CM 2002: Session J:10

Theme Session: Use of Marine Research Vessels in ICES – Options for the Future

RESEARCH VESSEL STANDARDS: UNDERWATER RADIATED NOISE

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ABSTRACT

ICES effectively created a standard for the underwater radiated noise of research vessels by issuing the Cooperative Research Report, No. 209 (Anon,1995). Recommendations contained therein are being adopted by a number of countries as new vessels are designed and built, because there is a need for research vessels to sample fish populations in their natural, undisturbed state. This paper addresses the problem of fish avoidance behaviour caused by vessel noise. It shows the levels at which noise has the potential to affect assessment made by using acoustics and/or trawl methods. Comparisons are made of the ranges at which some of the current research vessels may cause avoidance behaviour by the fish they wish to sample.

Over recent decades the power of vessels has increased significantly, with a consequence that higher underwater noise levels are inevitable, unless suitable measures are taken. The chief sources of noise within the hearing frequencies of fish are the main engines and the propeller. Available technologies have enabled a combination of machinery to be formulated which, when combined with suitable isolating and insulating techniques, can reduce the radiated noise to an acceptable level. The aim is to prevent any reaction to the vessel from fish at a distance of more than 20 metres. Because acoustic methods of stock assessment are used, it is also necessary to ensure that noise at echo sounder frequencies does not obscure or contaminate data obtained in this way. It may be unrealistic to expect that every vessel used in research surveys will be noise-reduced in the near future, but it is important that a nucleus of such vessels is available to minimise bias due to vessel noise and thereby assist in providing the necessary quality assurance of data collected for fishery management purposes.

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INTRODUCTION

For many decades reports have been made quoting observations of fish avoidance behaviour in relation to research vessels; it was clear that this affected the quality of data collected for fishery management purposes. To examine this problem ICES first set up a working group in 1975 to make a report, “Research on sound and vibration in relation to fish capture”. It was another twenty years before techniques to reduce vessel noise were well developed and by then the situation for fisheries management was becoming more critical. This prompted ICES to set up a Study Group within the Fisheries Acoustic Science and Technology (FAST) working group in 1993 to examine the situation and to make recommendations. The Study Group report to Council in 1994 was approved and in 1995 the Cooperative Research Report No. 209 was published. Its recommendation for maximum allowable radiated noise levels has become known as the ICES Standard for vessels used in fisheries research.

There has been a significant overall increase in the level of noise in the sea over the past four or five decades because the number of ships at sea steadily increased, although this trend has declined in recent years. In many parts of the world there was an increase of over 3 times in low frequency noise between 1950 and 1975. But, more importantly, the power of propulsion systems used to drive ships has increased dramatically (Ross, 1987). Noise from these shipping sources forms a background in the sea which has local variations of intensity and frequency.

Although fishing and research vessels contribute to the overall noise level, it is only in a very local context that we need to consider their effects. Most fish are capable of hearing sounds over a distance of many kilometres but do not react to them until a certain level above their hearing threshold is reached. There is some variability in the hearing sensitivity between fish species, the most sensitive being cod and herring. Because fish have the facility to sense the direction from which a sound is coming they can move away when the level becomes too intense. Such avoidance behaviour has a potentially serious impact on the effectiveness of research surveys being carried out, either by trawl or when making acoustic assessments.

Some variability of fish response to sound has been noted and this may, under certain circumstances, be due to environmental conditions. For example, ambient noise in the sea can increase and decrease according to the strength of the wind agitating the surface and this may be sufficiently high to mask fish hearing. Also, the propagation of sound waves is affected by thermal changes in the sea that may result in bending of those waves. This can be enough to direct noise radiated from the vessel away from the position of the fish, or to reduce its intensity as perceived by the fish.

There are considerable variations in noise level from vessel to vessel, which is not surprising because research organisations usually want a vessel designed to meet their own particular needs. This leads to differences in hull design and especially to the choice of machinery and its layout when installed onboard. These matters have a bearing on the pattern and intensity of external radiated noise which is discussed later. Research vessels are the most important tools available to fishery scientists so it is essential that they can sample with the minimum of disturbance to fish from their underwater radiated noise.

