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METHODOLOGY

Our experiment is derived from the method described by Olsen (1979). It was performed by day on surface schools of Spanish sardine *S. aurita* off Venezuela, easy to detect by eye. A dinghy carrying the sounder was located on the route of a moving school and stopped waiting for its passage (Fig. 1). The research vessel R/V 'Nizery' (24 m) was then contacted by radio and passed over the same school 1 min later (around 50 m from the dinghy). This method allows the diving behaviour of the school under the vessel to be measured, which in turn permits an estimation of its tilt angle.

The dinghy was equipped with a Simrad EY-M portable sounder (70 kHz) (Simrad, Horten, Norway) with a narrow beam transducer (11° at −3 dB point) installed starboard, 50 cm under the surface, and a portable digital audio tape-recorder (DAT). The equipment was powered by a 12 V battery, so that the dinghy was completely noiseless. The signal was then processed in the laboratory by echo-integration, for each transmission and for the whole school. Narrow depth intervals (1 m) were used to estimate properly the centre of gravity of densities in each transmission. Aboard R/V 'Nizery', a Simrad EK-S sounder (120 kHz) (Simrad, Horten, Norway) was used with a hull-mounted transducer (10° at −3 dB point).

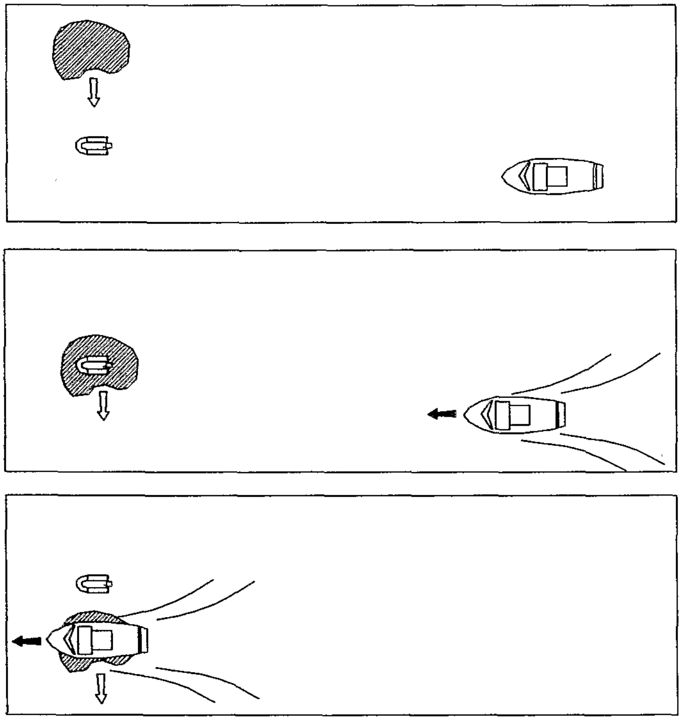

Fig. 1. Description of the methodology used to compare the position and movement of a single fish school under natural and stressed conditions.

Additional observations were made in the same area and on the same species by R/V 'Capricorne' (46 m) using a Simrad EK 400 sounder (120 kHz) (Simrad, Horten, Norway) and a hull-mounted transducer (10° at −3 dB point). Schools were tracked by sonar and overpassed for sounder recording at a speed of 4 knots.

RESULTS

Five fish schools were observed successively by the drifting dinghy and immediately afterwards by the research vessel. Their vertical distribution is presented in Fig. 2.

