Reactions of herring schools to the sound field of a survey vessel

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Abstract

The underwater sound of R/V "Johan Hjort" as a function of aspect angle has been mapped by cruising along parallel transects at various distances from the recording unit. At frequencies over 125 Hz there was a minimum in front of the vessel, and lobes of higher intensity on both sides. About 20% of the herring schools recorded during a survey in the North Sea seemed to react to the survey vessel. The distance at which the schools reacted varied from about 25 m and up to about 1 000 m in front of the vessel. Within a sector of 20° on each side of the path of the vessel, the fraction of schools reacting increased to about 50%. Most of the schools that reacted seem to be herded in front of the vessel. This reaction pattern may indicate either that the schools reacted to the higher sound intensity to the side of the vessel or that the pattern occurred because of a "pursuit effect". Despite the apparent herding, more than 40% of the schools in front of the vessel were not recorded by the echo sounder. It is therefore argued that horizontal avoidance close to the vessel may have caused an underestimation of the biomass of herring of about 20%.

Keywords: Vessel noise, fish school, herring, avoidance, swimming behaviour, sonar.

Réactions des bancs de harengs aux bruits émis par un navire de recherche.

Résumé

Les bruits rayonnés par le navire de recherche « Johan Hjort », ont été analysés au cours de « radiales » parallèles parcourues à différentes distances d'une base d'enregistrement munie d'hydrophones. Dans les fréquences supérieures à 125 Hz, un minimum de bruit a été enregistré à l'avant du navire tandis que le niveau augmentait sur les côtés. Environ 20 % des bancs de harengs enregistrés lors d'une campagne en mer du Nord, semblent réagir aux bruits. La distance, à laquelle les bancs réagissent, varie entre 25 et 1 000 m environ, en avant du navire. La fraction des bancs réagissant augmente de 50 % dans un secteur de 20° à l'avant du navire, la plupart des réactions se traduisent par un rassemblement à l'avant du navire. Ce comportement pourrait indiquer que, soit les bancs réagissent aux bruits latéraux, soit répondent à un « effet poursuite ». En dépit de cet éventuel rassemblement, plus de 40 % des bancs en avant du navire n'ont pas été enregistrés par l'écho-sondeur. L'évitement horizontal, proche du navire, entraînerait donc une sous-estimation de la biomasse de hareng d'environ 20 %.

Mots-clés : Bruits de navire, bancs de poisson, hareng, évitement, comportement de nage, sonar.

INTRODUCTION

Measurements of vessel sound are normally presented as the spectral distribution of the source level at the moment of passing the recording hydrophones. According to Urick (1967) the sound intensity of vessels may vary as a function of aspect angle. The sound generated by propeller cavitation may be shadowed by the hull. This results in a "butterfly" pattern with a minimum in front and lobes of higher intensity on each side of the vessel. A similar tendency has been observed in sound intensity measurements of a passenger ferry (Scrimger and Heitmeyer, 1991). It has been suggested that a "butterfly" pattern in the distribution of sound from vessels may partly explain the avoidance behaviour of herring schools when approached by survey vessels (Misund and Aglen, 1992; Misund *et al.*, 1993). To investigate this hypothesis further, we mapped the horizontal sound intensity distribution of R/V "Johan Hjort" and compared it with observations of the swimming behaviour of schools of herring (*Clupea harengus* L.) recorded during a survey in the North Sea in July 1991.

MATERIALS AND METHODS

Vessel sound measurements

The sound intensity measurements were carried out in a sheltered, deep fjord (the Herdla Fjord), about 10 nautical miles north of Bergen, Norway. The measurements took place about 300 m from the shore at about 380 m depth. A small vessel, R/V "Fjordfangst" (20 GRT) was used as a platform for the recording instruments. The small vessel was drifting during the measurements, and all machinery was turned off. The sound emitted by R/V "Johan Hjort" (1950 GRT, 64.4 m LOA) was detected through two hydrophones (Brüel & Kjaer 8104) positioned at depths of 5 m and 8 m. The signals from the hydrophones were preamplified and recorded by a DAT tape recorder (Sony TCD 10pro). The distance between the vessels was measured by a 24 kHz SIMRAD SR240 sonar onboard R/V "Johan Hjort". The sonar has a beam-width of 12° (between −3 dB points) both horizontally and vertically.