FISH HEARING

Fish hearing mechanisms are described in ICES CRR 209 so will not be discussed here. Although some research continues into the hearing capabilities of fish, it is mostly at frequencies very low, <20 Hz and very high, >10kHz, where the effects appear to be of short range, only a few metres (Sand & Karlsen, 1986) (Astrup & Møhl, 1993). However, for many commercial fish, enough is already known about their hearing from research carried out about thirty years ago, e.g., Chapman & Hawkins, 1973 and Enger, 1967.
The actual frequency bandwidths and degrees of hearing threshold sensitivity do vary with species, so figures for the most sensitive (cod) and the widest band (herring) are combined and used for reference purposes. Such knowledge helps to define levels at which these fish react to vessel noise. Distances have been measured at which reaction has been observed to

vessels with known noise signature levels. The result is that an excess of about 30 times over the fish hearing threshold seems sufficient to cause avoidance behaviour. Figure 1 shows portions of the noise signatures from three currently operating research vessels in relation to the reaction levels of five species of fish. The noise reduced vessel will have no effect but one of the others will affect cod, herring and haddock whilst the noisiest will have an effect on all five species.

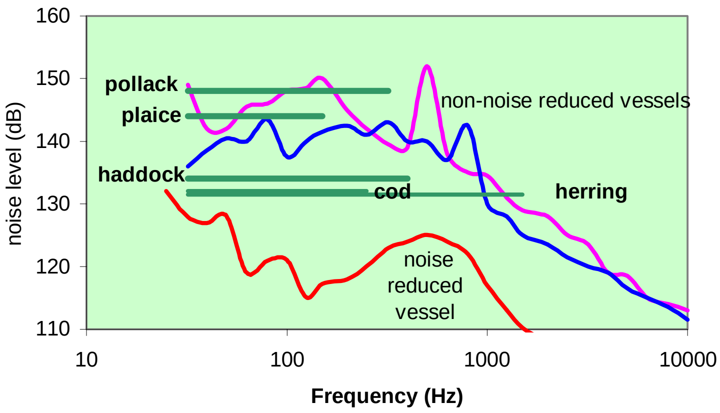

Figure 1. The reaction levels of 5 fish species in relation to frequency and to the signatures of 3 research vessels.

Less is known about the hearing of tropical fishes but there is no doubt of their sensitivity to noise and examples of reaction to vessels are given in Brehmer et al., 2000. These authors point out that several factors can have an influence on avoidance behaviour, including environmental, biological, physiological, hydrological, and other matters. For the most sensitive cold water species, the hearing range extends from about 25 Hz to almost 2 kHz, so vessel noise frequencies in this band must be controlled and their radiation into the sea strictly limited.

VESSEL GENERATED NOISE

The vessel noise signature is made up of sounds from all items of machinery. Rotating and reciprocating machines invariably produce both airborne and structure-borne noise (vibration) by their nature and vessels contain many such items, all with characteristic noise signatures which combine to result in an overall signature for the vessel. Knowing the frequencies and levels of noise that may cause fish avoidance behaviour leads to an examination of machinery used in fisheries research vessels.

ENGINE AND GENERATOR UNITS

For the present, the only successful formula to meet the low noise requirement is based on diesel-electric propulsion. Figure 2 shows a layout of the section of a vessel where most of the main machinery is housed.

The sources of power are the so-called ‘gensets’. These are units of combined diesel engine and alternator (AC). Typically, there may be two,

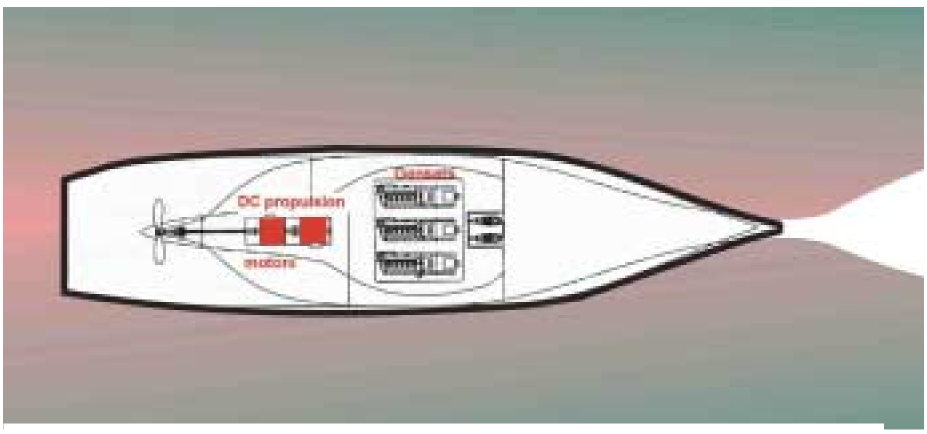

Figure 2. The main units of propulsion machinery. Note multiple ‘gensets’ and tandem motors for operational flexibility.

