Symp. 196: 108-112

Facay, D.E., McCleave, J.D. and G.E. Doyon. 1977. Response of Atlantic salmon parr to output of pulsed ultrasonic transmitters. Trans. Am. Fish. Soc. 106 (5)

Fay, R.R. 1984. The goldfish ear codes the axis of acoustic particle motion in three dimensions. Science, 225: 951-954

Fay. R.R., 1988. Hearing in vertebrates: a pyschophysics databook. Heffernan Press, Hill-Fay Assoc. Winnecta, Illionis, 621p

Fish, M.P. and W.H. Mobray. 1970. Sounds of Western North American Fishes, John Hopkins University Press, Baltimore

Foote, K.G. 1980. Effect of fish behaviour on echo energy: the need for measurements of orientation distributions. J. Cons. int. Explor. Mer. 39(2): 193-201

Francois, R.E. and G.R. Garrison. 1982. Sound absorption based on ocean measurements: Boric acid contribution and equation for total absorption. J. Acoust. Soc. Am. 72(6):1879-1890

Furduev, A.V. 1966. Under surface cavitation as a source of noise in the ocean. Atmos. Oceanic Phys. 2: 314

Gjestland, T. 1971. Noise measurement in fishing vessels. Int. Working Group for Fishing Technology, 9th Meeting, Acoustic Lab. SINTEF, NTH, Norway

Goncharov, S.M., E.S. Borisenko and A.T. Pyanov. 1989. Jack mackerel school defence reaction to a surveying vessel. "Progress in Fisheries Acoustics" Inst. Acoust. (UK) 11(3): 74-78

Halldorsson, O. 1983. On the behaviour of the Icelandic summer spawning herring (C *harengus* L.) during echo surveying and depth dependence of acoustic target strength *in situ*. ICES CM.1983/H:36; 35pp

Harden Jones, F.R. and R.B. Mitson. 1982. The movement of noisy sandwaves in the Strait of Dover. J. Cons. int. Explor. Mer. 40(1): 53-61

Hawkins, A.D. and O.Sand. 1977. Directional hearing in the median vertical plane by the cod. J. Comp. Physiol. 122: 1-8

Hawkins, A.D. and K. Horner. 1981. Directional characteristics of primary auditory neurons from the cod ear. In Hearing and Sound Communication in Fishes. Ed. W.N. Tavolga, A.N. Popper and R.R. Fay. pp, 311-327

Haan, D. de, 1992. The underwater sound emission of research vessels and the beam trawler TX48. ICES C.M. 1992/B:37; Fish Capture Comm.

Hughes, B. 1976. Estimates of underwater sound and infrasound produced by nonlinearly interacting ocean waves. J. Acoust. Soc. Amer. 60, 1032.

Johnson, P. and T.C. Muir. 1960. Acoustic detection of sediment movement. J. Hydraul. Res., 7: 519-40

Kalmijn, A.J. 1988. Hydrodynamic and acoustic field detection. In Sensory Biology of Aquatic Animals, Eds. J. Atema, R.R. Fay, A.N. Popper and W. N. Tavolga Springer-Verlag, Berlin pp 83-130

Karlsen, H.E. 1992b. Infrasound sensitivity in the plaice (*Pleuronectes platessa).* J. Exp. Biol. 171, 173-187

Karlsen, H.E. and O. Sand. 1987. Selective and reversible blocking of the lateral line in freshwater fish. J. Exp. Biol. 133: 249-262

Karlsen, H.E. 1992. The inner ear is responsible for detection of infrasound in the perch (*Perca fluviatilis)* J. Exp. Biol. 171: 163-172

Kay, B.J., Jones, D.K. and R B Mitson. 1991. FRV CORYSTES: A purpose-built fisheries research vessel. The Royal Institution of Naval Architects, London. Paper 6. 12p.

Kerman, B.R. 1984. Underwater sound generation by breaking waves. J. Acoust. Soc. Am. 75, 149-165.

Kibblewhite,A.C. and K.C.Ewans. 1985. Wave-wave interaction, microseisms and infrasonic ambient noise in the ocean. J. Acoust. Soc. Am. 78 (3): 981.

Knudsen, V.O., Alford, R.S. and W. Emling. 1948. Underwater ambient noise. J. Mar. Res.7: 410-429.

Lewis, E.R. 1984. Inertial motion sensors. In Comparative Physiology of Sensory Systems. Eds. L. Bolis, R.D. Keynes and S.H. P. Maddrell, pp. 587-610. Cambridge University Press.

Lynch, J.F., X.Wu., R. Pawlowski., F. Worcester., R.E. Keenan., C. Graber., O.M. Johannessen., P. Wadhams and R.A. Shuchman.1993. Ambient noise measurements in the 200 - 300 Hz band from the Greenland Sea tomography experiment. J. Acoust. Soc. Am. 94 (2) Pt 1: 1015-1033

McCartney, B.S. 1971. Ambient noise in the sea. Encyclopaedic Dictionary of Physics. Supp. vol. 4. Ed. J. Thewlis. Pergamon Press. Oxford & New York.

McCartney, B.S. and A.R.Stubbs., 1971. Measurements of the acoustic target strength of fish in dorsal aspect, including swimbladder resonance. J. Sound. Vib. 15(3): 397-420

McCreery, C. S., F.K. Duennebier and G.H. Sutton. 1993. Correlation of deep ocean noise (0.4-30 Hz) with wind and the Holu Spectrum - A worldwide constant. J. Acoust. Soc. Am. 93 (5): 2639-2648

Mellen, R.H. 1952. Thermal-noise limit in the detection of underwater acoustic signals. J. Acoust. Soc. Am. 24: 478.

Millard, N.W. 1976. Noise generated by moving sediments. Paper 3.5. Proc Conf. Recent Developments in Underwater Acoustics. Inst. Acoust. St. Albans. U.K.

Misund, O.A. and A. Aglen. 1991. Swimming behaviour of fish schools in the North Sea during acoustic surveying and pelagic trawl sampling. J. Cons. int. Explor. Mer. In press

Mitson, R. B. 1993. Underwater noise radiated by research vessels. ICES mar. Sci. Symp., 196: 147-152

Myrberg, A.A.Jnr, S.J. Ha and M.J. Shamblott. 1993. The sounds of the bicolor damselfish (*Pomacentrus partitus*): Predictors of body size and a spectral basis for individual recognition and assessment. J. Acoust. Soc. Am. 94(6): 3067-3070

Neproshin, A. Yu. 1979. Behaviour of the Pacific mackerel (*Pneumatophorus japonicus*) when affected by vessel noise. J. Ichthyol. 18(4): 695-705

Nestler, J.M., Ploskey, G.R., Pickens, J., Menezes, J. and C. Shilt. 1992. Responses of blueback herring to high frequency sound with implications for reducing entrainment at hydropower dams. J. Nth. Am. Fish. Mangmt. 12(4): 667-681

Nichols. R.H. 1981. Infrasonic ambient ocean noise measurements: Eleuthera, J. Acoust. Soc. Am. 69(4): 974-981

Nicholson, M., Rackham, B. and R.B.Mitson. 1992. Measuring the effect of underwater radiated noise on trawl catches. ICES, FTFB and FAST Working Group, Bergen.

Nunnalee, E.P. 1991. An investigation of the avoidance reactions of Pacific whiting (*Merluccius productus)* to demersal and midwater trawl gear. ICES C.M. 1991/B:5; Session U

Ojak, W. 1972. Vibration and Noise on Fishery Research Vessels. Report of the André Mayer Research Fellow to FAO (Rome). 117pp

Ojak, W. 1988. Vibrations and Waterborne Noise on Fishery Vessels. J. Ship Res. 32 (2): 112-133

Olsen, K. 1969. Directional responses in herring for sound and noise stimuli. ICES CM. 1969/B:20; 8p. Mimeo

Olsen, K. 1971. Influence of vessel noise on the behaviour of herring. In Modern Fishing Gear of the World. Ed. H. Kristjonsson. 291-293pp Fishing News (Books) Ltd. London

Olsen, K. 1976. Directional hearing in the cod (*Gadus morhua*). In Sound Reception in Fish. Eds. Schuijf and Hawkins, Elsevier Publ. Co. Amsterdam. 257-270.

Olsen, K. Angell, J., Pettersen, F. and A. Lovik. 1983a. Observed fish reactions to a surveying vessel with special reference to herring, cod, capelin and polar fish. In Nakken, O. and Venema, S.C., (Eds) Symp. on Fisheries Acoustics, Bergen, Norway. FAO Fish Rep. 300: 131-138.

Olsen, K. Angell, J. and A. Løvik. 1983b Quantitative estimations of fish behaviour on acoustically determined fish abundance. In Nakken, O. and Venema, S.C.,(Eds) Symp. on Fisheries Acoustics, Bergen, Norway. FAO Fish Rep. (300): 139-149.

Ona, E. and O.Chruickshank. 1986. Haddock avoidance reactions during trawling. ICES Fish Capture Comm. C.M. 1986/B:36; 13pp

Ona, E. 1988. Observations of cod reaction to trawling noise. ICES, FAST WG. 20-22 April 1988, Ostend.

Ona, E. and R.Toresen. 1988a. Avoidance reactions of herring to a survey vessel, studied by scanning sonar. ICES CM 1988/H:46; 8pp

Ona, E. and R.Toresen. 1988b. Reactions of herring to trawling noise. ICES, C.M. 1988/B:36; 4pp

Ona, E. and O. R. Godø. 1990. Fish reaction to trawling noise: the significance for trawl sampling. Rapp. P.-v Réun. Cons. int. Explor Mer, 189: 159-166.

Purves, P.E. and G.E. Pilleri. 1983. Echolocation in Whales and Dolphins, Academic Press London, 261pp

Ross, D. 1976. Mechanics of Underwater Noise. Pergamon Press, New York, 375 pp

Ross, D., 1993. On ocean underwater ambient noise. Inst. Acoust. Bull. (UK) 18(1): 5-8

Sand, O. and P.S. Enger., 1973. Evidence for an auditory function of the swimbladder in the cod. J. Exp. Biol. 59: 405-414

Sand, O. and A.D. Hawkins. 1973. Acoustic properties of the cod swimbladder. J. Exp. Biol. 58: 797-820

Sand. O, 1974a. Directional sensitivity of microphonic potentials from the perch ear. J. Exp. Biol. 60: 881-889

Sand. O, and Karlsen, H.E. (1986) Detection of infrasound by the Atlantic cod. J. Exp. Biol., 125: 197-204

Schellart, N.A.M. and J.C. de Munck. 1987. A model for the directional hearing in swimbladder-bearing fish based on the displacement orbits of the hair cells. J. Acoust. Soc. Am. 82 (3):822-829

Shevelev, M.S., Dorchenkov, A.E. and A.P. Shvagzhdis. 1989. USSR research on cod and haddock in the Barents Sea and adjacent waters in 1988. ICES C.M. 1989/G:12

Tavolga, W.N. 1964. Marine Bio-acoustics, Ed. W.N. Tavolga. Pergamon Press, Oxford & New York, 269-279

Thorne, P. D. and D.J. Foden. 1988. Generation of underwater sound by colliding spheres. J. Acoust. Soc. Am. 84(6)

Urick, R.J. 1974. Sea-bed motion as a source of the ambient noise background of the sea. J. Acoust.Soc.Am.56 (3): 1010-1011

Urick, R.J. 1983. Principles of Underwater Sound for Engineers, 3rd ed. McGraw-Hill, New York. 384 pp

Urick, R.J. 1986. Ambient Noise in the Sea. Peninsula Publishing Library of Congress, 85-063685

Watkins, W.A., O.Tyack, K. Moore and J.E. Bird. 1987. The 20Hz signals of finback whales (Balaenoptera physalus). J. Acoust. Soc. Am. 82: 1901-1912

Wenz, G.M. 1962. Acoustic ambient noise in the ocean: spectra and sources. J. Acoust. Soc. Am. 34 (12): 1936-1956.

Wenz, G.M. 1972. Review of underwater acoustic research: noise. J. Acoust. Soc. Am. 51(3): 1010-1024

Wilson, J. H. 1980. Low frequency wind generated noise produced by the impact of spray with the ocean surface. J Acoust. Soc. Am. 68: 953-956

Zakarauskas, P., D.M.F. Chapman and P.R. Staal. 1990. Underwater acoustic ambient noise levels on the eastern Canadian continental shelf. J. Acoust. Soc. Am. 87(5): 2064-2071

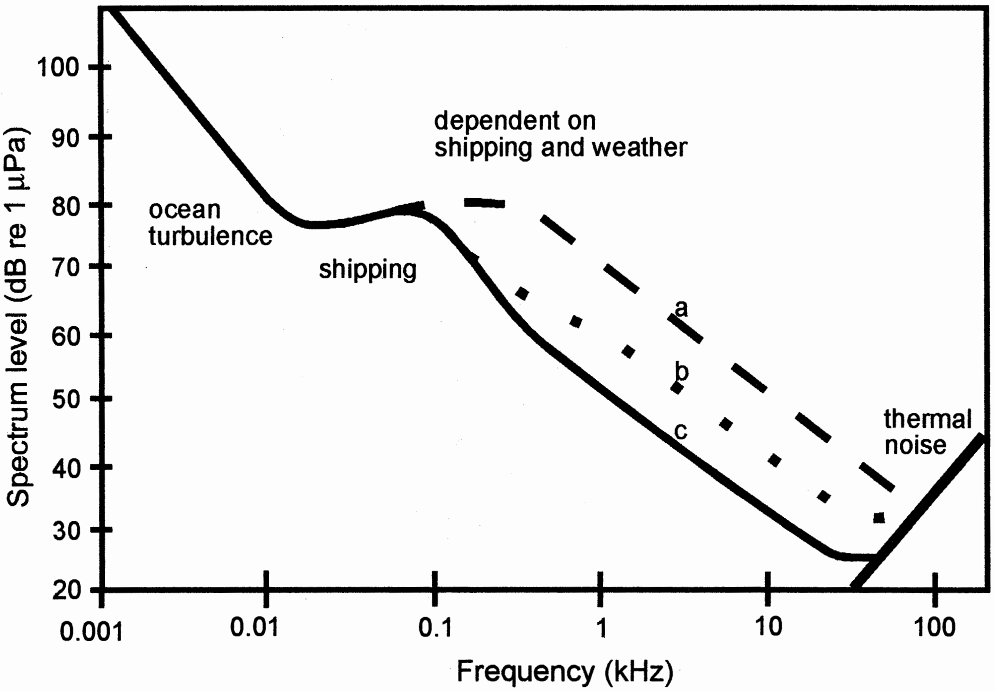


Figure 1. Ambient spectrum level of noise from 1 Hz to 200 Hz, re-drawn from Wenz (1962). Three unspecified levels of shipping and weather.