To obtain sufficient data on the horizontal directivity of the sound emitted by the vessel, the following measurement procedure was adopted: R/V "Johan Hjort" was run at its normal cruising speed of about 11 knots along seven straight transects to the side of R/V "Fjordfangst". The transects were run so that the vessel passed R/V "Fjordfangst" to both starboard and port. Sound recording started when R/V "Johan Hjort" was 500 m in front of the hydrophones and stopped when the vessel had passed them by about 300 m. While the transects were being run, the distance between the vessels as measured by the sonar was reported by VHF radio to R/V "Fjordfangst" where the true distance was logged along with the corresponding time on the time counter of the DAT tape recorder. This gave a number of discrete distance points with corresponding sound recordings for each transect.

The recorded sound was analysed on a Brüel & Kjaer realtime frequency analyzer at 1/1-octave bandwidths. The recordings from the two hydrophones appeared to be approximately similar, and we therefore present only the recordings from the hydrophone at 5 m depth. The distance points were calculated as x-y coordinates on the basis of the distance and the relative bearings of the vessels at each recording point, and at the moment when R/V "Johan Hjort" passed 90° to the side of R/V "Fjordfangst". Every centre frequency of the sound spectra from 8 Hz to 2 000 Hz was than sorted for each x-y coordinate. This resulted in data-sets with the sound level for 1/1 octave centre frequencies in an x-y coordinate system. The recordings were interpolated (bilinearly) and visualized using UNIRAS UNIMAP software.

Herring school recordings

Herring schools were recorded by SIMRAD SR240 sonar during an acoustic survey by R/V "Johan Hjort" in the Northern North Sea in July 1991. When a school was detected by the sonar, a cursor was placed at the centre of the school projection, and the target-tracking mode of the sonar was initialized. The sonar then tracked the school automatically, and calculated the vessel-to-school bearing and range, and the horizontal speed, depth and heading of the school. Together with data on vessel speed obtained from the ship's log and vessel heading taken from the gyrocompass, the sonar data were logged ping by ping on a HP 9000/720 workstation connected to the RS 232 serial port of the sonar. The observations were visualized in a coordinate system presenting the true motion of the schools in relation to the vessel as it moved along the Y-axis of the system (Hafsteinsson and Misund, 1994). The vessel was running at a speed of about 11 knots (5.5 m/s) during the survey, and the schools were therefore observed for an average of only about 70 seconds (maximum 180 seconds, minimum 20 seconds). The sonar was operated with rotational directive transmission in which a single 12° beam is transmitted sequantially over a 120° sector. This create a blind zone of about 25 m in front of the transducer so that recording of schools fade away at closer range. As a measure of the avoidance behaviour of the schools, the radial horizontal speed of the schools was calculated by multiplying the horizontal speed with the cosine of the relative angle between the school and the vessel (Misund and Aglen, 1992).

According to an avoidance behaviour model proposed by Olsen *et al.* (1983), fish start reacting to the approach of a survey vessel by turning and swimming radially away from the sound source. Thus, fish schools that avoid the vessel could be identified as those that change heading and swim away from the approaching vessel. As the distance to the vessel diminishes, the behaviour model predicts that the avoiding fish swim faster and start descending.

Depending on whether the herring reacted by avoiding the noise source, or the noise field of the vessel, different avoidance patterns may emerge. On the basis of the swimming tracks, the schools were therefore judged as *avoiding* when either of the following criteria were met (Hafsteinsson and Misund, 1994):

• Noise source avoidance: school heading sustained for more than 10 s changed by more than 45° and the school headed away from the vessel. After that the school did not change its new heading by more than 45°. The heading was maintained until the vessel had passed, or until the school disappeared from the sonar.

• Noise field avoidance: sustained school heading changed by more than 45°, towards the path of the vessel. The school might subsequently change its heading in any direction by more than 45°.

The schools judged by the first criterion were assumed to be displaying direct horizontal avoidance of the vessel. Schools satisfying the second criterion were thought to be trapped between the lobes of higher sound intensity to the sides of the vessel, and were trying to stay in the lower sound-intensity field in front of the vessel (Misund and Aglen, 1992). Schools that were moving in straight lines with a defined direction, or that performed irregular or small movements during the period of observation were considered *not reacting*.