three, or even four such genset units, depending on the power needs of the vessel. This arrangement means that the gensets can be individually isolated from the hull to reduce the transmission of vibration and therefore minimise noise radiation into the water. A system of isolation is used where the diesel engine and generator are attached by isolators to an intermediate frame. The underside of the frame then has another set of isolators by which it is fixed to the seatings in the hull. Although this sounds like a simple process, much careful calculation and design is needed. As a rough guide the vibration levels at the feet of the engine need to be reduced by a hundred times or more at the seating in the hull. Both the diesel engines and the alternators must be selected for inherently low levels of vibration which requires high-quality well-designed and balanced machines to ensure that the vibration and noise level requirements are met. It is easy to understand how noise occurs in the engines but there are also significant forces present in the alternators that must be controlled and prevented from exciting the hull plates.

PROPULSION MACHINERY NOISE

The power needed for the purposes of fisheries research vessels is likely to be from about 2 MW (2500 HP) to 6 MW (8000 HP) so large electric motors are required to drive the propeller. Vibration from a high quality electric motor largely reflects the nature of its power source so alternating current (AC) is not suitable and Direct Current (DC) becomes the obvious choice. We have already seen that the genset units contain alternators, so to drive the DC propulsion motor their output has to be converted to DC, using electronic systems that also allow precise control of vessel speed. Care has to be taken to avoid any residual of the frequencies from the drive control system (ripple) on the electrical supply to the motors because this would cause vibration. The large mechanical forces involved in propelling the vessels make it impractical to resiliently mount propulsion motors to isolate the inherently small vibration from the hull, instead, they are ‘hard-mounted’ in the vessel and directly coupled to the propeller shaft. Rotation of this shaft leads to the discrete ‘shaft rate’ frequency and its harmonics being generated and radiated into the sea. For a shaft turning at 150 RPM the frequencies would be 2.5, 5, 7.5 Hz, etc.

PROPELLER NOISE

The propeller is a major source of noise. Being located outside the hull the noise is transmitted directly into the water. A primary source of this noise is the phenomenon of cavitation where negative pressures occur as the propeller blades rotate, resulting in the formation of bubbles that subsequently collapse with a bang! From this source there is usually a broad peak of noise between about 100 and 500 Hz with, therefore, a potential to frighten fish. But because there is wide variation in the size of the bubbles, cavitation noise extends to the high frequencies used for echo sounding, so is also of importance in that respect. Other propeller noise is caused by pressure pulses generated when the blades pass close to the hull so this distance is kept as wide as possible. In figure 3 seven types of cavitation are shown but those most common are tip vortex, hub vortex and propeller hull

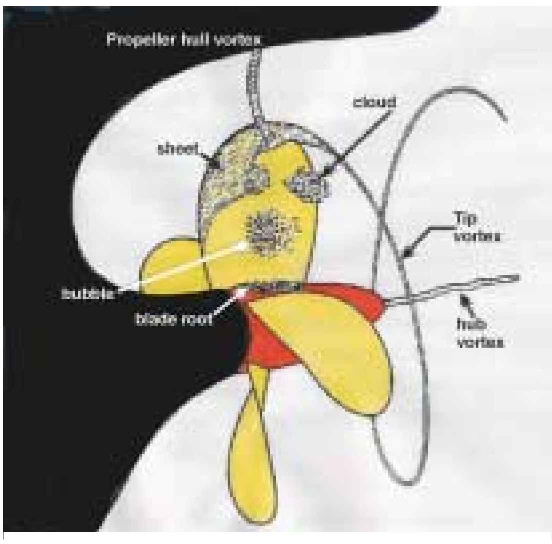

Figure 3. Illustrating the various forms of cavitation that can exist.

vortex. During propeller design, care is taken to eliminate, minimise, or to delay the onset of cavitation to beyond 11 knots. Propellers also produce discrete frequencies due to the rate at which the blades rotate. For a four-bladed propeller at 150 RPM the blade rate is 10 Hz. Most noise reduced vessels now use a five-bladed propeller so for the same RPM the blade rate frequency will be 12.5 Hz but it is often the harmonics of these frequencies that cause most concern.