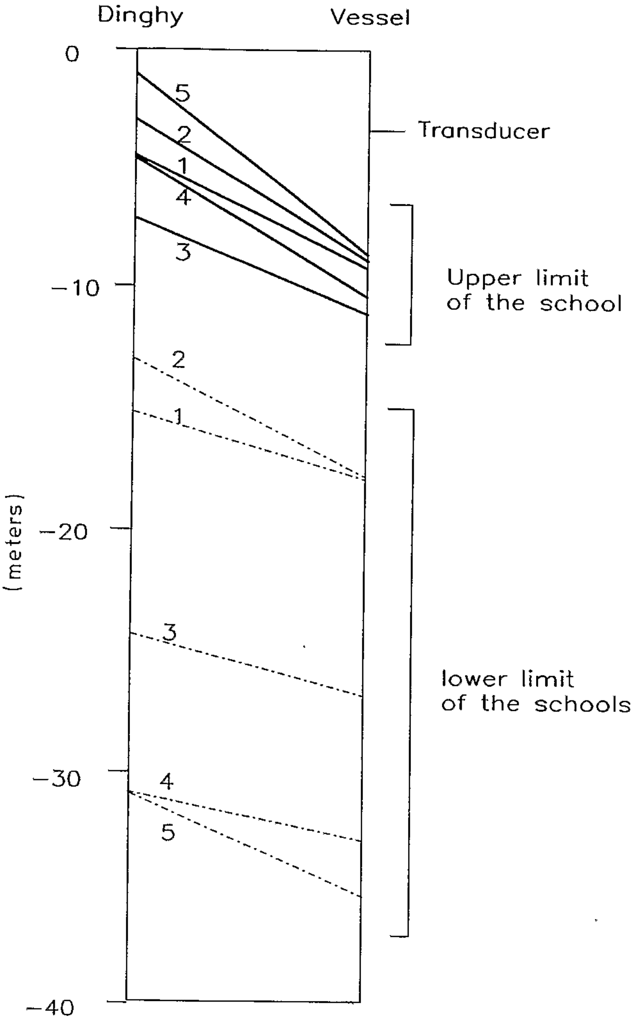

Fig. 2. Evolution of the mean depth of the tops (solid lines) and bottoms (broken lines) of five sardine schools observed successively under the dinghy (EY.M) and the research vessel (EKS).

Three conclusions can be drawn from these observations.

(1) All the schools dived before the passage of the boat, without exception, and the mean dive was 5 m.

(2) The school nearest to the surface dived deeper.

(3) In addition to the vertical migration a compression of the school was observed: the upper part dived deeper than the lower part (6.4 m and 3.5 m, respectively). We observed that the intensity of the fish reaction depends on the distance of the stimulus, which agrees with the model of Olsen et al. (1983).

A second measure of the vertical avoidance is obtained by processing the acoustic records transmission by transmission when overpassing a school. The actual centre of gravity of nine schools was calculated from the density by layer (Figs. 3A and 3B). The same overall result as previously was observed: surface schools present a stronger reaction to the boat than deep schools.

The interval between two consecutive transmissions is 0.33 s, thus the av-

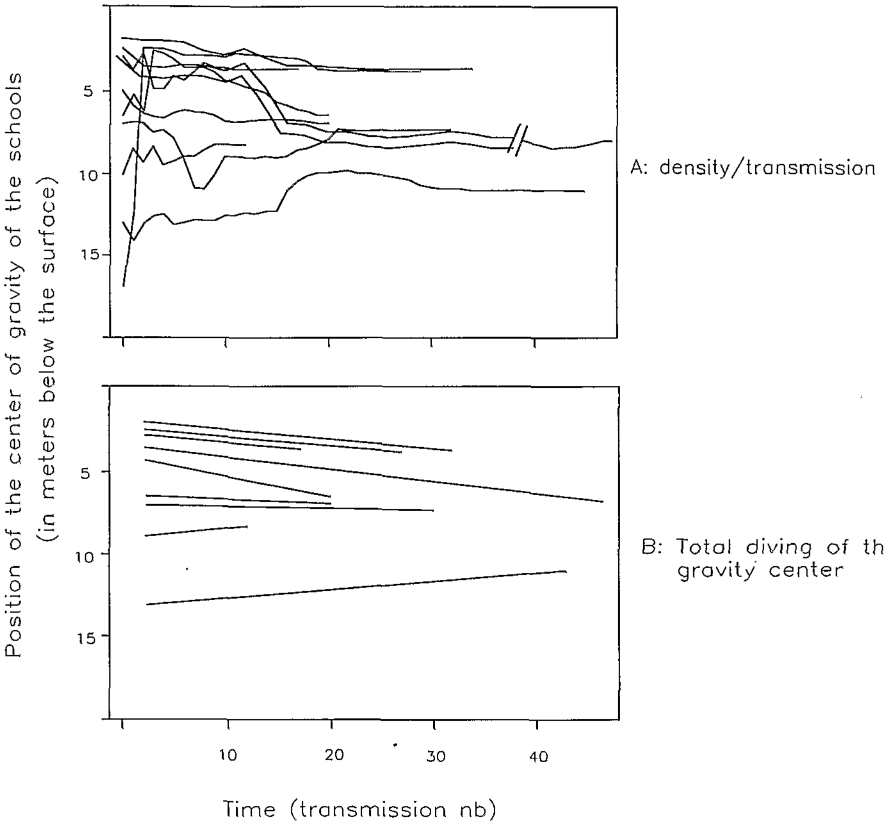

Fig. 3. Evolution of the school depth when overpassed by a vessel: (A) density transmission by transmission; (B) tendency of the density evolution (from A).

erage diving speed of the surface school has been estimated at 0.1 m s^{-1}. An interesting point is the difference in the displacement of the centre of gravity during the vessel's passage: it presents large amplitude movements at the beginning of the vessel passage and then becomes more stable (Fig. 3A).