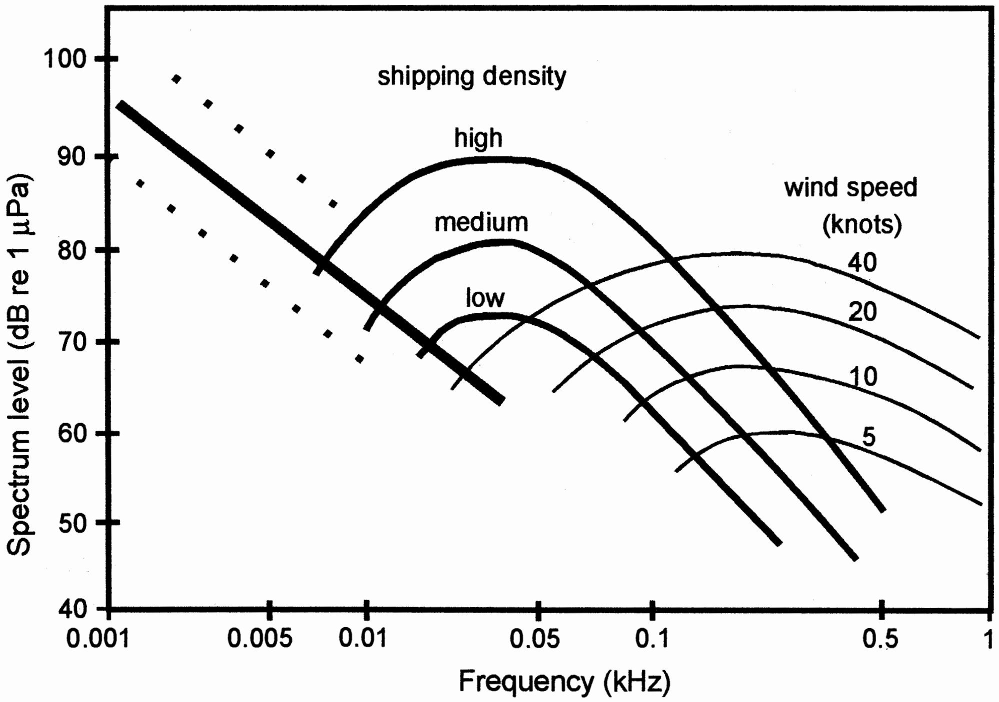


Figure 2. Ambient spectrum level of noise from 1 Hz to 1 kHz, re-drawn from Urick (1986) for different levels of shipping and wind.

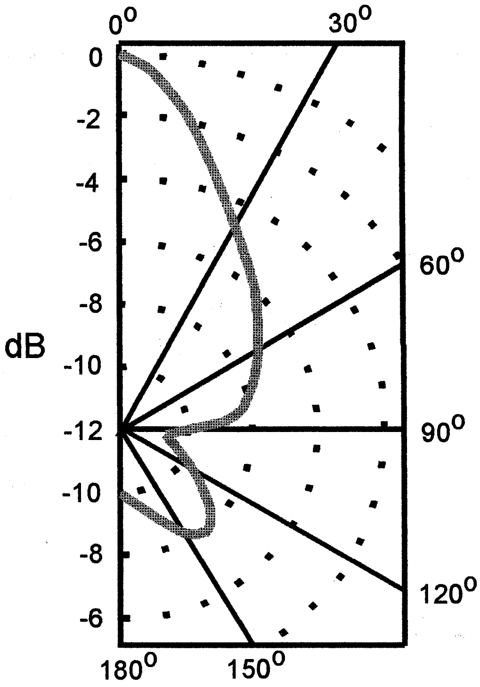


Figure 3. Vertical distribution of ambient noise measured at 45 m depth, sea state 3 (after Becken, 1964).

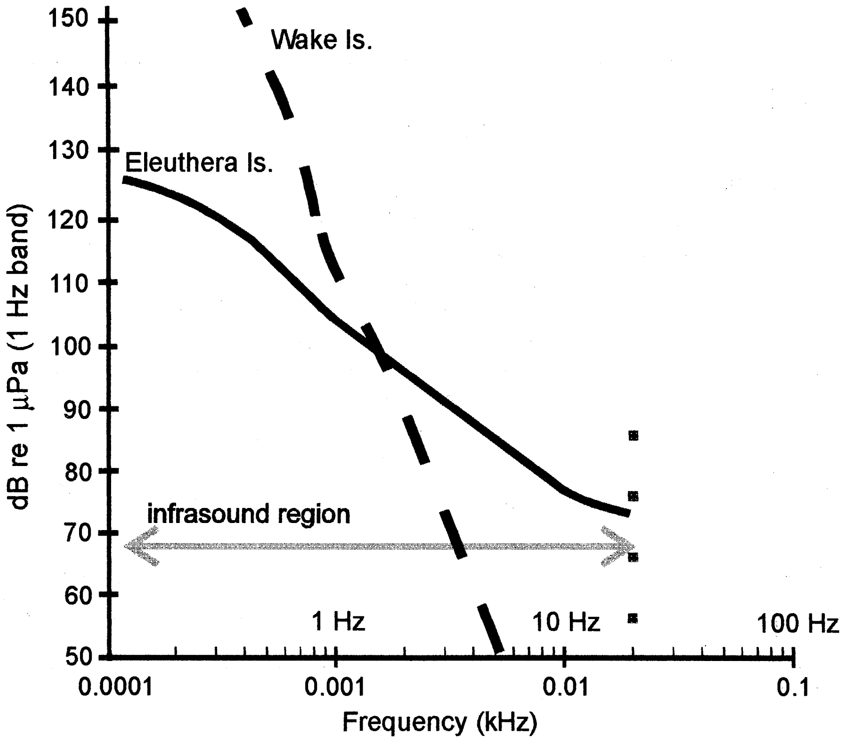


Figure 4. Infrasound noise levels from different areas and depths Redrawn from Nichols (1981) and McCreery, *et al.* (1993)

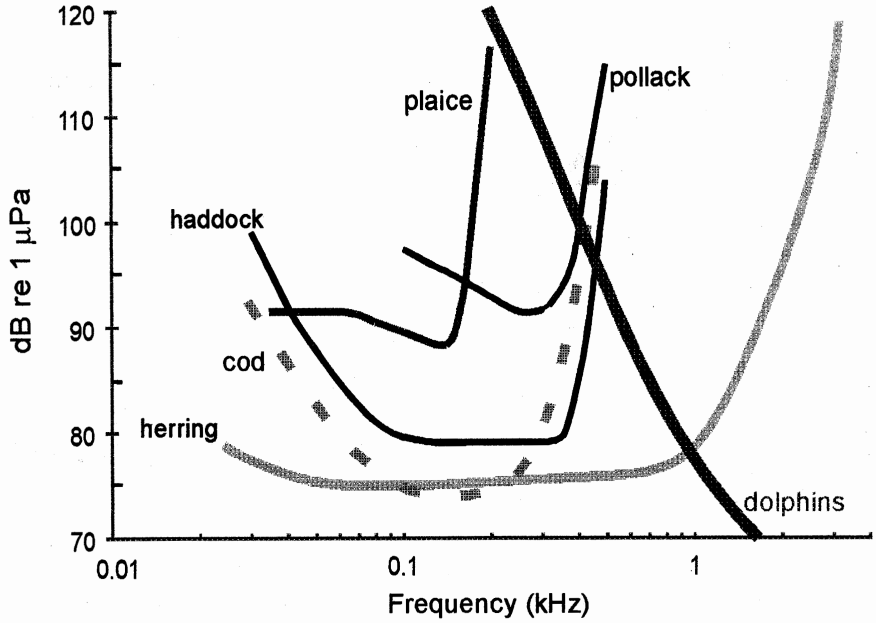


Figure 5. Fish hearing thresholds (sound pressure). This figure is compiled from various author's and shows the relative sensitivity of several species.

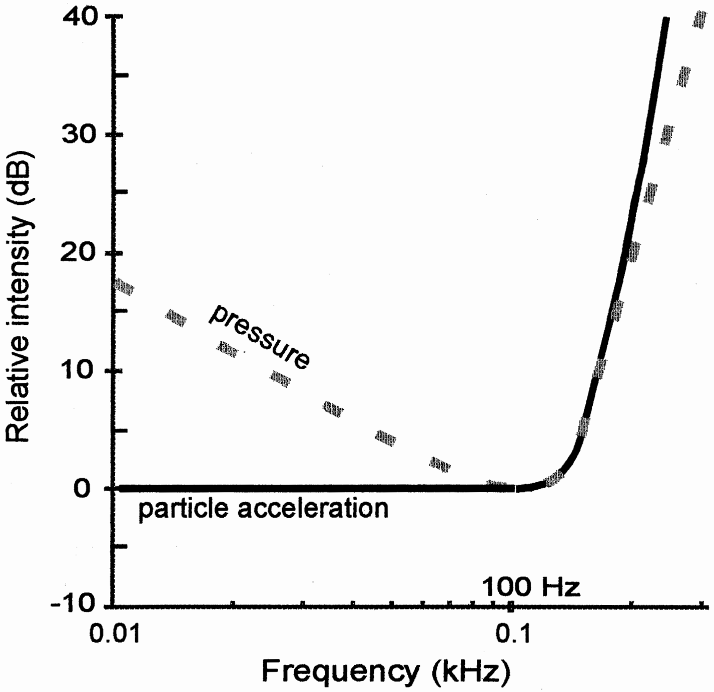


Figure 6. Hypothetical fish audiograms (after Enger, *et al.* 1993) illustrating the relationship between sound pressure and particle acceleration.

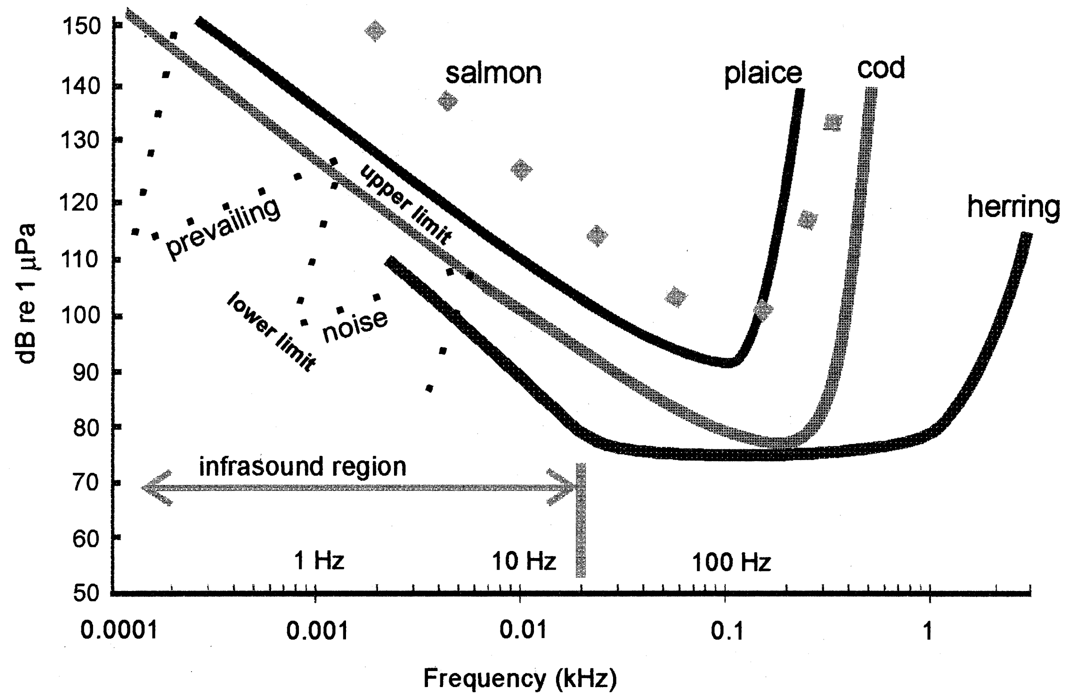


Figure. 7. Extended fish hearing thresholds in terms of sound pressure obtained by re-plotting particle acceleration data and linking it with earlier sound pressure measurements.
Predicted ambient noise levels in the infrasound region are also shown.

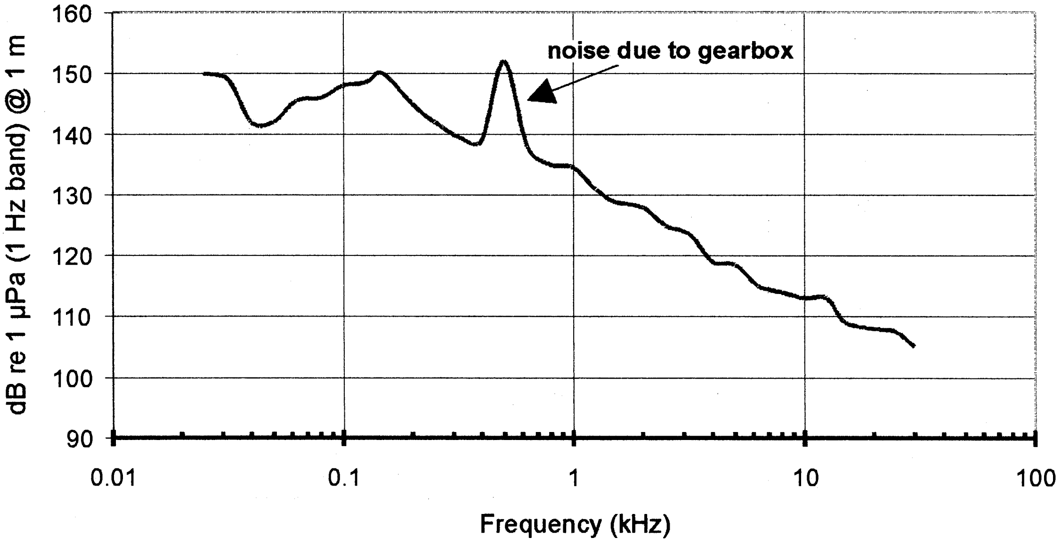


Figure 8. Noise signature for the new "Tridens" free-running at 11 knots, showing the high level "whine" from the gearbox (de Haan, 1992).

