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Hydroacoustic *ex situ* target strength measurements on juvenile cod (*Gadus morhua* L.)

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Most TS-measurements on fish have been carried out for 38 kHz, and the existing TS algorithm for 120 kHz on cod is based on measurements on stunned fish. The main objective of these experiments was to establish an empirical estimate of the relation between acoustic reflection (target strength, TS) and length of live juvenile cod (7–10 cm and 15–20 cm) at 120 kHz. This was done by recording the variation in TS of freely swimming cod tracking single fish targets for the two size groups within the acoustic beam field. The experiment was set up in an open air 2000 m^3 tank where the small 5–10 cm long fish were swimming freely during measurement in cages (1 × 1 × 3 m) within the acoustic beam under natural conditions in seawater with a salinity of 30 and a temperature of 11°C. An EY500 split-beam acoustic system was used to detect single fish passing through the acoustic beam field, which was video recorded in order to isolate the measurements on single targets and to get an indication of their angle. A mean target strength-to-size relation was calculated for small cod based on single fish tracks with total acoustic angles below 3.5° off axis in the beam field. This relationship is compared to other TS measurements on juvenile cod in literature. TS at 120 kHz for the investigated cod size range seems to decrease faster by length than the 20 logL relation used for larger cod. The results were used to check the expected range limits of TS for juvenile cod during survey, and are expected to be taken into consideration in density estimation of juvenile cod during acoustic surveys targeting young gadoids in general.

Key words: *ex situ* target strength (TS) detection, *ex situ* TS experimental design and setup, metamorphosed juvenile cod, single fish tracks, split-beam hydroacoustics, TS to size equation.

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Introduction

There is no well-established TS-to-size relation for 120 kHz for live, free swimming juvenile cod (*Gadus morhua*, L.). The established 38 and 120 kHz TS algorithms for gadoids and clupeoids are mainly based on measurements on larger specimens. The main objective of the present *ex situ* experiments was to make an empirical estimate of the relation between target strength and length of juvenile cod at 120 kHz and to estimate the variation in the single fish TS for live, free swimming fish under natural oceanic conditions by tracking single fish targets within the acoustic beam field. The EY500 120 kHz split-beam system used is the same as used in association with the hydroacoustic field studies related to cod recruitment mechanisms in the Central Baltic Sea under the EU AIR Baltic CORE programme which includes hydroacoustic young fish surveys directed towards juvenile cod (Nielsen *et al.*, 1997). The present study was started because it has so far been difficult to obtain sufficiently disperse single-species occurrences of juvenile cod in relevant size groups optimal for *in situ* single fish TS estimations during these surveys. The catches of small cod were almost always mixed with sprat and small herring (Nielsen *et al.*, 1997). The empirical TS estimate obtained here has been used to check if the TS-data obtained during the survey are within the expected range

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limits for juvenile cod. Moreover the estimates of the TS–length-relationship from this study are expected to be of interest in general in acoustic abundance estimations of gadoids such as those successfully being conducted for the cod in e.g. the Barents Sea (Godø *et al*., 1982; Hylen *et al*., 1986; Godø, 1989; Godø and Wespestad, 1993), even though *ex situ* TS values are never fully representative for those at sea.

Materials and methods

Choice of the *ex situ* method to measure juvenile cod TS

The basic TS (Target Strength) relation, where the target strength is expressed in decibels (dB) as the ratio of reflected acoustic intensity from a given target to the incident intensity, is given by:

$$TS = 10\ \log_{10}(\sigma/4\pi) = 10\ \log_{10}(I_1/I_0) \qquad (1)$$

where σ is the acoustic cross-section of the target, and I_1 and I_0 are the reflected and incident intensities (MacLKennan and Simmonds, 1992). As TS is used to convert area backscattering coefficient, Sa, to fish biomass, an accurate determination of TS is necessary. The methods used to estimate TS can be categorized as either *ex situ* or *in situ* and have been reviewed by MacLennan and Simmonds (1992) as well as Foote (1991). Most often the *ex situ* method has involved measuring TS of caged fish of known lengths and weights. In this way several biological and behavioural characteristics such as species, size class, tilt angle, directivity pattern, swimming speed, fish maturity, depth adaptation, and sometimes also swimbladder characteristics of the fish under study are known (e.g. Foote, 1987; Edwards *et al*., 1984). The tilt angles of fish in experiments should ideally reflect the tilt angles found at sea. However the method can have the disadvantage of constraining the fish and the cages may restrict swimming and natural behaviour, consequently affect tilt angle, which in turn will affect TS to an unknown degree (Nakken and Olsen, 1977). Because TS varies strongly with tilt angle it is necessary to take variations in tilt angle into account either by measuring it directly or, as here, to estimate a mean of the measured TS values for some period with varying swimming behaviour.

In spite of the risk of unnatural conditions influencing the *ex situ* method, this method was chosen in the present study because of the inherent problems in getting well-defined conditions when measuring *in situ*. Major problems are: unknown tilt angle in relation to vertical migrations (e.g. MacLennan and Simmonds, 1992; Arnold and Greer Walker, 1992; Clay and Castonguay, 1996), unknown changes in swimbladder shape because of compression or decompression and unknown changes in tilt angle when a fish is not neutrally buoyant because it has changed depth quickly during vertical migration (Arnold and Greer Walker, 1992; Clay and Castonguay, 1996), unknown fishing-gear selection effects (e.g. Engås, 1991; Godø, 1990; Godø and Wespestad, 1993; Fernø and Olsen, 1994; MacLennan, 1992; MacLennan and Simmonds, 1992; Clay and Castonguay, 1996; MacLennan and Menz, 1996), no possibility of matching specific single fish echoes with corresponding single fish in the catch by length because juvenile fish in nature seldom occur in unimodal patches (MacLennan and Simmonds, 1992; MacLennan and Menz, 1996) and, finally, the risk of detecting multiple targets as single fish targets which is especially a problem for schooling fish (e.g. MacLennan and Menz, 1996; Rose, 1992; Wardle, 1983).