THE RADIATED NOISE FIELD

The above brief descriptions give an indication of the major noise sources found in research vessels, the vibrations from which are coupled either through the hull or directly to the sea. The process of noise generation is dynamic and each vessel has a unique signature related to its speed, loading, trim and the amount and type of machinery running. To determine its signature, the vessel is run over a 'calibrated noise range' with particular attention to speeds up to and including 11 knots. Although this procedure may take place in widely separated countries, comparisons between vessels are possible because most ranges are operated for Naval purposes and they use similar equipment and techniques.

During the noise ranging, measurements are made of the levels at port and starboard aspects of the vessel and, more recently, of the keel aspect. Averaging of the port and starboard levels has been the practice to simplify the description of the noise signature but, as there can be important differences, data are kept for each aspect. The pattern of the radiated noise field depends on the shape of the hull, with the radiation on each side of the vessel having an increasing level as it moves down towards the keel area.

Because the shape of the vessel narrows towards the bow this gives rise to what is known as a butterfly pattern so there is a significant drop in noise level directly ahead of the vessel (see the illustration in figure 2). Fish have been shown to move from side to side in this area of low noise, changing direction when they meet the higher levels, Engås et al., 1991a. Sound in water travels at about 1500 metres per second whereas the vessel will be travelling at only about 5.5 ms^{-1} at 11 knots and around 2 ms^{-1} at trawling speeds, so noise reaches the fish long before the vessel is physically close.

From the viewpoint of a fish at some considerable distance from a vessel, there is a low level background noise in the underwater surroundings which may vary according to the amount of shipping activity and the strength of the wind acting on the sea surface. Into this relatively quiet area, an individual vessel is heard, the noise from which increases rapidly as it approaches the fish. Because many fish possess directional hearing which is acute in both azimuth and elevation (Hawkins and Sand, 1977; Schellart and Munck, 1987) they are able to predict the bearing of an approaching vessel and therefore, can be aware of the direction to take to move out of the noise field when the level becomes excessive. Such avoiding action may result in them swimming away laterally or diving.

RESEARCH VESSELS AND FISH AVOIDANCE

For many years the philosophy behind the design of vessels for fisheries research was simple, it was thought only necessary to add a few laboratories to a standard fishing vessel, perhaps in place of the fish hold. As the evidence grew about effects of vessel noise on fish, (Olsen, et al., 1983a; Misund, 1993) experiments were made which showed the main causes of high level noise radiation to be the diesel engine, the gearbox, and, particularly, the controllable pitch propeller. Despite this, the same formula for propulsion has continued to be used until relatively recently, which explains why many of the existing vessels are noisy. But the increasing complexity of research and the need for unbiased sampling of fish stocks has led to a reappraisal of requirements.