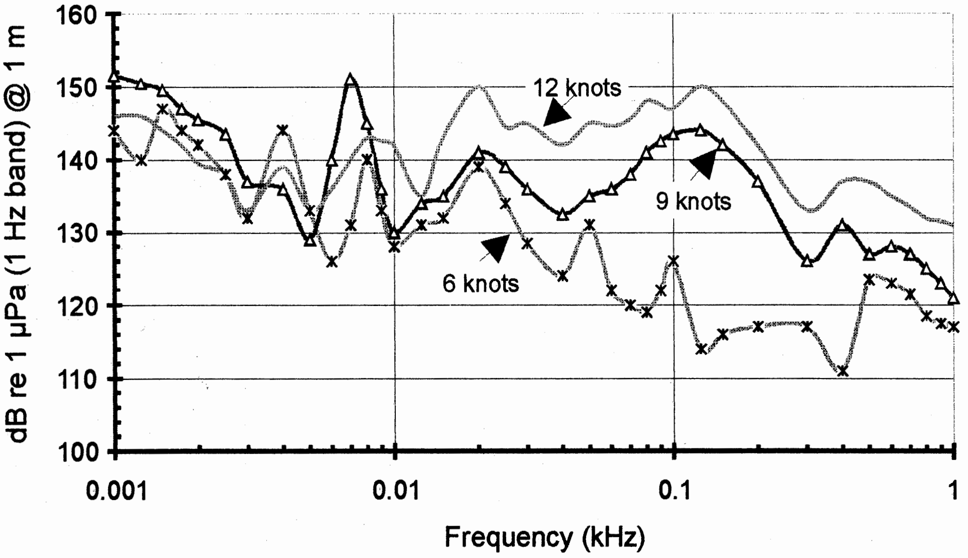


Figure 9. From "Cirolana", showing dynamic low-frequency noise levels

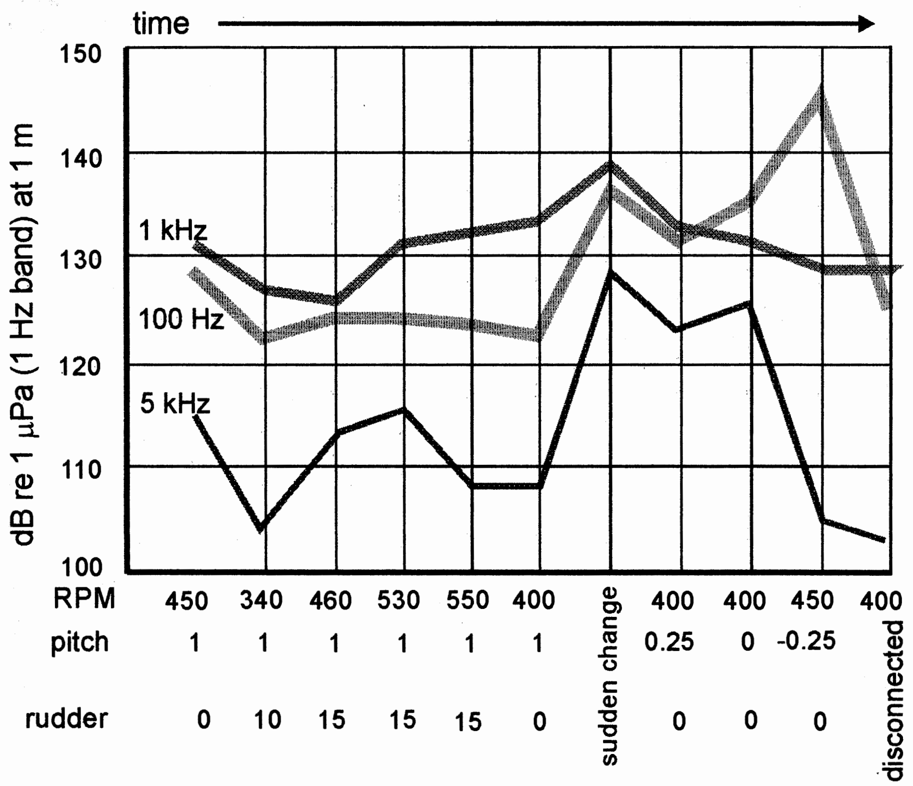


Figure 10. Changes of noise level at three discrete frequencies due to a CP propeller. Taken during a simulated purse seine operation. (after Gjestland, 1971).

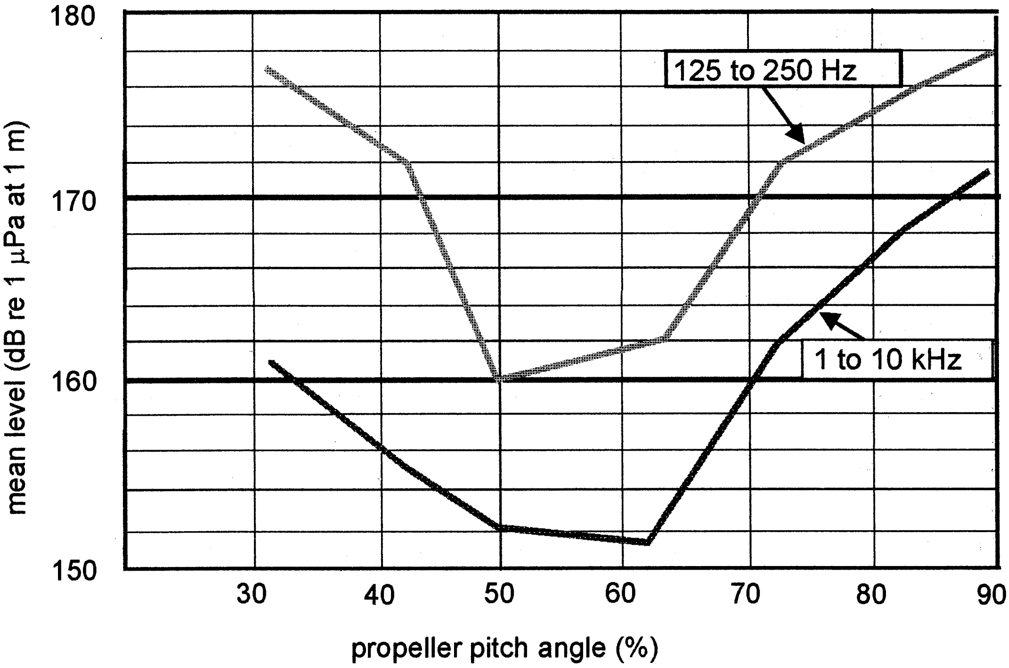


Figure 11. From the new "Tridens" showing the relationship between propeller pitch angle and noise in two frequency bands (after de Haan, 1992).

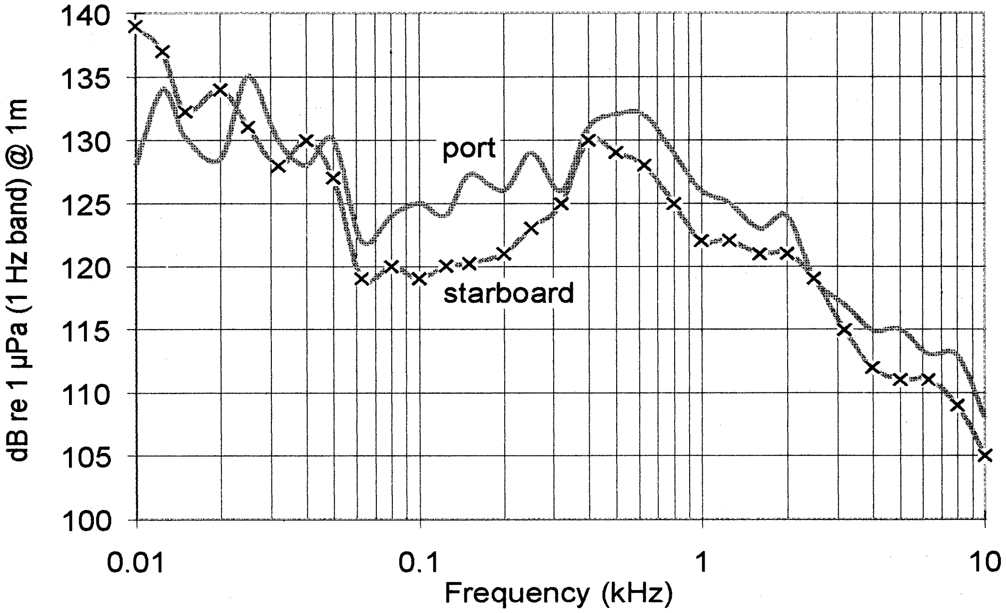


Figure 12. From "Corystes": differences between port and starboard sides at 11 knots (free-running).

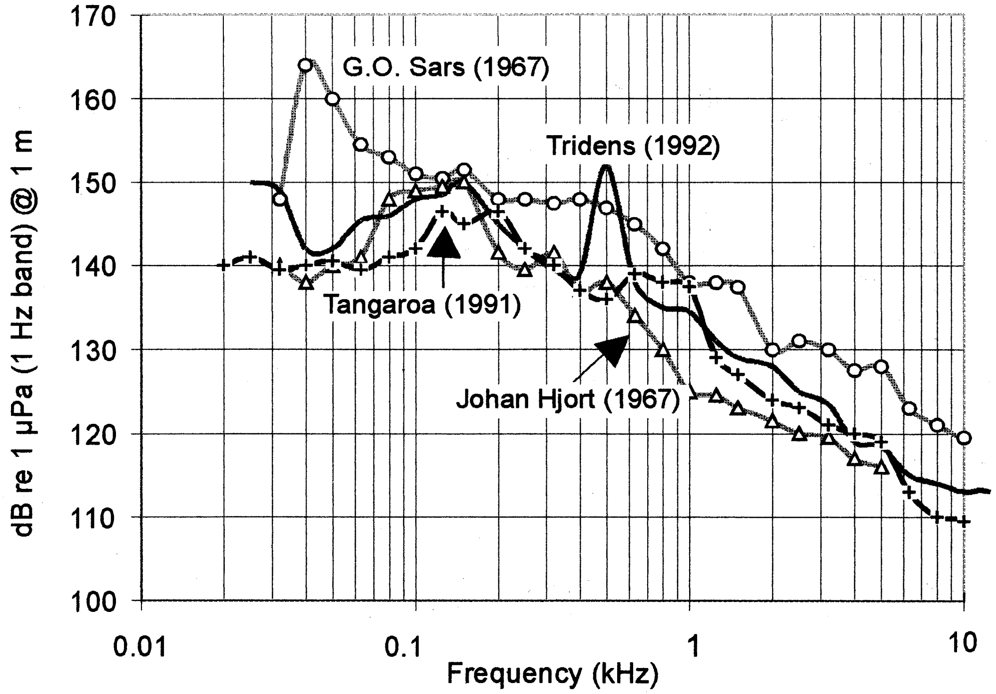


Figure 13. Comparison of noise levels between two vessels built in the 1960's and two built in the 1990's, all free-running at 11 knots.

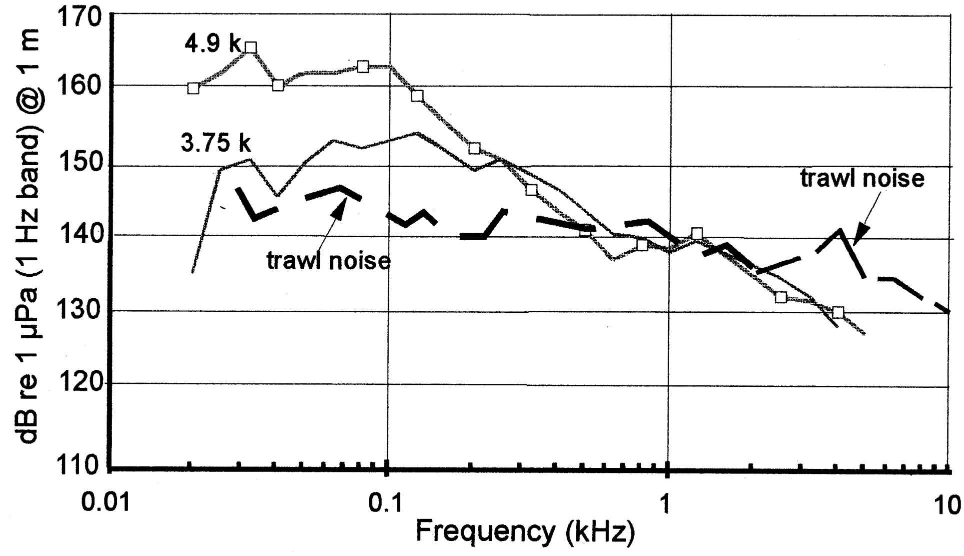


Figure 14. "Explorer" towing a bottom trawl at two speeds. Note that the trawl noise is less than the vessel noise below 500 Hz.

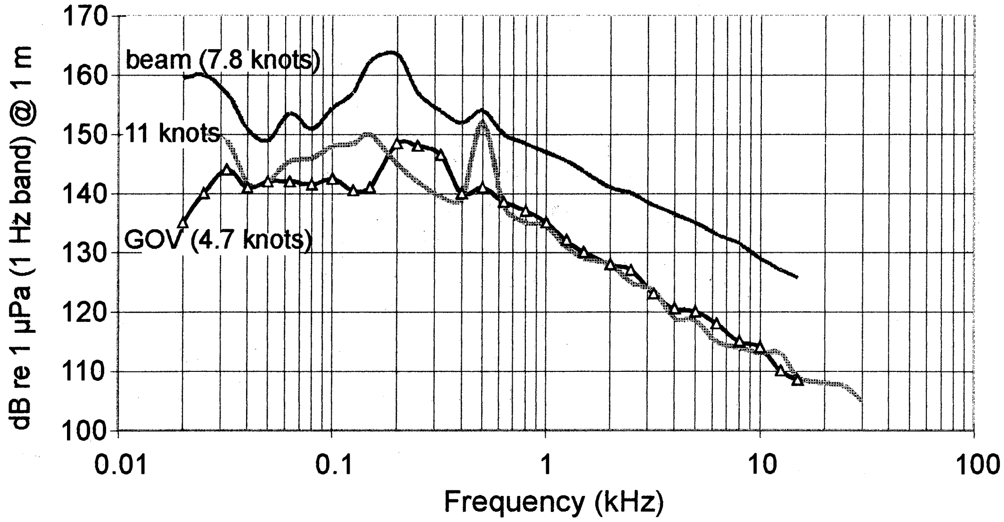


Figure 15. Noise levels for two trawling loads and a free-running speed of 11 knots for "Tridens" (after de Haan, 1992).