Choice of echosounder frequency in the experiments

Since measurements of this kind are performed on swimbladder fish it is expected that the targets resemble gas bubbles (Foote, 1980). For gas bubbles there is one resonance near the high-frequency limit of the Rayleigh scattering region (MacLennan and Simmonds, 1992, p. 31). A frequency of 120 kHz ($\lambda = 1.25$ cm) has been used in the present study ($L/\lambda \gg 1$), as well as during survey in the Baltic Sea, in an attempt to obtain linearity in the TS–size relations for juvenile cod, i.e. to minimize possible problems with the TS relationship caused by measuring in the Rayleigh region or in the resonance region of the bubble response curve. At intermediate sizes of the order of a wavelength where the dimensions of the physical (target) cross-section and the wavelength are similar, L/λ approaching 1, the scattered intensity increases rapidly to a peak at the resonance frequency of the bubble. At higher frequencies in the geometric region the frequency dependence of scattering strength of the gas bubble is small. Foote's (1987) TS relation for 38 kHz is valid for larger cod where the swimbladder size/wavelength relationship ($=L/\lambda$) is high ($\gg 1$). However this is not necessarily the case for small cod where the L/λ relationship is around or below 1. At 38 kHz λ is about 4 cm in sea water. When L/λ lies around 1 resonance might occur giving too large TS values for small cod. For L/λ smaller than 1 the acoustic cross-section area may decrease faster than the physical (target) cross-section area.

The maximum depth in the part of the central Baltic Sea where the field measurements on juvenile cod were performed does not exceed 100 m, and juvenile cod (<10–20 cm) has only been found in depths down to 90 m here (Nielsen *et al*., 1997). Furthermore the absorption of sound in the Baltic brackish water is significantly lower than for oceanic water. Consequently the 120 kHz echosounder can cover the whole water

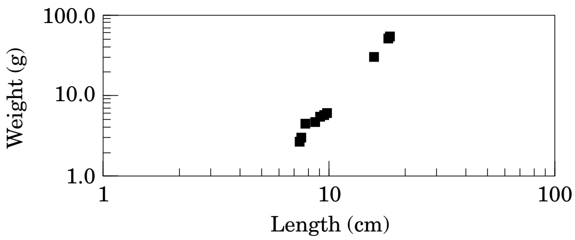

Figure 1. Size of the juvenile cod used in the experiments. Total length (mm) vs. wet weight (g) are shown on logarithmic scales.

column where juvenile cod occur in the survey area within its maximum reach.

Experimental facilities and materials

The *ex situ* measurements of TS on live juvenile cod were conducted in the period 2–11 October 1996. Measurements were made on two size groups of juvenile cod: one group consisting of seven 0-group cod of size 75–98 mm TTL (Total Tail Length) and another group consisting of three larger cod of size 159–188 mm TTL, respectively (Fig. 1). The cod used in the experiment were wild Skagerrak cod (ICES Subdivision IIIa) caught nearshore with beach seines in late September 1996. Because of relatively low sea temperatures in the summer of 1996, a consequence of the cold winter and spring, it was not possible to catch juvenile cod in suitable size groups nearshore until September. The experiments were conducted in a 2000 m^3, open air, concrete tank with a depth of 5 m and a diameter of approximately 22 m which is located at the North Sea Centre, Denmark. During the experiments concurrent TS measurements and video filming of the target volumes were performed in a net cage set up in the tank for several hours in daylight conditions each experimental day. The approach in the experimental design and set-up was to allow the fish to swim freely with some degree of natural schooling behaviour under natural physical conditions, and at the same time minimize acoustic reflections from the concrete tank walls, bottom, and centre pillar, as well as reflections from or signal reduction by the experimental set-up itself, especially the net cages and their attachments.

Experimental design and set-up in the experimental tank

The experimental set-up is outlined in Figure 2. On top of the tank is a bridge connecting the centre pillar with the tank sides. The bridge can be rotated all around the tank perimeter. On the bridge the transducer and video camera were mounted on special rigs that allowed the equipment to be placed at any suitable position in the water volume outside the net cages.

Three specially constructed net cages two of which are rectangular (1 m high × 1 m wide × 3 m long) and one trapeze shaped (the same dimensions as the rectangular cages but diminished by 5 cm on one vertical side) were made for the experiments. Three sides of the cages consisted of stiff monofilament polyethylene net with mesh size 2 mm and the fourth side was a transparent polyethylene window. Each end of the cages was stretched out by four polyethylene ribs 1 cm in diameter. Only one cage at a time was used in the experiment. The cage was held up and stretched out by 1.0 mm monofilament nylon lines, styrofoam floats, and sinkers on the cage, and anchors along the edge of the tank (Fig. 2). This system made it possible to manoeuvre and place the cage in whatever position and depth was needed to obtain optimal target reflection conditions and to minimize unwanted reflections. By hoisting the anchors the net cage could be taken to the surface to facilitate fish release and fish capture in the cage between the experiments. During an experiment the net cage was placed centrally between the centre pillar and the tank wall and typically in the middle of the vertical water column with its bottom 1–2 m above the tank bottom. The experiments were monitored and controlled from a small dry laboratory with a large (1.5 × 0.5 m) observation window into the tank.

Set-up of the echosounder system

The TS measurements were conducted with a portable SIMRAD EY500 120 kHz split-beam echosounder system with version 5.0 software (SIMRAD, 1996a). The transceiver in the dry lab was connected to an ES120-7 split-beam type with a 3 dB nominal beamwidth of 7° on the rig (Fig. 2).

The echosounder system was calibrated in the tank using the standard target method (Foote *et al.*, 1986; Degnbol, 1988; Degnbol *et al.*, 1990) with a 30.5 mm diameter copper sphere under conditions similar to the experimental conditions. The target distance was approximately 2.5–3.0 m. Echosounder settings during experiments and calibration were the following: ping interval ∼8 pings s^{-1}, TVG 40 logR, pulse length medium (0.3 ms), bandwidth wide, absorption coefficient 0.038 dB m^{-1}, two-way beam angle (directivity) −20.4 dB. The resulting calibration values from the Simrad LOBE calibration program were: TS transducer gain 27.1 dB, 3 dB beamwidth of 6.4° and 6.3° (T=19°) for alongships and athwartships directions, respectively, alongships offset 0.09°, athwartships offset −0.32°. Other parameter settings for the EY500 system during experiments were the following: minimum value for TS-detection −60 dB, minimum echo length 0.8, maximum echo length 1.5, maximum gain compensation 4.0 dB, maximum phase deviation 4.0.