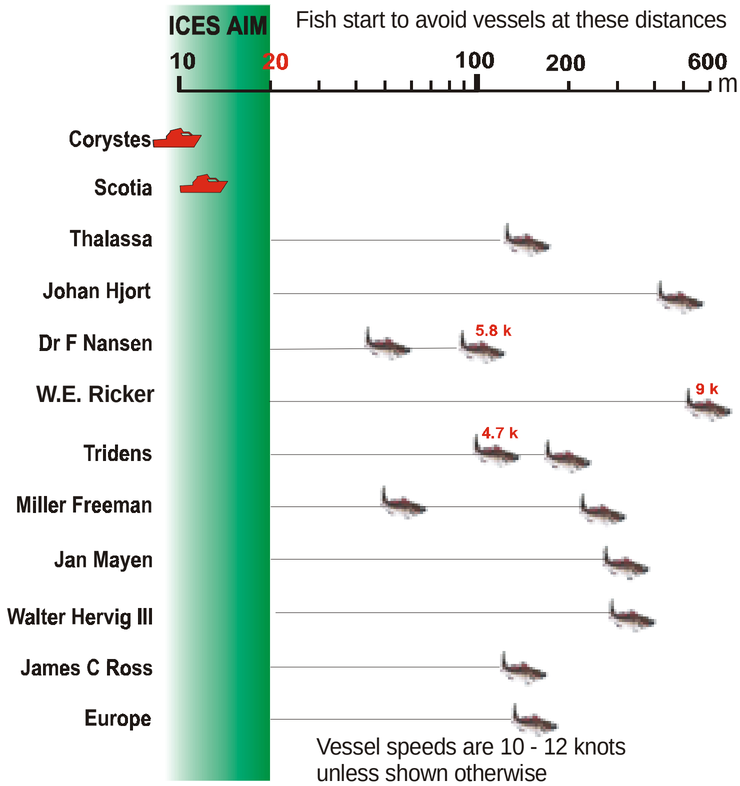

Figure 4. This shows the distances at which the listed vessels may cause fish avoidance behaviour.

A database comprising the noise ranging reports of many vessels has been built up over the past twenty years and from this it is possible to make comparisons between vessels and also to determine the likely range at which their noise levels will have an effect on fish. So what is the extent of the radiated noise problem from vessels? This can be answered by looking at the distances at which a number of currently operating research vessels have the potential to cause fish avoidance behaviour, see Figure 4. The noisiest two vessels use controllable pitch propellers, as do most of the others, although that is not the only significant factor contributing to their noise levels. Avoidance distances for most of the other vessels lies between 100 and 300 metres which must be a cause for concern. “Corystes” (Kay, et al., 1991) is still the quietest vessel, although Scotia is very close and neither should cause any fish avoidance problems.

Figure 5 is a part of a recording from a stationary 38 kHz echo sounder mounted in a floating buoy (Godø and Totland, 1999). In the top half it shows echoes from a school of herring at around 100 m depth. “Johan Hjort” started from a distance of about 1200 m from the buoy, running at 10 knots towards it and passing alongside within 8 to 10 m at 00:00 h. The effect of the vessel’s radiated noise on the school can be seen, although the depth scale is rather compressed. The time scale indicates when noise from the vessel began to affect the fish, with a downward trend starting from about 1.5 minutes prior to the closest approach.

The radiated noise level measured from “Johan Hjort” under fairly similar operating conditions has the potential to cause herring to react at a distance of about 500 m. A difference being that during the noise measurements the speed was 9.7 knots and the propeller pitch was 57 degrees, whereas for the buoy experiment it was 10 knots speed and 63 degrees pitch. Such an increase in pitch would result in an improvement in the propeller efficiency and thereby reduce noise slightly. The lower part of figure 5 is shown to the same time scale and helps to quantify the results of the avoidance behaviour. It shows how the mean depth of the echo energy changes significantly as the vessel approaches and passes the buoy, reaching a minimum level shortly after the passing. This clearly illustrates how the vessel radiated noise caused a disturbance in the herring school which resulted in a dramatic change to the measured acoustic intensity. When such an obvious reaction occurs, it demonstrates what a significant effect on sensitive fish like herring can take place even when the source of the noise is a long distance away.

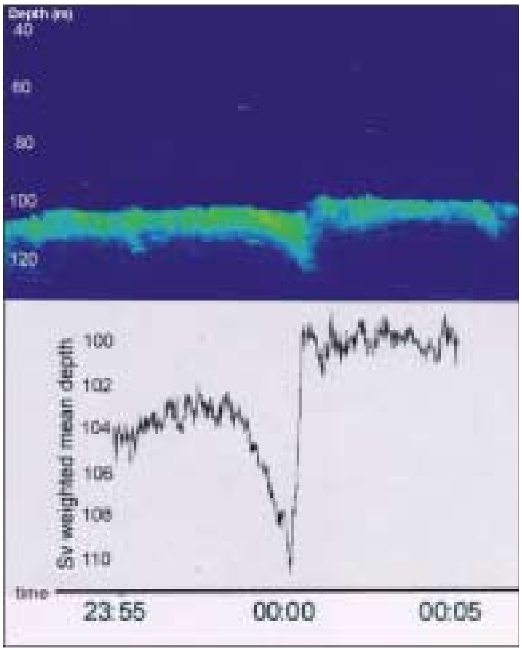

Figure 5. The top section shows an echo sounder recording of a herring school taken from a buoy.