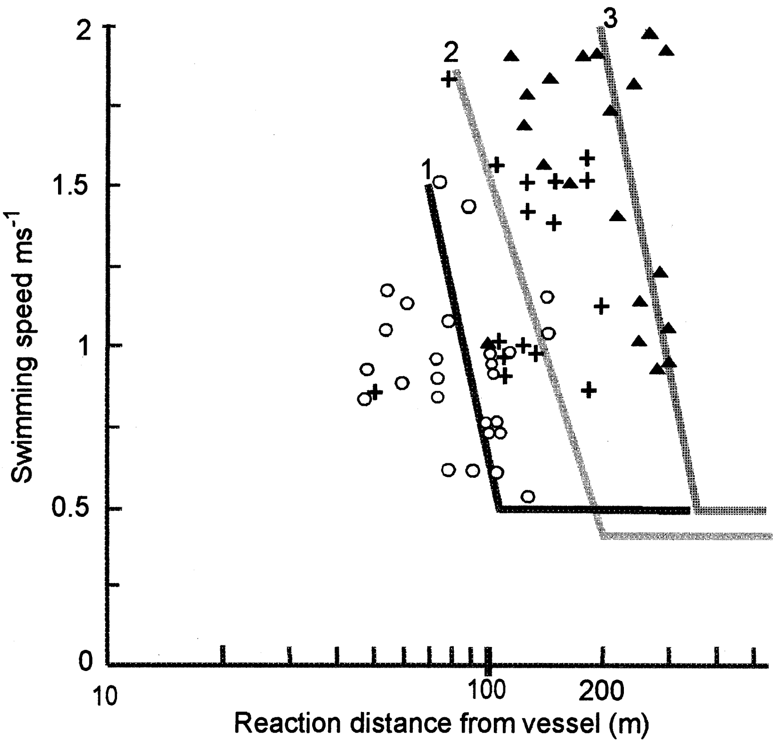


Figure 16. Showing a significant increase in swimming speed of jack mackerel to avoid the approaching vessel. Results from three different areas (1,2,3,) (after Goncharov *et al.*, 1989).

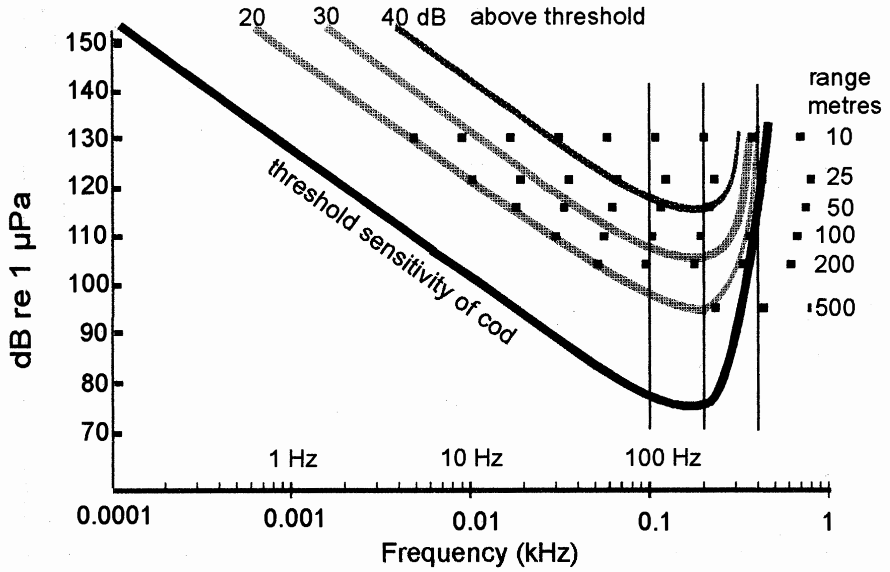


Figure 17. The hearing threshold for cod is shown, also, lines indicating levels 20, 30 and 40 dB higher. Dotted lines represent noise levels at the ranges indicated, based on a vessel with a level of 151 dB re 1 µPa (1 Hz band) @ 1 m. (150 Hz).

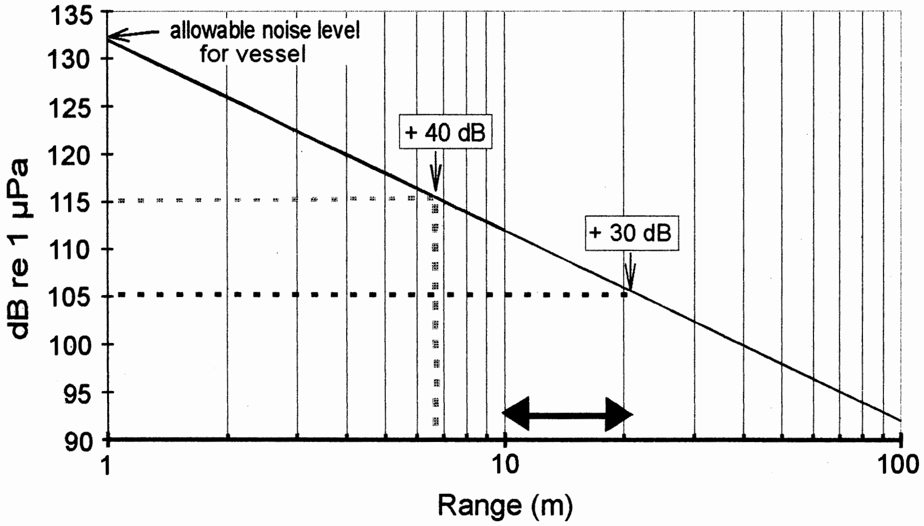


Figure 18. Determination of the low-frequency noise specification from the proposed maximum acceptable fish reaction range of 20 m. To achieve this the vessel noise must not exceed 132 dB re 1 µPa (1 Hz band) @ 1 m over the frequency band of 20 Hz to 1.2 kHz.

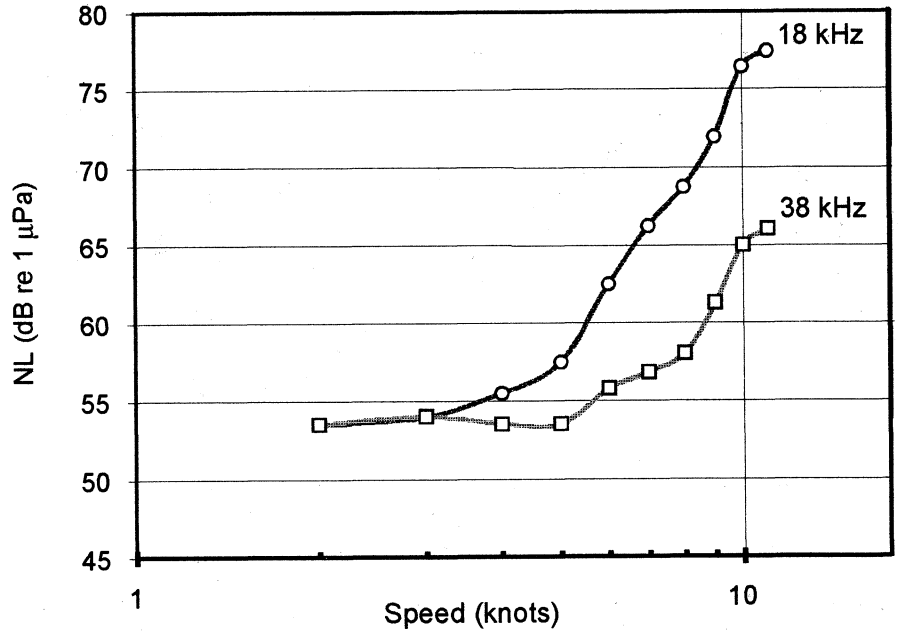


Figure 19. Noise levels measured on the "Bjarni Sæmundsson" (EK500)

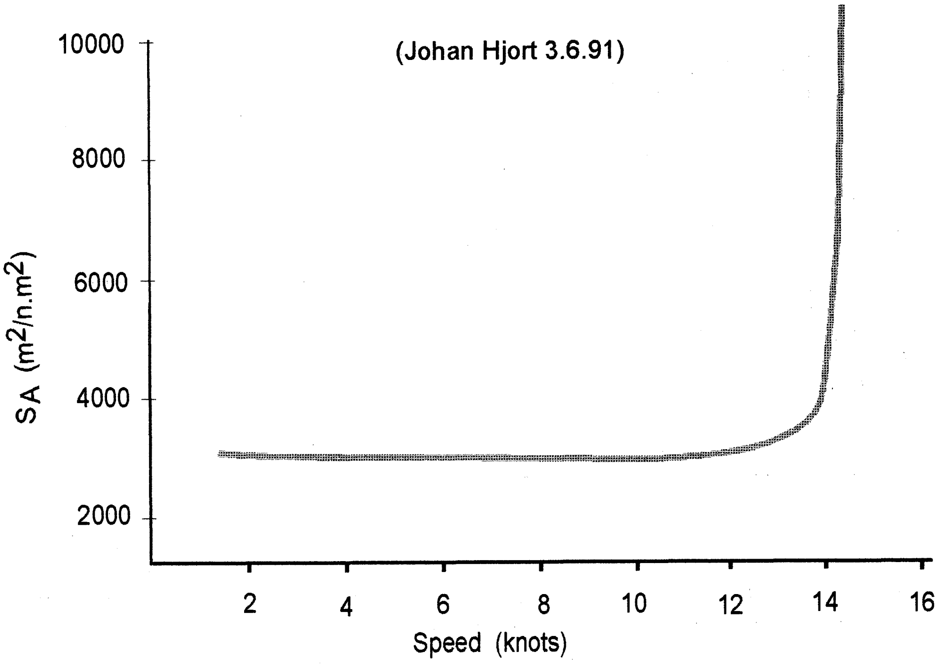


Figure 20. This illustrates the rapid growth of integrator level as propeller cavitation increases with speed.

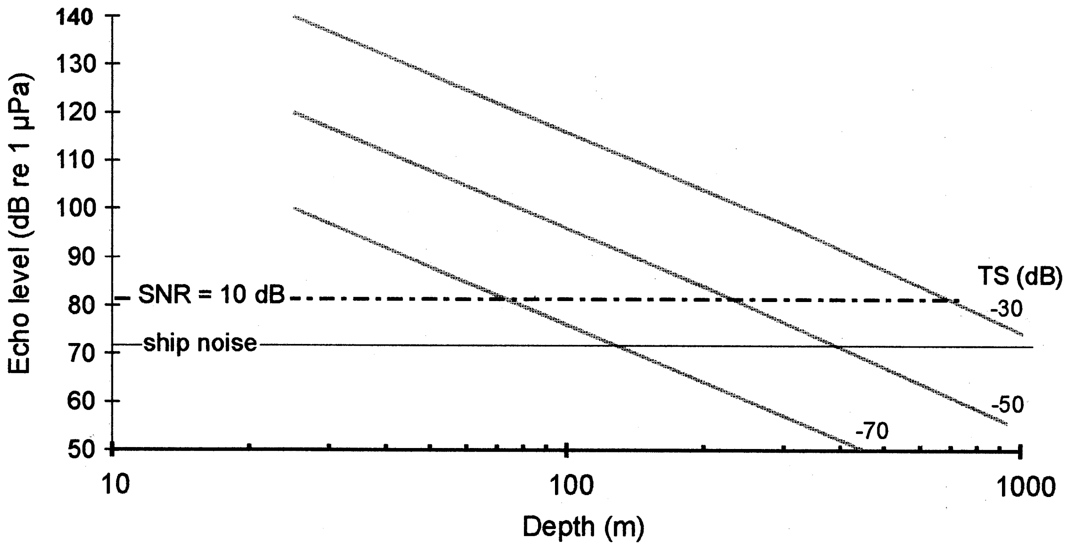


Figure 21. Detection of three classes of fish target strength at 38 kHz in relation to noise. This is based on a transducer being towed 15 m from the propeller. Echo-sounder SL =226 dB re 1 µPa @ 1 m.

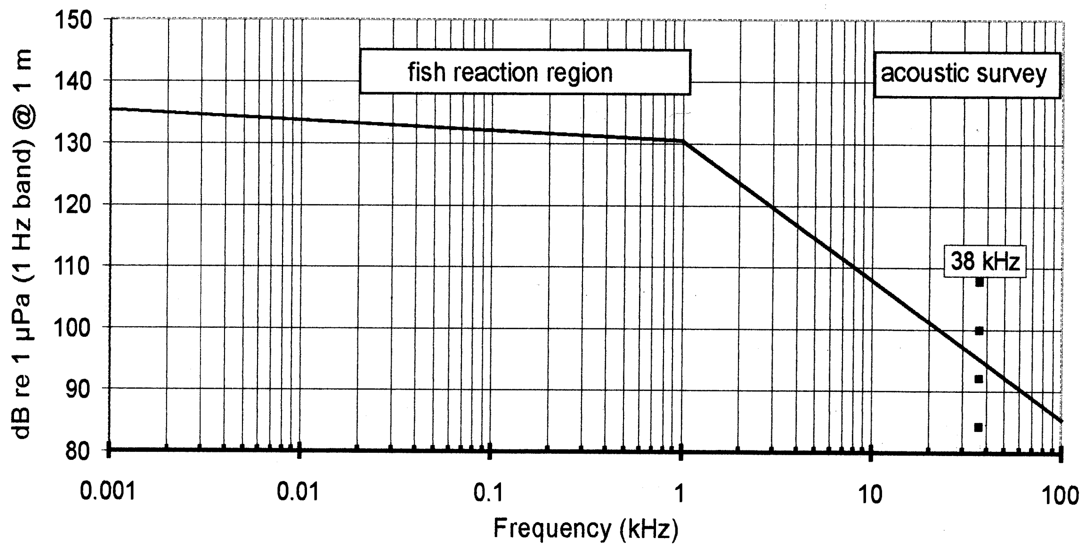


Figure 22. Proposed underwater radiated noise specification at 11 knots free-running for all vessels used in fisheries research.

