

# Causes and effects of underwater noise on fish abundance estimation

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## Abstract

The power of modern research vessels using diesel engines means significant levels of noise may be radiated underwater. At low frequencies a surveying vessel must not cause fish avoidance behaviour when it is using trawl or acoustic assessment methods. All the main mechanisms that form the essential propulsion system are described and discussed in terms of underwater radiated noise. Diesel engines, generators and propulsion motors contribute significantly to the low frequency spectrum and an illustration is given of underwater noise when an unsuitable propulsion system is used. Avoidance behaviour by a herring school is shown due to a noisy vessel, by contrast there is an example of no reaction of herring to a noise-reduced vessel. Propellers are major sources of both low and high frequency noise. The latter should not reduce echo sounder detection range, nor contaminate echo integrator recordings. Underwater noise levels from four vessels with different machinery and propulsion characteristics are seen in relation to ambient noise levels at 18 kHz. Fish detection is examined in relation to sea background noise and vessel self-noise. Calculated detection ranges for fish target strength classes from –30 to –60 dB at 38 kHz are shown for six vessels travelling at 11 knots, based on self-noise measurements. Echo sounder noise levels from several vessels at 120 and 200 kHz are tabulated. Beyond 100 kHz the effect of vessel-radiated noise is usually insignificant; levels up to that frequency are proposed in the International Council for the Exploration of the Sea (ICES) Cooperative Research Report No. 209 of 1995.

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## 1. Introduction

Fisheries management requires unbiased estimates of the stocks. Currently, the estimates are made mostly by trawl and acoustic surveys whose accuracy depends on sampling an undisturbed natural distribution of the populations. A survey vessel should ideally not affect the behaviour of fish in its vicinity and should be capable of using its scientific echo sounder and sonar systems to their maximum capabilities. A low underwater radiated noise signature is the key to success in these matters and this was recognised by the International Council for the Exploration of the Sea (ICES) with the publication of Cooperative Research Report No. 209 (CRR 209, Mitson, 1995). This document was the first in which a limiting noise level recommendation was made on the basis of available scientific evidence. In 1999 a guidance note on machinery characteristics, <http://www.ices.dk/pubs/crr/guide209.htm>, was issued to advise that a noise reduced

vessel should always be in this state when running at, or under, a speed of 11 knots. It is unacceptable for a vessel to have a special ‘survey’ mode.

A few noise-reduced fisheries research vessels were built more than 30 years ago but these fail to meet current noise recommendations by a significant margin. Although their machinery configuration was similar to more recent vessels, improvements in all aspects of the important technologies mean that it is now feasible to achieve low levels of underwater radiated noise as recommended by CRR 209. Prior to this report, FRV “Corystes” came into service in 1988, having been built to a stringent underwater noise specification set by the owners. A good result was reported by Kay et al. (1991) after modifications during the latter part of construction. This gave confidence when FRV “Scotia” was designed and built to a similar engineering specification where meeting the CRR 209 recommendations formed part of the building contract. Important lessons learned from FRV’s “Corystes” and “Thalassa” led to a satisfactory outcome when noise measurements were made in 1998.

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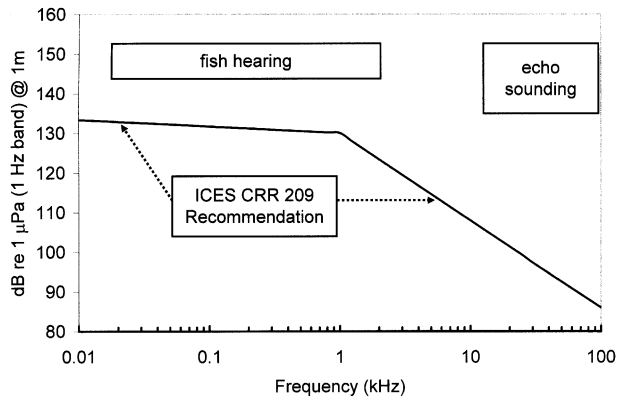


Fig. 1. This shows the maximum underwater radiated noise levels recommended by the ICES CRR 209 (1995) "Underwater Noise of Research Vessels: Review and Recommendations" at vessel speeds up to and including 11 knots. This report is referred to throughout the text as CRR 209.

## 2. Method

We examine matters relating to the implementation of noise reduction measures necessary to achieve the levels recommended in CRR 209, shown in Fig. 1. Precautions must be taken on many aspects of vessel design to meet these levels, which should not be exceeded at any vessel speed up to and including 11 knots over the frequency spectrum of 10 Hz to 100 kHz. To put the matter of underwater radiated noise and its potential to cause fish avoidance behaviour into perspective fish hearing is briefly mentioned.

The main machinery for running and propulsion of the vessel is examined in general terms with some details of successful and unsuccessful arrangements being identified. When a vessel has been constructed to meet the CRR 209 levels, proof of compliance has to be obtained and recommended measurement procedures are described.

Details from two separate experiments to determine the effects of a noisy vessel on herring concentrations are described and one experiment, also on herring, using a noise-reduced vessel. We consider the other important factor, the effect of high frequency underwater radiated noise on the detection capabilities of scientific echo sounders. Measurements from several vessels at 18, 120 and 200 kHz are compared. At 38 kHz the detection depths of six vessels are shown for a range of fish target strengths.

This paper aims to provide details of ambient sea noise and the origins and/or levels of vessel radiated and self-noise that can reduce the accuracy and effectiveness of acoustic and trawl surveys.

## 3. Results

### 3.1. Fish hearing in relation to vessel noise

It is appropriate to start by referring to fish hearing because of the importance of a survey vessel being able to sample by acoustics or trawl a natural fish distribution undisturbed by radiated noise. At frequencies below about 2 kHz,

the CRR 209 graph represents a level above which fish are likely to show avoidance behaviour. Although most commercial fish have a hearing capability extending from a few hertz (Sand and Karlsen, 1986) to possibly tens of kilohertz (Astrup and Møhl, 1993; Dunning et al., 1992) the lower and upper extremes have limited sensitivity. The lowest hearing threshold is 75 dB re 1  $\mu$ Pa at 150 Hz with a 6 dB bandwidth of about 220 Hz for cod (Chapman and Hawkins, 1973). Herring have the same sensitivity but a much greater bandwidth to about 1.5 kHz (Enger, 1967; Blaxter et al., 1981). Both cod and herring are important commercial species so the potential effect of vessel noise is based on their sensitivity and hearing bandwidth. For some other species the possible distances for avoidance behaviour are shown by Mitson (2000).