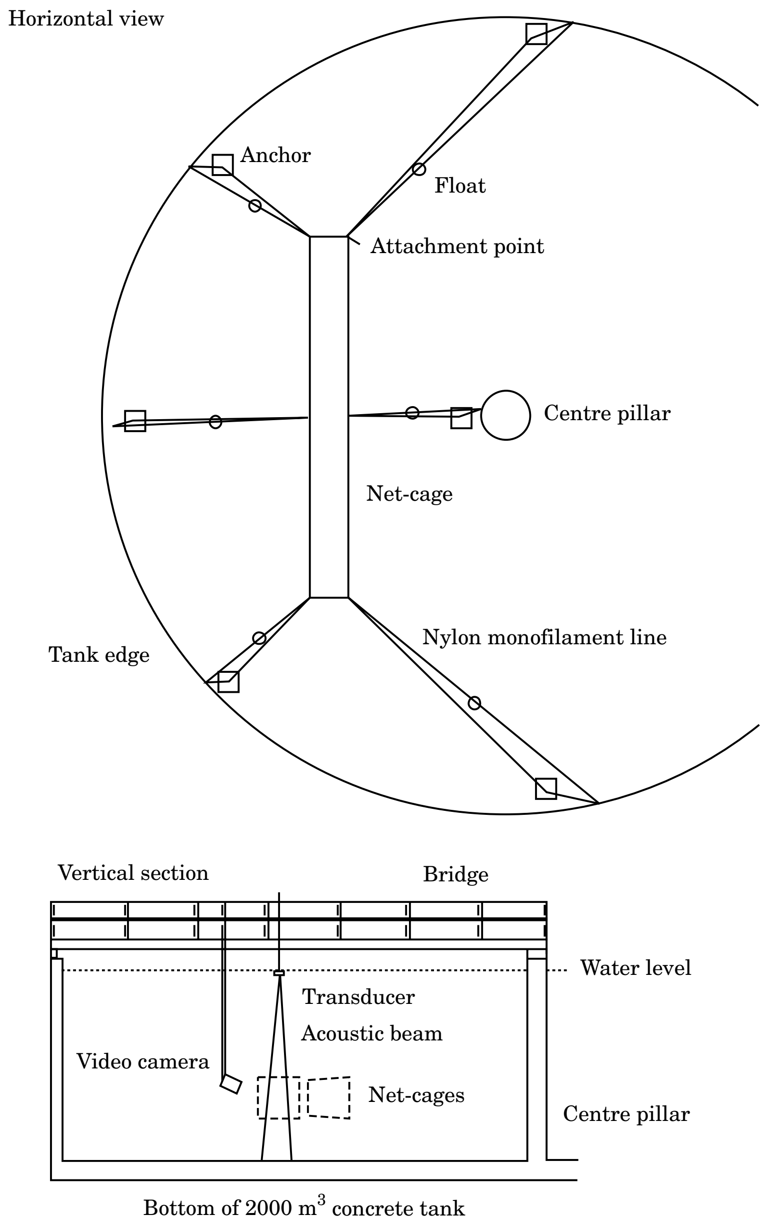

Figure 2. Schematic overview of the experimental set-up in the 2000 m^3 concrete tank.

The selection of minimum TS-thresholds on −60 dB was based on several replays in the EY500 software, as raw data had been sampled, where also lower levels of minimum TS thresholds were tested (−65 dB and −70 dB). No measurements in any of the tracks in any of these runs for the smaller group of juvenile cod showed lower TS values than −59 dB found for the smaller group of cod, and the TS variation in the single tracks did not change. This threshold also avoided noise from plankton organisms which also could be tracked when using a lower minimum threshold. The TS measurements were made using medium pulse length and wide bandwidth related to the small depth and the narrow range over which the measurements have been performed. With short pulse length the data would have had a better depth resolution, but this would have resulted in only few samples over depth resulting in badly defined mean angles and single echo selections (Soule *et al.*, 1997). A long pulse length would be of the same magnitude as the cage height and, consequently, would not be optimal.

With the above transducer parameters, and a typical placement of the cage-top at 2.2 m below the transducer, the beam is about 25 cm wide at the top of the cage and about 35 cm at its bottom, well below the width of the cage. The range of the sampling layer was 0.7 m with a range starting between 2.6 and 2.8 m. The distance of target measurement was between 2.79 and 3.21 m (Table 1) which was outside the near-beam field of the transducer, and assured that possible risks of interference effects were insignificant. The active diameter of the ES120-7 transducer is 107 mm. The near field range of the transducer is d^2/λ, where λ is 1500/120 = 12.5 mm (= sound speed in water/frequency), and consequently $107^2/12.5 = 916$ mm. SIMRAD specifies a distance of twice the near-field range as the critical working range, i.e. 1.83 m. Thus, the present measurements are made well within the far field of the transducer (H. Bodholt, SIMRAD, Norway, pers. comm.). The calibration of the transducer showed no obvious problems with variability in TS of the copper sphere.

In the experiment the magnitude of the reflection noise (ringing) from the tank wall, bottom, and centre pillar, and also acoustic reflection noise from the experimental set-up (cages, anchors, weights, floaters, monofilament lines, etc.) were checked. Most of this type of noise was at least 20 dB below the echo levels of the targets of interest when the ping rate was kept below 8 pings s^{-1}. The signal level of the reflections from the top of the net cage was of the same order of magnitude as the fish echoes. The acoustic damping by the upper side of the net cage was checked by lowering a spherical target through a small hole in the upper side of the cage and was found to be less than 0.3 dB. Only the reflection from the vertical cage sides could disturb the measurements but accurate positioning of the acoustic transducer avoided these reflections so only echoes from the top and bottom were visible. To remove gas bubbles both the upper side of the net cage and the transducer surface were treated with dilute soap solution before each experiment and checked regularly.