According to samples taken by pelagic trawl, the herring averaged about 28 cm in length. About 80% of the fish were still maturing while 20% were recovering from a previous spawning.

Distribution of vessel sound

At the moment at which it passed R/V "Fjordfangst", R/V "Johan Hjort" generated the highest sound intensities between about 125 Hz and 500 Hz (*fig.* 1). The highest source level (dB//1 μPa/1 m) reached 146 dB at 250 Hz. Sound intensity increased up to about 100 Hz, and leveled off for frequencies over about 500 Hz. At frequencies above about 125 Hz, sound intensity varied as a function of aspect angle, showing a characteristic "butterfly"-pattern with a clear minimum directly ahead of the vessel, and lobes of higher intensity on each side (*fig.* 2). The pattern was most pronounced for the 2 000 Hz centre-frequency. Due to the minimum directly ahead and the high intensity lobes to both sides, the gradients of rising sound intensity to the sides of the vessel path were sharpest within a sector of about 20° on both sides of the bow, and beyond 250 m ahead of the vessel (*fig.* 2).

Swimming behaviour

A total of 19% of the 110 herring schools recorded during the 1991 survey by R/V "Johan Hjort" in the Northern North Sea seemed to react to the approach of the vessel. Sixteen (84%) of the schools that reacted moved towards the path of the approaching vessel (*fig.* 3). These schools seemed to be influenced by the rising sound intensity to the side of the vessel path, and were herded ahead of the vessel. The herded schools first reacted to the approaching vessel at a distance of about 25 m to 1 000 m ahead, and within a sector of about 20° on each side of the vessel (*fig.* 4). Seventeen other schools detected within the same distance and

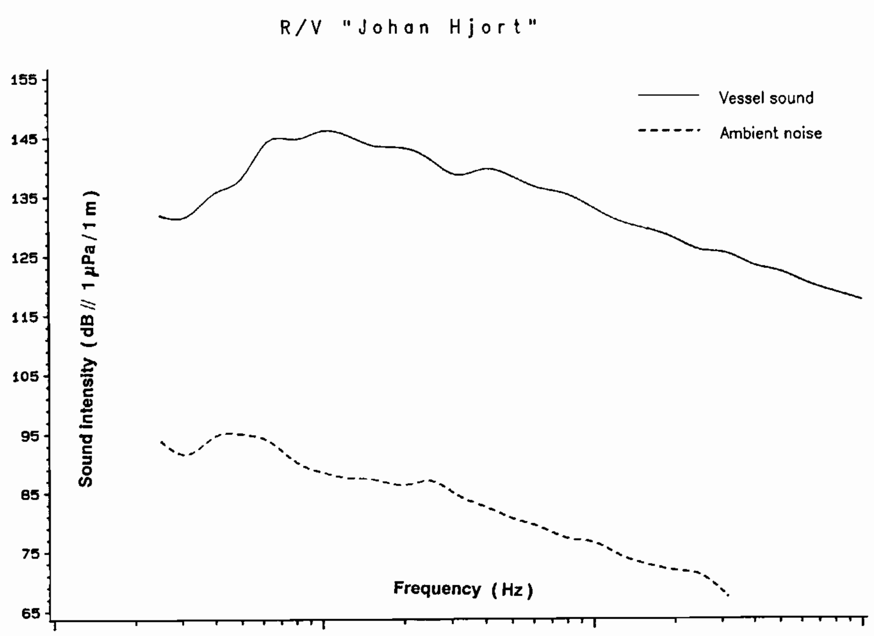

Figure 1. – Spectral distribution of the underwater sound of R/V "Johan Hjort" at the moment of passing the recording hydrophones.