### 3.2. Machinery configuration

Much of the necessary machinery to drive and operate a ship produces vibration, within the frequency range of 10 Hz to 1.5 kHz, with the consequence of radiation in the form of pressure waves from the hull. For economic and practical purposes, a distance limit has to be set beyond which no fish avoidance behaviour should occur and in CRR 209 this is set at 20 m from the vessel. To aim for a limit closer to the vessel would increase costs significantly and make the task of noise reduction more difficult.

Currently, the only proven method to produce a low noise vessel suitable for fisheries research is by use of diesel-electric propulsion. This arrangement has several advantages, including relative ease of isolating the main generators from the hull because no mechanical connection is needed to the electric propulsion motor. A successful arrangement has proved to be a 'generating set' (genset) comprising a diesel engine, coupled to an alternator, both of which are mounted on a rigid frame sometimes called a raft. Two stages of isolation by special mounts are arranged for the engine, typically allowing a reduction of vibration of more than 40 dB to be achieved between the engine base and its seating in the hull. To stiffen the raft the alternator is often bolted directly down with a flexible coupling driving it from the engine. Vibration from the alternator caused by magnetic forces has to be taken into account. A particular problem, which must be avoided is due to a form of alternator construction where straight 'slots' are used to accommodate the windings. This causes the generation of a "slot-passing" frequency,  $f_{\text{Hz}} = (\text{number of slots} \times \text{the engine rpm}/60)$ , with a subsequent high vibration level transmitted to the hull via the mountings which can occur in the range of fish hearing. Instead, it is necessary to use herringbone or skewed slot construction techniques to minimise this effect.

The size and number of gensets is chosen according to the power requirements of the vessel and varies between two and four sets for existing vessel designs. Construction of the hull seating for the gensets must aim to achieve maximum stiffness for the purpose of further reducing the transmission of vibration and the subsequent radiation of noise into the water.

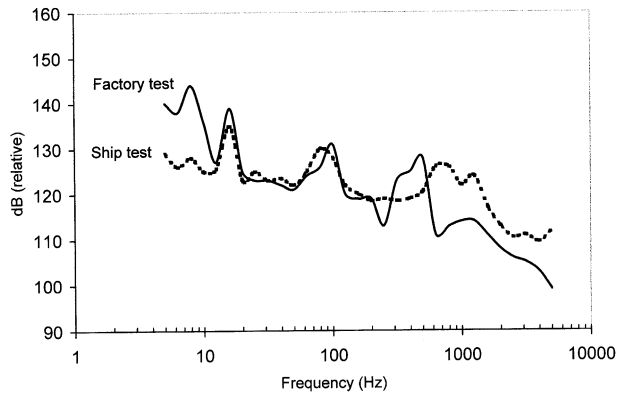


Fig. 2. Showing the measured vibration characteristics of a combined diesel engine and generator set (genset) on 85% load before and after its installation in a vessel.

An impression can be gained of the importance of this process in Fig. 2, showing the change of levels that occurred between factory testing and subsequent installation in the vessel. In this figure note the significant reduction in vibration below 10 Hz but an increase above 600 Hz. For herring, the increase between about 600 Hz and 1.5 kHz shown in this figure could be important. Such an example illustrates the attention to detail that has to accompany the design and construction of all noise reduced vessels and the installed machinery.

The convenience of alternating current (AC) as an electrical power supply is that the voltage supplied from the genset alternators can easily be transformed to different voltages to supply all the vessels requirements. But a propulsion system, known as AC/AC, is now proven to be unsatisfactory because it uses an AC motor where vibration, hence noise levels, are inherently high and this arrangement should not be used. An example of the underwater noise from such a system is seen in Fig. 3 when the vessel was moving at 10 knots. Such high levels of the noise peaks are unsatisfactory. The situation is made worse because a characteristic of this type of propulsion means that the frequency of these peaks varies as the

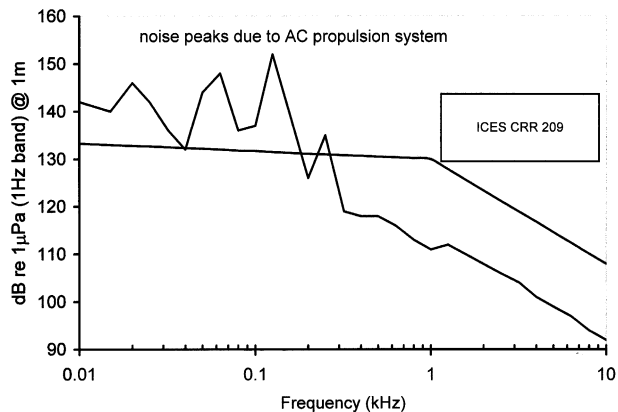


Fig. 3. Underwater radiated noise from FRV "Thalassa" at 10 knots. The peaks are associated with vibration of the propulsion motor due to the AC electrical drive used. Due to the excellent propeller design a very low level of propeller cavitation is evident above 300 Hz.

vessel speed changes, moving them across the frequency range of fish hearing.

For a low noise vessel, AC must be converted to direct current (DC), to provide a smooth drive with speed control to the propulsion motor. This system is known as AC/DC and is specified for all vessels currently building to meet the CRR 209 recommendation.

The DC propulsion motor is coupled directly to the propeller and handles the full power needed to drive the vessel so it is 'hard-mounted' to the hull and must, therefore, have a very low level of vibration. For this reason its construction must use a herringbone or skewed slot design technique as stated above for the alternators. From 0, to perhaps 150 or 180 rpm, the motor drives the propeller, which produces a broad frequency spectrum of noise but for the present, we consider only the low frequency aspects. As the number of propeller blades increases, the pressure per blade is less and the risk of the phenomenon of cavitation is reduced. However, the overall efficiency is also reduced and a satisfactory compromise has been accepted for most vessels with the use of five blades. FRV "Thalassa" is an exception with six blades and she has an excellent performance at high frequencies but any low frequency benefit is lost due to the AC propulsion.