At the bottom is a graph of the depth of the mean echo energy changing as the vessel approached and passed the echo sounder buoy (courtesy of Egil Ona, Institute of Marine Research, unpublished data).

POWER LEVELS AND NOISE

a) Acoustic survey

For an acoustic survey, only one of the two, three, or four, of the installed generator sets is likely to be required because the vessel is free-running (lightly loaded) at about 11 knots, well below maximum speed. This could lead to some asymmetry of noise radiation from the hull, depending on the position of the engine in use and the efficiency of the isolation measures. Changes in loading of the generator sets and propeller occur due to the vessel running before the wind, when the loading is very light. Then, on the next leg of the survey it may turn into the wind when resistance to its progress will be greater. This leads to increased loading of the propeller, often resulting in a higher level of cavitation and a consequent increase in noise level. The source of noise at these frequencies is not confined to the propeller. Pumps can create a great deal of noise and need to be carefully set up to meet the delivery requirements and must avoid exceeding them by any substantial amount. Likewise pipe-work has to be free of sharp bends which can cause cavitation.

In addition to the propeller, the ‘self-noise’ of a vessel also refers to noise which is generated on the vessel, or by it and received by the echo sounders. This can be due to orifices in the hull or projections from it. A rough hull with buckled plates, especially when high weld seams are present has the potential to increase the self-noise significantly, so it is necessary to pay careful attention to these aspects when a vessel is being constructed.

Echo sounder frequencies used for surveys are approximately 10 kHz to 200 kHz, although the spot frequencies of 38, 120 and 200 kHz, in that order, are most frequently used. Scientific echo sounders need to detect small organisms with correspondingly low target strengths and these produce small signals. This means that very high levels of sensitivity are necessary, so it is important that noise is minimised to allow the full potential of the echo sounders to be reached. As noise levels increase the effective detection range of individual fish decreases and the measurement of their target strength gets more problematic. Because of the dynamic nature of noise it is necessary to allow for an adequate signal-to-noise ratio, usually 10 dB for single echoes and 20 dB for schools. In addition to measurements of individual fish target strengths, surveys use an echo-integration technique to obtain estimates of overall populations. It is therefore important that there is no risk of contamination of the echo signals being received and processed for this purpose. To maintain the quality of data collection it may be necessary to reduce vessel speed, hence self-noise, but thereby lowering the overall efficiency of the survey by taking longer to complete.

b) Trawl survey

A trawl survey will require significantly more propulsive power, depending mainly on the net, the speed at which it is to be towed and the depth at which it is operated. Even with a small net, the extra power is likely to lead to an increase in noise as the gensets, and particularly, the propeller, become more heavily loaded, with the consequence that fish avoidance behaviour might occur at greater distances and echo sounders will receive more noise. Weather conditions can add to the loading as mentioned above for acoustic surveys and an example is shown in Figure 6 below. These curves relate to a noise reduced vessel being noise ranged whilst towing a PT 160 trawl at 30 m depth with 350m of warp, first with the wind, which was blowing at between 12 and 20 knots, then against it. The electrical power was monitored for each condition. An increase of 44 kW loading was seen with the vessel going against the wind, at a speed reduced by 0.2 knots. An important feature is the noise level which is up by about 3 times (10 dB) when going against the wind.

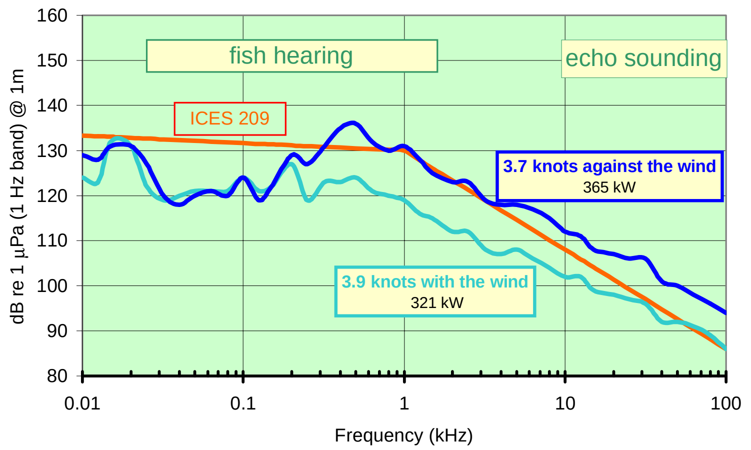

Figure 6. This shows the signature of a noise-reduced vessel towing a trawl when running with the wind and against it.

