Herring Tilt Angles, Measured through Target Tracking

E. Ona
Institute of Marine Research, Bergen, Norway

Abstract

The target strength of herring in captivity was monitored experimentally at three frequencies (18, 38, and 120 kHz) over a period of 3 years using split-beam echo sounders. One of the fundamental parameters of a target strength measurement, when performed on free-swimming fish, is angular orientation relative to the horizontal. This is usually defined as the tilt angle, when vertical echo sounding is conducted. The swimming angle of the targets was measured directly through split-beam target tracking with specialized split-beam hardware and software. As the swimming angle and the tilt angle are not always identical, underwater video analysis was used to measure the relation between the swimming angle and the actual tilt angle for herring at different depths.

Introduction

At the commonly used frequencies for acoustic abundance estimation of herring (30-120 kHz), the herring is a quite directive target (Haslett 1977, Nakken and Olsen 1977). A small change in orientation of the fish relative to the transducer surface may drastically change the target strength at these frequencies. In fish roll aspect, the fish is more or less omnidirectional (Nakken and Olsen 1977). This is due to the circularity of the cross section of the swimbladder in this plane, but also due to the small dimension of the cross section as compared with the wavelength of the acoustic signal. In the pitch plane of the fish, however, fish with a swimbladder, comparable or longer than the wavelength will be acoustically directive, and the backscattering amplitude will be dependent on the pitch angle of the fish, relative to the transducer. In acoustic abundance estimation, the mean target strength or mean backscattering cross section is needed when converting integrated echo energy to biomass (MacLennan 1990). The preferred mean target strength to be used in this conversion are those collected in a direct measurement, in situ, on the surveyed population (Ona

1999). For many fishes, however, the target strength estimates obtained in a survey situation may not be representative for the actual target strength, as the typical fish density recorded cannot be resolved for single target strength analysis. Herring is a typical representative for these species, where most of the abundance is recorded as schools or as dense layers at variable depths. The available technology for direct target strength analysis, the single-, dual-, and split-beam echo sounders, all phase the same problems in resolving the most important densities recorded on a survey into single targets for "safe" target strength analysis. Therefore, the target strength data on herring are with a few exceptions (Huse and Ona 1996, Ona et al. 2000a) collected in very loose aggregations, often at night. As the mean target strength estimate is a convolution of the directivity pattern of the fish and its tilt angle distribution (Foote 1980), the estimate is quite sensitive to changes in tilt angle distribution. If the tilt angle distribution inside dense schools of herring is different than in loose aggregations, the mean target strength may be biased. In fact, the target strength estimate should ideally contain information on tilt angle distribution if this was possible. Photographically, it has been determined that the tilt angle distribution of herring will vary with herring behavior, and in particular between the feeding situation and the schooling situation (Beltestad 1973), but also with depth and light intensity in a wintering situation where no feeding occurs (Huse and Ona 1996).

During experimental measurements of seasonal variation in target strength, a control of the swimming behavior was needed in order to separate the effect of tilt angle distribution from the other effects studied (Ona and others, submitted manuscript). This was tried using a single fish target tracking system (Ona and Hansen 1991) utilizing the data from a split-beam echo sounder to compute swimming parameters on single fish passing the beam of a stationary acoustic transducer. As this system records the three-dimensional movement of the target through the beam, computation of the fish swimming speed, swimming direction, and other related parameters are straightforward (Brede et al. 1990, Ona and Hansen 1991, Ehrenberg and Torkelson 1996). The actual tilt angle of the fish is, however, not a direct derivative. An underlying assumption when trying to compute this from information on geometrical position is that the vertical swimming direction of the herring is exactly along the longitudinal axis of the fish. For fishes with normally high swimming speeds, like Atlantic mackerel, this is usually confirmed (He and Wardle 1986), but negatively buoyant fish swimming at low speed (<0.8 body lengths per second) often swim with a slight head-up posture. Since the gas-producing capacity of the herring swimbladder is still unclear (Blaxter and Batty 1984, Ona 1990), negative buoyancy is likely to occur at depth, and a similar swimming strategy as for mackerel is expected in herring if additional lift is needed. A few observations, however, indicate that herring use another, commonly used compensatory strategy for negatively buoyant animals, namely the "rise and glide" method (Huse and Ona 1996). In order to evaluate if the target tracking method could be used to determine the actual tilt angle of the fish, a video analysis of herring swimming behavior was conducted. The results from these, with examples of tilt angle distributions computed by the tracking method, are reported here.