### 3.3. Vessel noise signatures

In addition to broad band propeller noise there is a phenomenon known as 'singing' where a discrete tone is produced by the propeller, usually due to physical excitation of the trailing edges of the blades. Despite this well-known effect, manufacturers often fail to provide an adequate anti-singing trailing edge on their propellers with the result that very high tone levels can occur in the frequency range of fish hearing.

Often the most prominent features in the low frequency signature of a noise reduced vessel are the propeller blade rate and twice this rate. Blade rate is the frequency  $f$  at which the blades pass the closest section of the hull, where  $f_{\text{Hz}} = (\text{number of blades} \times \text{propeller shaft rpm})/60$ . The level of these 'tones' can vary slightly according to the trim of the vessel. Another feature might be the propeller shaft rate. Bandwidths as narrow as 0.375 Hz are used to obtain measurements for identification of the major individual contributions to the signature. Two peaks might be due to a five-bladed propeller where the blade rate at 130 rpm is at 10.8 and 21.6 Hz at twice the rate. From the diesel engine, the cylinder firing rate  $\times 2$  and the crankshaft rate  $\times 1$  can usually be identified, with their harmonics blending into many other noises at higher frequencies. The running speed of the engine is  $f_{\text{Hz}} = (\text{rpm}/60)$ , typical engine speeds for noise reduced vessels are 750 or 1000 rpm. It is expected that the quality of machinery selected for vessels, plus associated isolation measures, will mean that transmission of line frequencies (tones) will be minimised.

The overall signature of a vessel comprises noise from many machinery sources. Pumps in particular are often sig-

nificant producers of noise from vibration and at higher frequencies from turbulent flow. Sharp angles and high flow rates in pipework can also cause cavitation and even small items of machinery might produce quite high levels. As noise and vibration levels of the main machinery items is reduced, the importance of smaller objects increases. For example, the ringing of a telephone hard-mounted on an engine room bulkhead, has been detected underwater at a distance of about 1 km.

### 3.4. Determining the vessel noise signature

Investigation of a noise signature involves two operations. A ‘static’ ranging with the vessel held securely between moorings. This provides an opportunity to identify the frequency spectrum and levels from particular pieces of machinery. A typical exercise of this sort involved 187 operations, with different items being switched on and off and results recorded from each of them. The main dynamic noise ranging operation involves a series of runs at specified speeds through a noise range. This comprises hydrophones about 100 m on either side of the vessel track for port and starboard (beam) measurements, preferably placed 30 m or more metres deep. The slant ranges between the centre point of the vessel and the hydrophones are corrected to 1 m. There are usually one or more hydrophones under the line of the vessel’s passage for keel aspect noise measurements. Noise ranges are normally operated for naval purposes and fisheries research vessels are recommended to use these amenities. This is because of the experienced staff with a high standard of facilities and procedures available, which are based on appendices A, B and C of NATO STANAG 1136. The NATO procedures do not require an allowance for Lloyd’s mirror effect. In some limited circumstances the use of a portable noise range described by Enoch and McGowan (1997) might be suitable for noise ranging FRV’s.

For any vessel, there are angular differences in radiated noise emanating from sections of the hull. Historically, the normal series of measurements made during noise ranging have been taken separately but simultaneously from the port and starboard sides. These often show differences in levels as a result of the layout of machinery within the hull. The third octave band measurements are reduced to a 1 Hz band then averaged to give a simplified picture of the noise signature. Simultaneously, narrow band measurements are made to determine if significant levels of line frequencies (tones) are present. Keel aspect noise levels can be important for a fisheries vessel because the directivity of the hull at low frequencies is greatest in that aspect. On one vessel, this was measured as 6 dB greater than the beam measurements at frequencies below 100 Hz. It is relatively recently that keel aspect noise levels have been specified but it is clear that knowledge of these levels is a necessary requirement. When a vessel runs over the top of a school, fish are suddenly subjected to a higher noise level, which may cause a sharp diving reaction as seen by Olsen et al. (1983).

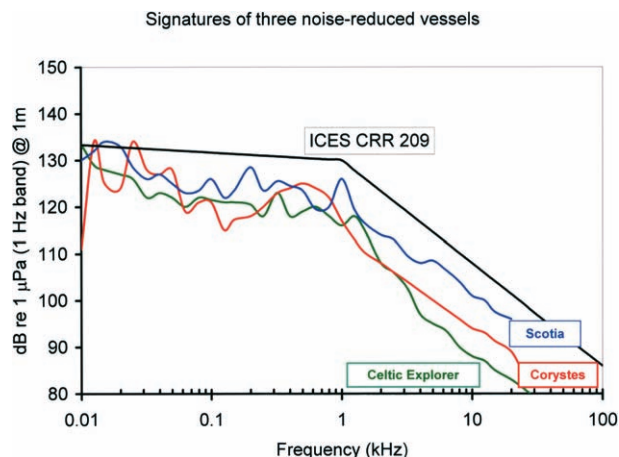


Fig. 4. Underwater radiated noise signatures of three noise-reduced vessels, FRV’s “Corystes” “Scotia”, “Celtic Explorer” shown for vessel speeds of 11 knots in relation to the CRR 209 levels.

Signatures of three noise-reduced vessels, whose measurements were carried out to the NATO standard, are compared in Fig. 4 to the CRR 209 recommended levels. These vessels were running at 11 knots and have similar configurations of machinery although the manufacturers are not the same for all items. FRV “Corystes” was built 7 years before CRR 209 was published. For her, the blade rate and twice the rate are seen to cross the line slightly but thereafter a significant margin exists. A more diffuse low frequency deviation is seen in the signature of FRV “Scotia” which is partly due to the blade rate and a flow induced resonance. The latest vessel is FRV “Celtic Explorer” whose blade rate level barely touches the line and at frequencies above 3 kHz the levels are very low, giving the potential for a good fish detection capability.