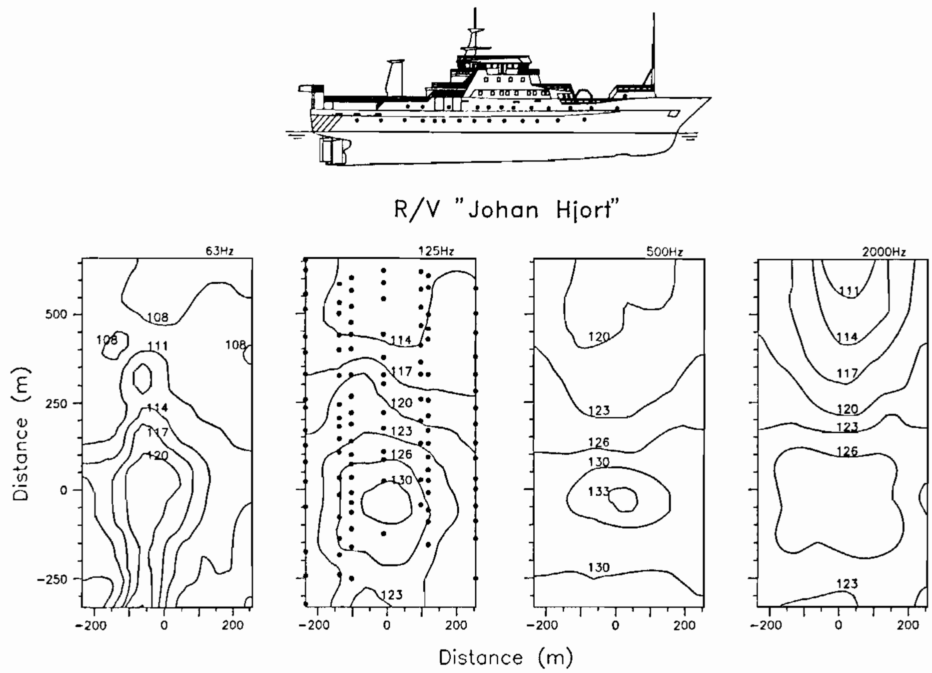

Figure 2. – Horizontal distribution of vessel sound at different centre frequencies in 1/1 octave bandwidth. The centre-frequency are noted above each plot. The dots in the 125 kHz plot mark the positions of the individual measurements. The isolines are interpolated using UNIRAS UNIMAP software, and the sound level in dB//1 μPa for each isoline is given in the figure.

sector limits did not react to the approach of the vessel. Of the 72 schools that were detected more than 20° to the side, only four schools (6%) seemed to react to the vessel. Thirteen (62%) of the avoiding schools reacted when slightly to starboard (*fig.* 4). The schools that reacted swam at an average horizontal speed of about 1.2 m/s, at an average radial horizontal speed of about 0.2 m/s, and at an average depth of 36 m, neither of which values were significantly different from those of the non-reacting schools (*table* 1).

DISCUSSION

The measurements showed that there were substantial variations in the underwater sound of R/V "Johan Hjort" as a function of aspect angle. For the 500 Hz and 2000 Hz centre-frequencies there were clear directional patterns with a minimum in front and lobes of higher intensity on both sides. The main source of sound is probably wide-band noise from the propeller (Urick, 1967). The forward scattering of the sound is interrupted by the hull that reflects the sound and thereby casts a "shadow" in the horizontal distribution of the sound intensity. Behind the vessel, air bubbles in the propeller wake may also reflect the vessel sound. The result is a "butterfly"-like pattern in the horizontal distribution of the underwater vessel sound (Urick, 1967). Compared with other contemporary fisheries research vessels, R/V "Johan Hjort" is medium noisy (Mitson, 1993), and similar variations in underwater sound as a function of aspect angle may therefore exist for other fisheries research vessels.

Herring are able to detect sounds up to about 2000 Hz at intensities that are just above the level of the background noise (Enger, 1967). This suggests that herring may be able to detect the sounds of R/V

Table 1. – Horizontal speed, radial horizontal speed and depth of the schools classified as not reacting and avoiding (SD: standard deviation, N: no. of schools).

	Horizontal spped		Radial horizontal speed		Depth		
	Average (m/s)	SD (m/s)	Average (m/s)	SD (m/s)	Average (m)	SD (m)	N
Not reacting	1.22	0.45	0.23	0.50	32	26	85
Avoiding	1.18	0.44	0.22	0.50	36	36	21
Wilcoxon 2-sample test	$p>0.05$		$p>0.05$			$p>0.05$	