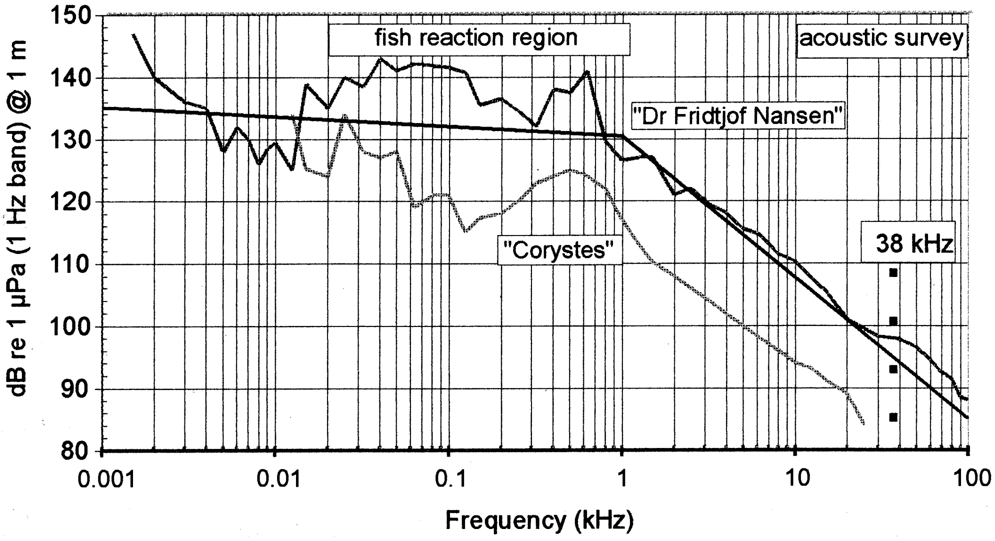
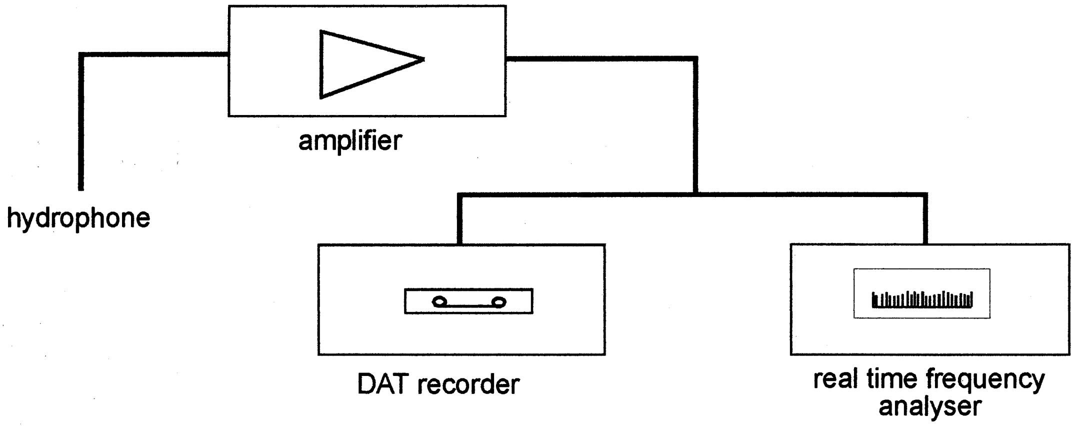


Figure 23. Noise signatures at 11 knots of two modern research vessels.



Instrument description

Hydrophone: 8103
Hydrophone calibrator: 4229
Amplifier: 2635
Analyser: 2143

numbers refer to Bruel & Kjaer instruments

other manufacturers equivalents may be used

Recorder: Sony DAT: Tcd-D10pro

Figure 24. Instrument configuration for vessel noise measurement

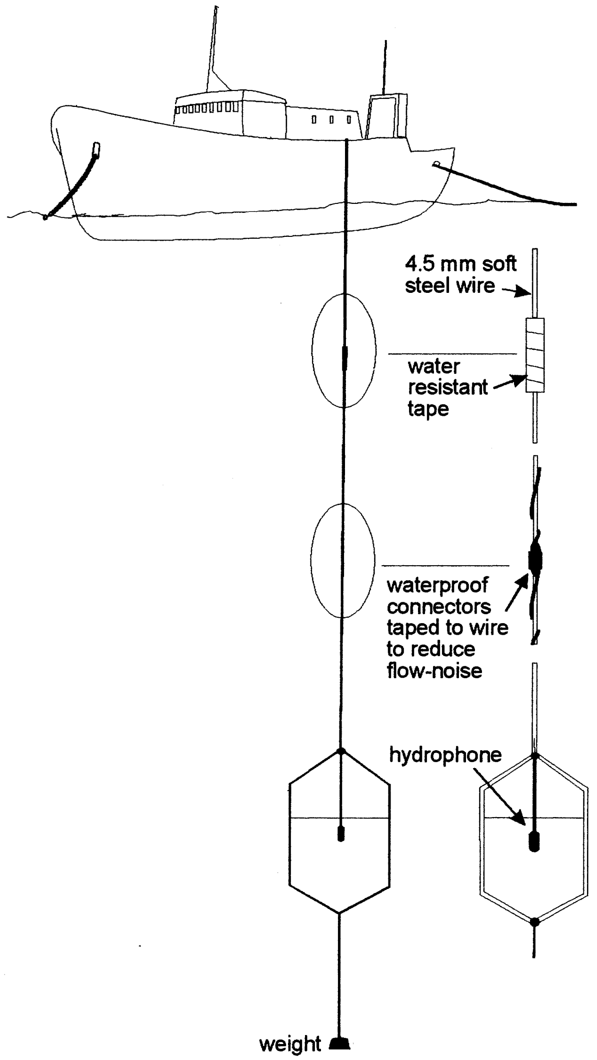


Figure 25. Typical method of hydrophone suspension for deep water measurements.

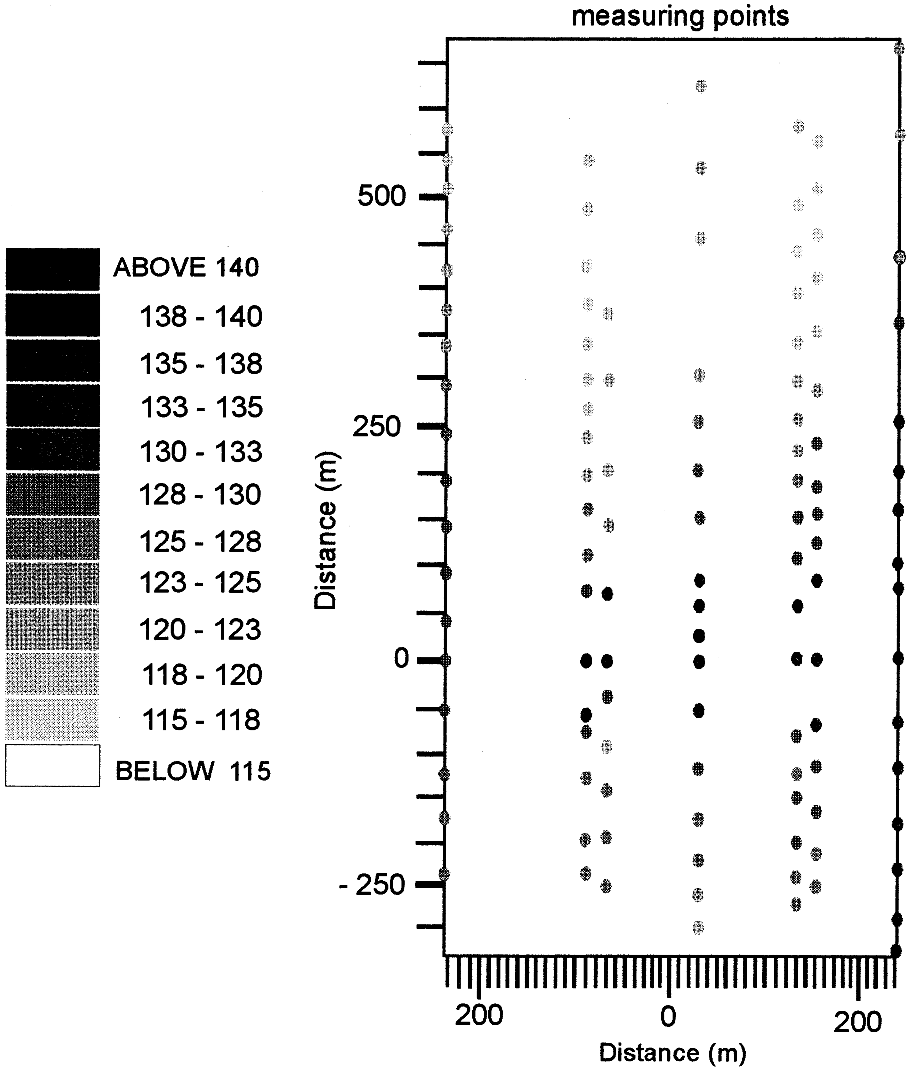


Figure 26. A method of obtaining the horizontal noise pattern radiated from a vessel. An example is shown of measured points in different transects.

APPENDIX 1

Measurement of Vessel Noise

1. Method

This is a short description of a system used by the Institute of Marine Research, Bergen, for the measurement of radiated underwater noise level from research vessels. These levels are normally given in terms of the so-called source level frequency spectrum., adjusted to a distance of 1 m prior to comparison with other measurements or with the noise specification.

Source levels of vessel noise signatures are commonly obtained from measurements, simply by assuming the ship to be a point source with spherical radiation. Hence, directional radiation characteristics of the ship are normally neglected and underwater sound pressure levels are assumed to decay by 6 dB per doubling of distance. That is at a rate of 20 log(R), where R is the distance between the ship and the measuring hydrophone. However, the radiation characteristics of a vessel can be found with the instrument set-up described later, by letting the vessel pass on both sides and at different distances from the hydrophone. Data from such measurements have been used to plot the aspect variation of vessel noise level, the so-called "butterfly" pattern. Although such noise data can be obtained by use of different types and combination of instruments the basic units are a hydrophone, an amplifier and a frequency spectrum analyser.

The arrangement may differ from range to range. On permanent ranges the hydrophones are normally placed on, or moored, to the seabed but at temporary ranges the hydrophone may be lowered from a boat. In the latter case the vessel to be measured should pass at safe distance from the hydrophone. The instruments and techniques used for vessel noise measurements at the IMR-Bergen during recent years are described below.

2. Instrument configuration

Instrument description, manufacturer and type number, other instruments may be used if they have equivalent specifications:

Hydrophone: Bruel & Kjær, 8103
Amplifier: Bruel & Kjær, 2635
Recorder: Sony DAT, Tcd-D10 pro

Analyser: Bruel & Kjær, 2143
Calibrator: Bruel & Kjær,hydrophone calibrator, 4229

Figure 24 shows the instrument set-up required for vessel noise measurements. Prior to measurements the hydrophone is calibrated, using the instrument in the above list. During measurements the signal from the hydrophone is amplified, recorded in DAT format, then analysed in 1/24, 1/3 or 1/1 octave bands.

3. Suspension of hydrophones

It is very important when suspending hydrophones that the recommended maximum working load on the cable is not exceeded. The strain should be taken by a line hitched along the cable at regular intervals. Further, a weight should be attached to the line to ensure that the hydrophone hangs vertically in the water. Figure 25 shows a typical suspension of a hydrophone for deep water measurements. precautions should be taken to prevent the strumming of cables in the water flow.

4. Weather and sea conditions

In addition to calibrated and accurate instrumentation, good measurements depend greatly on the weather and sea conditions. This is especially true when using the technique described here, with an anchored boat as platform for the hydrophone and measuring system. One of the main problems is that, because most hydrophones are pressure-sensitive they will respond to the change in ambient pressure with depth. Tides and waves cause hydrostatic pressure changes at the low-frequency end of the spectrum.

Sound waves arise when particle motion causes pressure and density fluctuations to propagate in the medium. Similar to a ship's motion, the hydrophone will move up and down in the water column and hence the pressure on the hydrophone will change, causing unwanted sound (noise) to be generated, if the boat's movement is too great. Noise measurements under normal conditions in water can never be below the inherent or ambient noise level. Details of the background noise of the sea (ambient noise level) can be found under Section 2 of this report.

5. Distance (range) to the hydrophone

Because the measured noise levels must be adjusted to the reference distance of 1 m from the source it is necessary to determine the exact distance between the hydrophone and the vessel radiating the noise. Typical ship's radar is too imprecise, sonar is better but an exact and easier method is to use laser distance measuring equipment. If sonar is used, detection of the platform can be enhanced by a float submerged to 5 m beneath the platform vessel.

6. Measuring area (noise range)

An area used for measurements should, as far as possible, be sheltered from winds, with little or no current and swell. The water depth should ideally be 80 - 100 metres, and the shore, or local shallow area, should be at a distance in order to avoid unwanted reflections. It is difficult to be precise about the minimum depth because of the dependence on bottom type and topography but 30 m should be regarded as just about feasible. In circumstances where it is believed that the bottom topography may vary considerably it will be desirable to map any prominent features.

Before commencing it is necessary to obtain measurements of conductivity (salinity), temperature and depth throughout the water column being used. This is to ensure that no gradients exist which might cause anomalous results to be obtained.

7. Measurement procedure

A small vessel used as platform for the recording instruments has normally been anchored during the experiments but a drifting platform has also been used. The noise from the vessel is detected through one, or more, hydrophones which have been placed at various depths from 5 to 30 m. First, decide on the measurements to be carried out. That is, the speeds and conditions of running. At least one run in each direction should be made at 11 knots which is a preferred speed for acoustic survey and allows comparison with other vessels.

8. Propellers

a) fixed blade:

For these vessels it is useful to start with a run during which speed is steadily increased to establish the speed at which the inception of cavitation occurs. It is then preferable to make a series of runs, each at a given speed with, perhaps a two knot increment between runs.

b) controllable pitch (CPP):

For vessels with a CPP it is particularly important to determine the best combination (lowest noise level) of blade pitch and shaft RPM. This can be a time-consuming operation but working at these settings can give noise levels 20 dB less than other settings which provide the same speed. When the most favourable operating conditions have been determined they should be recorded: subsequent measurements should always be under these same conditions.

Let the vessel start at a distance sufficient to ensure that she will reach the wanted speed before passing the hydrophone. When the vessel passes the measuring platform, report the distance via VHF-radio to the platform and, correspondingly, absolute time on the DAT tape recorder is logged. The distance to the propeller can then be calculated, (or the centre of vessel which is the normal datum at naval ranges).

9. Measurement of vessel noise pattern

To obtain sufficient data on the horizontal directivity in the sound emitted from the vessel, the following measurement procedure can be adopted: Let the vessel pass at wanted speed and conditions along straight. transects, and several transects at different distance on both sides of the platform. (see Fig. 26). The transects are run so that the vessel passes the hydrophone at fixed distances both to the starboard and port side. When running the transects, the distance from the vessel to the platform is measured and reported to the platform where actual distance is logged, along with the corresponding absolute time on the DAT tape recorder. This will give a number of discrete points with related sound recordings for each of the transects. The distance points can be calculated as x-y co-ordinates on the basis of the distance between the vessel and the platform vessel at the actual recording and at the moment when the platform vessel is 90° to the side of the vessel.