### 3.5. Observed effects of vessel low-frequency noise

There are many reports of fish avoidance caused by research vessels, e.g. Buerkle (1977), Olsen (1979), Diner and Massé (1987), Goncharov et al. (1989), Misund (1993), Soria et al. (1996), Arrhenius et al. (2000) and Vabø et al. (2002). The latter authors studied vessel avoidance behaviour of wintering spring-spawning herring during an acoustic abundance estimation survey being carried out by FRV “Johan Hjort”. Observations of echo energy from schools were made from a downward-looking echo sounder transducer submerged at 12 m when the survey vessel approached and passed the surface marker at close range. There is a difficulty in associating avoidance behaviour with the speed of this vessel because of the highly variable levels of noise that occur, primarily due to changes of propeller pitch. No details are given of the pitch settings used during the experiments but, for example, there are also two available propeller shaft speeds of 100 and 125 rpm, each of which can produce a vessel speed of 8 knots by different pitch settings. At this speed it can be seen from Fig. 5 that noise levels of either 164 or 144 dB occur. These translate into possible fish reaction ranges of 790 and 79 m, respectively.



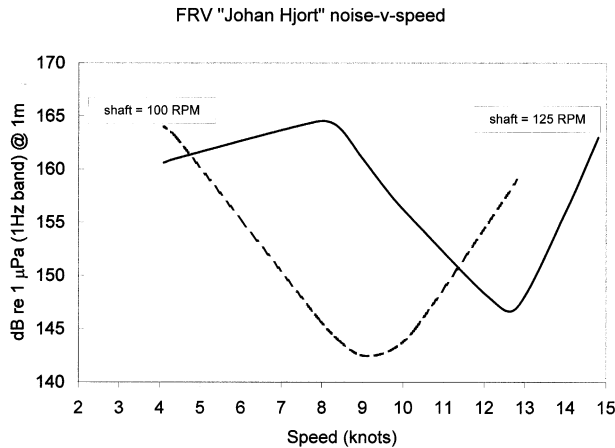


Fig. 5. Variation of underwater radiated noise with speed of FRV “Johan Hjort” resulting from changes of propeller pitch and the optional propeller shaft rpm of 100 or 125. These noise levels occur at a frequency of about 100 Hz.

FRV “Johan Hjort” was also used in 2002 for a large scale systematic investigation of how vessel avoidance by herring may affect abundance estimation. Data from one of about 50 passes made during the experiment are shown in Fig. 6A, B, illustrating the reaction of a herring layer to the approach of the vessel and the effect on the received echo energy. A full data analysis is in preparation for publication by Ona et al. The recordings were made from a stationary EK 60, 38 kHz echo sounder, mounted in a floating buoy system, described by Godø and Totland (1999) and Godø et al. (1999), when the research vessel passed close by. It seems clear from the recordings that the high power pulse transmission from the echo sounder had no effect on the fish aggregation. During the experiment, the 38 kHz echo sounder of FRV “Johan Hjort” was turned off so as not to disturb the buoy recordings, 18 kHz was used instead.

In Fig. 6A, the effects on the echo recording from the layer of herring are caused by FRV “Johan Hjort” running at a nominal 10 knots from a distance 1.2 km up to and passing alongside the buoy to within 8–10 m at 0 min, then receding. Fig. 6B helps to quantify the results of the avoidance behaviour by showing how the mean depth of the echo energy changed as the vessel approached and passed the buoy. The radiated level of noise from the vessel appears to start affecting the fish aggregation at about 1.75 min prior to the closest approach when a downward trend begins in the depth of the echo.

This corresponds to a distance of 540 m. FRV “Johan Hjort” was using a propeller shaft speed of 125 rpm, giving a radiated noise level sufficient to cause fish avoidance behaviour at 560 m distance when travelling at 9 knots but it reduces to 355 m at 10 knots. Fig. 5 shows that large changes in noise level occur for a small change in speed. Fig. 6A, B indicate a relatively quick recovery after the vessel’s closest point of approach. The nature of the curve that follows suggests abnormal fish activity continues for sometime as the vessel travels away from the buoy.

## Effects of vessel avoidance

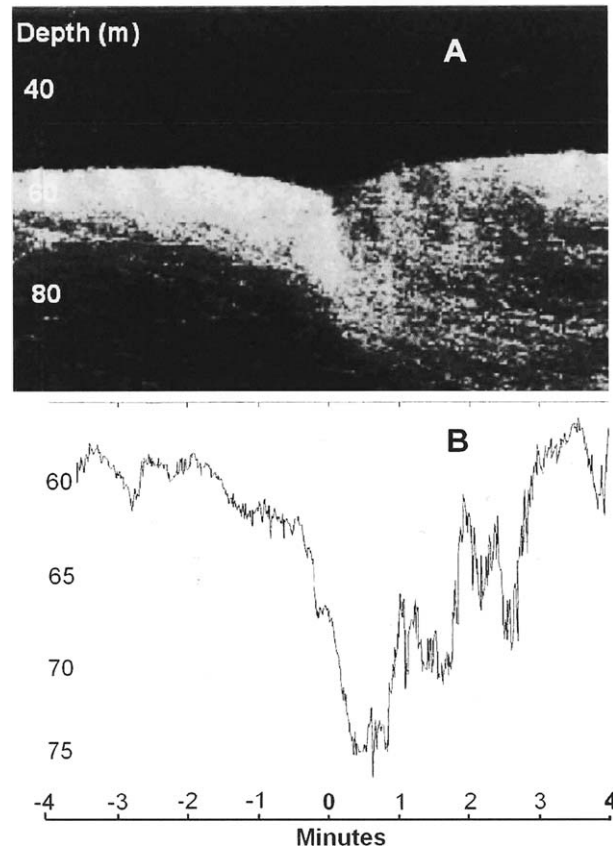


Fig. 6. (A) The time depth record was taken from a buoy mounted echo sounder and shows a herring school exhibiting vessel avoidance behaviour during a passage of the FRV “Johan Hjort” from about 1200 m to within 8–10 m of the recording buoy. (B) This shows the change in mean depth of the recorded echo energy due to the passage of FRV “Johan Hjort”.

Variability in the response of fish to nearby vessels has been reported and more observations are needed to investigate this matter. It might be due to the physiological state of the fish at different seasons of the year, or local environmental factors such as salinity, temperature or water transparency. Thermal gradients in the sea can cause radiated noise to be directed either upwards or downwards depending on the gradient. These may reduce or even prevent noise reaching the fish, the so-called ‘afternoon effect’ due to heating in the upper layers of water.