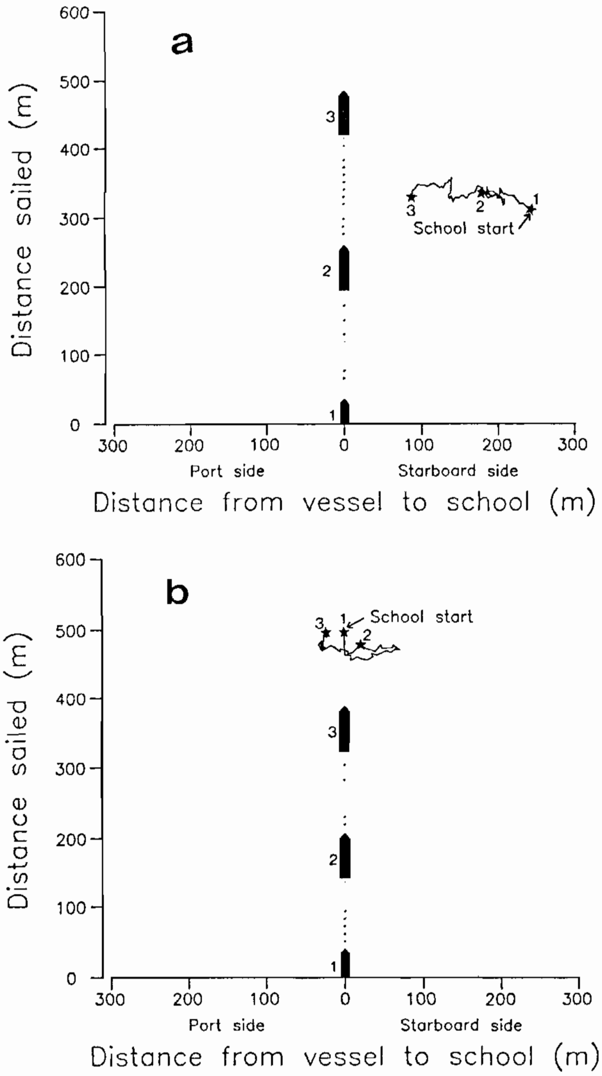

Figure 3. – (a) Swimming pattern of school not reacting to the survey vessel; (b) swimming pattern of school reacting by moving towards the path of the vessel.

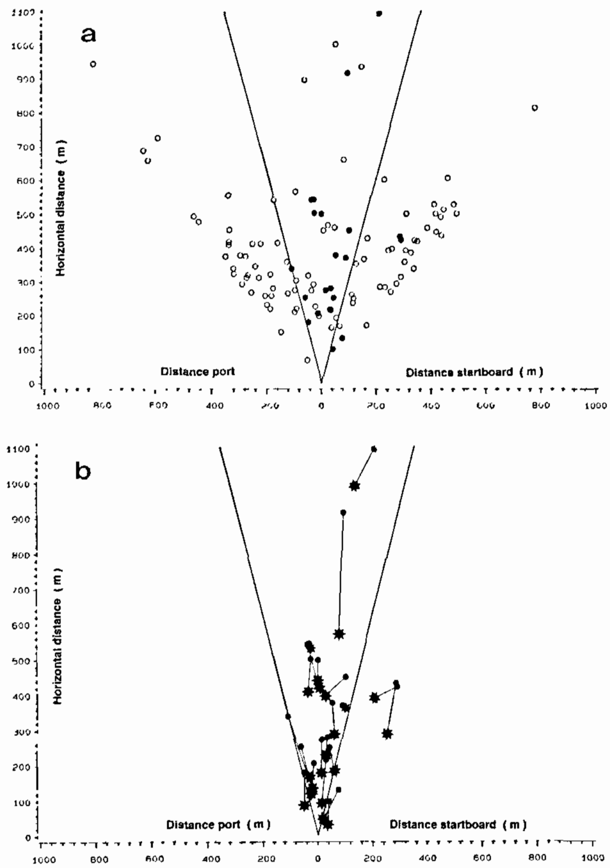

Figure 4. – (a) Horizontal distance to schools when first detected by the sonar. A 40° sector directed forward (20° to each side of the bow) is drawn. Open circles: schools not reacting to the vessel. Filled circles: schools reacting to the vessel; (b) distance at first detection (●) and distance when reaction to the vessel (✱) for the avoiding schools. The detection and reaction position for each school are joined by a line.