Material and Methods

During vertical excursion experiments with captive herring for target strength analysis (Fig. 1), the experimental pen ($12.5 \times 12.5 \times 21$ m; 4,500 m^3), was rearranged with a top frame and net into a cage. After careful transfer of 50 herring from the holding pen (see Ona et al. 2001 [this volume]), the cage was stepwise lowered to 50 m in one experiment in August 1996, and further to 100 m in April 1997. During the depth excursions, an underwater, 360-degree pan video camera was used to monitor the behavior of the herring inside the cage. The camera could be lowered from the top frame of the cage to the bottom by pulling the recorder cable, which was guided through a 50-mm nylon ring attached to the top panel. The image of a plumb line, attached to the camera, was used for vertical reference during video analysis of herring swimming behavior. Video recordings and target strength measurements were made sequentially, since the camera and cable interfered with the acoustic recordings. Based on the visual inspection of the video data, there seemed to be little difference between the swimming angle and the actual tilt angle of herring at any depth. To further quantify this, some of the recorded data were selected for a more detailed analysis. If a fish is swimming along a straight line through the acoustic beam, without changing depth, the recorded tilt angle between consecutive detections will be zero. If the fish is swimming along this line with a slight head-down or head-up posture (Fig. 2), however, the tilt angle and the swimming angle will be different. The tilt angle of the fish is measured as defined by Olsen (1971): The angle between the fish center line, or imaginary line running from the root of the tail to the tip of the upper jaw, and the true horizontal. To analyze the data, the recorder was connected to standard, commercial hardware and software for image analysis, and a videotape editing system. The movement of herring could here be displayed frame by frame on a PC display with an internal, two-dimensional pixel-based reference system.

When a single herring passed the vertical reference, oriented within $\pm 10°$ of the plane of the photographic axis, the video was stopped, slowly reversed, and further displayed one frame at a time. On the first frame, the exact position of the snout of the herring was tagged with a marker on the screen (Fig. 3). The film was then started, frame by frame, until the tail passed the marker and stopped. The distance from the marker to the imaginary line between the snout and the root of the tail was then measured digitally with the cursor. In order to make this measurement independent of distance from the camera, the units used were parts of tail-root width. For herring of this size, 32 cm, the unit corresponds to an angular resolu-