### 3.6. Low-noise research vessel survey

Fish avoidance behaviour experiments, using research vessels, can be expensive but it is hoped that effort will be directed towards such work as the number of noise-reduced vessels increases. Evidence is available from an example reported by Fernandes et al. (2000) to show that a vessel noise-reduced to the CRR 209 recommendation does not induce avoidance behaviour by fish. A herring survey in the North Sea was conducted during July 1999 by FRV “Scotia” during part of which an autonomous underwater vehicle (AUV) known as Autosub was used for comparative mea-

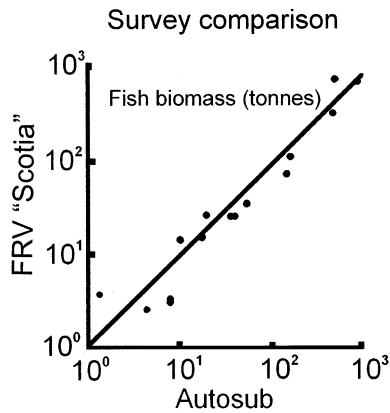


Fig. 7. Results from a herring survey made by FRV "Scotia" and the AUV Autosub, showing significant correlation ( $r = 0.935$ ,  $P < 0.001$ ) of the strata averaged biomass estimates from these vessels; after Fernandes et al. (2000). This indicates that the noise-reduced FRV "Scotia" did not cause any vessel avoidance behaviour to be exhibited.

surements on a large aggregation. This vehicle has an extremely low level of radiated noise, Griffiths et al. (2001), typically between 20 and 40 dB less than FRV "Scotia", by reason of being a small, battery powered device, with minimum moving parts. Autosub has a limited speed of about 4 knots, which had to be matched by FRV "Scotia" for this experiment. It was reasonable to assume that the results would be valid for the normal survey speed because the noise signature of FRV "Scotia" is almost identical at 4 and 11 knots up to 1 kHz. Autosub was deployed 200–800 m ahead of the FRV on eight transects in water 60–180 m deep using the same scientific echo sounder as the FRV. It passed very close indeed to the herring school but caused no more than a localised compression, typical of a close approach by a predator in visual range. If the FRV radiated noise was at a level to cause a reaction from these fish, it was expected that it would detect a smaller quantity than Autosub. The correlation between the two vessels is seen in Fig. 7, which indicates that no avoidance behaviour took place.

### 3.7. Noise at echo sounder frequencies

If a vessel is sufficiently quiet that it does not disturb fish in its vicinity it also needs the capability to detect them, determine their target strength (size) distributions and assess the population distribution and density (MacLennan and Simmonds, 1992). Very sensitive scientific echo sounders operating at frequencies above 10 kHz are used for these purposes (Mitson, 1983) and there are two main sources of noise that can restrict their capabilities, the ambient noise due to natural forces and vessel self-noise.

### 3.8. Underwater ambient noise

Ambient noise in the sea, due to sea-state, shows great variability as a result of the many sources from which it arises, so any levels quoted are averages from a number of situations (Ross, 1987). Wind blowing on the surface is a

significant cause (Urlick, 1983) but as frequency increases, typically above 100 kHz, thermal (molecular agitation) noise begins to increase and become more important (Mellen, 1952). In this paper, we will use metres per second,  $m s^{-1}$ , for the wind speed. For unusual local circumstances, such as heavy rain, noise can rise by about 20 dB for a wind speed of  $1.5 m s^{-1}$  when rainfall increases from 1 to 7  $mm h^{-1}$  (Scrimger et al., 1989). Below 1 kHz, ambient noise is not likely to affect fisheries acoustic surveys, although fish behaviour may be modified if the level is high enough to mask their hearing.

### 3.9. Fish detection

The ultimate theoretical limit, to detection of fish echoes, is the level of ambient noise in the sea. Echo sounders, operating at the lower frequencies, are most vulnerable to this noise because above 1 kHz it decreases by about 20 dB per decade. The lowest frequency normally used for fish detection and assessment purposes is 18 kHz, and at this frequency, a typical echo sounder might expect to receive a signal of 76 dB re  $1 \mu Pa$  from a single fish of  $-40$  dB target strength (TS) at 600 m depth. Ambient noise is about 22 dB re  $1 \mu Pa$  for a wind speed of  $1.5 m s^{-1}$ , and at  $20 m s^{-1}$  this has increased to 48 dB. When corrected for echo sounder bandwidth these levels become 49 and 76 dB re  $1 \mu Pa$ , respectively, so for the higher wind speed this fish would not be detected. There is little to be done about high ambient noise levels other than reduce the echo sounder receiver bandwidth which is usually linked to the transmitted pulse duration, so has other implications.

If weather conditions are good, fish detection is mainly limited by the self-noise of the vessel. This refers essentially to noise generated on, or by the vessel, which is received by the echo sounders and sonars, a major source being the propeller. It is noise due to the presence of the vessel and not to the surrounding medium. Mechanisms which cause self-noise are also capable of radiating noise into the sea but it is important to keep a clear distinction between self and radiated noise. Echo sounders and sonars are normally situated within the near-field of these sources and the noise they receive is different from that in the radiated far-field. At 18 kHz, the wind-induced noise is likely to be dominant but frequencies above 70–100 kHz are more prone to limitation by thermal noise. Fig. 8 compares the self-noise levels at 18 kHz of four research vessels running at speeds from 3 to 12 knots. Ambient noise levels related to wind speeds from 3 to  $20 m s^{-1}$  are included.

This figure shows that for FRV's "G.O. Sars" and "Johan Hjort" self-noise exceeds sea-state noise for wind speeds below  $5 m s^{-1}$ , whilst for FRV "Bjarni Saemundsson" self-noise rises sharply with vessel speed from a low level below ambient noise due to a wind of  $3 m s^{-1}$  almost reaching the level from a  $20 m s^{-1}$  wind at 11 knots. For FRV "Thalassa" the ambient noise at  $3 m s^{-1}$  wind speed is only slightly greater than vessel self-noise over much of her speed range. This is due to an exceptionally low noise propeller.