APPENDIX 2

Bibliography

i. Ambient noise and propagation

Arase, E.M. and T. Arase. 1966. Correlation of ambient sea noise. J. Acoust. Soc. Am. 40: 205

Banner, A. 1968. Measurements of the particle velocity and pressure of the ambient noise in a shallow bay. J. Acoust. Soc. Am. 44: 1741-1742

Buckingham, M.J. 1980. A theoretical model of ambient noise in a low-loss shallow water channel. J. Acoust. Soc. Am. 67: 1186-1192

Cato, D.H. 1984. Noise generation at the sea surface: Recent theoretical and experimental work. Int.Conf, Dev. in Marine Acoustics, Sydney, Dec.1984

Cato, D.H. 1984. The problems in predicting sea surface noise in the frequency band 10 Hz to 200 Hz. Int.Conf., Dev.in Marine Acoustics, Sydney, Dec.1984

Crum, L.A. Pumphrey, H.C. Prosperetti, A. And L. Bjorno. 1989. Underwater noise due to precipitation. J.Acoust. Soc. Am. 85 S1): 153

Dietz, F.T., Kahn, J.S. and W. B. Birch. 1960. Nonrandom associations between shallow water ambient noise and tidal phase. J. Acoust. Soc. Am. 32: 915

Fish, J.P. and W.C. Cummings. 1972. A 50-dB increase in sustained ambient noise from fish *Cynoscion xanthulus*). J. Acoust. Soc. Am. 52: 1266-1270

Fish, M.P. 1964. Biological sources of sustained ambient sea noise. In Marine Bio-Acoustics, Ed. W.N.

Tavolga, 175-194 pp, Pergamon Press, New York.

Greene, C. R., 1987. Characteristics of oil industry dredge and drilling sounds in the Beaufort Sea. J Acoust. Soc. Am. 82(4): 1315-1324

Johnson, B.D and R.C.Cooke. 1979. Bubble population and spectra in coastal waters. A photographic approach. J. Geophys. Res. 84, 3769.

Kerman, B.R. 1988. Audio signature of a breaking wave. In: Sea Surface Sound. (Ed: Kerman, B.R) Kluwer Academic Publisher, Dordrecht, 437-448.

Kibblewhite, A.C., Ewans, K.C. 1984. Infrasonic ambient noise in the ocean. Int.Conf, Dev. in Marine Acoustics, Sydney, Dec.1984

Kibblewhite, A.C. and K.C. Ewans. 1986. A study of ocean and seismic noise at infrasonic frequencies. In: Ocean Seismo-Acoustics. Eds Akal,T and J.M Berkson, Plenum Press, 731-741.

Kibblewhite, A.C. and C.Y. Wu. 1989. The generation of infrasonic ambient noise in the ocean by nonlinear interactions of ocean surface waves. J. Acoust.Soc.Am.85(5)

Kozhevnikova, I.N., Bjorno, L. 1993. Near sea surface bubble cloud oscillation as a potential source of ambient noise. In Natural Physical Sources of Underwater Sound (Sea Surface Sound (2)). Ed B.R. Kerman, Kluwer Academic Publishers, Dordrecht, 339-348.

Kuperman, W.A., and F, Ingenito. 1978. Surface-generated noise in shallow water. Conf. Sound propagation in the sea. Inst. of Acoustics. Imperial College, London. April 1978

Lu, N.Q., A. Prosperetti, and S.W. Yoon. 1990. Underwater noise emission from bubble clouds. IEEE J. Oceanic Eng. 15, 275-281.

Medwin, H and M.M. Beaky, 1989. Bubble source of the Knudsen sea noise spectra. J. Acoust. Soc. Am. 86, 1124-1130.

Miller, L.A., B. Møhl, A. Surlykke and J. Pristed. 199?. The echolocation signals of narwhals. Institute of Biology, Odenese Univ. DK-5230 Denmark

Mitson, R B (1990) Very high frequency acoustic emissions from the White-Beaked dolphin (*Lagenorhynchus albirostris*) NATO Advanced Research Workshop, Sensory abilities of cetaceans. Eds Thomas, J.E. and Kastelein, R.A. Series A: Life Sciences Vol. 196. Plenum Press. New York and London

Myrberg, A.A.Jnr., 1980. Ocean Noise and the behaviour of marine animals: Relationships and implications. In Advances Concepts in Ocean Measurements for Marine Biology. Eds F.P. Diemer, F.J. Vernberg and D. Z. Mirkes, University of Carolina Press, 572 pp

Naval Ordinance Laboratory. 1942. Measurement of background noise in the water at Cape Henry, Virginia, due to surf and marine life. N.O.L. Rep. 594.

Naidu, P.S. and P.G. Krishna Mohan. 1988. A study of the spectrum of an acoustic field in shallow water due to noise sources at the surface. J. Acoust. Soc. Am. 85(2): 716-725

Piggott, C.L., 1964. Ambient sea noise at low frequencies in shallow water of the Scotian shelf. J. Acoust. Soc. Am. 36: 2152-2163

Prosperetti,A, 1987. Bubble dynamics in ocean ambient noise. J. Acoust. Soc. Am. 84: 151-172.

Prosperetti,A, 1988. Bubble-related ambient noise in the ocean. IBID Ref. 15 pp. 1042-1054.

Pumphrey, H.C. and L.A. Crum. 1990. Free oscillations of near-surface bubbles as a source of the underwater noise of rain. J. Acoust. Soc. Am. 87 (1)

Ross, D, 1982. Role of propagation in ambient noise. In: Underwater Ambient Noise. (Eds: Wagstaff,RA; Bluy,OT) SANLANTCEN Conference Proceedings No. 32.

Ross, D. 1993. On ocean underwater ambient noise. Acoust. Bull. Inst. of Acoustics (UK) 18(1):5-8

Rudnick, P and E.D.Squier. 1967. Fluctuations and directionality in ambient sea noise. J. Acoust. Soc. Am., 41(5): 1347-1351

Scrimger, J.A., Ewans, D.J., McBean, G.A., Farmer, D and B.R. Kerman, 1987. Underwater noise due to rain, hail and snow. J. Acoust. Soc. Am. 81(1):79.

Scrimger, J.A., D.J. Ewans, G.A. McBean, D. Farmer and R.R. Kerman. 1987. Underwater noise due to rain, hail and snow. J. Acoust. Soc. Am. 81 (1): 79

Shang , E.C. and V.C. Anderson. 1986. Surface-generated noise under low wind speed at kilohertz frequencies. J. Acoust. Soc. Am., 79 (4): 964-982

Tavolga,W.N. 1964. Ed. Marine Bioacoustics, Pergamon Press, New York.

Voglis, G.M and J.C. Cook. 1970. A new source of acoustic noise observed in the North SeaUltrasonics, April 1970

Von Winkle, W.A., 1963. Vertical directionality of deep ocean noise. U.S. Navy Underwater Sound Lab. Rep. 600

Von Winkle,W.A. 1978. Background noise in underwater acoustic listening systems. Sound Propagation and Underwater Systems. Inst.of Acoustics, Imperial College, London

Wenz, G.M. 1961. Some periodic variations in Low-Frequency acoustic ambient noise levels in the ocean. J. Acoust. Soc. Am. 33: 64

Wille, P.C and D. Geyer. 1984. Measurements on the origin of the wind-dependent ambient noise variability in shallow water. J. Acoust. Soc. Am. 75: 173-185

Wilson, O.B.Jnr, Wolf, S.N and F. Ingenito. 1985. Measurements of acoustic ambient noise in shallow water due to breaking surf. J. Acoust. Soc. Am.,78(1): 190-195

Yen, N. and A.J.Perrone. 1978. Mechanisms of wind induced low frequency ambient sea noise in the deep ocean. Sound Propagation and Underwater Systems. Inst. of Acoustics, (UK) Imperial College, London

Yoon, G. D., 1975. The sea noise of the moving trawl net. Bull. Korean Fish. Soc., 8(1): 1-6

ii. Fish hearing

Alexander, R. McN. 1959. The physical properties of the swimbladder of fish other than cypriniformes. J. Exp. Biol. 36: 347-55

Alexander. R. McN. 1966. Physical aspects of swimbladder function. Biol. Rev. 41: 141-76

Andreeva, I. B. 1964. Scattering of sound by air bladders of fish in deep sound-scattering ocean layers. Sov. Phys. Acoust. 10: 17-20

Bergeijk, W.A. van, 1964. Directional and nondirectional hearing in fish. In Marine Bioacoustics. Ed. W.N. Tavolga, Pergamon Press, Oxford, 1: 281-299

Bigelow, H.B., 1904. The sense of hearing in the goldfish *Carassius auratus* L. Am. natst. 38: 275, 284

Buxey, S., and T. Malar. 1973. Fish response to underwater sound at discrete frequencies. Roy. Can. Military Coll. Sci. Elect. Eng. Tech. Rep. 73/2

Cahn, P.H., W. Siler and A. Auwater. 1971. Acoustico-lateralis system of fishes: Cross modal coupling of signal and noise in the grunt, *Haemulon parrai*. J. Acoust. Soc. Am. 49:591-94

Chapman, C.J. 1964. Responses of herring to sound. In Report of the Fourth I.F. Meeting, Hamburg, 19-20 Oct. 1964.

Chapman, C.J. and A.D.Hawkins. 1969. The importance of sound in fish behaviour in relation to capture by trawls. FAO Fisheries Report 62 (3): 717-729

Chapman, C.J. and A.D.Hawkins. 1970a. Field studies of hearing in cod. Proc. Challenger Soc. 4:59-60

Chapman, C.J. and A.D.Hawkins. 1970b. Further field studies of hearing in teleost fish. Proc. Challenger Soc. 4: 90-91.

Chapman, C.J. and A. D. F. Johnstone. 1974. Some auditory discrimination experiments on marine fish. J. Exp. Biol. 61: 521-528

Coombs, S. and A.N. Popper. 1979. Hearing differences among Hawaiian squirrelfish (family Holocentridae) related to differences in the peripheral auditory system. J. Comp. Physiol. 132: 203-7

Coombs, S. and J. Janssen. 1990. Behavioural and neurophysiological assessment of lateral line sensitivity in the mottled sculpin, *Cottus bairdi*. J. Comp. Physiol. A 167: 557-567

Coombs, S. and R. Fay. 1993. Source level discrimination by the lateral line system of the mottled scuplin (*Cottus bairdi)*. J. Acoust. Soc. Am. 93 (4): 2116-2123.

Denton, E., J.A.B. Gray and J.H.S. Blaxter. 1979. The mechanics of the clupeid acoustico-lateralis system: Frequency responses. J. Mar. Biol. Assn. UK 59: 27-47

Dijkgraaf, S. 1960. Hearing in bony fishes. Proc. Roy. Soc. (B) 152: 51-64

Dijkgraaf, S. 1963. The function and significance of the lateral-line organs. Biol. Rev. 30: 51-105

Dijkgraaf, S. 1964. The supposed use of the lateral line as an organ of hearing in fish. Experimentia 20 (10): 586-7

Dilco, E.A. 1960. Sound discrimination by males of two cyprinid fishes. Tex.J.Sci. 12: 48-54

Enger, P.S. 1969. Sound reception in teleost fishes in relation to the sound source distance. FAO Fish. Rep., (62) 2: 247-252

Enger, P.S., and R. Andersen. 1967. An electrophysiological field study of hearing in fish. Comp. Biochem. Physiol. 22: 517-525.

Enger, P.S., Hawkins, A.D., Sand, O. and C.J. Chapman. 1973. Directional sensitivity of saccular microphonic potentials in the haddock. J. Exp. Biol. 59: 524-533

Fay, R.R., 1974. Masking of tones by noise for the goldfish (*Carassius auratus*). J. Comp. Physiol. Pyschol. 87: 708-716

Fay, R.R. and A.N. Popper. 1974. Acoustic stimulation of the ear of the goldfish (*Carassius auratus*). J. Exp. Biol. 61: 243-60

Fay, R.R. 1978. Sound detection and sensory coding by the auditory systems of fishes. In "The Behaviour of Fish and Other Aquatic Animals". ed. D. Mostofsky Academic Press. 197-236

Fay, R.R., W. Ahroon and A. Orawski. 1978. Auditory masking patterns in the goldfish (*Carassius auratus*): Psychophysical tuning curves. J. Exp. Biol. 74: 83-100

Fay, R.R., 1980. Psychophysics and neurophysiology of temporal factors in hearing by the goldfish: amplitude modulation detection. J. Neurophysiol. 44: 312-332.

Fay, R.R., 1985. Sound intensity processing by the goldfish. J. Acoust. Soc. Am. 78: 1296-1309

Fine, M., H. Winn and B. Olla. 1977. Communication in fishes. In How Animals Communicate. ed. T. Sebeok. Univ. Indiana Press. 472-518

Fish, J.F. and G.C. Offutt. 1972. Hearing thresholds from toadfish (*Opsanus tau*) measured in the laboratory and field. J. Acoust. Soc. Am. 51: 1318-132\f1.

Flock, A. 1971. Sensory transduction in hair cells. In Handbook of Sensory Physiology: Principles of receptor physiology. ed. W.R. Lowenstein, Springer-Verlag. 396-411

Gray, J.A.B. and A.C.G. Best. 1989. Patterns of excitation of the lateral line of the ruffe. J. Mar. Biol. Ass. U.K. 69: 289-306

Griffin, D.R. 1950. Underwater sounds and the orientation of marine animals, a preliminary survey. Tech. Rep. (ONR and Cornell Univ.) 3.

Griffin, D.R. 1955. Hearing and acoustic orientation in marine animals. Deep Sea Res. 3 (Suppl.) 406-417

Harris, G.G., and W.A. van Bergeijk. 1962. Evidence that the lateral-line organ responds to near field displacements of sound sources in water. J. Acoust. Soc. Am. 34: 1831-1841.

Hassan, E.S. 1989. Hydrodynamic imaging of the surroundings by the lateral line of the blind cave fish. *Anoptichthys jordani*. In The Mechosensory Lateral Line: Neurobiology and Evolution. Ed. S. Coombs, P.Görner and H. Münz. Springer-Verlag, New York.