Data from trawl surveys can be distorted when noise drives fish out of, or into, the path of nets. In some instances, vessels have approached a pelagic school, only to watch it on the sonar split in two and pass on either side, then join up again some distance astern (Diner and Masse, 1987). Ona and Godo, 1990, discussed the significance for trawl sampling when fish reacted to trawling noise. At present there is little information to show how noise levels change on different vessels when trawls are being towed. As more noise-reduced vessels come into operation we may expect that further experiments to determine this important factor will be carried out. Within the next year another three noise-reduced vessels should be in operation and each will have undertaken noise measurements when towing a trawl during the noise ranging process.

Discussion

This paper has given a brief account of the need for noise-reduced vessels for fisheries research and the processes involved in achieving this goal. The starting point in determining the extent of design measures necessary to meet the aim of causing no adverse effects on fish in the vicinity of the vessel, is their hearing threshold. There are differences between species but the thresholds of the two most sensitive, cod and herring, are almost identical so these are used for the purpose of calculation. Because of their low hearing thresholds fish can hear sounds over long distances but the levels must be about thirty times the threshold before active avoidance takes place. The next important factor is the frequency band over which response occurs. The herring has the widest hearing bandwidth so this is used as a reference.

Given the information on reaction level to noise over the known frequency band, we can specify the maximum allowable noise level that can be radiated from a vessel to meet those criteria. For practical reasons a realistic distance has to be chosen beyond which the allowable noise level will not affect the fish. For the purpose of the ICES recommendation in CRR 209 this was set at d = 20 m. This helps to limit the cost of noise reduction measures but as more experience is gained and techniques improve, this distance should be reduced. Having the above parameters we can now calculate the maximum allowable radiated noise at fish hearing frequencies from:

$$\text{Vessel noise (Vn)} = 20 \log d + ht + 30$$

where ht = fish hearing threshold in dB re 1 μPa

Maximum vessel noise (Vn) is: 132 dB re 1 μPa (1 Hz band) at 1 metre

At the upper end of the frequency spectrum we must specify the maximum noise level allowable at the face of the echo sounder transducers. The ultimate limit to detection of small fish or organisms is the ambient noise in the sea. Wind generated noise decreases at a rate of about 10 times per decade from about 1 kHz, then, as frequency increases, the effect of thermal noise becomes dominant. However, propeller noise due to one of the forms of cavitation is likely to decide the detection depths possible. Fortunately, this noise also falls off at about 10 times per decade so operation at 38 kHz has an advantage over lower frequency echo sounders in this respect. It is beyond the scope of this paper to explore the details of fish detection but for the purpose of the ICES 209 report a figure of 95 dB re 1 μPa was derived as a maximum level of vessel radiated noise at 38 kHz. This leads to maximum allowable noise levels between 1 kHz and 100 kHz of :

$$N_L = 130 - 22 \log f_{(kHz)}$$

Having explained the reasoning behind the low and high frequency limits for underwater radiated noise in CRR 209, it is hoped that new vessels will be built to, and comply with, this standard. It is necessary to include the words “and comply with” because every step of the way has to be carefully monitored. Vessels have been built where the ICES CRR 209 was part of the contract but have subsequently failed to meet the recommended limits due to incorrect machinery selection and lack of supervision during construction.

The best solution to prevent fish avoidance behaviour is to use noise-reduced vessels but this will not be feasible for all users in the short term. As for noisy vessels, it is not possible to provide a model that will allow correction to be made to survey data biased by these vessels, but a possible first stage in minimising noise from some of them is suggested by Mitson, 2000.

Vessels are the most important and valuable tools that scientists use so they should be made as fully effective as possible. A major source of fish avoidance behaviour will be removed if all new vessels do meet the ICES Standard CRR 209. If a vessel cannot carry out its main functions without causing fish to take avoiding action it will be producing biased data which may be of insufficient quality for management purposes.

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