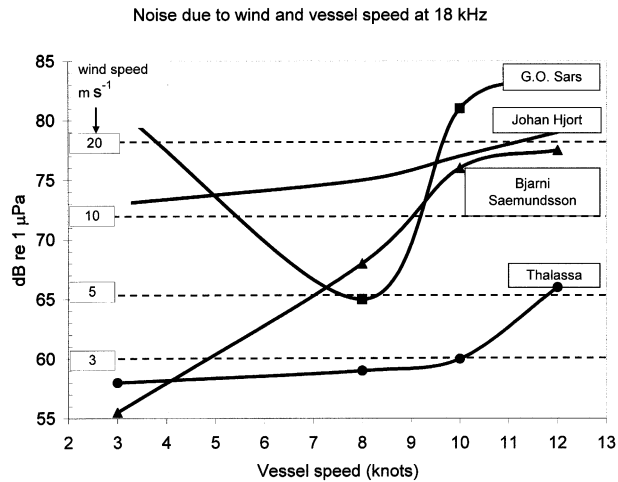


Fig. 8. A comparison of the self noise measured on four vessels at a frequency of 18 kHz when travelling at speeds between 3 and 12 knots. Ambient noise levels in the sea due to wind speed are also shown.

At echo sounder frequencies, the propeller is the most significant source of self-noise, although orifices in the hull, projections, and rough surfaces, can also play a part. This noise becomes severe when one or more of the common types of propeller cavitation, tip, blade, sheet, hub is fully established. The use of controllable pitch (CP) propellers in vessels means that alteration of the blade pitch angle, sometimes combined with changes of propeller shaft speed, results in a highly variable generation of noise as seen in Fig. 5. Another example of this is FRV “G.O. Sars” in Fig. 8. This type of propeller is discredited for vessels used in fisheries research. For present day purposes, attention is given to the design of fixed pitch propellers where high frequency noise is more directly related to shaft speed as seen for FRV “Thalassa” in Fig. 8. Such designs must adequately meet the criteria of low noise, whilst being capable of achieving sufficient pulling power for trawls and the desired maximum free-running speed. The approximate rate of reduction in propeller noise is 20 dB per decade. In ICES CRR 209, the aim above 1 kHz was to achieve a maximum limit of  $130-22 \log f_{\text{kHz}}$  at vessel speeds up to, and including, 11 knots. In choosing a maximum of 11 knots for the low noise condition, the ICES Study Group took into account the fact that few of the vessels existing at that time were capable of exceeding such a speed without risking corruption of the echo integration process due to self-noise. Difficulties in realising a propeller design to meet the three conflicting criteria above were also recognised. Progress is being made in this respect with FRV “Thalassa” being one example and a recent design for FRV “Celtic Explorer” has achieved very low levels of noise, particularly at high frequencies.

Detecting individual fish is a demanding task, depending on the actual target strength and range from the transducer. Taking these factors into consideration, as range increases so the received signal grows weaker until it is ultimately at the same level as the noise and cannot be detected. At lower frequencies, although absorption losses are less, wind in-

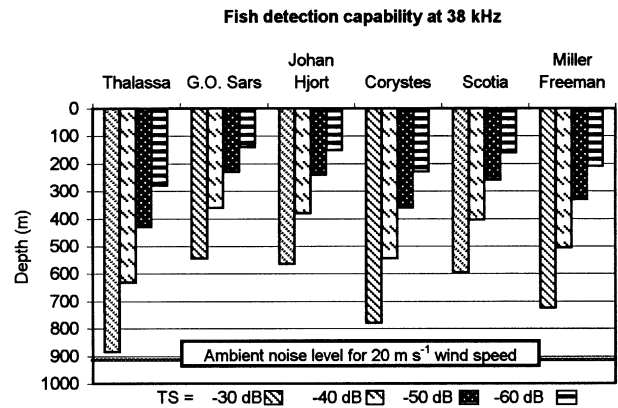


Fig. 9. The fish detection depth capability of six vessels at 38 kHz is shown for four classes of fish target strength. Calculated from self noise and radiated noise measurements.

duced noise is higher, so this carries the risk of reducing the detection range of the echo sounder. Noise levels for three wind speeds at 18 kHz are shown in Fig. 8 but results are not available from vessels built to the ICES CRR 209 recommended levels at this frequency.

When the wind speed is high it also induces motion of the vessel, causing turbulence and air bubbles beneath the hull. This has a deleterious effect on the performance of transducers mounted there through attenuation and signal blocking. In the past this has meant restricting the speed of the vessel. Now, the problem has been reduced in some vessels by the use of a ‘drop keel’ or ‘centreboard’ projecting to about 3 m below the hull with transducers fitted at the bottom surface, an idea introduced by Ona and Traynor (1990). As a result of this innovation there is greatly improved performance in bad weather and the limiting factor to surveying may no longer be noise from turbulence, or from signal blocking, but safety to engage in tasks such as trawling or other overboard activities.

Fig. 9 shows the fish detection predictions for six vessels at 38 kHz, related to their noise levels when operating at 11 knots. The signal to noise ratio used was 10 dB and the fish target strengths are from  $-30$  to  $-60$  dB. A bandwidth of 976 Hz was assumed. The same source level was used for each vessel calculation. For reference purposes the detection limit due to ambient noise is shown for the wind blowing at  $20 \text{ m s}^{-1}$ . It is interesting to note the difference in detection range of the vessels, which is directly related to the performance of their propellers. Those for FRV’s “Corystes”, “Thalassa” and “Miller Freeman” were optimised for low noise and consequently these vessels have the better fish detection capabilities. FRV “Thalassa” has an excellent six-bladed propeller but those on FRV’s “Corystes”, “Scotia” and “Miller Freeman” are five-bladed. The latter has a new design of highly skewed propeller provided at a recent refit. FRV “Scotia” noise measurements were taken with the drop-keel down at 3 m. When it was at 0 m, with the transducer face flush to the hull, the 38 kHz noise level was 2 dB greater. This vessel does not have an optimised propeller so her detection capability is slightly less than that should be. Both

Table 1  
Self noise levels (dB re 1  $\mu$ Pa) relative to vessel speed measured at 120 and (200) kHz

Vessel	Speed (knots)					
	2	4	6	8	10	11
B. Saemundsson	75.5	75.5	75.5	75.5	75.5	75.5
G.O. Sars	67 (78)	67 (78)	67 (78)	67 (78)	67 (78)	67 (78)
Johan Hjort	74 (95)	74 (95)	74 (95)	74 (92)	74 (92)	74 (94)
Scotia			62 (62.5)	62 (63.8)	63.5 (64.8)	64 (64.8)
Thalassa	66.5	66.5	66.5	66.5	67	67
Miller Freeman	63.6	63.6	64.2	63.7	63.7	64.1

the FRV's "G.O. Sars" and "Johan Hjort" have controllable pitch, four-blade propellers.