Hawkins, A.D. and C.J. Chapman. 1966. Underwater sounds of the haddock (*Melanogrammus aeglefinus*). J. mar. biol. Ass. UK. 46: 241-247.

Hawkins, A.D., 1973. The sensitivity of fish to sounds. Oceanogr. Mar. Biol. Ann. Rev. 11: 291-340

Hawkins, A.D. and C.J. Chapman. 1975. Masked auditory thresholds in the cod, *Gadus morhua* L. J. Comp. Physiol. 103: 209-226

Hawkins, A.D. 1986. Underwater sound and fish behaviour. In The behaviour of Teleost Fishes. Ed T.J. Pitcher, Croom Helm, London and Sydney.

Hawkins, J.E. and S.S. Stevens. 1950. The masking of pure tones and of speech by white noise. J. Acoust. Soc. Am. 22: 6-13.

Iversen, R.T.B. 1969. Auditory thresholds of the scombrid fish *Euthynnus affinis* with comments on the use of sound in tuna fishing. FAO Fish. Rep. (62) 3: 849-859

Jacobs, D. and W.N.Tavolga. 1967. Acoustic intensity limens in the goldfish. Anim. Behav. 15: 324-335.

Janssen, J. 1990. Localisation of substrate vibrations by the Mottled Sculpin, *Cottus bairdi*. Copeia 1990 (2): 349-355

Jones, F.R.H. 1963. Sound and shoaling in fishes. Anim. Behav. 11: 400-407

Karlsen, H.E. and O.Sand. 1991. Infrasound detection in fish. Biomedical Research 12, Supp. 2, 217-219

Kleerekoper, H. and E.C. Chagnon. 1954. Hearing in fish, with special reference to *Semotilus atromaculatus* (Mitchell) J. Fish. Res. Bd. Can. 11: 130-152

Knudsen, F.R., Enger, P.S. and O. Sand., 1992. Awareness reactions and avoidance responses to sound in juvenile Atlantic salmon, *Salmo salar* L. J. Fish Biol. 40: 523-534

Kroese, A.B.A. and N.A.M. Schellart. 1987. Evidence for velocity and acceleration-sensitive units in the trunk lateral line of the trout. J. Physiol. 394: 13

Kuiper, J.W. 1956. The microphonic effect of the lateral-line organ. Biophys. Group, Natuurkundig Lab. Groningen, 159pp.

Løvik, A. and J.N.Hovem. 1979. An experimental investigation of swimbladder resonance in fishes. J. Acoust. Soc. Am. 53: 1515-1529

Lowenstein, O. 1957. The sense organs. 2. The acoustico-lateralis system. In The physiology of fishes. Ed M.E.Brown New York, Academic Press. 155-186

Manteifel, B.P., Radakov, D.V. and A.V. Nikonorov. 1969. Main trends and some results of fish behaviour studies in USSR. FAO Fish Rep 62(3)

Maliukina, G.A. 1960. Hearing in certain Black Sea fishes in connection with ecology and particulars in the structure of their hearing apparatus. Zh. obshoh.Biol. 21: 198-205

Maliukina, G.A. and V.R. Protasov. 1960. Hearing and voice in fish and their reactions to sound. Usp.sovrem.biol., 50: 215-217

Maniwa, Y. and T. Hashimoto. 1970. Research on the luring of fish schools by utilizing acoustical equipment. Can. Fish. Rep. (15): 588-91

Moulton, J.M., and J.M. Lerner., 1963. The ear-air bladder connections of the menhaden. Am. Zoolst, 3: 498

Moulton, J.M., and R.H. Dixon, 1966. Directional hearing in fishes. Symp. on Marine Bio-Acoustics 13 - 15 April 1966 Port Washington, New York.

Moulton, J.M., and R.H. Dixon, 1967. Directional hearing in fishes. In Marine Bio-acoustics, Ed W.N. Tavolga, Pergamon Press, Oxford, 2: 187-233

Myrberg, A.A. Jnr. and J. Y. Spires, 1972. Sound discrimination by the bicolor damselfish, *Eupomacentrus partitus.* J. Exp. Biol. 57: 727-735

Myrberg, A.A. Jnr. and J. Y. Spires, 1977. Comparative analysis of hearing among damselfishes of the genus *Eupomacentrus.* Abstr. 57th Ann. Meeting, Amer. Soc. Ichthy. and Herpeto. Gainesville, U.S.A.

Myrberg, A.A. Jnr. 1980. Ocean noise and the behavior of marine animals: relationships and implications. Advanced Concepts in Ocean Movements for Marine Biology.

Nelson, D.R., 1967. Hearing thresholds, frequency discrimination and acoustic orientation in the lemon shark (*Negaprion brevirostris)* (Poey) Bull. mar. Sci. 17: 741-768.

Nestler, J.M., G.R. Ploskey., J. Pickens., J. Menezes and C. Schilt. 1992. Responses of Blueback Herring to High-Frequency Sound and Implications for Reducing Entrainment at Hydropower Dams. Nth. Am. J. Fish Manag. 12(4): 667-681

Netten, S.M. van. 1991. Hydrodynamics of the excitation of the cupola in the fish canal lateral line. J. Acoust. Soc. Am. 89: 310-319

O'Connell, C.P. 1955. The gas bladder and its relation to the inner ear in *Sardinops caerulea* and *Engraulis mordax.* Fishery Bull. U.S. Fish. Wildl. Serv. 56(104): 506-533

Offut, G.C. 1968. Auditory response in the goldfish. J. Aud. Res. 8: 391-400

Offut, G.C. 1974. Structures for the detection of acoustic stimulii in the Atlantic codfish, *Gadus morhua.* J. Acoust. Soc. Am. 56: 665-671

Olsen, K. 1967. A comparison of acoustic threshold in cod with recordings of ship noise. FAO Fish. Rep.62(2): 431-438

Packard, A., H.E. Karlsen and O. Sand. 1990. Low frequency hearing in cephalopods. J. Comp. Physiol. 166A, No. 4: 501-505

Parker, G.H. 1904. Function of the lateral-line organs in fishes. Bull. Bur. Fish.,Wash. 24: 185-207

Parker, G.H. 1908. Structure and functions of the ear of the squeteague. Bull. Bur. Fish.,Wash. 28: 1213-1224

Podlipalin, Iu. D., 1965. Ability of some Black Sea fishes to orientate themselves towards the sound source. Problemy Ikhtiol., 2: (4) 25

Popper, A.N., and N.L. Clarke, 1976. The auditory system of the goldfish (*Carassius auratus*) : effects of intense acoustic stimulation. J. Comp. Biochem. Physiol. 53A: 11-18

Popper, A.N., and R.R. Fay, 1973. Sound detection and processing by teleost fishes: a critical review. J. Acoust. Soc. Am. 53: 1515-1529

Popper, A.N. and C. Platt. 1979 The herring ear has a unique receptor pattern. Nature. 280: 832-33

Popper, A.N., and S.Coombs, 1980. Auditory Mechanisms in Teleost Fishes.

Popper, A.N., Rogers, R.H., Saidel, W.M. and M. Cox. 1988. Role of the fish ear in sound processing. In Sensory biology of aquatic animals. Eds J. Atema, R.R. Fay, A.N. Popper and W.N. Tavolga, Springer-Verlag, New York

Protasov, V.P. Bioacoustics of fishes. Delft, European Transl. Centre. TT-66-32410, 218 pp. Russian original publ. as Bioakustica ryb, Moskva, Nauka 207pp.

Pumphrey, R.J. 1950. Hearing. Symp. Soc. exp. Biol. 4: 1-18

Rogers, P.H. and M. Cox. 1988. Underwater sound as a biological stimulus. In Sensory Biology of Aquatic Animals. Eds J. Atema, R.R. Fay, A.N. Popper and W. N. Tavolga Springer-Verlag, Berlin pp 83-130

Sand, O. and A.D. Hawkins. 1974. Measurements of swimbladder volume and pressure in the cod. Norw. J. Zool. 22: 31-34

Sand. O, and P.S. Enger, 1974. Possible mechanisms for directional hearing and pitch discrimination in fish. Rheinisch. Westfälische Akad. L. Wiss. 53: 223-242

Sand, O. And A. Michelsen. 1978. Vibration measurements of the perch saccular otolith. J. comp. Physiol. 123: 85-89

Schuijf, A., 1974. Field studies of directional hearing in marine teleosts. PhD. Dissert. Univ. of Utrecht. 119 pp

Schuijf, A., and M.E. Siemelink. 1974. The ability of cod (*Gadus morhua*) to orient towards a sound source. Experientia 30: 773-773

Schuijf, A., 1975. Directional hearing of cod (*Gadus morhua*) under appropriate free field conditions. J. Comp. Physiol. 98: 307-332

Schuijf, A. and A.D. Hawkins. 1976. Sound reception in Fish. Elsevier Publishing Company, Amsterdam, 228 pp.

Shishkova, E.V. 1973. Study on the bearings of biological noise. ICES, Symp. Acoustic. Meth. Fish. Bergen, 1973. Res., 47.

Sorokin, M.A., Penkin, S.I. and A.N. Lebedeva. 1988. On the distance of directional sound discrimination by fishes. J. Ichthy. 28 (1) 157-160.

Stapells, D.R., Picton, T.W. and A.D. Smith. 1982. Normal hearing threshold for clicks. J. Acoust. Soc. Am. 72:74-79

Tavolga, W.N. 1965. Masked auditory thresholds in teleost fishes. In Review of Marine Bio-acoustics. State of art: 1964. Tech Rep. Navtradevcen 1212-1., 100pp

Tavolga, W.N. 1965. Masked auditory thresholds in teleost fishes. In Marine Bio-acoustics, Ed.W. N. Tavolga, Pergamon Press, Oxford, 2: 247-261

Tavolga, W.N. 1965. Auditory capacities in fishes: threshold variablity in the blue-striped grunt *Haenulon sciurus.* Anim. behav. 13: 301-311

Tavolga, W.N. 1972. Sound production and detection. In Fish Physiology. Ed. W.S. Hoar and D.J. Randall. Acad. Press, New York 5: 135-205.

Tavolga, W.N and Wodinsky, J., 1963. Auditory capacities in fishes. Pure tone thresholds in nine species of marine teleosts. Bull. Am. Mus. nat Hist. 126: 179-239

van Bergeijk, W.A. 1964. Directional and non-directional hearing in fish. In Marine Bio-acoustics, Ed. W. N. Tavolga, Pergamon Press, Oxford, 269-280

van Bergeijk, W.A. 1966. Evolution of the sense of hearing in invertebrates. Am. Zoolst. 6(3): 371-7

van Derwalker, J.G. 1967. Response of salmonids to low-frequency sound. In Marine Bio-acoustics, Ed. W. N. Tavolga, Pergamon Press, Oxford, 2: 45-58

von Frisch, K. 1938. The sense of hearing in fish. Nature, London 141: 8-11

Weiss, B.R., 1967. Sonic sensitivity in the goldfish *Carassius auratus* In Local line detectors, Ed P. Calin, Indiana Univ. Press. 249-264

Wersäll, J., Flock, Å, and P.G. Lundquist. 1966. Structural basis of directional sensitivity in cochlear and vestibular sensory receptors. Cold Spring Harb. Symp. quant. Biol. 30: 115-132.

Wisby, W.J. et al. 1964. Sound perception in elasmobranchs. In Marine Bio-acoustics, Ed. W. N. Tavolga, Pergamon Press, Oxford, 255-268

Wodinsky, J. and W.N. Tavolga. 1964. Sound detection in teleost fishes. In Marine Bio-acoustics, Ed. W.N. Tavolga. Pergamon Press, Oxford, 269-279

iii. Vessel noise

Anon. 1975. Report of the working group on research on sound and vibration in relation to fish capture. C.M. 1975/B:29; 4pp

Auppeile, F.A. and R.F. Lambert. 1973. Acoustic radiation from plates excited by flow noise. J. Sound and Vibration, 26(2): 223-245

Barger, J.E., J.A. Spencer., R.A. Wagner and J. Marchment. 1969. Simulated full-scale hull vibration noise in flush mounted hydrophones. Bolt Beranek and Newman Inc. Report No. 1725

Borud, A. 1969. Wideband noise measurements on the Columbian R/V CHOCO. Simonsen and Mustad. A/S Horten, Norway, Int. Rep. 34-1969

Brehme, H. 1967. Vom Propeller verursachte Geräusche (Propeller induced noise) Schiff Hafen, 6: 418

Doust, D.J. and J. Logan. 1970. Noise and vibration aspects of fishing vessel design. FAO, FII:FF/70/52

Freytag, G. and W. Karger. 1969. Investigations on noise caused by fishing vessels and their sources. ICES C.M. 1969/B:12;

Friedrich, T., 1962. Acoustic measurements in connection with development of a pelagic one-boat-trawl. WG for development of a pelagic one-boat-trawl. Blindern, Oslo. 27 pp.

Furasawa, M and Y. Takao. 1992. Acoustic specifications of fisheries research vessel "Kaiyo-maru" ICES. Joint session FAST and FTFB Working Groups, Bergen, Norway

Goetz, V., 1980. On the correspondence of ship propeller cavitation forms and noise spectra measured on board. 10th Int. Congr. on Acoustics, Sydney, Aust.

Gray, L.M. and Greeley, D.S. 1980. Source level model for propeller blade radiation. J. Acoust. Soc. Am. 67: 516

Greenway, M.E., and C.J. Wood. 1973. The effect of a bevelled trailing edge on vortex shedding and sound. J. Fluid Mech. 61(2): 323-335

Hawkins, A.D and C.J. Chapman, 1969. Noise Trials, MV "SEMLA" unpublished internal report of the Marine Laboratory, Aberdeen.

Hawkins, A.D. and D.N. MacLennan. 1971. Measurement of gear and ship noise. ICES, C.M.1971/B:12; 4pp (mimeo)

Hinich. M. J., Marandino, D. and E.J. Sullivan. 1989. Bispectrum of ship-radiated noise. J. Acoust. Soc. Am. 85 (4): 1512-1517

Kane, J., T.D. Richmond and D.N. Robb. 1966. Noise in hydraulic systems and its suppression. I.Mech. E, UK, Proc. 1965-66. 180(3L).