"Johan Hjort" that are emitted with a minimum in front and higher intensity to the sides of the vessel. It is also possible that herring swimming out of the path of the approaching vessel will sense the gradients of increasing sound intensity when coming out of the vessel path and slightly to the side of the vessel. Fish are able to discriminate between sounds that differ in amplitude by only about 1.3 dB (Hawkins, 1993). For a herring school 50 m in diameter, swimming out of the vessel path at right angles to the intensity gradients of the sound from R/V "Johan Hjort" at a 2 000 Hz centre-frequency, the intensity may vary over the area covered by the school by about 3 dB. This means that the sound intensity at the leading edge of the school is twice as high as at the rear of the school. Under such circumstances, it is possible that individuals near the front may start turning, and through quick synchrokinesis (Kils, 1986) the whole school may turn and swim towards the path of the approaching vessel and lower sound intensity. Such a reaction may explain the avoidance behaviour shown by the 16 herring schools that seemed to be herded in front of the approaching vessel.

Alternatively, the vessel avoidance pattern of the reacting schools may be a result of directional orientation. Olsen (1969) demonstrated that penned herring responded directionally to low-frequency sound sources. If the herring detect the direction to the approaching vessel, the herding ahead of the vessel may be explained by an "effect of pursuit" (Misund, 1994). *In this avoidance pattern the animal being* pursued moves directly in front of the pursuer as long as the distance between them is above a critical range. If the pursuer comes too close, the animal attempts to escape to the side.

There were no significant differences in horizontal speed, radial horizontal speed or swimming depth between the avoiding and non-reacting schools. For both horizontal speed and swimming depth this is in accordance with the avoidance behaviour model proposed by Olsen *et al.* (1983) which assume that fish start reacting to an approaching survey vessel just by adjusting the swimming direction away from it. Similarly, Schwarz and Greer (1984) and Engås *et al.* (1995) observed that penned herring responded to playback of vessel sound by avoidance swimming without a noticeable increase in speed. That the avoiding schools did not move at a higher radial horizontal speed than those not reacting is because most of the avoiding herring schools seemed to react to the noise field by swimming nearly perpendicularly towards the path of the approaching vessel.

The great variation in distance when the schools reacted to the approaching vessel may be due to variations in sound intensity emitted from the vessel due to downward bending of the sound waves (Misund and Aglen, 1992), variations in the level of background noise, or variations in motivational state and thereby reaction threshold among the schools. These factors may also explain why about 50% of the schools detected within the 20° sector to both sides of the bow did not react to the approaching vessel at all.

The "shadowing" by the hull and reflection by the air bubbles in the propeller wake are probably most significant for that part of the sound waves scattered nearly horizontally, and the directional pattern of the sound intensity probably decreases with increasing depth.

Nevertheless, some of the herring schools that seemed to be herded ahead of R/V "Johan Hjort" were swimming at depths of about 100 m. However, it is less probable that the directional pattern of the distribution of sound intensity may influence the swimming behaviour of demersal species such as cod, which are virtually deaf to frequencies above 500 Hz (Chapman and Hawkins, 1973), and therefore are probably unable to detect the directional pattern, which is most pronounced at higher frequencies.

Will the tendency to herding of schools ahead of the vessel lead to an upward bias in acoustic estimates of fish density? This is unlikely because schools may react by strong horizontal avoidance close to the vessel (Diner and Massé, 1987). When investigating the data collected by R/V "Johan Hjort" during the 1991 herring cruise in the northern North Sea, Misund *et al.* (1993) found that 44% of the schools recorded within 50 m on either side of the path of the approaching vessel and from 50 m to 200 m ahead of it, were not recorded by the echo-sounder. The schools missed were smaller and swam at shallower depths than those that were recorded. Similarly, Misund and Aglen (1992) observed that about 35% of selected herring schools in the North Sea aimed at by the vessel were not recorded on the echo-sounder. It was estimated that 13% of the schools made horizontal movements to evade the vessel, 14% were above the upper blind zone of the echo sounder (about 10 m), while about 8% were randomly missed. Both these investigations suggest that the biomass of herring was underestimated by about 20% due to horizontal avoidance (Misund and Aglen, 1992; Misund *et al.*, 1993). Similarly, Fréon *et al.* (1993) suggests that a diurnal variability in biomass estimates of small pelagic species in tropical waters is caused by horizontal avoidance of schools during daytime.

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