Setup of the video recording system

In order to make it possible to monitor the number of fish in the acoustic beam, and to have some indication of their swimming direction and body tilt, a video recording system (ROS Nuclear Products Division) was used. The position of the camera in the experimental setup is shown in Figure 2. The system includes an underwater, environmental colour TV camera unit with a 6-to-1 zoom lens and with a complete remote control of pan and tilt, zoom, focus, and iris. The video monitor connected to the recorder and the camera makes it possible to view the images while both recording and replaying. A PC was connected by a special interface to the remote control connector of the video recorder in order to acquire the tape counter data as a function of time for synchronization with the acoustic data.

Progress and sequence of tank experiments

Immediately before the experimental period the wild juvenile cod were transferred to an open, fish-holding jar system. They were kept in a flow of Skagerrak sea water for some days so that they became acclimatized to tank conditions (t = 11°C; S = 30). The cod swimbladders were pressure adapted as the cod were caught in shallow water. Each size group of cod was transferred to the experimental set-up in turn to make separate TS measurements on each group. In order to minimize the effects of algae blooms the tank was cleaned and filled directly to a depth of 5 m with fresh Skagerrak seawater filtered through a natural sand filter just before the start of the experiments. The hydrographic conditions in the tank stayed reasonably constant during the experimental period with no thermo- or haloclines present. Only data from 3 and 10 October are included in the analyses, both being 1 day after tank refill.

Data analysis methods and data-selective criteria

For logistic reasons the echosounder was calibrated after the measurements. Acoustic raw data was replayed in the EY500 software with optimal parameter settings and the new calibration constants. The maximum allowable phase deviation was set to 4.0 and maximum allowable amplitude compensation was set to 4 dB for the echo-tracing routine in the EY500 system. The replayed data were then analysed by performing trace tracking of single fish echoes in selected layers and obtaining mean TS-values for the tracks. Tracking was performed to ensure that the mean value is calculated on the same fish in each case. The identification of tracks was performed with the EP500 software (SIMRAD, 1996b) and echo-trace data was extracted by software developed by the authors and scrutinized to include all consecutive pings actually occurring in a track. The tracks were defined as consisting of at least five consecutive pings on targets within a maximum mutual distance of 30 cm between successive target positions. Other selective criteria for data acceptance were:

- When a fish had not been within the centre of the beam field (inside a maximum total beam angle of 1.5° off axis of the acoustic beam – see below) in a track the data were rejected.
- Only measurements located within 3.5° off axis of the acoustic beam based on the calibration measurements have been included.

This means that the fish should have entered both the centre and, of course, also the periphery of the beam for data acceptance. A relatively wide margin, usually

Table 1. Mean TS, velocity (average swimming speed), depth of measurement, and number of track pings and of single fish targets as well as variation (Coeff. Var.) in backscattering cross-section and uncertainty in velocity. Also minimum and maximum TS per track, for each track is given. Comments of visually estimated tilt angle or swimming behaviour observed on the video recordings are furthermore given for each track. The tracks are subdivided by size group of juvenile cod, i.e. by date of measurement.

Date and size group	Track no.	Velocity (ms^{-1})	Uncertainty (of Vel. in %)	Target distance from transducer (m)	Pings (number)	Record duration (s)	Mean TS (dB)	CV (of bs. cross-sect.)	Min TS (dB)	Max TS (dB)	Comments and visually estimated tilt angle based on video recordings
3 Oct. 1996 Large size group cod	1	0.099	5.3	3.15–3.21	22	2.8	− 40.1	22.2	− 41.2	− 37.7	Swims straightly (largest fish).
	3	0.050	90.1	3.06–3.06	5	0.6	− 41.2	45.8	− 43.4	− 38.8	Swims straightly.
	5	0.165	4.1	3.00–3.09	21	2.6	− 44.5	40.7	− 45.7	− 40.9	Swims straightly to slightly downwards (medium sized fish).
	6	0.085	20.2	3.15–3.15	10	1.3	− 44.9	103.9	− 57.1	− 39.4	Swims straightly first and then downwards (medium sized fish).
	7	0.338	11.3	3.15–3.15	6	0.8	− 41.5	40.9	− 46.7	− 40.4	Swims straightly.
	8	0.152	5.3	3.06–3.15	17	2.1	− 46.5	25.0	− 49.9	− 45.3	Swims tilted.
	9	0.210	18.3	2.79–2.85	6	0.8	− 39.1	10.2	− 39.6	− 38.6	Swims straightly (largest fish).
	10	0.203	16.7	3.03–3.06	6	0.8	− 44.4	94.7	− 50.3	− 40.2	Swims slightly tilted.
	11	0.116	9.4	3.00–3.03	13	1.6	− 43.7	38.9	− 49.8	− 42.0	Swims slightly tilted.
	12	0.121	2.7	3.09–3.18	36	4.5	− 41.4	55.7	− 47.6	− 37.0	Swims slightly tilted.
10 Oct. 1996 Small size group cod	1	0.159	5.0	2.82–2.82	17	2.1	− 51.1	35.7	− 54.9	− 48.9	(Camera not directed correctly).
	2	0.176	10.1	3.00–3.00	10	1.3	− 51.6	17.5	− 52.5	− 50.4	Swims first slightly tilted and then straightly.
	3	0.416	11.3	2.91–2.91	5	0.6	− 57.5	20.7	− 58.7	− 56.4	Swims straightly.
	4	0.102	3.0	2.85–2.91	38	4.8	− 54.5	93.4	− 55.6	− 44.8	Swims straightly.
	5	0.407	7.0	2.91–2.97	6	0.8	− 47.0	34.5	− 49.2	− 45.1	Dives steeply.
	6	0.102	4.3	2.91–2.94	30	3.8	− 51.9	62.8	− 56.6	− 48.9	Swims slowly straight forwards.
	7	0.080	6.4	2.82–2.85	18	2.3	− 56.6	17.1	− 57.6	− 55.0	Rising slightly.
	8	0.131	13.0	2.91–2.91	10	1.3	− 57.0	34.6	− 58.3	− 54.6	Swims straightly.
	9	0.066	23.5	2.91–2.91	10	1.3	− 47.1	20.3	− 48.8	− 45.7	Same fish diving steeply.
	10	0.138	7.6	2.85–2.91	13	1.6	− 51.8	18.1	− 53.5	− 50.4	Swims straightly.
	11	0.126	5.5	2.94–2.97	19	2.4	− 52.7	32.9	− 59.1	− 50.8	Swims first straightly then slightly downwards
	12	0.145	22.4	2.82–2.85	6	0.8	− 58.1	17.3	− 59.0	− 57.1	Swims straightly.
	13	0.129	10.0	2.94–2.94	10	1.3	− 58.5	13.3	− 59.8	− 57.5	Swims straightly.
	14	0.093	4.3	2.82–2.94	32	4.0	− 53.8	37.6	− 59.6	− 50.2	Swims straightly.
	15	0.091	6.1	2.94–2.94	23	2.9	− 57.7	38.4	− 59.5	− 54.8	Swims straightly.

within a distance of 20 cm, from the cage top and bottom were excluded from the analysis field in order to avoid possible interfering echoes. Multiple targets were to a large extent excluded from the analyses by the tracing routines but furthermore by examination of the concurrent video recordings. Consequently when there were more than one fish, or even the smallest risk of there being more than one, in the acoustic beam, the data were rejected.