DISCUSSION

Vertical avoidance, tilt-angle and bias

Although the modelling of fish behaviour with respect to the vessel distance proposed by Olsen et al. (1983) seems to represent the observed behaviour of *S. aurita*, it is difficult to apply to our data, owing to the lack of information about vessel noise. Moreover, the results obtained in Venezuela are somewhat different from those of other authors. If the general avoidance pattern is similar to the observations made on other Clupeoids such as herrings (Olsen et al., 1983; Misund, 1990) or sardines (Diner and Massé, 1987), in Venezuela the diving reaction concerns only the sub-surface school. At more than 20 m depth the fish reaction is negligible, whereas Olsen et al. (1983) observed diving reactions up to 40 m using a boat similar to ours.

In order to estimate the mean tilt angle of the fish when diving we assume that the tilt angle of the fish corresponds to the angle of the flight. The maximum horizontal speed has been estimated as 4 knots (Hara, 1987; Misund, 1990). Then the assumption that most of the school flights are along the boat route axis was made (negligible lateral avoidance). This assumption is based on three arguments.

(1) If, following Olsen (1979), the propeller noise is considered as the main stimulus, the distribution of sound pressure obtained by Urick (1975) shows that the fish schools located exactly on the route of a boat are 'trapped' inside the acoustic shadow of the hull: when trying to escape laterally, they are deflected by an increasing noise gradient from one side to the other, until they are overpassed by the boat (Fig. 4).

(2) This hypothesis, first stated by Gerlotto and Fréon (1988) may explain the results obtained by Misund (1990) when measuring with a multibeam sonar the mean horizontal flight angle of the schools a few minutes before passing them over. It fits more or less the diagram of sound pressure. Moreover, Misund (1990) points out that during the few last seconds preceding the ship's passage, the lateral avoidance would be very low because only two of the 43 overpassed schools were not detected by the vertical sounder. A similar experiment (Aglen and Misund, 1990) largely confirms this.

(3) Using light as an additional stimulus, Levenez et al. (1987) and Gerlotto et al. (1990) observed reactions of *S. aurita* layers during experiments at night off Venezuela. The avoidance reactions were not linked to a decrease of the insonified biomass when the light was switched on, suggesting that the

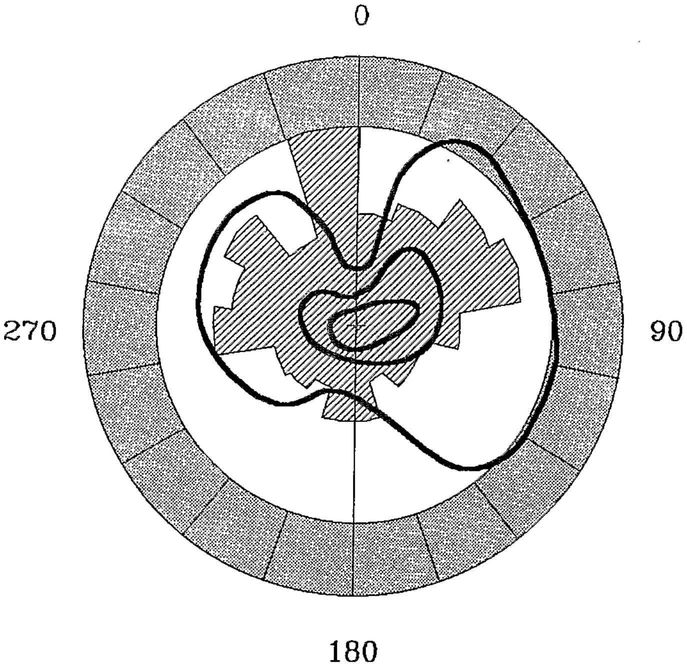

Fig. 4. Relationship between the sound pressure around a boat and avoidance reaction of schools (from Gerlotto and Fréon, 1988): propeller noise directivity (solid line, from Urick, 1975) compared with avoidance directions (20° dashed sectors, from Misund, 1987).

fish remain inside the acoustic shadow of the hull with no change in the tilt angle (constant target strength distribution).