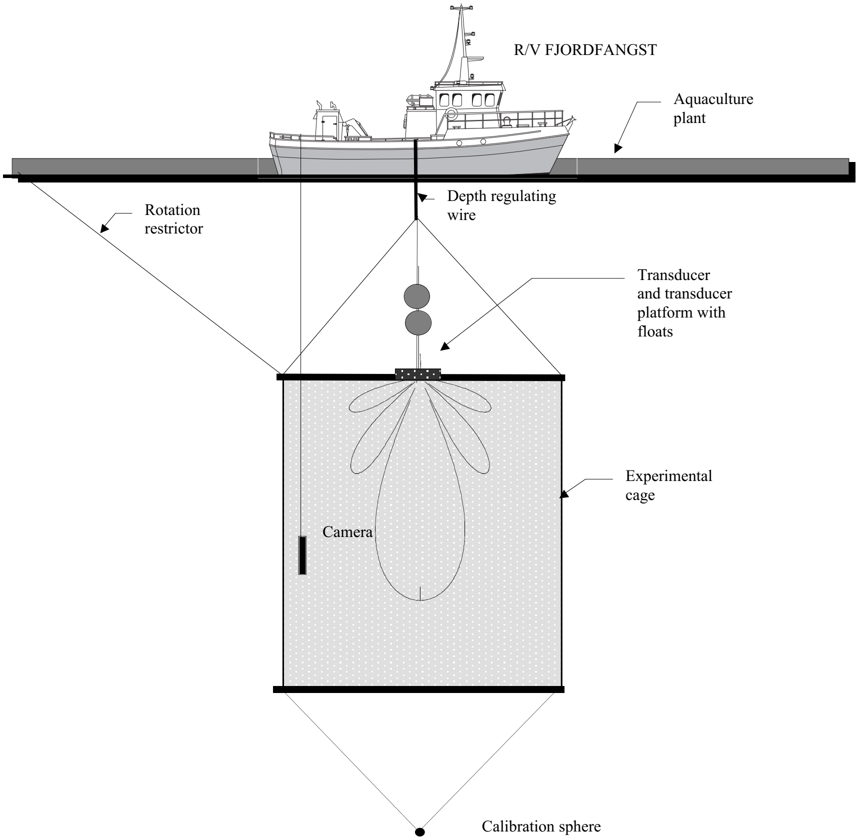

Figure. 1. Simple sketch of the experimental set-up for target strength measurements and video analysis of herring swimming behavior. Cage dimensions are 12.5 ×12.5 × 21 m.

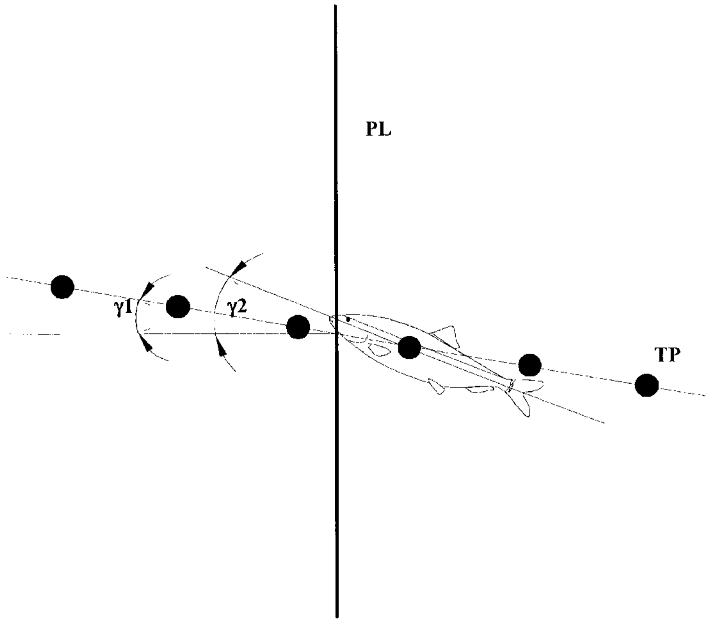

Figure 2. Specification of the difference between the swimming angle, γ1, and the actual tilt angle, γ2. The detected target positions are marked, TP, and the vertical reference plumb line, PL, is shown.

tion of about 1° or, more exactly, 1.16°, as determined from a series of measurements of the ratio between root-of-tail width and the length of herring, as when displayed on the screen.

Examples of estimated swimming angles for herring are made using the Simrad EK-500 split-beam echo sounder, 120-kHz system with a digital resolution of 3 cm in the range measurements (Bodholt et al. 1989). The transducer, with a full beam width of 8.6°, circular, has an angular resolution of 0.13°. The standard target strength and angular data for the echo sounder were used for target tracking (Ona and Hansen 1991) and further to compute the swimming angles of the fish.

Results and Discussion

The results from the video analysis are summarized in Table 1. The carefully selected data from 5 depth intervals, from 5 to 40 m, show that the herring generally swim straight along its imaginary center line, and that the difference between actual tilt angle and swimming angle are small at

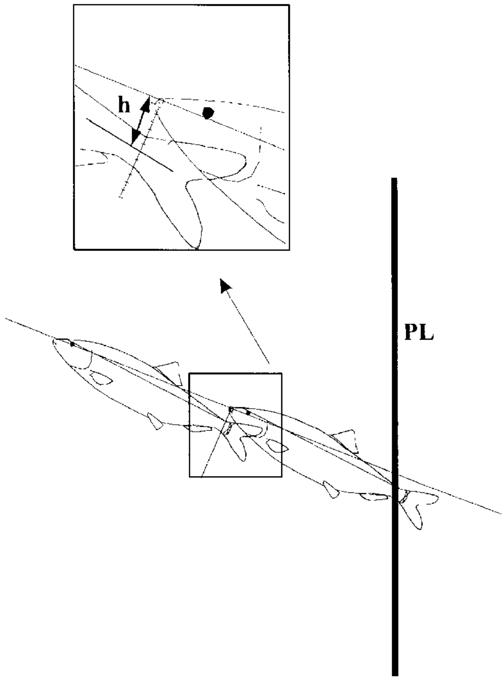

Figure 3. Measurement of the difference between swimming angle and the tilt angle, made from video recordings. PL, plumb line; h, distance. The measurement procedure is described in the text.