Higher frequencies of 120 and 200 kHz are used in some surveys and it can be seen from the measured self-noise levels in Table 1 that vessel speed has little effect, except perhaps in the case of FRV's "Scotia" and "Thalassa", where there is a slight increasing trend at 120 kHz. FRV "Miller Freeman" uses a CP propeller for speed control and a small variability is seen but the flat response from the other vessels could be due to detection of thermal noise level in the sea. At 120 kHz, this is about 26 dB re 1  $\mu$ Pa, resulting in 61 dB for a bandwidth of 3096 Hz. In some instances internal receiver noise or electrical interference can be significant at these frequencies. At 200 kHz, the thermal level is about 30 dB, so in a bandwidth of 1953 Hz the receiver level would be 63 dB. At this frequency, there is little indication of vessel speed affecting results, apart from FRV "Johan Hjort" where some variation is seen but her levels are much higher than the other vessels, probably due to receiver noise.

#### 4. Discussion

The effects of vessel radiated noise on fish and on their detection by echo sounder have been well recognised and documented in many papers and reports. Here we have attempted to expand details in some of the important areas to explain causes and possible effects of such noise on surveys of fish abundance. Firstly, vessel mechanisms that produce low frequency noise within the hearing frequencies of fish. We then draw attention to aspects of high-frequency underwater noise, including vessel self-noise and ambient levels in the sea with comparison of their effects where appropriate. The most significant effect on fish abundance estimation is likely to be that of low-frequency noise causing vessel avoidance behaviour by fish which can bias acoustic and trawl survey results. Problems may be compounded when results are needed from the combination of acoustic data with bottom trawl data, as is the case for pelagic and semi-demersal species. Fish may be driven out of the path of the vessel where they will be missed by the echo sounder, or, into or out of the path of a trawl. Some reports show that fish may be driven into the path of a net which otherwise would not have been caught (Saetersdal, 1969; Ona and Godø, 1990; Dorchenkov, 1986) thereby distorting the natural distribution estimates.

At echo sounding frequencies the noise levels for several vessels have been taken as the basis for calculating detection

depths of several target strength classes in Fig. 9. Considerable differences are seen between the vessels, thereby emphasising the need for low noise propellers to obtain maximum performance from the echo sounders. In the case of older fixed pitch propellers, where noise is a problem, a palliative is reduction of speed. For vessels with CP propellers this remedy is not effective because of the extreme variability of radiated noise with change of blade pitch, hence speed.

Ambient noise levels in the sea are unlikely to have a major effect on acoustic or trawl surveys unless conditions are exceptional, or when working in deep water with fish recorded as single targets (Reynisson, 1996). At frequencies greater than 100 kHz the performance restrictions may be due to limitations of the echo sounder receivers rather than thermal noise in the sea, or possibly to electrical interference on the vessels. Turbulence and bubble sweep down under the hull will remain a problem where vessels are not fitted with a drop keel, or do not use a towed transducer.

Is there an alternative to the type of noise reduced vessel outlined in this paper? For a full capability in fisheries and oceanography research the answer appears to be no. However, AUV's have a potential for very low noise levels shown by measurements on Autosub and the experiment to survey a herring aggregation in conjunction with FRV "Scotia" was reported above. Such a vehicle might be usefully employed where circumstances are favourable, e.g. using it when controlled from a noisy vessel. This use would require careful planning in regard to the distance at which the AUV could 'safely' be deployed (relative to the noise of the parent vessel). When used from a noise-reduced vessel an extended survey area could prove an advantage but obtaining a representative trawl sample from the recorded fish would be a drawback.

Fisheries research vessels will continue to be designed and built. Due to the long time interval between the building of a vessel and its subsequent replacement, to say nothing of the cost, it is vital that lessons learned in the building and construction process of each vessel are carefully assessed and appropriate action taken to benefit from them. It is suggested that the ICES community should take steps to publish details of their vessels design and performance achieved because of the need to not only set suitable standards but to minimise the cost of these projects.

The major engineering design problems appear to have been solved by:



- careful attention to detail in the selection of high quality, low vibration diesel engines and alternators for the main generating sets. These items must be adequately isolated and the composite assemblies installed on stiff seatings in the hull. Associated pipe work has to be isolated to reduce transmission of vibration.
- Use of a DC propulsion motor with a low level of vibration when running from an electrical drive with a minimum of 24-pulses (the so-called AC/DC system). This motor must be firmly seated in the hull. Four new vessels including FRV's "Celtic Explorer", "CEFAS Endeavour", the replacement "G.O. Sars" and the "Oscar Dyson" use AC/DC propulsion. Investigations show there are no significant differences between the installed costs of AC/DC and AC/AC propulsion systems. Since high power electronic control systems are used for propulsion there is a need to ensure that electromagnetic compatibility (EMC) is carefully specified to reduce the effects of electrical interference on the scientific echo sounders and other instruments.
- Having specially designed, noise-reduced, multi-bladed, fixed-pitch propellers with anti-singing features. The new fisheries research vessels for Ireland, the UK, Norway and the USA, built to conform to the ICES CRR 209 (Mitson, 1995) recommendation will be coming into service during the next year and it is hoped that information on their design and performance will be made available to add to current knowledge on the subject of underwater radiated noise and its effect on fish abundance estimation.