Two software programs were developed for synchronization: one creates a file table with tape count from the video recorder vs. time in seconds. The other reads the EY500 files and creates a pingnumber vs. time table which is useful when searching for particular events during trace tracking.

Besides estimating mean TS values for the investigated fish, a principal objective of the experiment was to look at the variation in TS for a single fish in relation to its position (angle) in the acoustic beam field and its swimming speed when performing natural swimming behaviour. From the athwartships (α) and alongships (β) angles of the target in the beam field the total angle off axis (θ) in degrees from the acoustic axis can be calculated as follows:

$$\theta = \sqrt{(\alpha^2 + \beta^2)} \quad (2)$$

The mean TS for each track was calculated from the mean backscattering cross-section obtained by averaging the backscattering cross-section values for each ping measured along the track. The average swimming speed (v) was obtained by:

$$\bar{V} = \bar{d} * \Delta\theta / \Delta t \quad (3)$$

where $\Delta\theta$ is the total smoothed track length in radians and $\bar{d}$ is mean depth and Δt is total track time interval. Smoothing has been performed by averaging the length of sub-tracks which are formed by using every second ping along the track.

Results

The TS measurements for each single fish track for the juvenile cod in the small (seven individuals) and large (three individuals) size groups, respectively, are shown in Table 1. Figure 3 shows in detail four examples of single fish tracks for juvenile cod in both size groups measured over a relatively large number of pings. Single ping target measurements for all the pings in selected single fish tracks are presented. In total 15 tracks for the small size group and 10 tracks for the larger size group of juvenile cod were recognized which fulfil the above given selective criteria (Table 1; Fig. 3). Although experiments were performed over some days these selective criteria, together with the use of a low ping rate to avoid reflection noise from the experimental set-up, resulted in limited data sampling and only a few usable data series to be analysed. Long stretches of data were rejected. The low number of measurements increases the variance for the mean TS due to the combined effect of tilt and directivity and weakens the TS–length-regression (Table 1). However the selected data with single ping TS measurements of one individual fish among the group of fish, within a limited size range, must, because of these selective criteria, be classified as well filtered and of relatively high quality. Longer data time series would either have prevented free swimming behaviour, e.g. the fish would have been "fixed", or the experiments should have run over months instead of days and weeks. The latter was impossible given the use of wild animals of particular size groups which had to be kept alive in natural conditions apart from the practical difficulties of preventing the stock growth outside the size range needed.

The variation in the TS measurements is calculated as the coefficient of variation (CV) of the acoustic backscattering cross-section (Table 1). The uncertainty in the target velocity is determined partly by the uncertainty in the determination of the angles of the target in both track end points, i.e. the angular deviations around the end pings. Furthermore, the uncertainty i.e. 2* angular deviations around the end pings/total track length in angular units (Table 1), is, of course, dependent on the number of pings (observations) in each track which give the track length.

For the smaller juvenile 0-group cod single ping TS values in the range of − 59.8 to − 44.8 dB were measured. However, in general the highest single ping TS measurements for this size class are around − 46 dB (Table 1; Fig. 4). For the 15 tracks found for this cod size group the mean TS value varied from − 58.5 to − 47.0 dB (Table 1). For the larger juvenile cod single ping TS values from − 57.1 to − 37.0 dB were measured as the extremes but most values lie within the range − 48 to − 46 dB in the lower end to a level around − 37 to − 36 dB in the higher end (Table 1; Fig. 5). For the 10 tracks found for this size class the mean TS values range from − 46.5 to − 39.1 dB (Table 1).

In order to illustrate the variations occurring within and between the tracks Figures 4 and 5 present selected single fish tracks in which the fish can be followed both near the centre and close to the edge of the beam field. Figure 4 shows data for the group of larger cod and Figure 5 for the group of smaller fish. In general along most of the tracks the TS value varies moderately with the position of the fish in the beam field, but there are occasionally sudden or gradual large excursions of the TS value. The total variation of the TS values within each size group cannot be explained by a $20 * \log_{10} L$ relationship but may be due to either variations in tilt angle or sound incidence angle in relation to the