It is obvious that lateral school avoidance exists in many cases (Olsen, 1990; Diner and Massé, 1987; Goncharov et al., 1989). In the case of *S. aurita* the same horizontal reaction is observed, although it is probably not so strong. In this work, however, we consider exclusively the schools which were observed on the echogram. For these schools, the tilt angle θ of the fish is given by the simple equation

$$\theta = \text{arc tg}\ (V_v / V_h)$$

where V_h is the horizontal flight speed and V_v is the vertical diving speed. The relationship between the variables θ, V_h and V_v is given in Fig. 5.

Owing to the small number of observations, the present analysis is limited to the estimation of the tilt angle in order to see if it may bias the estimation of the biomass. If we consider the mean values of the centre of gravity (Fig. 3B) we can see that even for the surface school the mean vertical speed is around 0.1 m s^{-1}. At this vertical speed, a horizontal speed lower than 0.3 m s^{-1} would be required in order to obtain a tilt angle greater than 10°. The

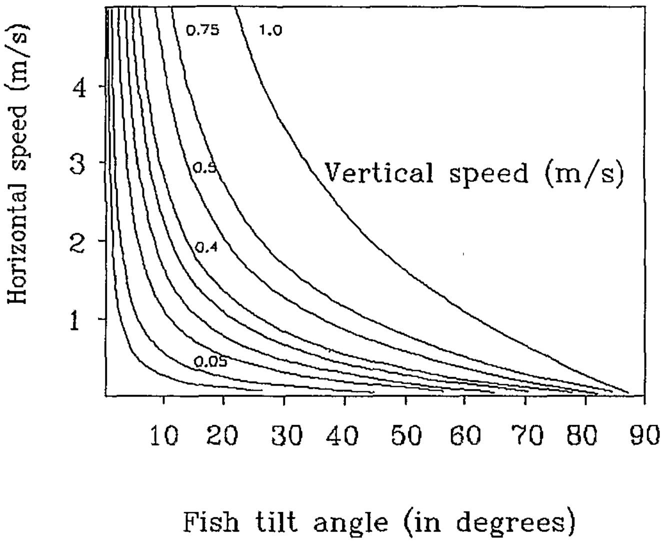

Fig. 5. Theoretical relationship between vertical speed, horizontal speed and tilt angle for schools of *Sardinella aurita.*

estimated horizontal speed of the schools leads to a tilt angle of less than 5°, which has a negligible influence on density estimations.

Avoidance and vertical school distribution

The vertical mapping of school distribution is one of the results of an acoustic survey and can be of considerable interest. For instance, the artisanal sardine fishery in the Gulf of Cariaco (Venezuela) uses surrounding nets, allowing only the catch of coastal surface schools. Therefore, the precise vertical mapping of the resource is essential for stock management purposes, and correction factors due to reactions of fish to the survey vessel must be applied to survey data.

The diving reaction is inversely proportional to the initial depth of the school and becomes negligible over 20 m depth. Even though our data are not numerous enough for modelling the behaviour, they allow the calculation of a preliminary rough correction consisting of a reduction of 5 m of the detection depth for the school located between 0 and 20 m.

In the particular case of the sardine stock of Venezuela, the vertical avoid-

The diving reaction of *S. aurita* is rather limited in comparison with herring schools. This reaction is only sensitive in the first 20 m and its mean amplitude is about 5 m. This amplitude is inversely proportional to the initial school depth. Such a limited amplitude allows the estimation that the fish tilt angle is less than 10° when the school is overpassed. Therefore, the underestimation of density is probably negligible.

This low effect is probably due to attenuation by the hull of the propeller noise in front of a vessel. The resulting funnel-shaped acoustic shadow should be responsible for the limited lateral avoidance reaction observed when the fish previously located on the vessel route is overpassed. This hypothesis, if confirmed, would invalidate the use of a lateral towed body close to the hull. It could also explain the surprising differences between the apparently reasonable mean densities recorded at night on a fish layer when the hull transducer is used during a routine survey, and the very poor detections recorded in experiments using a stationary transducer near which the vessel is passing (Olsen, 1979; Levenez et al., 1990). In this latter case it is likely that the fish previously located laterally to the vessel route present a strong lateral avoidance.

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