Kozacka, E. 1978. Sound radiation produced by a ship propeller. Nav. Coll, Gdynia, Arch. 4(3): 221-243

Kozacka, E. 1981. Influence of a ship propeller loading on the shape of the underwater sound power spectrum. Int. Conf. Noise Control Eng. Netherlands Acoust. Soc. Delft, 199-202

Liaaen, M. 1967. Some notes of the relation between noise and the performance of a particular controllable pitch propeller. Skipsmodelltanken, 99 pp

Maniwa, Y. 1968. Studies on the underwater noise of fishing boats. In Second FAO. Conf. onResearch Craft. Seattle, USA. 18-24 May. FR:FRC/68/NP-Gen.4.2/IV, 10p

Maniwa, Y. 1970. Effect of vessel noise in purse seining. FAO Tech Conf. Fish-finding, purse seining and aimed trawling. Reykjavil, 24-30 June 1970. FII:FF/70/28

Mitson, R.B. 1989. Ship noise related to fisheries research. Proc. Int. Conf. Progress in Fisheries Acoustics, Lowestoft. I.O.A, St Albans, UK, 11 (3): 61-67.

Mitson, R.B. 1991. Ship noise in relation to fisheries research. ICES FTFB and FAST Working Groups joint session, Ancona. Italy. 5p.

Mitson, R. B. 1992. Research Vessel Noise Signatures. ICES FTFB and FAST Working Groups joint session, Bergen, Norway.

Ojak, W. 1970. Programme and code of the measurements of the structureborne vibrations and radiated noise to the water for mechanical and hydrodynamical noise sources on R/V "G.O. SARS". avforskningsinstitutt, Bergen.

Pettersen, P. 1968. Wideband noise measurements on the Peruvian R/V SNP1. Simonsen and Mustad A.S., Horten, Norway Internal Report No. 91-1968.

Ross, D., 1981. Noise sources, radiation and mitigation. Underwater Acoustics and Sig. Proc. NATO, ASI, Math and Phys. Sc. 66: 3-28

Shiskova, E.V. 1958. Concerning the reactions of fish to sounds and the spectrum of trawler noise. Ryb. Khoz. 34: 33-39

Shibata, K. 1976. On the shipborne noise of purse seiners. Bull. Faculty. Fish.Nagasaki.Univ.,21

Strawderman, W.A. and R.A. Christman. 1972. Turbulence-induced plate vibrations: some effects of fluid loading on finite and infinite plates. J. Acoust. Soc. Am. 52(5 ii): 1537-1552

Takao, Y. and M. Furasawa., 1992. Noise measurement by echo-integrator. ICES, FAST WG Bergen, Norway.

Traung, I.O. 1969. Study of vessel noise and its effect on fishing. Fishing News International ?

Vatz, I.P. and R.F. Williams. 1962. Development of noise control specifications for the Woods Hole Oceanographic Research Vessel. In Herreshoff, H.C. (ed.) Proc. Soc. Naval Architects and Marine Engineers, New England Section. Bethlehem Steel Co., Massachusetts, USA, 1962

Ward, G. and A. Hoyland. 1979. Ship design and noise levels. Trans.North East Coast Ins.of Eng.and Ships. UK. 95 (4)

Weinstein, M. 1978. The interaction of ship radiated noise with the sea surface. In Proc. Sound Propagation and Underwater Systems, Inst. Acoust., Imperial College, London. (6.4)

Wereldsma, R. 1967. Some aspects of the research into propeller induced vibrations. Int. Shipbldg Prog. 14: 154

iv. Fish reaction to vessels

Aglen, A. and O.A, Misund. 1990. Swimming behaviour of fish schools in the North Sea during acoustic surveying and pelagic sampling trawling. ICES C.M.1990/B:38; 12pp. mimeo

Anon. 1975. Report of the Working Group on Research on sound and vibration in relation to fish capture. Ostende, 21-22 April 1975 ICES C.M.1975/B:29; (mimeo)

Balchen, J.G. 1984. Recent progress in the control of fish behaviour. Modelling, Identification and Control. 52(2): 113-121

Banner, A. and M. Hyatt., 1973. Effects of noise on eggs and larvae of two estuarine fishes. Trans. Amer. Fish. Soc. 102: 134-136

Beamish, F.W.H. 1966. Reactions of fish to otter trawls. Fish. Can. 19: 19-21

Bercy, C and B. Bordeau. 1987. Effects of Underwater Noise Radiated by Tuna Fishing boats on Fish Behaviour. Int. Symp. Fisheries Acoustics, National Marine Fisheries Service, Seattle, Washington, USA. Paper 8 b (unpublished).

Blaxter, J.H.S. and D.E. Hoss. 1981. Startle response in herring: the effect of sound stimulus frequency, size of fish, and selective interference with the acoustico-lateralis system. J. Mar. Biol. Assn. 61: 871-879

Blaxter, J.H.S. and R.S. Batty. 1987. Comparisons of herring behaviour in the light and dark: changes in activcity and responses to sound. J. Mar. Biol. Assn. 67: 849-860

Boklach, G.A. 1989. The effect of fishing vessel acoustic fields on the behaviour of speedy fish concentrations. “Progress in Fisheries Acoustics” Inst. Acoust. (UK) 11(3): 68-73

Burner, C.J. and H. L. Moore, 1953. Attempts to guide small fish with underwater sound. Spec. scient. Rep. U.S. Fish. Wildl. Serv. 111: 38 pp

Busnel, R.G. 1959. Étude d'un appeau acoustique pour la pêche, utilisé au Sénégal et au Niger. Bull. Inst. fr. Afr. noire (A) 21(1): 346-360

Class, C.W. and Wardle, C.S. 1989. Comparisons of the reaction of fish to a trawl gear, at high and low light intensities. Fish. Res., 7: 249-266

Dalen, J. and Raknes, A. 1985. Scaring effects on fish from three-dimensional seismic surveys. Report FO 8504. Inst. Mar. Res., Bergen Norway. 22 pp

Erickson, G.J. 1979. Some frequencies of underwater noise produced by fishing boats affecting albacore catch. J. Acoust. Soc. Am. 66 (1): 296-299

FAO, 1968. Report on a meeting for consultations on underwater noise. Rome, Italy 17-19 Dec. 1968 FAO Fish. Rep. 76: 32pp

Foote, K.G. 1980. Comment on, "Some frequencies of underwater noise produced by fishing boats affecting albacore catch", J. Acoust. Soc. Am. 67: (3) 1064

Freon, P., Gerlotto, F and M. Soria. 1990. Evaluation of the influence of vessel noise by night on fish distribution as observed using alternately motor and sails aboard. ICES FAST Working Group, Rostock 1990.

Gerlotto, F., C. Bercy and B. Bordeau. 1989. Echo-integration survey around offshore oil-extraction platforms off Cameroon: observations of the repulsive effect on fish of some artificially emitted sounds. Progress in Fisheries Acoustics. Inst. Acoust. (UK) 11(3): 79-88.

Greene, C.R. 1985. A pilot study of possible effects of marine seismic airgun array operation on rockfish plumes. For Seismic Steering Comm. by Greeneridge Sciences Inc. Santa Barbara, California.

Hawkins, A.D. 1986. Underwater sound and fish behaviour. In The behaviour of teleost fishes. Ed T.J. Pitcher. Croom Helm, London and Sydney. p 114-151

Hashimoto, T. and Y. Maniwa. 1967. Research on the luring of fish shoals by utilising underwater acoustical equipment. In Marine Bioacoustics, Ed. W. Tavolga . Pergamon Press

Hashimoto, T. and Y. Maniwa. 1971. Research on the luring of fish shoals by underwater sound. In Modern Fishing Gear of the World: 3. Ed. H Kristjonsson. Fishing News Books Ltd. London

Haymes, G.T. and P.H. Patrick. 1986. Exclusion of adult alewife, *Alosa psuedoharengus* using low-frequency sound for application at water intakes. J. Can. Fish. Aquat. Sci. 43: 855-862

Hering, G., 1964. Avoidance of acoustic stimuli by the herring. ICES C.M. 1968/H:18; 5p mimeo

Iversen, R.T.B. 1969. Auditory thresholds of the scombrid fish *Euthynnus affinis,* with comments on the use of sound in tuna fishing. FAO Fish Rep. 62(3): 849-859

Knudsen, F.R., Enger, P.S. and O. Sand. 1992. Awareness reactions and avoidance responses to sound in juvenile Atlantic salmon, *Salmo salar* L. J. Fish Biol. 40: 523-534

Løkkeborg, S. 1991. Effects of a geophysical survey on catching success in longlining. ICES. C.M. 1991/B:40; 9 p

Løkkeborg, S. and Soldal, A.V. 1993. The influence of seismic exploration with airguns on cod. *Gadus morhua* behaviour and catch rates. ICES mar. Sci. Symp. 196 (in press)

Maliukina, G.A. and V.R. Protasov. 1960. Hearing and voice in fish and their reactions to sound. Usp.sovrem.biol., 50: 215-217

Mohr, H. 1964. Reactions of herring to fishing gear revealed by echo-sounding. In Modern Fishing Gear of the world. Ed. H. Kristjonsson. Fishing News (Books) Ltd. 2: 253-257

Moore, H.L. and H.W. Newman, 1956. Effects of sound waves on young salmon. Spec.scient.Rep. U.S. Fish Wildl. Serv. (Fish), (172): 19pp

Moorhouse, V.H.K. 1933. Reactions of fish to noise. Contr. Can. Biol. Fish., 7: 465-475

Misund, O.A. 1990. Sonar observations of schooling herring. School dimensions, swimming behaviour, and avoidance of vessel and purse seine. Rapp. P.-v. Réun. Cons. Int. Explor. Mer. In press.

Moulton, J.M. 1956. The movements of menhaden and butterfish in a sound field. Anat. Rec., 125: 592

Moulton, J.M., 1963. Acoustic behaviour of fishes. In Acoustic Behaviour of Animals, Ed. R.G. Busnel, 655-693, Elsevier, Ams.

Moulton, J.M., and R.H. Backus, 1963. Annotated references concerning the effects of man-made sounds on the movements of fishes. Circ.Me. Dep. Sea Shore Fish., 17: 1-7

Nunnalee, E.P. 1991. An investigation of the avoidance reactions of Pacific whiting (*Merluccius productus)* to demersal and midwater trawl gear. ICES C.M. 1991/B:5; Session U

Olsen, K. 1969a. A comparison of acoustic threshold in cod with recordings of ship noise. FAO Fish. Rep. 62(2): 431-438.

Olsen, K. 1969b. Directional responses in herring to sound and noise stimuli. ICES C.M. 1969/B:20; 8pp

Olsen, K. 1979. Observed avoidance behaviour in herring in relation to passage of an echo survey vessel. ICES C.M. 1979/B:18; 8pp

Pearson, W.J, Skalski. J.R., and C.I. Malme. 1992. Effects of sounds from a geophysical survey device on behaviour of captive rockfish *Sebastes* sp. Can. J. Fish. Aquat. Sci., 49: 1343-1356

Schwarz, A.L. and G.L.Greer. 1984. Responses of Pacific herring, *Clupea harengus pallasi,* to some underwater sounds. Can. J. Fish. Aquat. Sci. 41: 1183-1192.

Shishkova, E.V., 1958. Fish reaction to sound and to noise spectra of a trawler. Rybnoe Khoziaistvo (3): 33-39

Skalski. J.R., Pearson, W.J and C.I. Malme. 1992. Effects of sounds from a geophysical survey device on catch-per-unit-effort in a hook and line fishery for Rockfish *Sebastes* sp. Can. J. Fish. Aquat. Sci., 49: 1357-1365

Suzuki, H. and Y. Maniwa. 1974. Field studies on the effect of artificial underwater sound in the attraction of fish schools. In IEEE Int. Conf. Engr. in the Ocean Environment. New York

Thorne, R.E. and E. S. Kuehl. 1989. Impacts of noise on the estimation of downriver migrating smolts. Proc. Int. Conf. Progress in Fisheries Acoustics, Inst. Acoust. (UK) 11(3): 89-95

Traung, I.O. 1969. Study of vessel noise and its effect on fishing. Fishing News International

Urquhart, G. G. and A.D. Hawkins, 1975. Sound, fish behaviour and fishing. In Oceanology International 75, 16-21 March, Brighton, England pp 220-4

v. Effects of noise on instrumentation

Elminowicz, A. 1969. R.V. "Professor Siedlecki" echo-sounder and sonar self noise measurements. MIR, UNDP, FAO, Polish-UNSF High Seas Fish. Res. Proj

Rao, V.B. 1983. Flow-induced noise of a sonar dome - Part 1 Applied Acoustics, 18: 21-31

Rasmussen, R.A. Head, N. 1971. Target detection in homogeneous noise backgrounds using a time/bearing display format. Scripps Inst. Oceanogr.,San Diego, 71-30

Stewart, J.L., Westerfield, E.C. and Brandon, M.K. 1980. Optimum frequencies for noise-limited active sonar detection. J.Acoust. Soc.Am.,75(5): 1336-1338

Tucker, D.G. and Griffiths, J.W.R. 1957. Detection of pulse signal in noise, trace-to-trace correlation in visual displays. The effect on visual detection of the area of the signal paint J.Brit.I.R.E.,17 (6): 319-338

APPENDIX 3

Study Group meetings and membership

Terms of reference. To specify and summarise available information on the essential noise requirements for research vessels with a view to recommending measuring procedures.

The group held two one-day meetings. First in Gothenburg, Sweden, on 19 April 1993, from which an interim report was issued (C.M. 1993/B:5;) then in Montpellier, France, on 26 April 1994 where the second draft was discussed and suggestions were made for revision which resulted in the final report (C.M. 1994/B:5;).

Members of the group:

Dr G P Arnold, UK
Dr H Bethke, Germany
Mr E. Götze, Germany
Dr D V Holliday, USA
Mr J.A. Jacobsen, Faroes
Mr B Lundgren, Denmark
Mr R Mitson, UK. (Chairman)
Mr E J Simmonds, UK
Mr D. Swain, Canada
Mr B. Thomsen, Faroes
Dr J.J. Traynor, USA

Participants in Gothenburg

Dr G P Arnold, UK
Ms C Goss, UK
Dr D V Holliday, USA
Mr H P Knudsen, Norway
Mr C Lang, Canada
Mr B Lundgren, Denmark
Mr J Milne, Ireland
Mr R Mitson, UK
Mr E J Simmonds, UK
Mr I Svellingen, Norway

Participants in Montpellier

Dr G P Arnold, UK
Mr N Diner, France
Ms C Goss, UK
Dr D V Holliday, USA Mr
J A Jacobsen, Faroes
Mr C Lang, Canada
Mr B Lundgren, Denmark
Mr R Mitson, UK
Mr E J Simmonds, UK
Mr I Svellingen, Norway
Dr J J Traynor, USA