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### References

- Arrhenius, F., Bethke, E., Cardinale, M., Hakansson, N., 2000. Intercalibration of nautical area scattering coefficients between research vessels. *Arch. Fish. Mar. Res.* 48, 31–42.
- Astrup, J., Møhl, B., 1993. Detection of intense ultrasound by the cod (*Gadus morhua* L). *J. Exp. Biol.* 182, 71–80.
- Blaxter, J.H.S., Gray, J.A.B., Denton, E.J., 1981. Sound and startle responses in herring shoals. *J. Mar. Biol. Assoc. UK* 61, 851–869.
- Buerkle, U., 1977. Detection of trawling noise by Atlantic cod (*Gadus morhua* L). *Mar. Behav. Physiol.* 4, 233–242.
- Chapman, C.J., Hawkins, A.D., 1973. A field study of hearing in the cod (*Gadus morhua* L). *J. Comp. Physiol.* 85, 147–167.
- Diner, N., Massé, J., 1987. Fish school behaviour during echo surveys observed by an acoustic device. Proceedings of International Symposium on Fisheries Acoustics 21–24 June. Seattle, WA, USA, pp. 14.
- Dorchenkov, A.E., 1986. Estimation of fish numbers and biomass in the bottom zone through acoustic technique. *Rybnoe Khozyaistvo* (in Russian) 5.
- Dunning, D.J., Quentin, E., Ross, D., Geoghegan, P., Reichle, J.J., Menzies, J.K., Watson, J.K., 1992. Alewives avoid high-frequency sound. *N. Am. J. Fish. Manage.* 12, 407–416.
- Enger, P.S., 1967. Hearing in Herring. *Comp. Biochem. Physiol.* 22, 527–538.
- Enoch, P.J., McGowan, S., November 1997. Accurate Measurement of Ownship Acoustic Signature. *Sea Technol.*, 15–20.
- Fernandes, P.G., Brierley, A.S., Simmonds, E.J., Millard, N.W., McPhail, S.D., Stevenson, P., Squires, M., 2000. Fish do not avoid survey vessels. *Nature* 604, 35–36.
- Godø, O.R., Totland, A., March 1999. Bergen Acoustic Buoy (BAB)—A Tool for Remote Monitoring of Marine Resources. Joint IASA/EASA meeting, Berlin Paper 2 p. A010. p. 4.
- Godø, O.R., Somerton, D., Totland, A., 1999. Fish behaviour during sampling as observed from free floating buoys—Application for bottom trawl survey assessment. *ICES CM* 1999/J:10.
- Goncharov, S.M., Borisenko, E.S., Pyanov, A.T., 1989. Jack mackerel school defence reaction to a surveying vessel. *Prog. Fish. Acoust. UK Inst. Acoustics* 11, 74–78.
- Griffiths, G., Enoch, P., Millard, N.W., 2001. On the radiated noise of the Autosub autonomous underwater vehicle. *ICES J. Mar. Sci.* 58, 1195–1200.
- Kay, B.J., Jones, D.K., Mitson, R.B., 1991. FRV Corystes: A purpose-built Fisheries Research Vessel. The Royal Institution of Naval Architects, London, pp. 12 (Spring meetings 1991).
- MacLennan, D.N., Simmonds, E.J., 1992. Fisheries Acoustics. Chapman and Hall, London.
- Mellen, R.H., 1952. Thermal noise limit in the detection of underwater acoustic signals. *J. Acoust. Soc. Am.* 24, 478.
- Misund, O.A., 1993. Avoidance behaviour of herring (*Clupea harengus*) and mackerel (*Scomber scombrus*) in purse seine capture situations. *Fish. Res.* 16, 179–194.
- Mitson, R.B., 1983. Fisheries Sonar. Fishing News Books. Blackwell Science, Oxford, UK.
- Mitson, R.B. (Ed.), 1995. Underwater Noise of Research Vessels: Review and Recommendations. *ICES Coop. Res. Rep. No.* 209, 61.
- Mitson, R.B., 2000. Fish avoidance: the vessel noise factor. *ICES ASC: Incorporation of External Factors in Marine Resources Surveys (K) CM* 2000/K:16.
- Olsen, K., 1979. Observed avoidance behaviour in herring in relation to passage of an echo survey vessel. *ICES CM B:* 19 (mimeo).
- Olsen, K., Angell, J., Pettersen, F., Løvik, A., 1983. Observed fish reactions to a surveying vessel with special reference to herring, cod, capelin and polar fish. In: Nakken, O., Venema, S.C. (Eds.), Symposium on Fisheries Acoustics, Bergen, Norway. *FAO Fish. Rep.* 300, 139–149.
- Ona, E., Godø, O.R., 1990. Fish reaction to trawling noise: the significance for trawl sampling. *Rapp. P-v Réunion. Cons. Int. Explor. Mer.* 189, 159–166.
- Ona, E., Traynor, J.J., 1990. Hull mounted protruding transducer for improved echo integration in bad weather. *ICES CM B:* 3, 1–10.
- Reynisson, P., 1996. Evaluation of threshold-induced bias in the integration of single fish echoes. *ICES J. Mar. Sci.* 53, 345–350.
- Ross, D., 1987. Mechanics of Underwater Noise. Pergamon Press (reprinted Peninsula Publishing (1976 Chap. 4, 8, 10).
- Saetersdal, G., 1969. Review of information on the behaviour of gadoid fish. *FAO Fish. Rep.* 62, 210–215.
- Sand, O., Karlsen, H.E., 1986. Detection of infrasound by the Atlantic cod. *J. Exp. Biol.* 125, 197–204.
- Scrimger, J.A., Evans, D.J., Yee, W., 1989. Underwater noise due to rain—Open ocean measurements. *J. Acoust. Soc. Am.* 85, 726–731.
- Soria, M., Fréon, P., Gerlotto, F., 1996. Analysis of vessel influence on spatial behaviour of fish schools using a multi-beam sonar and consequences for biomass estimates by echo sounder. *ICES J. Mar. Sci.* 53, 453–458.
- Urlick, R.J., 1983. Principles of Underwater Sound. McGraw-Hill Book Company.
- Vabø, R., Olsen, K., Huse, I., 2002. The effect of vessel avoidance of wintering Norwegian spring spawning herring. *Fish. Res.* 58, 59–77.