all depths. The recordings were made under natural light conditions with no artificial light. The exact swimming speeds were not recorded in the video analysis, but the split-beam tracking system recorded a mean speed of 35 cm per second, or about 1.1 body lengths per second. A slightly negative mean head-down posture, –1.61°, was recorded at the 5-m depth, while the mean values at 20, 25, 30, and 40 m were either close to zero, or slightly head up. As the demand for angular measurements is strict with respect to orientation relative to the photographic axis, only 362 measurements were accepted. If all data are grouped (Fig. 4), the recorded deviation between mean swimming angle and mean tilt angle is close to zero (–0.06°, S.E. = 0.10°).

The herring is a constant swimmer, and is seldom observed swimming below 0.8 body lengths per second, even when hibernating in the wintering areas of the stock (Huse and Ona 1996). When schooling and feeding, individual swimming speeds are presumably larger (Harden-Jones 1968). Hydrodynamically, the herring is also shaped like a fast swimmer,

Table 1. Results from the analysis of difference between swimming angle, γ1, and actual tilt angle, γ2, from video analysis.

Date	Time	Camera depth (m)	Mean $\Delta\gamma$ (deg.)	N	S.E.
18 Aug. 1996	1200-1300	5	–1.61	90	0.18
23 Aug. 1996	1200-1400	25	+0.49	24	0.39
27 Aug. 1996	1000-1400	40	+1.12	91	0.16
28 Aug. 1996	1100-1200	30	+0.41	62	0.22
29 Aug. 1996	1600-1700	20	–0.19	95	0.10
All data			–0.06	362	0.10

The mean difference, $\Delta\gamma$, number of measurements, and standard error of the mean are given for each series. Negative values indicate that the center of the root of the tail is passing below the snout marker. The actual tilt angle is then larger than the swimming angle; i.e., $\gamma 2 = \gamma 1 - \Delta\gamma$.

and only at very low speeds, or at large negative buoyancy, are deviations between swimming angle and actual tilt expected.

From our analysis, we may conclude that this difference is so small that its effect on estimates of actual tilt angle measurements from target tracking is comparable to the accuracy in photographically estimated tilt angles. If these are made with single-frame cameras, the precision of an individual tilt angle is about 1° when only selecting fish perpendicular to the photographic axis (Olsen 1971). The use of stereo-camera methods may increase this accuracy.

Examples of tilt angle distributions obtained by target tracking are shown in Figs. 5 and 6. The first two distributions are recorded on a single individual herring, 34 cm, freely swimming inside the experimental pen for a period of 30 hours. Two estimates of the overall tilt angle distribution may be made from the tracking data. If the herring passes the beam along a fairly straight line, the mean tilt angle may be computed from the entire passage (Fig. 5a). Depending on target range, swimming speed, and pulse repetition rate, the fish is detected several times during the passage, and tilt angle between successive detections may be computed (Fig. 5b). Both methods show that this herring, mainly swimming at shallow depths in the pen, passes the transducer beam at a nearly horizontal angle (–1.1° and –0.7°) with a standard deviation of about 10°. These distributions are close to photographically estimated tilt angle distributions of herring under similar conditions. Ona (1984) measured the tilt angle distributions of herring in net pens at several adaptation depths. His photographic measurements showed that for herring at depths of 1.5 and 4 m, the tilt angle distributions were –3.9° (S.D. = 12.8°) and 0.2° (S.D. = 11.9°), respectively. Beltestad (1973) recorded distributions of 3.8° (S.D. = 6.0°) during the day and –3.2° (S.D. = 13.6°) at night. An example of a larger sample (Fig. 6) recorded at night in March 1997, where