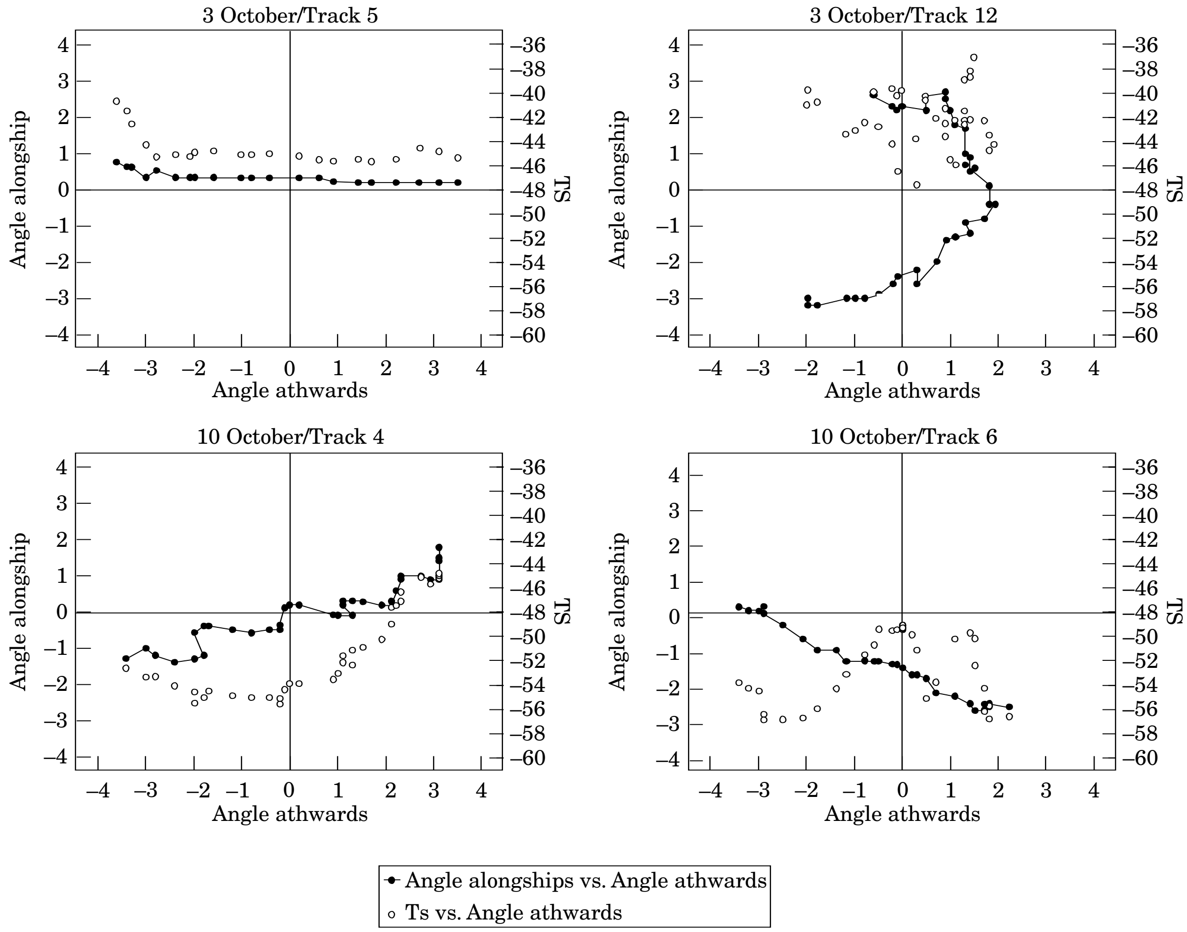

Figure 3. Plots of four examples of single fish tracks (tracks 5 and 12 from 3 October and 4 and 6 from 10 October) for juvenile cod in both the small and the large size group circulating around the centre of the beam field. These track data fulfil the criteria of at least five consecutive pings in the same track and only one fish in the beam. The plots show single ping angle alongships vs. angle athwards (in degrees) of the targets in the beam (filled circles), as well as single ping TS values vs. angle athwards (open circle) for each track.

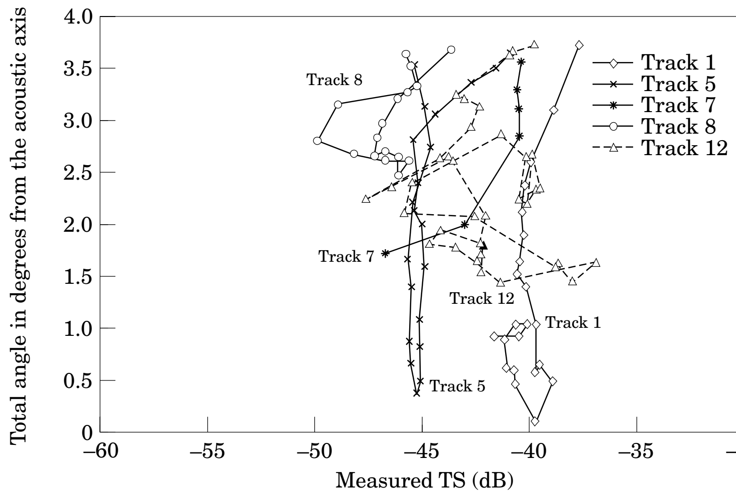

Figure 4. TS vs. total angle (degrees) for a selection of the observed single fish tracks where individuals from the large size group of juvenile cod (3 October) could be followed both in the edge and in the centre of the beam field.

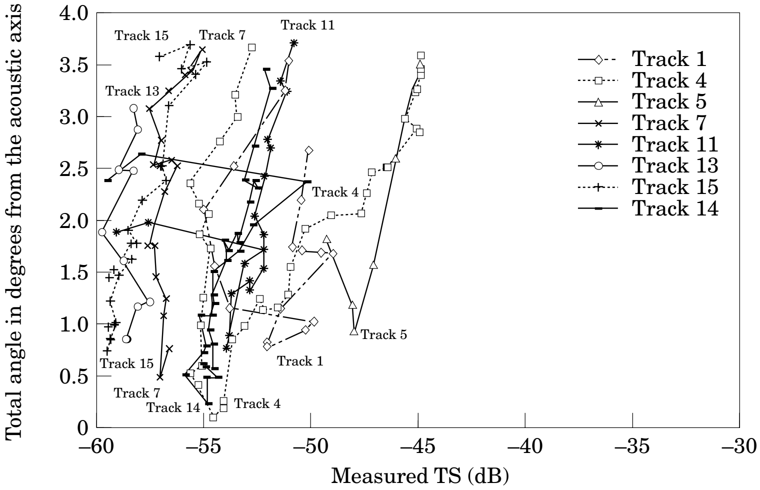

Figure 5. TS vs. total angle (degrees) for a selection of the observed single fish tracks where individuals from the small size group of juvenile cod (10 October) could be followed both in the edge and in the centre of the beam field.