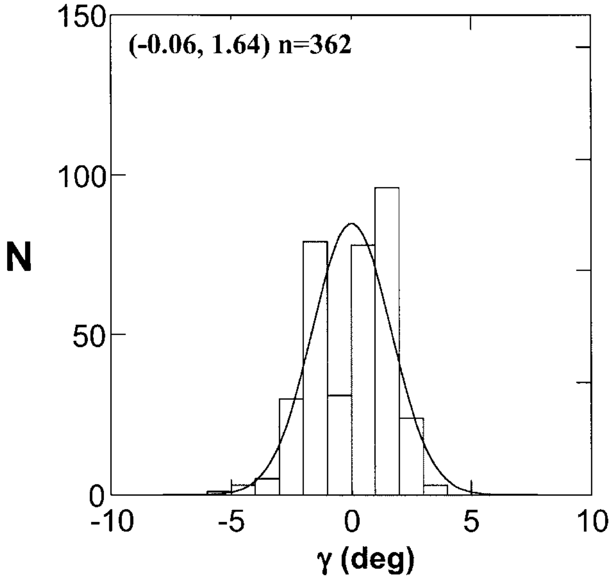

Figure 4. *Overall distribution of the difference between swimming angle and tilt angle of herring. Mean = –0.06°, S.D. = 1.94°.*

the mean tilt is –3.1° and the standard deviation is 14.2°, is also very close to photographically determined tilt angle distributions. The accuracy of the tracked angle is dependent on the range resolution of the split-beam system, its angular resolution, and the horizontal movement of the fish. If the movement of the fish is small compared to the range resolution, as is the case at the lower frequencies of the split-beam system used, sudden steps in angular estimates are seen, connected to the steps in range bins. With the 120-kHz system, however, the accuracy of each angular measurement on herring swimming at 35 cm per second is estimated to be about 2°. In most cases, this is sufficient accuracy to describe the main properties of the tilt angle distribution. Technical improvements of the method have already been made at the lower echo sounder frequencies, and parallel estimates of tilt angle distribution at three frequencies are now possible. In particular this improvement was needed when establishing a methodology for in situ target strength measurements on herring at 38 kHz in deep water or inside layers with high volume density, as described by Ona and others (submitted manuscript). The method described may only be used when the conditions for single target recognition by split-beam echo sounder systems are fulfilled, i.e., in low-density situations or at short range. When herring are schooling at high density during daytime, tilt angles may not be measured by this method.

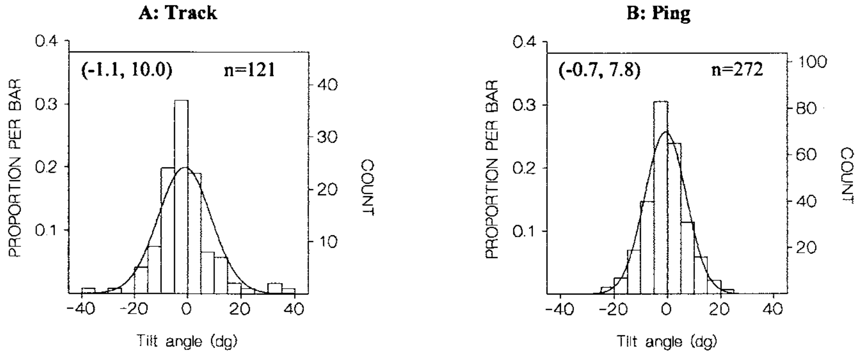

Figure 5. *The apparent tilt angle distribution of a 34-cm herring observed by the 120-kHz transducer during a 30-hour period. The superimposed are the fitted truncated Gaussian (normal) distribution. Also shown in the parentheses are the means and the standard deviations, respectively. A, mean track tilt angle; B, ping-to-ping tilt angle.*

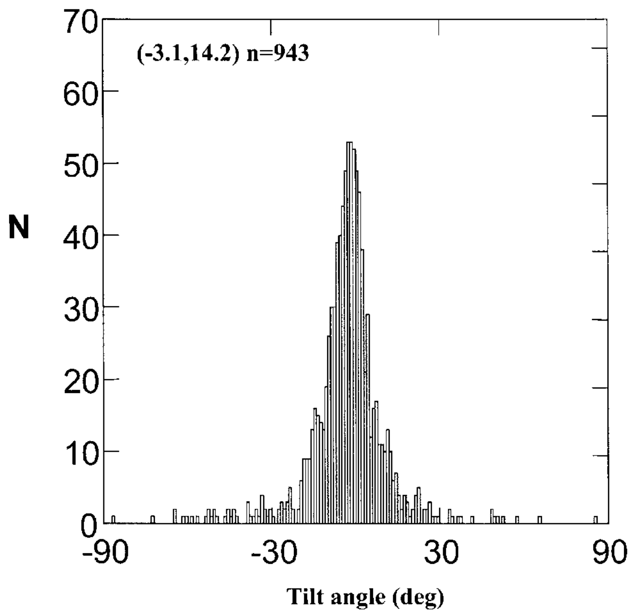

Figure 6. *Estimated tilt angle distribution from target tracking at 120 kHz in March 1997, recorded over 5 hours at night. The parameters for the normal distribution are indicated.*