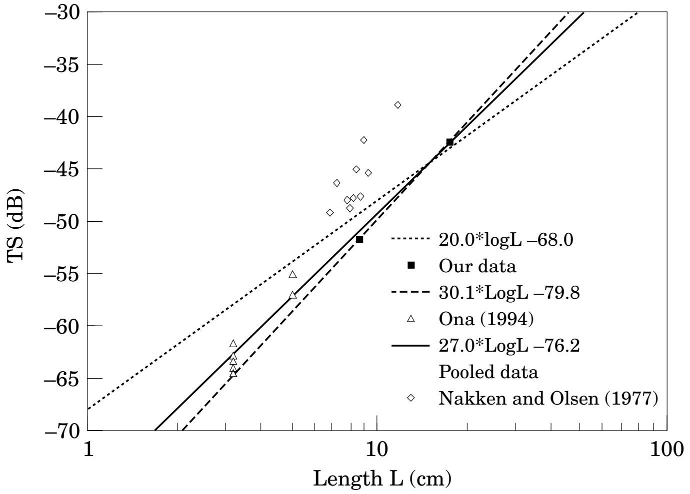

Figure 6. Plot of mean TS vs. $\log_{10}(L)$ for the two investigated groups of free swimming, juvenile cod at 120 kHz in the present study (filled squares), and the regression line (dashed) through these data. For comparison mean TS data at 120 kHz on juvenile cod measured by Ona (1994) (triangles) are shown as well as a regression line (solid) obtained by pooling our data with Ona's data. Finally data from the lower end of Nakken and Olsen (1977) plot of TS values at 120 kHz for stunned and fixed as well as anaesthetized cod are plotted (diamonds). The stippled line shows the standard TS-size relation suggested by Foote (1987).

directivity pattern of the fish, or swimbladder shape between individuals. For some tracks there might be a slight tendency towards an increase of the TS value with increasing total angle in the group of small cod. This tendency is not systematic for all tracks however and is discussed later.

When comparing the tracks for the two size groups of juvenile cod it is clear that the TS values in general are, as expected, significantly larger for the group of larger cod but the difference seems to be larger than could be explained by a $20 * \log_{10}L$ relationship. Since the number of tracks is low and it is not possible to relate the single tracks to a particular individual fish among the cod in the groups, and because not all fish within each size group necessarily are equally represented in selected tracks, the mean TS values for the two groups may be biased. However in order to illustrate the tendency Figure 6 shows the mean TS values for the two size groups under study plotted vs. the $\log_{10}$ (mean length). Mean TS is calculated as:

$$\text{mean TS} = 10 * \log_{10}(1/n\Sigma 10^{0.1 * TS_n}) \quad (4)$$

where TS_n represents the mean TS values for the separate tracks shown in Figures 4 and 5. The equation for the connecting line between the two size groups in Figure 6 is:

$$TS = 30 \log_{10}(L) - 80 \quad (5)$$

When pooling the present data with the results obtained by Ona (1994) at 120 kHz on juvenile cod the following TS relation is obtained:

$$TS = 27 \log_{10}(L) - 76 \quad (6)$$

Thus these results indicate a significantly steeper slope in the relationship between TS and fish length for juvenile cod than the traditionally assumed $20 \log_{10}L$ relationship.

Discussion

TS measurements on Atlantic cod

In reviewing TS studies of gadoids at 38 kHz Foote (1987) found that, when *in situ* measurements are not available, mean TS can approximately be estimated from:

$$TS = 20 \log_{10}L - 67.5 \quad (7)$$

where L is the mean body length (cm) of the fish (MacLennan and Simmonds, 1992). However this TS algorithm for 38 kHz is based on measurements only on larger cod.

Nakken and Olsen (1977) performed *ex situ* experiments making TS measurements on, among other species, both smaller and larger cod using 38 and 120 kHz frequencies. They found mean TS values between − 47 and − 40 dB (38 kHz) and − 49 and − 38 dB (120 kHz) for 12 small cod between 6 and 13 cm. In order to obtain these measurements though each subject fish was anaesthetized and fixed in the acoustic field (beam) by two strings. This, of course, prevented the free swimming of the fish which we have tried to ensure in the present study. Nakken and Olsen (1977) found a variability in TS from below − 45 dB to more than − 27 dB for the same cod (45 cm) measured at 120 kHz according to different tilt angles. As TS varies with swimbladder shape and this is regulated physiologically by the animal meeting different surrounding conditions, i.e. pressure variation related to depth and hydrography, and furthermore, the TS is dependent on the fish's natural behaviour, these TS measurements might be biased or uncertain because they are not made in a natural environment. This should be seen in light of Foote's (1980) estimate that the swimbladder is responsible for approximately 90% of the energy reflected from a fish with a swimbladder. Nakken and Olsen (1977) summarized their measurements on cod with the regression lines: $TS = 24.6 \log_{10}L - 66.6$ at 38 kHz and $TS = 24.6 \log_{10}L - 67.6$ at 120 kHz. However, the TS values measured for small, juvenile cod in these results deviate from the overall TS algorithm (regression line) for the data set covering all size groups of cod.

Ona (1994) performed *in situ* target strength measurements at 120 kHz with an ES120-7 transducer on reared juvenile cod in the size class 3–8 cm TTL (mean length 5.1 cm), and at 38 and 120 kHz on naturally living juvenile cod in the length group 2–6 cm TTL (mean length 3.1 cm) caught at sea. The measurements on the reared cod were performed within varying depth ranges, i.e. 2–7 m in the pond, and 0–45 m at sea with highest concentrations of juveniles around 15–25 m, respectively, from surface. A mean TS of − 55.1 dB (range − 66 to − 48 dB) during evening and of − 57.1 dB (range − 69 to − 48 dB) during night-time were estimated for the reared juvenile cod at 120 kHz. For the naturally occurring cod a mean TS of approximately − 60 dB was calculated based on a selective acceptance of targets only within the mean TS range from − 58.2 to − 60.4 dB – the total measured TS range at 38 kHz at the locality was − 78 to − 47 dB. Based on this study the following working TS equation for juvenile cod at 38 kHz was calculated assuming a $20 \log_{10}L$ relationship: $TS = 20 \log_{10}L - 70$ [dB], (L = 3–10 cm). Comparative TS measurements on the naturally living juvenile cod at 38 and 120 kHz indicated a mean TS about 2–3 dB lower at 120 kHz than at 38 kHz. No TS algorithm related to length for juvenile cod at 120 kHz was given here. The problem of the swimbladder-frequency response (L/λ-relationship) as previously described might be the reason why Ona (1994) had lower values of TS at 120 kHz than expected from the standard relation for the larger cod at 38 kHz.