Acknowledgment

Partial financial support from European Union research project EU (AIR-CT94-2142) for this investigation is acknowledged.

References

Beltestad, A.K. 1973. Feeding behavior and vertical migration in 0-group herring (*Clupea harengus L.*) in relation to light intensity. Cand. Real. thesis, University of Bergen. (In Norwegian.)

Blaxter, J.H.S., and R.S. Batty. 1984. The herring swimbladder: Loss and gain of gas. J. Mar. Biol. Assoc. U.K. 64:441-459.

Bodholt, H., H. Nes, and H. Solli. 1989. A new echo-sounder system. Int. Conf. Progress in Fisheries Acoustics, Lowestoft. Proc. I. O. A., St. Alban, U.K. 11(3):123-130.

Brede, R., F.H. Kristensen, H. Solli, and E. Ona. 1990. Target tracking with a split-beam echo sounder. Rapp. P.-V. Reun. Cons. Int. Explor. Mer 189:254-263.

Ehrenberg, J.E., and T.C. Torkelson. 1996. Application of dual-beam and split-beam target tracking in fisheries acoustics. ICES J. Mar. Sci. 53:329-334.

Foote, K.G. 1980. Averaging of fish target strength functions. J. Acoust. Soc. Am. 67(2):504-515.

Harden-Jones, F.R. 1968. Fish migration. The Camelot Press Ltd., London. 325 pp.

Haslett, R.W.G. 1977. Automatic plotting of polar diagrams of target strength of fish in roll, pitch and yaw. Rapp. P.-V. Reun. Cons. Int. Explor. Mer 170:74-82.

He, P., and C.S. Wardle. 1986. Tilting behavior of the Atlantic mackerel, *Scomber scombrus*, at low swimming speeds. J. Fish Biol. 29(Suppl. A):223-232.

Huse, I., and E. Ona. 1996. Tilt angle distribution and swimming speed of overwintering Norwegian spring spawning herring. ICES J. Mar. Sci. 53:863-873.

MacLennan, D.N. 1990. Acoustical measurement of fish abundance. J. Acoust. Soc. Am. 87:1-15.

Nakken, O., and K. Olsen. 1977. Target strength measurements of fish. Rapp. P.-V. Reun. Cons. Perm. Int. Explor. Mer 170:52-69.

Olsen, K. 1971. Orientation measurements of cod in Lofoten obtained from underwater photographs and their relation to target strength. ICES C.M.1971/B:17. 8 pp.

Ona, E. 1984. Tilt angle measurements on herring. ICES C.M. 1984/B:19.

Ona, E. 1990. Physiological factors causing natural variations in acoustic target strength of fish. J. Mar. Biol. Assoc. U.K. 70:107-27.

Ona, E. (ed.). 1999. Methodology for target strength measurements. ICES Coop. Res. Rep. No. 235. 59 pp.

Ona, E., and D. Hansen. 1991. Software for target tracking with split-beam echo sounders: User manual. Institute of Marine Research, Bergen, Norway.

Ona, E., X. Zhao, I. Svellingen, and K.G. Foote. 1996. Some pitfalls of short-range standard-target calibration. ICES C.M. 1996/B:36.

Ona, E., X. Zhao, I. Svellingen, and J.E. Fosseidengen. 2001b. Seasonal variations in herring target strength. In: F. Funk, J. Blackburn, D. Hay, A.J. Paul, R. Stephenson, R. Toresen, and D. Witherell (eds.), Herring: Expectations for a new millennium. University of Alaska Sea Grant, AK-SG-01-04. Fairbanks. (This volume.)

Zhao, X. 1996. Target strength of herring (*Clupea harengus* L.) measured by the split-beam tracking method. M. phil. thesis, University of Bergen, Norway.