The single ping measurements at 120 kHz in the present study on juvenile cod within the size range 75 to 98 mm lies within the TS range from − 59.8 to − 44.8 dB. Furthermore, the TS measurements on larger juvenile cod within the size range − 57.1 to − 37 dB. Thus the variability in the present TS measurements according to fish size is actually lower than the variability in TS found in the previously performed and comparable studies on juvenile cod. The large difference obtained between 120 kHz mean TS-values for larger cod from literature and the group of smaller cod obtained in the present experiment suggests that TS for small cod decreases much faster than has been suggested by the standard $20 \log_{10}L$ relationship. This seems to agree with the tendency in Ona's (1994) data which indicates that a mean length ratio of 5.06/3.14

corresponds to a decrease of about $(-56)-(-63)=7$ dB instead of about 4 dB decrease as suggested by the standard relationship. A similar tendency is indicated by the data in Nakken and Olsen (1977), where all the data points in the lowest end lie to the left of the 120 kHz regression line. Assuming a $20 \log_{10}L$ relationship as used by Ona (1994) at 38 kHz [or a $24.6 \log_{10}L$ relation as fitted by Nakken and Olsen (1977) at 120 kHz] when measuring juvenile cod in the field on surveys then the abundance of the smaller size groups of cod will be grossly underestimated if a $30 \log_{10}L$ or a $27 \log_{10}L$ relationship is actually valid. However even though measuring at 120 kHz the problem of the swimbladder–frequency response (L/λ-relationship) cannot totally be excluded in this present study too.

The variation in TS reflects mainly variation in tilt angle of the fish, directivity of the fish itself and the behaviour of the fish. In relation to the directivity diagram of the fish the change in TS of the fish is caused by the gradual change of the sound incidence angle in relation to the location of the fish in the beam field when the fish passes (e.g. directly) through the beam (at e.g. one defined tilt angle). These factors influence the present results significantly without a doubt. A possible effect of an increase in TS of 2–3 dB as the fish moves from axis towards the border of the beam should be noted but is not found in all tracks of the smallest group of juvenile cod (Fig. 5). It is not seen, for example, in tracks 1, 13, and 14, i.e. in three out of the eight tracks for the small juvenile cod group. Attention should, of course, be paid to a possible trend here in relation to calibration but because it is not unambiguous care has to be taken in drawing conclusions from it.

The measured range of TS values for each size group of juvenile cod covers a variety of fish tilt angles and fish directivity diagrams as well as the different swimming behaviour to be expected from wild juvenile cod. The experimental cod did not show stress behaviour or significant escape behaviour during the experiments. The present data do not allow for calculation of an accurate TS relation in interpreting hydroacoustic survey results for exact biomass estimates but give a good indication of the expected range in TS for young gadoids. It should be noted that the results in this experiment were obtained in water with higher density than found in the Baltic Sea survey area. However the results give an impression of the order of magnitude of the underestimation of biomass if the standard gadoid TS algorithm is extrapolated to small size groups. The results lie within the expected range of TS values for these fish performing natural swimming behaviour and is in the same range as those presented by Ona (1994) and also in Nakken and Olsen (1977). In the present *ex situ* experiments the salinity was 30. While Baltic juvenile cod typically occur in salinities of maximum 20. This is a problem when using the present TS measurements for Baltic juvenile cod as the target strength of a fish also depends on the swimbladder morphology, which may change with seawater salinity as the fish seeks to establish neutral buoyancy. This salinity difference may cause the swimbladder volume to be slightly larger for cod in the Baltic than in the North Sea or elsewhere.

Experimental design, set-up, and *ex situ* method

The experimental design and set-up has proved to be suitable and efficient for making *ex situ* TS measurements on juvenile gadoid fish swimming freely in the acoustic beam under natural physical conditions. The experimental set-up with 3 m^3 cages may not reflect natural swimming behaviour even though the experimental fish were small juveniles for which 3 m^3 is a relatively large volume. The juvenile cod have, furthermore, been kept in groups of at least three fish in order to assure some degree of natural schooling behaviour and active swimming behaviour all over the cage. When working with a single cod in the experimental set-up pilot investigations showed that fish stayed permanently inactive in one corner of the cage or on odd occasions, swim very close to the cage bottom. The video recordings ensured that we were only measuring TS for one fish at a time in the acoustic beam. The experimental design also made it possible to calibrate easily the echosounder system in the experimental environment within the actual range of the beam where the TS measurements took place.

Suggestions for future studies

TS measurements in this experiment could only be related to single fish of known size in very few cases even though there were very few fish in each size group in the cage during each experimental series. The measured TS values are consequently only average estimates for each size group of fish with a variety of tilt angles performing nearly natural swimming behaviour. Future experiments could use all or some of the following in combination:

(1) more (two or three) video cameras in the set-up to make it possible not only to detect the presence of single fish but also to be able to estimate the exact position and tilt angle of a fish in the acoustic beam. This would require a more advanced synchronization system between video recording and acoustic data sampling than was used in these experiments;

(2) groups of fish each with a colour tag or with coding in order to visually identify and register single fish with known length and weight in the beam field from the video monitoring;

(3) smaller cages with only 1 fish in each, in order to obtain data for the exact TS range in tracks for individual fish of known size, combined with tilt angle measurements from video recordings with more than one video camera;
(4) round cages containing a known number of fish with a known length frequency distribution, to measure the mean TS for a group of fish within a given well defined size group. In this case the measurements would be based on knowing the exact number of fish in the cage and knowing the cage volume and based on the assumption that the fish on the average is randomly distributed in the cage. This could be tested by video recording.

The frequency of 120 kHz is far above the known hearing frequency range of juvenile cod and therefore avoidance behaviour related to the beam field is not expected. A study at 38 kHz (Astrup and Møhl, 1993) indicates that cod possibly do not detect high-intensity, high-frequency sound. Future studies could include investigations of avoidance reactions via video recording, for example, abrupt changes in swimming speed, swimming direction, or tilt angle, when entering the beam field. Finally future experiments could count the frequency of fish entering the beam field or estimate the density of fish in the beam when the transducer is switched on compared to when the transducer is switched off, all other conditions being equal. This would give a quantitative estimate of avoidance even when there is more than one fish in the cage.

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